# International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI)

**Presents**

A George P.L. Walker symposium
on Advances in Volcanology
Reykholt, Borgarfjordur, W-Iceland
12–17 June 2006

Abstrats and program

George P.L. Walker

# Program for Walker meeting.

| Conveners: | S. Self | | Th. Thordarsson | | | RSJ. Sparks | | A. Hoskuldsson | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Time | 12 June | | 13 June | | 14 June | 15 June | | 16 June | | 17 june |
| 08:00 | Drive from Reykjavik to Reykholt | | | | Field trip to Snæfellsnes volcancic peninsula. Guides Haraldur Sigurdsson and Haukur Johannesson | | | | | Trip from Reykholt to Reykjavik via Husafell ignimbrite and Kaldidalur/Thingvellir. Guides Gretar Ivarsson, Kristjan Sæmundsson |
| 08:30 Keynote | | | Calderas (2.1) | P. Lipman | | Expl. Volc. (3.1) | L. Wilson | Dikes (4.1) | A. Gudmundsson | |
| 09:00 | | | | *Bacon* | | | *Sparks* | | *Menand* | |
| 09:15 | | | | *Brum-Silveira* | | | *Salemo* | | *Canon-Tapia* | |
| 09:30 | | | | *Marti* | | | *Neri* | | *Valentine* | |
| 09:45 | | | | *Burchart* | | | *Vergniolle* | | *Nakada* | |
| 10:00 Coffee | | | | | | | | | | |
| 10:30 Keynote | Basalt (1.1) | A. Harris | Ignimbrites (2.2) | P. Kokelaar | | Experiments (3.2) | H. Huppert | Modelling (4.2) | C. Jaupart | |
| 11:00 | | *Guilbaud* | | *Trofimovs* | | | *Tuffen* | | *Mahony* | |
| 11:15 | | *Spampinato* | | *Brown* | | | *Gaffney* | | *Doyle* | |
| 11:30 | | *Karson* | | *Roche* | | | *Clarke* | | *Witham* | |
| 11:45 | | *Hoskuldsson* | | *Calder* | | | *Kavanagh* | | *Masterlark* | |
| 12:00 Lunch | | | | | | | | | | |
| 13:15 Keynote | Floodbasalt (1.2) | Th. Thordarson | Tephra (2.3) | G. Larsen | | Plate/deform (3.3) | Þ. Árnadóttir | Magmas (4.3) | F. Sigmundsson | |
| 13:45 | | *Canon-Tapia* | | *Carey* | | | *Hjartarson* | | *Genereau* | |
| 14:00 | | *Passmore* | | *Johannsdottir* | | | *Keiding* | | *Óladóttir* | |
| 14:15 | | *White* | | *Ernst* | | | *Pedersen* | | *Miller* | |
| 14:30 | | *Passey* | | *Hoskuldsson* | | | *Sturkell* | | *Kelley* | |
| 14:45 Coffee | | | | | | | | | | |
| 15:00 Keynote | Basalt expl. (1.3) | B.Houghton | Posters Oral (5.1) | Oral Poster Presentation | | Posters Oral (5.2) | Oral Poster Presentation | Iceland (4.4) | K. Sæmundsson | |
| 15:30 | | *Mattsson* | | | | | | | *Flude* | |
| 15:45 | | *Brown* | | | | | | | *Tegner* | |
| 16:00 | | *Sharma* | | | | | | | *Fridleifsson* | |
| 16:15 | | *Ernst* | | | | | | | *Pope* | |
| 16:30 Posters | | | | | | | | | | |
| 20:00 | RSJ. Sparks | | | | | H. Jóhannesson | | | | |

## Science steering and editorial committee

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# George Patrick Leonard Walker, 1926–2005

George P.L. Walker was born in London on March 2, 1926 and grew up there and in Northern Ireland. As a youth he became fascinated with the geology and minerals in basalt lavas of Antrim, Ireland. He studied at the Queen's University of Belfast and Leeds University, earning a doctorate degree in mineralogy.

Walker taught mineralogy, geology and volcanology at the Imperial College in London from 1951 to 1978. During that time he did extensive research on old lava flows in Iceland and on volcanoes in Italy. In 1954 he began a ten year research project on the basaltic plateaus that make up the whole of eastern Iceland. His early work included documenting the geological mechanism of sea-floor spreading by dyke injection and observations of burial metamorphism from zeolite zones that showed the inter-relationships of spreading, subsidence, tilting, and erosion. For his seminal contributions to the understanding of the geology of Iceland Walker was awarded the Order of the Falcon by the Icelandic government in 1977.

In the 1960s and 1970s, Walker focused on the geology and eruptions of young active volcanoes, advancing understanding of the structure of volcanoes and establishing new ways to assess volcanic hazards. In 1967 he defined a relationship between the thickness of lava flows and the slope over which they flowed. In a 1971 research paper, he related lava flux to the formation of simple and compound flow units. In a 1973 study, he related the length of lava flows to the average lava eruption rate. In 1978 he accepted a Captain James Cook Research Fellowship from the Royal Society of New Zealand and studied young explosive volcanism of the North Island. In the 1970ies and 1980ies Walker and his co-workers published a series of papers on explosive eruptions and their products. Quantification of key characteristics of tephra deposits and linking them to particular types of activity was a major achievement that guided a generation of volcanologists towards better understanding of explosive volcanism.

Walker was the first to hold the Gordon A. Macdonald Chair in Volcanology established in 1979 in the University of Hawaii, from which he retired in 1996. In Hawaii he returned his attentions to basaltic volcanoes and the structural relationships of high level intrusions and lavas. He became an honorary D.Sc. from the University of New Zealand in 1988 and dr. scient. hon. c. from the University of Iceland in 1988.

A world-renowned volcanologist, Walker authored several hundred papers in volcanology on a broad range of important topics ranging from hazard mitigation, lava flows, and explosive volcanism. Indeed, such was his impact that the majority of volcano scientists refer to some fundamental aspect of his work in almost every piece of research they carry out.

George Walker received many awards throughout his illustrious career, including the Lyell Medal of the Geological Society of London in 1982; the UH Board of Regents Award for Excellence in Research in 1985; the prestigious Thorarinsson medal from the International Association of Volcanology and Chemistry of the Earth's Interior in 1989; the Wollaston Medal, given by the Geological Society of London, in 1995. He was one of few foreigners to receive the Icelandic Order of the Falcon, the equivalent of a knighthood, conferred by the president of Iceland in 1977.

(Information from various sources).

## The meeting is sponsored by:

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1 Snorrastofa - Poster sessions
2 Heimskringla - Poster sessions

3 The church of Reykholt
4 Rectory
5 Statue of Snorri Sturluson

6 The Conference hall

7 Snorri hot water tub
8 Archaeological excavation
9 The Old Church
10 The tomb of Sturlungar

11 Hotel Reykholt

# Final programme

## Monday, 12/06/2006

10:30–12:00 **1.1 – Basaltic lava flows**

**Heat Loss Models for Active Lava Channels and Tubes: Controls on Flow Cooling and Length**
Keynote speaker: A. Harris, United States of America

**Internal textures and cooling histories of rubbly pahoehoe lavas**
Presenting author: Marie-Noelle Guilbaud, United Kingdom

**Development of a complex lava tube network during the 2002–03 Stromboli effusive activity detected using a handheld FLIR thermal camera**
Presenting author: L. Spampinato, United Kingdom

**Crustal Accretion in Iceland and at Mid-Ocean Ridge Spreading Centers**
Presenting author: Jeffrey Karson, United States of America

**Hekla 2000 eruption, effusion rate linked with eruption style**
Presenting author: Armann Höskuldsson, Iceland

12:00–13:15 Lunch

13:15–14:45 **1.2 – Flood basalts**

**Flood Basalt Eruptions: Eruption Dynamics, Volatile Release and Atmospheric Effects**
Keynote speaker: Thorvaldur Thordarson, United Kingdom

**Formation of Continental Flood Basalts: The Volcanic Systems perspective**
Presenting author: Edgardo Canon-Tapia, United States of America

**Quantifying geochemical variation in basalt from Laki, southeast Iceland**
Presenting author: Emma Passmore, United Kingdom

**Not the usual fissure? Explosive eruptions, country-rock avalanches and sill-lid breakup in the Ferrar Large Igneous Province, South Victoria Land, Antarctica**
Presenting author: JDL White, New Zealand

**Lithostratigraphic framework for the Faroe Islands Basalt Group, NE Atlantic Ocean**
Presenting author: Simon Passey, Faroe Islands

14:45–15:00 Coffee

15:00–16:30 **1.3 – Basaltic pyroclasts**

**Basaltic explosive volcanism**
Keynote speaker: B.F Houghton, United States of America

**Contemporaneous phreatomagmatic and effusive activity along the Hverfjall eruptive fissure, mingling of explosive and effusive deposits**
Presenting author: Hannes Mattsson, Iceland

**Progressive enlargement and infill of a kimberlite pipe: K2 pipe, Venetia Kimberlite Field, Limpopo Province, South Africa**
Presenting author: Richard Brown, United Kingdom

**Explosive basaltic volcanism and $SO_2$ emissions: The 1730–36 eruption of Lanzarote, Canary Islands**
Presenting author: Kirti Sharma, United Kingdom

**Violent-strombolian eruptions : Revisited**
Presenting author: Gerald Ernst, Belgium

## Tuesday, 13/06/2006

08:30–10:00 **2.1 – Calderas**

**Incremental Assembly and Prolonged Consolidation of Cordilleran Magma Chambers: The Ignimbrite-Caldera Record**
Keynote speaker: Peter Lipman, United States of America

**Effusive and explosive volcanism, caldera formation, lavaice interaction, and magma evolution at Mount Veniaminof in the Aleutian arc**
Presenting author: Charles Bacon, United States of America

**The summit depression of Fogo Island (Cape Verde): caldera and/or flank collapse?**
Presenting author: A. Brum da Silveira, Portugal

**A genetic classification of collapse calderas based on field studies, analogue and theoretical modelling**
Presenting author: Joan Marti, Spain

**Structural Geology of the Geitafell Volcano, Southeast Iceland**
Presenting author: Steffi Burchardt, Germany

10:00–10:30 Coffee

10:30–12:00 **2.2 – Ignimbrites**

**Emplacement of a large-volume, spatter-bearing ignimbrite in a caldera lake: Scafell caldera, England**
Keynote speaker: Peter Kokelaar, United Kingdom

**Submarine pyroclastic flows; Soufrire Hills volcano, Montserrat, West Indies**
Presenting author: Jess Trofimovs, United Kingdom

**Progressive, diachronous inundation of extensive volcano flanks (>500 km2) by sustained pyroclastic density currents: insights from the internal architecture of a well-exposed ignimbrite on Tenerife**
Presenting author: Richard Brown, United Kingdom

**Dam-break experiments on water and gas-fluidised granular flows: insights into the physics of fines-rich pyroclastic flows**
Presenting author: Olivier Roche, France

**Surface wave instabilities and pyroclastic flow emplacement**
Presenting author: Eliza Calder, United States of America

12:00–13:15 Lunch

13:15–14:45 **2.3 – Tephra**

**The tephra archives: Notes on the application of tephra in volcanological and environmental studies**
Keynote speaker: G Larsen, Iceland

**Askja 1875, a complex plinian eruption: Welding and its implication for eruption dynamics**
Presenting author: Rebecca Carey, United States of America

**Early Holocene Tephrochronology in West Iceland and its Application for Paleoclimate Studies**
Presenting author: Gudrun Johannsdottir, Iceland

**Dispersal Dynamics from Phreato-Sublinian Eruptions; The 1937 Vulcan Eruption, Rabaul Caldera, Papua New Guinea**
Presenting author: Gerald Ernst, Belgium

**The Landbrotshlar pseudocraterfield, characteristics of rootless cone tephra**
Presenting author: Armann Höskuldsson, Iceland

14:45–15:00 Coffee

15:00–16:30 **Oral Poster Presentation**

## Wednesday, 14/06/2006

**Field trip to Snæfellsnes volcanic peninsula**
Guide; Haukur Johannesson

## Thursday, 15/06/2006

08:30–10:00 **3.1 – Explosive Volcanism**

**Modelling eruption clouds and fall deposits from explosive volcanic eruptions**
Keynote speaker: Lionel Wilson, United Kingdom

**Large explosive volcanic eruptions: completeness of the Holocene record and application of extreme value statistics**
Presenting author: Stephen Sparks, United Kingdom

**First 12-month of high-term resolution $SO_2$ flux measurements using an automated UV s canner array on Mt. Etna (Italy)**
Presenting author: Giuseppe Giovanni Salerno, United Kingdom

**Column collapse and pyroclastic flow dynamics by using 3D multiphase flow simulations**
Presenting author: Augusto Neri, Italy

**Listening to fire fountains at Etna volcano (italy)**
Presenting author: Sylvie Vergniolle, France

10:00–10:30 Coffee

10:30–12:00 **3.2 – Experiments**

**The influence of laboratory experiments in volcanology**
Keynote speaker: Herbert Huppert, United Kingdom

**Experimental fracture and flow of rhyolitic magma in shear triaxial deformation experiments on obsidian**
Presenting author: Hugh Tuffen, United Kingdom

**Topographic and Structural Effects on Dike Propagation and Eruption**
Presenting author: Edward Gaffney, United States of America

**Investigating the dynamics of Vulcanian explosions: scaled laboratory experiments of particle-laden puffs**
Presenting author: Amanda Clarke, United States of America

**An experimental investigation of sill formation and propagation in layered elastic media**
Presenting author: Janine Kavanagh, United Kingdom

12:00–13:15 Lunch

13:15–14:45 **3.3 – Deformation**

**Plate boundary deformation in Iceland observed by GPS**
Keynote speaker: Thora Arnadottir, Iceland

**Excess drift in Iceland**
Presenting author: Arni Hjartarson, Iceland

**Current Plate Boundary Deformation and the State of Stress on the Reykjanes Peninsula, South Iceland**
Presenting author: Marie Keiding, Iceland

**What controls the level of earthquake activity associated with magmatic intrusions?**
Presenting author: R Pedersen, Iceland

**Present-day volcano deformation in Iceland**
Presenting author: Erik Sturkell, Iceland

14:45–15:00 Coffee

15:00–16:30 **Oral Poster Presentation**

## Friday, 16/06/2006

08:30–10:00 **4.1 – Dikes**

**Geometry and emplacement of dykes in composite volcanoes and rift zones**
Keynote speaker: Agust Gudmundsson, Germany

**An experimental investigation of the emplacement and dynamics of sills in layered elastic media**
Presenting author: T Menand, United Kingdom

**Theoretical aspects of particle movement in flowing magma: implications for the anisotropy of magnetic susceptibility of dykes**
Presenting author: Edgardo Canon-Tapia, United States of America

**Emplacement of shallow dikes and sills beneath a small basaltic volcanic center – the role of pre-existing structure (Paiute Ridge, southern Nevada, USA)**
Resenting author: Greg Valentine, United States of America

**Conduit dike swarm in Unzen Volcano: Scientific drilling**
Presenting author: Setsuya Nakada, Japan

10:00–10:30 Coffee

10:30–12:00 **4.2 – Modelling**

**Long-term evolution of volcanic systems: Coupling between edifice growth, magma storage and transport at shallow crustal levels**
Keynote speaker: Claude Jaupart, France

**Cladistic analysis applied to the classification of volcanoes.**
Presenting author: Susan Mahony, United Kingdom

**Application of granular column collapse physics for modelling pyroclastic flows.**
Presenting author: Emma Doyle, United Kingdom

**The role of degassing and magma convection in magma chamber dynamics and the formation of igneous cumulate deposits.**
Presenting author: Fred Witham, United Kingdom

**Magma intrusion and deformation predictions: Sensitivities to homogeneous, isotropic, Poisson-solid, and half-space assumptions**
Presenting author: Timothy Masterlark, United States of America

12:00–13:15 Lunch

13:15–14:45 **4.3 – Magmas**

**Magma flow, storage and emplacement in the Icelandic crust: Constraints from space and terrestrial geodetic observations**
Keynote speaker: Freysteinn Sigmundsson, Iceland

**Magma dynamics revealed by SIMS depth-profiling of plagioclase from Soufrire Hills Volcano**
Presenting author: Kimberly Genareau, United States of America

**Tephra reveals Holocene magmatic evolution and eruption frequency of the subglacial Katla volcano, south Iceland**
Presenting author: Bergrún Arna Óladóttir, France

**Record of T-time-composition histories of magmas preserved in zircon zoning**
Presenting author: Calvin Miller, United States of America

**Petrologically determined depths to magma chambers in Icelnad's active rift zones.**
Presenting author: Daniel Kelley, United States of America

14:45–15:00 Coffee

15:00–16:30 **4.4 – Iceland**

**Notes on George Walkers contribution to the geology of Iceland. Controversies and a discovery of fundamental significance**
Keynote speaker: Kristjan Saemundsson, Iceland

**Eruptive history of Ljósufjöll volcano, Iceland: mush, mixing and Milankovitch?**
Presenting author: Stephanie Flude, United Kingdom

**Iceland Magma Chambers: Petrology of the Austurhorn and Vesturhorn Igneous Centres, SE Iceland**
Presenting author: Christian Tegner, Denmark

**Hydrothermal Heat Sources in Icelandic Central Volcanoes – Lesson learned from South Eastern Iceland –**
Presenting author: Gudmundur Fridleifsson, Iceland

**Investigation of basalt-fluid interaction using stable isotopes in Reykjanes magma-hydrothermal system**
Presenting author: Emily Pope, United States of America

## Saturday, 17/06/2006

**Trip from Reykholt to Reykjavik via Husafell ignimbrite and Kaldidalur/Thingvellir**
Guides; Gretar Ivarsson and Kristjan Saemundsson

# Abstracts

# 1.1 – Basaltic lava flows

## 1 Oral

### Heat Loss Models for Active Lava Channels and Tubes: Controls on Flow Cooling and Length

*A. Harris, HIGP/SOEST, University of HawaiI, HONOLULU, HAWAII, United States of America*

Walker's 'lengths of lava flows' paper of 1973 (Phil. Trans. R. Soc. Lond., 274) linked lava flow length and effusion rate. This sparked a body of literature aimed at determining the volume- and cooling- limits on lava flow emplacement. Here I review subsequent work aimed at determining the cooling limits on lava flow length. Heat loss from a flow surface plays a fundamental role in determining core-cooling rates, thereby influencing cooling-limited flow extension. Insulation in turn controls heat loss, and thus core cooling rates. Through field measurements we can classify three types of flow in terms of insulation and efficiency of heat loss: heavily crusted, tube-contained, and poorly crusted.

(1) Heavily Crusted. A thermally efficient means of lava transport is achieved when thick crusts cover the flow surface. Thus, although silicic lava flows at Santiaguito (Guatemala) have extremely low effusion rates (0.5–1.6 $m^3$/s), thick and cool crusts (30–150 °C) reduce surface heat loss. In these cases core cooling to reduced to 10–12 °C/km. These well-insulated flows have the potential to extend 17–20 km before the core cools by 200 °C, despite low effusion rates.

(2) Tube-contained. If the crust becomes rooted and stationary then tubes form. The roof presents extremely effective insulation reducing heat losses and cooling rates. Several studies have used field measurements and/or models to determine lava tube cooling rates of 0.3–2.0 °C/km. The effective insulation provided by the roof means that tube-fed flow has the potential to extend tens-to-hundreds of kilometers before the core cools by 200 °C, in-spite of low (1–4 $m^3$/s) effusion rates.

(3) Poorly crusted. Heat losses at open channels with thin, hot surface crusts will exhibit highest heat losses. We completed a FLIR thermal camera survey of a proximal section of active lava channel at Etna (Italy) during 2001. The channel was fed by an effusion rate of 0.1–0.7 $m^3$/s and pixel-integrated surface temperatures varied between 220 and 980 °C (mean = 680 °C). Heat losses were large and resulted in cooling rates of 50–180 °C/km. Poor insulation meant that the flow had the potential to extend 1–4 km at these effusion rates before the core cooled by 200 °C.

Two end-member types of emplacement can thus be defined: poorly insulated and well insulated. As we move from the poorly insulated to the and well insulated case, reduced heat losses increase the length a flow can extend at a given effusion rate.

## 2 Oral

### Internal textures and cooling histories of rubbly pahoehoe lavas

*Marie-Noelle Guilbaud[1], S. Blake[1], S. Self[1], T. Thordarson[2], L. Keszthelyi[3]*
*[1]The Open University, MILTON KEYNES, United Kingdom*
*[2]School of Geosciences, EDINBURGH, United Kingdom*
*[3]US Geological Survey, FLAGSTAFF, United States of America*

Young Icelandic basaltic lava flow-fields produced by the AD 1783–84 eruption of Laki and historical fissure eruptions in the Reykjanes Peninsula, and sheet lobes of the Grande Ronde Basalt from the Columbia River Province, are covered by a thick layer of rubble formed by disruption of earlier-formed pahoehoe lobes. The petrography and texture of tephra and lava samples from the surface and through flow interiors were studied to infer lava emplacement and solidification processes. The results reveal correlations between the average size, number density and aspect ratio of groundmass plagioclases in the lava. These relate, in turn, to the eruptive style and emplacement mechanisms of the flows inferred from field study of lava surface morphologies and internal structures, and aerial photo analysis for the Icelandic flows. Patterns of increasing average size and decreasing number density of groundmass plagioclase with increasing depth in these flows indicate sharply decreasing inwards solidification rates. Calculated from crystal size distribution (CSD) analysis, plagioclase growth and nucleation rates changed from about $10^{-7}$ to $10^{-10}$ cm/s and $10^{1}$ to $10^{-1}$ $cm^3$/s, respectively, as the solidification front propagated through the lava interior, indicating decreasing degrees of melt undercooling that promoted interface-controlled crystal growth. Clear textural differences between sections are attributed, in part, to the role of the degree of undercooling of the erupted lava and the mode of transport of the flows in controlling the extent and mode of groundmass plagioclase crystallization in fluid lava. Lava solidification rates were mainly controlled by duration of lava inflation, incorporation of rubble in lava core, and water infiltration in fractures through lava upper crust. Building on other textural studies, a model correlating lava surface morphologies with textural parameters derived from CSD analysis of groundmass plagioclase in samples from flow interiors is presented. Pahoehoe and 'a'a have low and high plagioclase number densities respectively ($< 10^9/cm^4$ compared to $> 10^{11}/cm^4$), which are inversely correlated with plagioclase average size and aspect ratio through the total crystal content; rubbly pahoehoe lavas have intermediate characteristics. This method may prove a useful tool for interpreting the mode of eruption and emplacement of ancient lava flow-fields.

## 3 Oral

### Development of a complex lava tube network during the 2002–03 Stromboli effusive activity detected using a handheld FLIR thermal camera

*L. Spampinato[1], L. Lodato[2], A. Harris[3], S. Calvari[2], J. Dehn[4], M. Patrick[3]*
*[1]INGV Catania IT; University of Cambridge, CAMBRIDGE, United Kingdom*
*[2]INGV Catania Section, CATANIA, Italy*
*[3]HIGP/SOEST, University of Hawail, HONOLULU, HAWAII, United States of America*
*[4]Alaska Volcano Observatory, FAIRBANKS, ALASKA, United States of America*

On 28 December 2002 Stromboli Volcano (Aeolian Islands, Italy) experienced a new effusive activity characterised by the emplacement of lava onto the steep slopes of the Sciara del Fuoco (Calvari et al. 2005). Effusion resulted in two lava flow fields, separated in space and time and fed by different vents. The first flow field formed in the middle of the Sciara del Fuoco and was fed by a vent located at 550 m a.s.l.. Activity lasted until 15 February 2003, and resulted in a compound flow field of numerous overlapping 'a'a flow units. The second flow field was emplaced in the upper eastern part of the Sciara del Fuoco and was fed by a main vent located at 670 m a.s.l. Activity here lasted until the end of the eruption on 21 July 2003, and formed a thick compound lava shield containing a complex lava tube network (Lodato et al., submit. in 2005). Daily handheld Forward Looking InfraRed (FLIR) thermal camera helicopter surveys were carried out. These allowed us to record: (1) the development of lava channels and tubes, (2) the formation of tumuli, (3) the opening and closure of ephemeral vents, and (4) the discrimination of active lava flows. Using these data, it was possible to track the evolution of the lava flow field and associated channel-tube system, including the establishment of the main lava tube, expansion of the network resulting from branching of the tube system, and the shut down of the system during July 2003. Thermal measurements also permitted lava tube mapping and the discrimination of three orders of tumuli (Lodato et al., submit. in 2005). The development and stability of these lava flow field structures are the result of the interaction between different parameters including effusion rate and topographic gradient.

## 4 Oral

### Crustal Accretion in Iceland and at Mid-Ocean Ridge Spreading Centers

*Jeffrey Karson*
*Syracuse University, SYRACUSE, NY, United States of America*

The geology of Iceland has long been recognized as an important analog for processes that occur in much less accessible parts of the mid-ocean ridge system. A number of important geological relationships that currently frame investigations on spreading centers were first recognized in Iceland by George Walker and Icelandic geologists. Today, decades later, detailed investigations of oceanic crust in the deep sea may help provide fresh insights into spreading processes in Iceland. One of the fundamental observations of accreting plate boundaries is that they are composed of discrete tectonic/magmatic/hydrothermal units. In Iceland these are commonly referred to as 'rift zones' but on spreading centers they are now called 'spreading segments'. In both cases, faulting and magmatism define discrete intervals of accreting plate boundaries that may be linked end-to-end by as yet poorly known features variously referred to as non-transform offsets, overlapping spreading centers or accommodation zones. Deeply eroded areas in Iceland provide excellent 3-dimensional exposures of some of these features that can be related to similar features found along oceanic spreading centers.

Documentation of the regional westward-dip of lava flows in eastern Iceland led to a model of inward-dipping lavas at depth below subhorizontal lavas of the neovolcanic zone and more localized 'flexure zones'. The implied kinematic pattern of coordinated subsidence and magmatic construction inspired models for the cross sectional evolution of Icelandic crust. Much later, these general concepts were suggested for oceanic crust and ophiolites. Only in the last few years have geologic and seismic data emerged from spreading centers and major escarpments in the oceanic crust that show a similar, 'inward-dipping' pattern of lava flows. In both Iceland and fast-spread crust dramatic subaxial subsidence is implied. How this subsidence may be related to the along-strike expression of segments (or rift zones) and deeper level processes is not yet know.

In both of these examples, spreading processes first identified in Iceland have proven to be fundamental to understanding spreading on mid-ocean ridges in general. With new methods of investigation and focused studies of mid-ocean ridges, new insights seafloor studies may now offer some new ideas to apply to Iceland.

## 5 Oral

### Hekla 2000 eruption, effusion rate linked with eruption style

*Armann Höskuldsson*
*Institute of Earth Sciences, University of Iceland, REYKJAVIK, Iceland*

The 18th eruption of Hekla started on 26th February, 2000. It was a short – lived but intense event, emitting basaltic andesitic pyroclastic fragments and lava. During the course of the eruption, monitoring was by both instruments and direct observations, together providing unique insight into the current activity of Hekla. The eruption started in a highly explosive manner giving rise to a sub-plinian eruptive column and consequent pyroclastic flows fed by column collapses. Once this explosive phase was over, the eruption went through three more phases, namely fire-fountaining, strombolian bursts and lava effusion. All phases produced identifiable patterns of eruption tremor. By use of an empirical formula of McNutt (1994) that links eruption tremor to explosive activity we can approach minimum effusion rate for the duration of the eruption. Further we are able to show that effusion rate can be linked with classical eruption styles, such as Hawaiian fire-fountaining and strombolian bursts. In this talk we describe the eruption of Hekla, its magma, and show that the eruption tremor is linked with a high effusion rate during peak explosive phase in the first hours of the eruption. Also we shall show that the eruption phases observed in Hekla can be linked with inferred magma chamber overpressure prior to the eruption.

# 1.2 – Flood basalts

## 6 Oral

### Flood Basalt Eruptions: Eruption Dynamics, Volatile Release and Atmospheric Effects

*Thorvaldur Thordarson*
*University of Edinburgh, EDINBURGH, United Kingdom*

What distinguishes flood basalt volcanism from other basaltic magmatism is the repeated effusion of huge batches of magma, ~$10^3$ $km^3$, that produce vast flood basalt lava flow fields (~$10^5$ $km^2$) from 10s–100s km-long fissures. Our work on Columbia River basalt flows indicates that typical flood basalt eruptions lasted for years to decades and estimated mean eruption rates are between $10^3$–$10^4$ $m^3$/s DRE (~ $3x10^7$–$1x10^8$ kg/s). To put this into perspective, about 10 years of activity at the AD1783 Laki peak eruption rate (1.2 x $10^7$ kg/s) would produce a lava flow field of flood basalt dimensions.

Mass eruption rates would vary depending on the duration of effusion and the length of active fissure at any one time; ~3.5x $10^3$ kg/s/m (m = meter length of fissure) for a 2-km-long active fissure, down to ~100 kg/s/m for a 75-km-long active fissure. The occurrence of deposits of spatter, spatter-fed lava, and scoria along eruptive fissures suggests that flood basalt eruptions featured recurring explosive phases of subplinian intensities which were capable of supporting >15-km-high eruption columns.

Estimates on the volatile mass released by a flood lava eruptions are ~10 gigaton (Gt) $SO_2$ and ~1–2 Gt HF+HCl per 1000 $km^3$ of magma erupted. The amount of $H_2O$ and $CO_2$ released is likely of the same magnitude as the $SO_2$ emissions. More than 70% of this volatile mass was liberated at the vents and lofted by the eruption columns to stratospheric altitudes where they produced aerosol plumes that most likely had global dispersal. Subsequently, some flood basalt eruptions may have produced atmospheric perturbations of the magnitude predicted for a severe 'volcanic' winter that may have lasted for a decade or more.

## 7 Oral

### Formation of Continental Flood Basalts: The Volcanic Systems perspective

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A comparison between the inferred melt distributions associated to many Continental Flood Basalt provinces (CFBs) and those associated to present day Mid Ocean Ridges, subduction zones and intraplate volcanoes reveals that the total amounts of magma contained within the corresponding regions of partial melting (RPMs) has the same order of magnitude in all of these cases. This result is not entirely compatible with the interpretation of CFB volcanism as the consequence of periods of larger than normal magma production rates, and it presents the problem of explaining the absence of large volume eruptions at present. A solution for such apparent paradox is provided here by examining the mechanism of melt extraction from the RPM within the framework of the model of volcanic systems. Two key elements of the proposed model of formation of large volume eruptions are 1) the identification of the trigger mechanism that initiates the rupture of the solid rock overlying the RPM, and 2) the shape of the melt distribution as a function of depth within the RPM at the time of such rupture. The first of these factors is shown to be easily quantified by applying a fundamental hydrostatic principle (Pascals law) that is generally applicable to volcanic systems around the world. The second of these factors, more specific for the formation of CFBs, is likely to be the result of a prolonged period of evolution of the RPM when two-phase flow may have been dominant. The model developed here also helps to explain the discrete nature of the eruptive events that formed any CFB, which is a factor commonly overlooked by solely considering the average magma production rates of any province.

## 8 Oral

### Quantifying geochemical variation in basalt from Laki, southeast Iceland

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The 1783 A.D. Laki fissure eruption is one of the largest in Icelands recorded history (Thordarson and Self, 1993; Thordarson et al., 1996). Lavas from this eruption have previously been considered geochemically uniform (Sigmarsson et al., 1991). However, recent studies of individual Icelandic and MORB flows using high-precision modern analytical techniques show that significant intra-flow chemical variation can exist in MORBs (Rubin et al., 2001; Maclennan et al., 2003), although the causes of such small-scale variation remain poorly understood, and merit further examination.

Whole-rock major- and trace element XRF analyses of 42 Laki basalt samples, and electron probe analyses of crystal phases and glass from a subset of these samples have been conducted at the University of Edinburgh. The XRF results indicate that statistically significant variations in trace-element concentrations and ratios exist within Laki lava, and show that the products of individual fissures differ geochemically from one another, but do not appear to show a simple evolution in composition through time.

Relative abundances of phenocryst phases and groundmass in each lava sample have been measured by point-counting. The amount of phenocrysts in the lavas varies from 7–29% by volume, and relative proportions of crystals vary between different lavas, with plagioclase consistently being the dominant phase. It is clear that accumulation of crystals within the lava will ultimately have an effect on the whole-rock composition. Concentrations of individual trace elements vary linearly with mass fraction of total phenocrysts. If the variation in concentration were due solely to crystal accumulation, then the slopes of regression lines fitted to the data arrays would reflect the apparent compatibilities of the respective elements. Regression coefficients were used to calculate concentrations at 0% crystal mass fraction (i.e. liquid composition) and 100% crystal mass fraction (i.e. bulk solid composition). The ratio of these gives the apparent bulk D value. For most elements this value was very different from that expected for an extract composed of ~55% plagioclase, 33% augite and 12% olivine. For example, the apparent bulk D for the most incompatible elements (Nb, Zr, Rb) was ~0.8. This implies that crystal accumulation was not the dominant control on the Laki lava composition and that other processes, such as mixing of discrete batches of magma, must have been involved. The linear correlation between the observed mass of accumulated crystals and the trace element concentrations indicates that the process that controls the variation is coupled to accumulation.

## 9 Oral

### Not the usual fissure? Explosive eruptions, country-rock avalanches and sill-lid breakup in the Ferrar Large Igneous Province, South Victoria Land, Antarctica

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Ferrar Group igneous rocks in South Victoria Land comprise extensive sills, dikes, and volcaniclastic rocks, at one site overlying a country-rock debris avalanche deposit. Crosscutting relationships incompletely constrain relative ages: avalanche deposits are overlain by pyroclastic flow deposits, and crosscut by vents filled with primary volcaniclastic deposits. Primary volcaniclastic deposits contain fragments from dikes and/or sills and/or lavas, but are crosscut by both dikes and sills. Shallow sills contain large blocks of country rock and primary volcaniclastic rocks. Flood lavas are largely removed from the area, but where present overlie primary volcaniclastic rocks. No flood lavas are 'attached' to the country-rock blocks within the sills.

Each pair of elements in this story is explicable. The debris avalanche deposit soles 200m below the top of the section and contains basaltic blobs, suggesting that dike intrusion triggered avalanching into an erosional valley. Large blocks of country rock are in the sills because shallow sill intrusion buoyed up, fractured, and engulfed layered sandstones near the pre-Ferrar surface. Primary volcaniclastic rocks both contain fragments of, and are cut by, intrusive rocks because intrusions began before and continued after the eruptions. The observed relationships are simply a reflection of complexity.

More satisfying explanations for these features, all formed in the early stages of magmatism, would relate them to one another. An example of such an explanation, physically plausible and consistent with field evidence in areas we've studied, is this. As Ferrar magmatism developed, sills extended and stepped outward and upward through layered sedimentary rocks under static (triaxial) stress conditions from multiple supply points in crystalline basement rock a few km below the surface. Dikes driven from supply points during magma-pressure excursions interacted with inclined segments of the sills, with first breaches to the surface triggering phreatomagmatic eruptions that excavated large vent complexes. Country-rock failure along excavation margins stripped some areas of shallow strata; subsequent failures triggered by sparse new dikes outside the vent complex locally buried these stripped zones beneath avalanche deposits, subsequently penetrated by small phreatomagmatic eruptions above other dikes. Pyroclastic flows from later explosive eruptions covered sites near vent complexes. Surface uplift driven by continued intrusion of sills to shallow levels was accompanied by country rock breakup. Magma release to the surface, largely beyond vent-complex margins, was through a network of steep sheets (dikes) driven between the subsiding fragments of the broken country-rock lid, and initiated flood-basalt burial of the region.

## 10 Oral

### Lithostratigraphic framework for the Faroe Islands Basalt Group, NE Atlantic Ocean

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The Palaeogene Faroe Islands Basalt Group (FIBG) covers an area of at least 120,000 km$^2$ of the NE Atlantic Ocean although only 1400 km$^2$ are exposed on the Faroe Islands. On the Faroe Islands, the FIBG has a stratigraphic thickness of ca. 6.6 km, of which 3.4 km is proven by the onshore borehole Lopra-1/1A. The FIBG is composed almost exclusively of subaerial basalt lava flows, rare pyroclastic lithologies and a variety of associated volcaniclastic strata. Since the publication of the last geological map in 1969, there have been significant advances in the understanding of the processes that occur in volcanic settings and this, associated with the developments in volcanic classification schemes, has led to our development of a revised lithostratigraphic framework for the Faroe Islands following the guidelines of the International Subcommission on Stratigraphic Classification. We have subdivided the FIBG into seven formations based upon the recognition of widespread disconformities and lithological changes. The base of the FIBG is composed of the ca. 1000 m thick Lopra Formation, a volcaniclastic strata and hyaloclastite-dominated sequence, which is overlain by the ca. 3300 m thick Beinisvr Formation composed of aphyric tabular lava flows. There is a marked disconformity at this level and these lavas are overlain by the 3–15 m thick Prestfjall Formation, composed of coals, mudstones and sandstones. Volcanism resumed with the eruption of tuffs and lapillistones preserved intercalated with volcaniclastic sedimentary conglomerates and sandstones of the ca. 50 m thick Hvannhagi Formation. This was followed by the eruption of the ca. 1300 m thick compound lava flow sequence of the Malinstindur Formation. Another disconformity is recognised at the top of the Malinstindur Formation and is overlain by the 1–30 m thick Sneis Formation composed of volcaniclastic sandstones and conglomerates. The Sneis Formation is overlain by the Enni Formation, composed of interbedded compound and tabular basalt lava flows and is at least 900 m thick. The recognition of a number of distinct lava flow packages (e.g. olivine microporphyritic compound flows) and key stratigraphic marker beds (e.g. the Argir Beds) may enable future subdivisions of the stratigraphy and lead to a better understanding of the evolution of the lava field.

# 1.3 – Basaltic pyroclasts

## 11 Oral

### Basaltic explosive volcanism

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Basaltic explosive volcanism takes place over a range of scales from weak Strombolian discrete explosions to Plinian eruptions of moderate intensity ($10^3$–$10^7$ kg/s$^{-1}$).

Deposit geometry: The products of well-documented historical eruption often contain both cone-building and sheet forming elements over this entire range of scales but the proportion of mass partitioned into the cone varies inversely with eruption intensity- e.g. 94% for the Hawaiian fire fountains of Kilauea Iki 1959 versus 1% for the 1886 Plinian eruption of Tarawera. Cone growth across this wide intensity range reflects the influence of non-sustained proximal processes of clast transport and deposition during even sustained eruptions.

Microtextures: Vesicles and microlite populations, are sensitive indications of complex conduit processes in most basaltic eruptions, implying a delicate balance between mechanical coupling and uncoupling of the gas phase from the rising melt. Bubble number densities vary from $10^2$ to $10^8$ bubbles per cm$^3$ reflecting contrasting rates of decompression scaling with eruptive intensity. During Strombolian eruptions, the conduit contains a complex mixture of fluid phases: slugs of uncoupled large bubbles, newly arrived, vesiculating melt accompanying the gas slugs, more mature melt resident in the conduit through the passage of multiple gas slugs, and populations of smaller gas bubbles that show variable degrees of mechanically coupling to the melt phases. This heterogeneity is present on time scales as short as single explosions but the proportions of the phase shift on time scales of days to months, reflecting the relative timing and size of gas slugs. Studied Plinian melts (e.g., Tarawera 1886, Etna 122 BC) contain significantly larger numbers of markedly smaller bubbles and a conspicuous population of microlites. The microlites play a key role in modifying effective viscosity of the melt phase which feeds back to promote disequilibrium degassing and 'closed system' behavior.

## 12 Oral

### Contemporaneous phreatomagmatic and effusive activity along the Hverfjall eruptive fissure, mingling of explosive and effusive deposits

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By use of stratigraphic relations the course of events during the Hverfjall fissure eruption are reconstructed. The deposits suggest that the eruption occurred along ~5 km long NNE-SSW trending fissure, and that several vents were active during the eruption. Stratigraphic successions indicate that activity started in the southern part of the fissure, which extended into proto lake Myvatn and thus erupted in a shallow lacustrine setting. The Hverfjall tuff cone formed on this part of the fissure. From Hverfjall to the Jarðbaðshólar scoria cone, the eruptive fissure is dotted with smaller craters. Activity within the southernmost part was dominated by interaction between magma and surface water, initially forming phreatomagmatic ash fall. This is characterized by continuous, massive to normally graded layers that are relatively well-sorted. Patchy distribution of scoriaceous fallout within the lowermost deposits suggests that a landward extension of the fissure was active contemporaneously, producing highly vesicular scoria and reticulite that mix with the phreatomagmatic ash. The northernmost part of the fissure comprises the Jarðbaðshólar scoria cones and associated lava flows. The scoria cones are underlain by fallout deposits from Hverfjall and covered by a surge sequence from Hverfjall. This indicates that while Jarðbaðshólar was at its maximum, the deposition rate was fast enough to dominate over that of Hverfjall. Activity was presumably ongoing at the Hverfjall vent. However, it is difficult to quantify the mixing of fine-grained Hverfjall ash with the coarser Jarðbaðshólar deposits due to percolation of the fine-ash fraction through the coarse-grained framework of the latter. The Jarðbaðshólar lava flow classifies as rubbly aa, with a scoriaceous surface of approximately 1 m. The scoriaceous flowtop displays complex embedding relations with the Hverfjall surge deposits. In places the scoria is plastered with the surge deposits and in other places it has been deformed by the scoria. This suggests that the lava flow was active and moving when the surges passed over it. Cessation of strombolian activity at Jarðbaðshólar occurred earlier than at the Hverfjall vent, as indicated by the Jarðbaðshólar section. Base surge deposits are found both north and south of the Hverfjall vent and can be traced as far as 5 km N from the vent (and up to ~100 m uphill on Námafjall). The base-surge deposits indicate that during flow it was 'dried-up' as proximal parts of them display wet features, such as plastering, accretionary lapilli, and soft sediment deformation (within a radius of approximately 2 km from the vent). On the other hand distal surges deposits (exceeding 2 km from the vent) all display dry features such as strongly grain-segregated layers. The change in depositional regimes, i.e. the change from domination of fallout to surges at Hverfjall, and strombolian to quiet effusive activity at Jarðbaðshólar, is attributed to an overall lowering of the volumetric eruption rate.

## 13 Oral

### Progressive enlargement and infill of a kimberlite pipe: K2 pipe, Venetia Kimberlite Field, Limpopo Province, South Africa

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The conduit processes and eruption history of a complex kimberlite pipe (K2 kimberlite pipe, South Africa) have been investigated using a combined field-mapping, core-logging and petrographic approach. The pipe is broadly divisible into a western half comprising lithic breccias and an eastern half consisting of quasi-homogeneous volcaniclastic kimberlite. The lithic breccias form debris fans that dip into the pipe on the western side at angles around and above the expected angle of repose. These fans are interbedded with layers of variably lithic-rich volcaniclastic kimberlite. The eastern half forms a steep-sided pipe shaped body that post-dates the lithic breccias. Drill core data indicate that this geometry is consistent for ~ 300 m depth. We propose that the eruption was driven by the catastrophic exsolution of magmatic volatiles. Excavation occurred from the top-down during the opening stages of the eruption as the pipe widened and deepened by gravitational collapses (rock falls and rock slides, debris avalanches) of the pipe walls, rock spalling and the explosive expulsion of fragmented country rock. During the waning stages, pyroclastic material and collapsing country rock was increasingly confined within the pipe. Material built up as a series of inward-dipping fans in the pipe. Pronounced rounding of country rock clasts may have occurred by thermal spalling following exposure to hot magma and gases in the conduit and by attrition during clast interactions. A late-stage resurgence in explosive activity partly excavated the accumulated breccias and deposited finer-grained volcaniclastic kimberlite. Pyroclastic textures in volcaniclastic kimberlite interbedded with the lithic breccias and from rocks at deeper (>300 m depth) levels in the pipe are tentatively interpreted as welding fabrics. Transitions are seen from granular, non-welded pyroclastic deposits through to coherent porphyritic kimberlite, interpreted as densely-welded pyroclastic material. Transitional deposits comprise intimately mixed patches of non- and densely-welded material. Normal eutaxitic welding textures are not seen and may not be expected given the high crystal content of the erupting magma, low magma viscosity (0.1-1 Pa s) and the general nature of the juvenile pyroclasts (dominantly solid crystal/lithic kernels surrounded by very thin magmatic rims). The evidence presented implies a protracted excavation and infill history and is consistent with recent physical models for kimberlite eruptions.

## 14 Oral

### Explosive basaltic volcanism and $SO_2$ emissions: The 1730–36 eruption of Lanzarote, Canary Islands

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The AD 1730–36 eruption of Lanzarote (Canary Islands) is the third largest basaltic fissure eruption known to have occurred in the last 1000 years, after the Icelandic events of Laki (AD 1783–84) and Eldgja (AD 934). Our new volume estimate suggests that the Lanzarote eruption produced a minimum of 5 $km^3$ of alkali basalt magma erupted from a 15-km long, E-W trending fissure. Eruptive activity occurred in five distinct phases. Each phase began with Strombolian fire fountain activity, building large spatter and scoria cones. This was accompanied and followed by effusive aa and pahoehoe lava flow emplacement. As studies in Iceland have shown, this type of sustained fissure eruption can release large amounts of $SO_2$ to the atmosphere, leading to the formation of sulphate aerosol clouds and causing widespread environmental damage and human suffering. Matrix glasses in scoria and surface lava samples have 80–300 ppm S (EMPA) and 300–600 ppm $H_2O$ (FTIR), whereas glass inclusions in olivine have 420–2650 ppm S and 1000–5000 ppm $H_2O$. Low sulphur inclusions are believed to be partially degassed, representing melt that was trapped during degassing-induced crystallization that occurred as a result of shallow decompression. The inclusions with the highest sulphur contents trap the original un-degassed melt. The high sulphur contents are also consistent with our finding, from olivine-spinel equilibria, that the magma was relatively oxidized therefore favouring the formation of sulphate species and preventing sulphide saturation. Petrologic estimates of the S release indicate that ~44 Mt of $SO_2$ was injected into the upper troposphere lower stratosphere via 12-16-km-high eruption plumes and that over half this amount was released during the first year of activity. This figure correlates with published Greenland ice-core (GISP-2) data that shows an acidity spike in 1731, suggesting stratospheric transport of sulphate aerosol north during the first year of eruption. Historical records note the presence of a dry fog over much of Europe during 1733. This, together with proxy climate indicators such as a marked tree ring anomaly in 1732 and a known decrease in the Northern hemisphere surface temperatures suggests that the Lanzarote eruption had some impact on Northern Hemisphere climate in the years following the activity.

## 15 Oral

### Violent-strombolian eruptions: Revisited

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The eruptions of El Jorullo (1759-74) and Parícutin (1943-1952), in Guanajuato, México, generated substantial (300–400m high) pyroclastic cones, extensive ash blankets and lava flow-fields. The cones have the aspect of scoria cones such as those that result from the normal Hawaiian-Strombolian styles of explosive volcanism, but both cones and tephra blankets are composed predominantly of submillimetre particles. Eruptions that produce such deposits have previously been called "violent strombolian". We find that pyroclasts of a given size travelled moderately further from the source than in the normal-Hawaiian-strombolian cases; the eruption dynamics appear similar at first. A key difference resides in the much finer grainsize population of these so-called violent strombolian types. A higher degree of fragmentation could result from the hydromagmatic activity, but the deposits lack evidence for significant external water involvement. The tephra blanket of El Jorullo contains hundreds of strictly parallel laminae, evidence for deposition by fallout from a great number of explosions (as was observed on Parícutin). The predominantly fine grainsize, more strikingly shown by El Jorullo, constitutes about half of the total erupted volume. At El Jorullo, lava flow units vary from 10 to 50m thick. The great thickness and steep-sided form argues for high-viscosity and high yield strength. The latter, by restricting growth and movement of gas bubbles, may have contributed to the high degree of pyroclast fragmentation. The following scenario is consistent with the field observations and ongoing laboratory experiments on particle-laden gas jets (in progress at U. Ghent) and is thought to play a crucial role in "violent strombolian" eruptions:

The Parícutin and Jorullo cones are particularly large for "strombolian cones" and are also characterised by unusually wide and deep craters. Material depositing on the crater rim is too fine-grained to weld despite high accumulation rates. A thick crater-rim tephra pile is therefore inherently unstable, producing grainflow avalanches back into the vent (and down the outer flanks). The recycled material is thus submitted to secondary fragmentation, contributes to periodic overloading of the particle-laden eruption jet, and in turn recurrently increase the fall rate onto the crater rim, repeating the cycle. The system can thus become highly intermittent, be characterised by extensive fragmentation/milling of a "dry slurry" in a sort of "dry surtseyan" style of eruption or recycling-dominated subplinian-style and generate an exceptional proportion of fine ash. George told us that the system made him think of "a washing machine": one with just powder and no added water ! By inspiring this work, George appears to have pointed us toward the description of a distinct eruptive style, previously known as "violent strombolian", and for which we are now seeking a better name.

# 2.1 – Calderas

## 16 Oral

### Incremental Assembly and Prolonged Consolidation of Cordilleran Magma Chambers: The Ignimbrite-Caldera Record

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Recent inference that Mesozoic Cordilleran plutons grew incrementally during >$10^6$-year intervals, without presence of voluminous eruptible magma at any stage, minimizes close associations with large ignimbrite calderas. Alternatively, multi-stage histories of magma accumulation, fractionation, and solidification in upper parts of many large plutons suggest 'large-tank'episodes when sufficiently liquid to erupt ignimbrites with volumes of 1–5x$10^3$ $km^3$ and accommodate caldera collapse. Spacing of Tertiary calderas at distances of 10s to 100s of km is comparable to pluton spacing for similar durations. Individual calderas, to 75 km across with 2–5 km subsidence, are direct evidence for shallow magma bodies comparable to the largest granitic plutons. Downwind ash in eastern Cordilleran sediments records large-scale explosive volcanism concurrent with Cretaceous batholith growth. Nested calderas that erupted compositionally diverse tuffs document deep composite subsidence and rapid evolution in subvolcanic magmas. Mineral fabrics and compositional gradients record late flowage of pluton interiors before complete solidification, and some plutons contain ring dikes or other textural evidence for roof subsidence. Geophysical data shows that low-density upper-crustal rocks, inferred to be plutons, are 10 km or more thick beneath many calderas. Most ignimbrite compositions are more evolved than associated plutons, requiring that subcaldera chambers retained voluminous residua from fractionation. Initial incremental pluton growth in the upper crust is likely recorded by modest eruptions from central volcanoes; preparation for caldera-scale ignimbrite eruption must involve recurrent magma input and homogenization high in the chamber. Some eroded calderas expose shallow granites of similar age and composition to tuffs, recording sustained postcaldera magmatism. Plutons thus provide a composite record of prolonged magmatic evolution, while volcanism offers snapshots of conditions at earlier stages. Some evidence cited for early incremental pluton assembly more likely records late events during/after volcanism. Lack of geophysical evidence for voluminous magma beneath young calderas suggests that near-solidus plutons can be rejuvenated rapidly by mantle melts, causing large explosive eruptions with only brief precursors.

## 17 Oral

### Effusive and explosive volcanism, caldera formation, lava ice interaction, and magma evolution at Mount Veniaminof in the Aleutian arc

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Mount Veniaminof, one of the largest Aleutian arc volcanoes, lies near the tip of the Alaska Peninsula 800 km SW of Anchorage. The 2500-m-asl edifice has basal diameter of 40 km, volume of 350 $km^3$, and an 8-km-diameter ice-filled caldera. Steep walls to 600 m high bound the N half of the caldera and ice spills from its broad, low S rim. Chill-jointed lavas and palagonitic breccias record eruptions during times of more extensive ice cover. Nearly 30 such occurrences dated by $^{40}Ar/^{39}Ar$ and K/Ar that provide measures of ice thickness variations suggest a climatic history that is consistent with the marine isotope record.

Argon geochronology establishes that from 250 ka to 130 ka Veniaminof erupted medium-K tholeiitic basalt and basaltic andesite, including lavas as primitive as 9.4% MgO and 130 ppm Ni at 50% $SiO_2$. Differentiated phenocryst-poor andesites and dacites (to 68% $SiO_2$) vented beginning ~130 ka. Voluminous basaltic andesite, andesite, and dacite also effused from a 35-km-long NW-trending set of flank vents as recently as 36.4±6.5 ka (±1 sigma). Geochemistry, lack of hydrous phenocrysts, and apparently fluid dacitic lavas suggest that the magmatic system is relatively dry, hot, and reduced. Intermediate and evolved lava compositions are readily explained by crystallization differentiation.

Voluminous andesitic eruptions ~9000 and 3700 $^{14}C$ yr B.P. emplaced pyroclastic-flow deposits as far as 50 km from source. Extensive lahar, lahar-runout, and hyperconcentrated-flow deposits that reached the Bering Sea and North Pacific Ocean require volumes of water such that an ice-filled caldera must have present at 3700 yr B.P. Although caldera collapse likely occurred during these Holocene eruptions, thick dacite lava that chilled against intracaldera ice demonstrates that a caldera was present by 336 ka. Remnants of dacitic pyroclastic-flow and fall deposits may record the eruption responsible.

Gabbro, diorite, and miarolitic granodiorite ejected in the 3700-yr-B.P. eruption are fragments of a shallow pluton consisting of cumulate mush and vapor-saturated residual melts. SHRIMP $^{238}U$-$^{230}Th$ zircon isochron ages are 17.5±1.8 ka and 11.7 +4.7/-4.5 ka (2 sigma) for granodiorite and diorite, respectively. Zircons from two gabbros give $^{238}U$-$^{230}Th$ model ages of 36.6 +7.1/-6.7 ka and 26.4 +6.7/-6.4 ka. Although in the last 200 yr Veniaminof produced small-volume crystal-laden basaltic andesite in strombolian eruptions and lava effusion, recent prehistoric eruption of crystal-poor dacite pumice (63.5% $SiO_2$) shows that crystallization differentiation produced a significant body of segregated melt and that explosive eruptions remain possible.

## 18 Oral

### The summit depression of Fogo Island (Cape Verde): caldera and/or flank collapse?

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A single central polygenetic stratovolcano forms the Island of Fogo, located in the south-western part of Cape Verde Archipelago. This structure is truncated by an 8 km wide summit depression partially delimited by the vertical Bordeira rim walls rising 1000m from a flat area (Chã das Caldeiras) at an average altitude of 1600–1700m. Inside this depression an 1100m high cinder cone (Pico do Fogo) grew up to the maximum altitude of the island (2.829m). The absence of the Bordeira wall and the presence of NW-SE and NE-SW trending scarps on the eastern slope of Fogo are also significant geomorphic features.

One important question concerns the origin of the summit depression of Fogo: was it created by caldera event(s), or, was it produced by a unique giant lateral gravitational collapse?

Based on geomorphologic, volcanologic and petrological evidence, discussed below, we interpret this structure as a caldera generated in two collapse episodes followed by a flank collapse(s) to the east.

Geomorphologic analysis on the summit depression revealed two circular shaped basins separated by a prominent spur that represent two intersecting calderas, the northern of which is smaller, deeper and younger.

Recent fieldwork recognized deposits of five successive pyroclastic flow events overlying pre-caldera sequences and covered by post-caldera lava flows. These block and ash flow deposits are related with caldera collapse event(s), therefore, representing a key stratigraphic marker, separating pre and post caldera volcanic sequences.

Geothermobarometry of post-caldera (mela)-nephelinites indicates crystallisation temperatures of ~1100–1200°C and pressures 1–11kb with a cluster at 5–8 kb, suggesting a main fractionation event within the mantle (15–30km depth) followed by short residence in crustal magma chambers before eruption. In contrast, the barometric data from most evolved pre-caldera magmas (phonotephrites and tephriphonolites) points to crystallization at much shallower depths (~5km; P~1.5kb; ~1030°C), indicating a more important role of crustal magma chambers on their genesis. These shallow level magma chambers may have induced gravitic/mechanical instability, triggering caldera collapse.

At least one, or two, catastrophic large-scale landslides shattered a 65 wide sector of the Fogo volcano oriental flank, after the caldera event(s) and prior to the growth of Pico do Fogo. These lateral collapse events opened the caldera depression to the east and originated debris avalanches that flowed downslope to the sea. This is corroborated by recently acquired multibeam swath bathymetry of the submarine east flank of Fogo Island indicating numerous and extensive turbidite and debris flow avalanche deposits.

## 19 Oral

### A genetic classification of collapse calderas based on field studies, analogue and theoretical modelling

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Collapse calderas represent one of the most catastrophic volcanic events on Earth. Their potential role on climate changes and mass extinctions has been invoked several times and their direct impact on neighbouring or on relatively distal areas has been dramatically illustrated by some historical or recent eruptions. Additionally, collapse calderas are significant geological structures as in several cases they host important ore deposits. Furthermore, collapse calderas are also of interest because they represent the culmination of long term geological processes that involve particular lithospheric dynamics, which conduct to an exceptional behaviour of some volcanic systems. Generally, studies on collapse calderas are based on fieldwork and tend to offer detailed descriptions of particular examples and to explain their origin from the available field data. Caldera morphology and structure inform us about the subsidence mechanism and some geometrical aspects of the associated magma chamber, while the study of the caldera products addresses us to the magma chamber and eruption dynamics. In addition, a few field based studies offer a more generalised approach comparing different caldera types and classify them according to the coincidence in some of the apparent caldera characteristics. However, although field studies constitute an essential step in the study of collapse calderas, in most cases they do not allow to determine the exact mechanisms of their formation and, consequently, to classify calderas using criteria other than their resulting morphology or their assumed collapse mechanism. New complementary lines of research, based on the application of analogue and mathematical modelling, are progressively emerging and becoming essential to understand the causes of the formation of collapse calderas. In this contribution, we present a comprehensive analysis of field studies of several well known collapse calderas, and compare the field data available in order to establish similarities and differences among all them. This allows us to distinguish between different caldera types and to determine a physical scenario for of each of them. Comparison of field data with analogue and numerical models permits to establish a relationship between each caldera type with its particular genetic pattern, so that a new classification scheme, based on the conditions that lead to caldera-formation, is proposed.

## 20 Oral

### Structural Geology of the Geitafell Volcano, Southeast Iceland

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The Geitafell Volcano is an extinct central volcano that was active around 5 Ma ago in the Tertiary rift zone in Iceland. Because of deep glacial erosion, the interior of the volcano is exposed down to the top of the extinct crustal magma chamber, currently represented by gabbro bodies. Surrounding and in direct contact with the magma chamber, there is a dense swarm of inclined sheets which were injected from the magma chamber. The flanks of the volcano consist primarily of basaltic, intermediate, and acid lava flows, tuffs and hyaloclastites, that is, layers of contrasting mechanical properties.

Field studies of the attitude, thickness, and lithology of 557 inclined sheets and dykes in the Geitafell Volcano indicate that the sheet swarm is bowl-shaped and consists mainly of basaltic inclined sheets and radial dykes. Field and remote-sensing studies of the gabbro bodies indicate that when it reached its maximum size the magma chamber was sill-like and with a diameter of 8 km. Measurements of the attitude of 1100 joints in the gabbros show three main sets of cooling joints: one set strikes NW-SE, another NE-SW, and the third NNE-SSW. During the lifetime of the Geitafell Volcano meteoric water circulated through the joint systems and generated a high-temperature geothermal system. Consequently, there is a dense network of mineral veins in the gabbros. The attitudes of 400 measured mineral veins coincide with those of the cooling joints. The cooling joints were also used as pathways for some late-formed sheets injected from the still-molten interior of the cooling magma chamber.

Using the estimated dimensions of the magma chamber, together with data on the mechanical properties of the main layers that constitute the Geitafell Volcano, we made numerical models of the local stress field around the magma chamber. The model results agree well with the common attitudes of the inclined sheets. Numerical models were also made so as to explain the formation of the collapse caldera in the Geitafell Volcano which had a maximum diameter of about 10 km. The model results indicate that tension and/or doming of the crustal segment hosting the sill-like magma chamber may have triggered caldera-fault initiation and subsequent collapse in the Geitafell Volcano.

# 2.2 – Ignimbrites

## 21 Oral

### Emplacement of a large-volume, spatter-bearing ignimbrite in a caldera lake: Scafell caldera, England

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The Scafell caldera-lake volcaniclastic succession is one of the best exposed in the world. At the eastern margin of the caldera a large andesitic explosive eruption (>5 km$^3$) generated a high-mass-flux pyroclastic density current that flowed into the caldera lake and deposited the extensive Pavey Ark ignimbrite, with a thick, proximal, scoria-rich breccia. Similar proximal breccias have been reported from the subaerial flanks of flooded calderas elsewhere (e.g. Campi Flegrei, Santorini and Taal), but the subaqueous counterparts are generally inaccessible and so have not previously been documented. The eruption involved pyroclasts that ranged widely in size and density, and extreme ignimbrite lithofacies diversity resulted via particle segregation and selective deposition from the current, which was sustained for several hours. The proximal lacustrine ignimbrite breccia, 125 m thick, mainly comprises clast- to matrix-supported blocks and lapilli of variably vesicular andesite, but includes many layers rich in spatter rags (=1.7 m diameter) that were emplaced in a ductile state. This breccia grades both upwards and distally into massive and diffuse-bedded lapilli-tuff, which in turn grades upwards into fine- and extremely fine-grained tuff showing evidence of soft-state disruption. Proximally, rapid deposition of blocks caused displacement of interstitial fluid and elutriation of the ash upwards, so that it was retained in the current and thus overpassed to medial and distal reaches. Medially, the lithofacies architecture records partial blocking, channelling and reflection of the depletive current by basin-floor topography, as this was gradually buried. Diffuse layering reflects surging of the sustained current, and the overall normal grading reflects gradually waning flow with, finally, a transition to suspension sedimentation from an ash-choked water column. The fine- to extremely fine-grained tuff forms ~25% of the whole and is the aqueous equivalent of co-ignimbrite ash; its great thickness (=55 m) formed because the suspended fine ash was trapped within an enclosed basin and could not drift away. The ignimbrite architecture records widespread caldera subsidence, involving volcanotectonic faulting of the lake floor during the eruption. The eruption was enhanced by explosive disruption of a hydrothermal system adjacent to the magma reservoir.

## 22 Oral

### Submarine pyroclastic flows; Soufrire Hills volcano, Montserrat, West Indies

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What happens when pyroclastic flows enter the ocean? To date, the subject of submarine pyroclastic flow behaviour has been controversial. Ambiguity results from inconclusive evidence of a subaqueous depositional environment in ancient successions, to difficulty in sampling the in situ products of modern eruptions.

A research voyage of the RRS James Clark Ross (9–18 May 2005) sampled 52 sites offshore from the volcanic island of Montserrat. The Soufrire Hills volcano, Montserrat, has been active since 1995 with eruptive behaviour dominated by andesite lava dome growth and collapse. Over 90% of the pyroclastic material produced has been deposited into the ocean. In July 2003 the Soufrire Hills volcano produced the largest historically documented dome collapse event. 210 x $10^6$ m$^3$ of pyroclastic material avalanched down the Tar River Valley, southeast Montserrat, to be deposited into the ocean. A sophisticated monitoring network recorded in detail the subaerial expression of the dome collapse. However, little was known about the flow behaviour or deposits after the pyroclastic flow entered the submarine environment.

Bathymetric imaging and coring of offshore pyroclastic deposits, with a specific focus on the July 2003 units, reveals that the pyroclastic flows mix rapidly and violently with the water as they enter the ocean. Mixing takes place between the shore and 500 m depth where the deposition of basal coarse-grained parts of the flow initiates on slopes of 15 or less. The coarse components (pebbles to boulders) are deposited proximally from dense basal slurries to form steep sided, near linear ridges that amalgamate to form a kilometre-scale submarine fan. These proximal deposits contain <1% of ash-grade material. The finer components (dominantly ash-grade) are mixed into the overlying water column to form turbidity currents that flow distances >30 km from source.

The total volume of pyroclastic material off the east coast of Montserrat exceeds 280 x $10^6$ m$^3$, with 65% deposited in proximal lobes and 35% deposited as distal turbidites. This broadly correlates with the block and ash components respectively, of the source subaerial pyroclastic flows. However, the efficient sorting and physical differentiation of the submarine flows, in comparison to original mixture of their subaerial counterparts, suggests that the pyroclastic flows mix thoroughly with seawater and generate sediment gravity currents, which are stratified in grain size and concentration.

## 23 Oral

### Progressive, diachronous inundation of extensive volcano flanks (>500 km$^2$) by sustained pyroclastic density currents: insights from the internal architecture of a well-exposed ignimbrite on Tenerife

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Understanding of the nature and behaviour of pyroclastic density currents has focussed recently on observed small-volume dome-collapse and Vulcanian eruptions (e.g., at Unzen, Lascar and Montserrat). The observed currents were short-lived, small-volume depletive types and affected relatively small areas, mostly along valley floors. In contrast, large-volume, radiating pyroclastic density currents associated with some large Plinian eruptions pose a far greater hazard: they are regionally extensive, and they inundate vast areas including over topographic highs within in short periods (seconds to days). We present detailed field data from a widespread (>500 km$^2$) ignimbrite sheet deposited across irregular terrain from laterally extensive currents that radiated across the flanks of Las Caadas volcano, Tenerife. The data underpin a high-resolution reconstruction of the temporal and spatial variations within at least four sustained and widespread particle-laden currents during a single explosive eruption. Compositional zoning and lithostratigraphy define time-surfaces (entrachrons) within the ignimbrite, and the entrachron architecture reveals how each pyroclastic current developed marked local and regional spatial variations in response to progressive burial and modification of the topography. At a single instant, the base of a current was a granular-fluid in some locations but fully dilute and turbulent elsewhere, and these locations shifted as the topography changed during the eruption. The variations in the current are recorded by numerous superbly-exposed gradational transitions from stratified to massive facies, both laterally and in the flow direction. We demonstrate that, in contrast to the commonly accepted paradigm, regionally widespread currents deposit in restricted, localised zones. Surrounding these depositional zones the currents bypass without depositing. The locations of deposition then gradually shift with time, and the sheet is assembled beneath the sustained current in a diachronous fashion. Onlap relationships indicate that the base of the Poris ignimbrite sheet, and even bases of individual flow-units, are markedly diachronous: deposition of a flow-unit commenced and ceased at different times in different places. Our study suggests that: (A) models of density currents that incorporate only pre-existing topography (e.g. from DEMs) may give misleading results for hazard assessment, because the topography changes during emplacement; (B) during hazard assessments, the likelihood of bypassing and non-deposition must be considered to avoid significantly under-estimating the frequencies and scales of previous pyroclastic currents from pyroclastic successions; and (C) the entire flow history of a current at a given site is commonly not recorded by the deposit at that site, even where preservation appears to be complete.

## 24 Oral

### Dam-break experiments on water and gas-fluidised granular flows: insights into the physics of fines-rich pyroclastic flows

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We carried out dam-break experiments on water flows and made comparison with published works on equivalent flows of mixtures of gas and particles, in order to investigate the physics of fines-rich pyroclastic flows. The experiments consist of the instantaneous release of a volume of water, initially at rest in a reservoir, thus generating a transient flow that propagates into a horizontal channel. The experimental apparatus consists of a 10 cm wide and 3 m long channel connected to a reservoir of the same width. We investigated reservoir aspect-ratios (height/length) of 0.25–8. Experiments were recorded using high-speed video. Image analysis was used to describe flow shape and velocity. We made comparison with experiments on initially fluidised, dense granular flows carried out in an apparatus of same dimensions and with similar volumes of material released. The particles used are nearly spherical glass beads with a density of 2500 kg m-3 and grain size in the range 45 to 90 m. The particles are fluidised in the reservoir, and the flow defluidises as it propagates, as no air flux is provided from the base of the channel. During initial stages of emplacement following release, height (hf) and front velocity (U) of the water flows are similar to those of equivalent fluidised granular flows. This suggests a fluid-like, Newtonian behaviour with negligible inter-particle friction for these dense granular flows. Both types of flows propagate at nearly constant height and velocity. The ratio of the flow height over the initial height in the reservoir is hf/h0=0.16–0.19 and 0.19–0.22 for water and granular flows respectively. In both cases, the initial Froude number Fr0=U/(gh0)1/2 and the flow Froude number Fr=U/(ghf)1/2 are independent of the reservoir aspect ratio. Fr0=1.2–1.4, similar for both water and granular flows, and is only slightly less than the value of 1.41 expected for orifice flow. In contrast, Fr for granular flows is about 2.6, which is somewhat lower than the value of about 3.2 for water flows. This is explained in terms of enhanced energy dissipation caused by momentum exchange between the interstitial gas and the particles. After the initial phase, granular flows suddenly come to halt and form a deposit whose height is similar to that of the parent flow, whereas water flows propagate and thin until viscous forces dominate. It is argued that fines-rich, dense pyroclastic flows can be modelled as Newtonian fluids, except at late stages just before final deposition.

## 25 Oral

### Surface wave instabilities and pyroclastic flow emplacement

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We draw evidence from the 1993 pyroclastic flow deposits at lascar volcano, Chile, for composite pyroclastic deposit fans having been emplaced by granular flows that exhibited inertial instabilities on their flow surfaces. The instabilities played an integral role in flow emplacement, generating unsteadiness and the development of successive waves, which in the final stages of runout, emplaced discrete onlapping units now identifiable within the deposit lobes. Visualization of these features is aided by the unique perspective provided by ground-penetrating radar (GPR), a tool that we believe has remarkable potential in unraveling transport processes of geophysical mass flows. Surface wave instabilities are already known from other types of natural and experimental granular flows, and on a theoretical basis are anticipated within the context of volcanic granular avalanches. Their existence is relevant to a series of on-going debates including the significance of flow units, interpretation of source-versus flow-derived current unsteadiness, and the nature of density profiles through pyroclastic density currents. This work will use the convincing evidence from Lascar to 1) present a case for considering the role surface wave instabilities may have played during deposition at other sites, and 2) strongly advocate using geophysical tools, such as GPR, for advancing our understanding of deposit-wide as well as detailed field relationships.

# 2.3 – Tephra

## 26 Oral

### The tephra archives: Notes on the application of tephra in volcanological and environmental studies

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The objective of this presentation is twofold. Firstly, I will present a brief summary of the contribution made by the two pioneers in the field, namely Sigurdur Thorarinsson and George Walker. Secondly, I will give an overview of Holocene explosive volcanism in Iceland.

The term tephra was brought into modern terminology in 1944 by Sigurdur Thorarinsson to describe all pyroclasts that leave a volcanic vent by air, regardless of type, size or shape. Thorarinsson developed the concept of tephrochronology, the application of layers of tephra as time-parallel marker horizons in regional studies of the environment and as a tool to reconstruct the eruption history of Icelandic volcanoes. He intergrated tephra stratigraphy and written accounts of historical eruptions into a detailed tephrochronological framework that was expanded into the prehistoric by mapping of major tephra layers as regional markers.

Individual tephra layers are records containing information on intensity and mechanism of the eruption that produced the deposit – more specifically it provides information on the type of activity, on the magnitude of the eruption, on the course of eruptive events, on the vigour with which the magma was erupted, on the destruction potential of the eruption, etc. Many researchers have helped to decipher these records. The person who contributed most to our understanding of these records and who demonstrated their potential to us was – in my view – George Walker. He did so in a series of publications in the 1970ies and 1980ies. Quantification of the key characteristics of the tephra deposits and linking them to particular types of activity was a major achievement that catapulted a generation of volcanologists towards better understanding of volcanoes and their behaviour.

Explosive volcanic eruptions constitute a very substantial part of volcanism in Iceland. Of about 200 confirmed eruptions since ~870 AD nearly 65% left tephra layers as the only evidence of the eruption, over 75% emitted a tephra layer and four out of every five tephra layers are of basaltic composition. Close to 100 silicic tephra layers of Holocene age have been identified in Icelandic terrestrial soils. Volumes of uncompacted silicic tephra layers range from < 0.01 $km^3$ to >10 $km^3$, with nearly 50% of known tephra volumes lying between 0.1 and 0.5 $km^3$. Deposition of ~800 basaltic tephra layers during the last 9000 years is anticipated but only a part of that record is preserved in terrestrial soils. Volumes range from <0.01 $km^3$ to >10 $km^3$, the majority lying between 0.1 and 1 $km^3$.

## 27 Oral

### Askja 1875, a complex plinian eruption: Welding and its implication for eruption dynamics

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The climactic plinian eruption of Askja Volcano 1875 was accompanied by low fountaining eruptions along a fissure segment extending to the north and the southwest from the main plinian vent as well as dry pyroclastic surges originating from a southwestern vent. The proximal deposits of the plinian phase thus exhibit very complex relationships; a sequence of widely dispersed fall, pyroclastic surge and low fountaining deposits which are often welded and rheomorphosed locally around the northern and southwestern rim. We focus here only upon the welded deposits on the northern rim of the caldera.

The proximal deposits on the northern rim can be separated into alternating white, non-welded pumice fall that can be traced outwards to merge with the widespread medial distal fall and grey/black sometimes welded deposits which have a markedly more restricted dispersal and coarser grain size including pumice bombs up to 9 meters in diameter.

Welding is concentrated in the dark layers but not confined to them, impinging on the intervening white layers and appears to be due to a combination of a) the thermal contribution of large meter-sized spatter bombs which locally weld surrounding finer clasts and b) heat intrinsic to the deposit, in regions remote from spatter bombs.

From the patterns of welding of the dark low fountaining deposits we infer vent positions both northeast and southwest of the plinian vent. Welding together with detailed stratigraphic mapping suggests that the period of proximal plinian sedimentation also included intense but short-lived fire fountaining from vents adjacent to that feeding the main plume.

## 28 Oral

### Early Holocene Tephrochronology in West Iceland and its Application for Paleoclimate Studies

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Tephrochronology plays a prominent role in Holocene paleoclimate studies and tephra layers have been widely used for age determinations and correlations throughout the North Atlantic area. We have established the tephra stratigraphy of four lacustrine-sediment cores, lying on a transect from south to northwest Iceland, collectively providing a near-continuous high-resolution tephrochronological record extending as far back as 12 ka BP. Here we focus on the period from 4 to 12 ka BP. The geographical positions of the lakes relative to the active volcanic zones in Iceland allow us to discriminate between marker layers of regional and local importance. A total of 86 layers have been analyzed in the cores for the period in question; 80 are basaltic, 3 dacitic and 3 rhyolitic. Most of the layers (94%) are produced by subglacial phreatomagmatic eruptions at ice-capped volcanoes in the Eastern Volcanic Zone (EVZ).

Thus far we have identified 6 large regional marker layers in the period of concern; the Vedde tephra (~11,980 cal BP), the SILK A9 and A8 layers (~7,500 and 7,300 cal BP) and the H5 and H4 layers (~7,000 and 4,260 cal BP). We have also identified three successive layers at ca. 10,000 cal BP formed by eruptions spaced over approximately 100 years. These three layers are identical in major element composition to the Saksunarvatn tephra (10,180 cal BP) but which of the three is Saksunarvatn is not known at this stage. We have identified 12 layers of more local importance that can be correlated between at least two sites and dated them to within approximately 100 years, using the regional markers. These are three layers with chemical affinity to the Veiðivötn volcanic system (ThE-1 ~9,400 cal BP, ThB-2 ~8,700 cal BP and ThB-1 ~8,550 cal BP), two mildly alkaline layers most likely originating in the Hekla or Vatnafjöll volcanic systems (AlB-1 ~9,100 cal BP and the T tephra ~6,100 cal BP), five layers of typical Katla composition that are distinguished on the basis of differences in major element composition (AlA-5 ~8,950 cal BP, AlA-4 ~7,100 cal BP, AlA-3 ~6,800 cal BP, AlA-2 ~6,700 cal BP and AlA-1 ~6,300 cal BP), one layer originating in the Grímsvötn volcanic system resembling the composition of the Saksunarvatn tephra but with a slightly lower TiO2 content (ThA-1 ~8,700 cal BP), and one layer with low Na2O and K2O contents, presumably originating in the Western Volcanic Zone (ThH-1 ~8,600 cal BP).

## 29 Oral

### Dispersal Dynamics from Phreato-Sublinian Eruptions; The 1937 Vulcan Eruption, Rabaul Caldera, Papua New Guinea

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The 1937 phreato-subplinian Rabaul eruption, which built a tuff cone, is one of the 10 worst volcanic disasters since Krakatau. It had not been studied in detail. 40 outcrops were visited in 1985 (GPLW). Thickness was measured, samples grainsize-analysed. Observations from 1937 have been reanalysed. Water-magma interactions produced mainly fine ash at the Vulcan vent, windblown to W/WNW. The dispersal pattern is near-identical to that of the 1994 Vulcan eruption during which an 16–20km high, ice-rich, bent-over eruption column depositing abundant mud-rain was observed from space. The 1937 and 1994 eruptions have highly similar thickness decay rates (among steepest on record). Ice-coated ash particles/aggregates are much larger, leading to premature fallout in turn accounting for the steep decay rate. The 1937 trend displays a break-in-slope confirming Ht ~ 15–20km. Both eruptions produced damaging mud flows and deep gullies from wholesale column collapse at eruption switchoff. Some 1937 accounts contain evidence for hazardous volcanogenic tornadoes generated by a bifurcating, bent-over eruption column. Grainsize analyses are very similar in the fine grainsizes indicating an ashcloud flushing process dominated dispersal. The eruption was also accompanied by the fiercest electrical storm ever reported in the area. Only the coarse-tail grainsizes are locally variable. This indicates alternance between wet subplinian and dry strombolian fragmentation, from rapidly alternating ingression and outflux of external water into the vent. Generally, it emerges that phreato-subplinian eruptions have much more in common with severe thunderstorms than previously recognised: they generate water and ice-rich updrafts (leading to premature fallout), form (ash-filled) hailstones and (mud)rain, produce brief intense flashfloods (at switchoff) and deep gullying, are associated with fiercest lightning and hazardous tornadoes. This is an end-member case where an eruption generates its own severe weather, which in turn controls ash dispersal and hazards.

## 30 Oral

### The Landbrotsholar pseudocrater field, characteristics of rootless cone tephra

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The Landbrotsholar pseudocraters field covers an area of some 50 $km^2$. It is therefore the largest pseudocraters field in Iceland. Number of craters, within the Landbrotsholar area, run on thousands. Highest crater within the field rises 65 m above sea level, with its rims rising 20 m above its surrounding. The pseudocraters field of Landbrotsholar is situated in a lava flow that has been named locally, Landbrotshraun. Some discussion has been about its origin. Thoroddsen (Thoroddsen 1894) was the first to suggest that the lava was originated in the Eldgja eruption in the 10th century. Thorarinsson (Thorarinsson 1951; Thorarinsson 1981) had some doubts first when he started research in the area but finally concluded that the lava was originated in the Eldgja eruption. Later Larsen (Larsen G 1979) confirmed the findings of Thorarinsson and showed that the Landbrotshraun was related to Eldgja 934 AD eruption. Jonsson (Jonsson 1987) has pointed out the highly complex tephrocronology of the Landbrotsholar region and reported findings of wood stubs in layers covering the lava. The wood was $^{14}C$ dated as far back as 2000 years. Here we will describe two key sections within the pseudocraters field. These two sections give insight into the complexity of the local stratigraphy within pseudocraters fields, also it is going to give valuable information on the processes active when pseudocraters are formed. Several other sections were analyzed but all the sections are into scoria quarries, excavated into pseudocraters. Thus those sections show the inner structure of the cones. SEM and microscopic studies of the tephra grains show that underlying strata play important role in crater formations. Fragments of magmatic origin show complex viscous textures commonly observed in high viscosity magmas but not in basaltic magmas as those forming the Eldgja lava.

# 3.1 – Explosive Volcanism

## 31 Oral

### Modelling eruption clouds and fall deposits from explosive volcanic eruptions

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My interest in understanding the physics of volcanic eruptions was triggered by a conversation that I had with George Walker in 1969. George had accumulated a very large amount of detailed quantitative information on the dispersal of fall deposits from, mainly, silicic eruptions. He had already evolved a qualitative understanding of the implications of variations of grain size with position in such deposits and was looking for someone to help him quantify his ideas on eruption clouds. I was looking for some way of developing and verifying models of how the physical environments (acceleration due to gravity, atmospheric pressure and temperature) on planets other than the Earth would influence the emplacement of volcanic deposits, and so it seemed logical that we should begin to collaborate on developing a quantitative, general model of pyroclast dispersal. We first investigated the speeds at which particles of various shapes and densities fell through gases, focussing on the Earth's atmosphere. I subsequently evolved a theoretical model of eruption cloud rise and pyroclast release for the Earth. The model went through various stages of elaboration and the basic ideas were subsequently taken over and extended by others, mainly Steve Sparks and Steve Carey, Andy Woods, and Lori Glaze. I shall discuss the issues on which further work is still needed in relation to such theoretical models, for Earth and, especially, for Mars. As it transpired, George and I did not publish many analyses of specific terrestrial deposits. I have therefore collected together all of the field data sets that George sent me over the years and applied our original model to them, generating a collection of values of eruption cloud height and mean horizontal wind speed for a large number of eruptions, especially from volcanoes in Italy, New Zealand and the Azores. Although there may be some systematic errors in the absolute values of cloud heights and wind speeds, the results provide a useful insight into patterns of activity over time in these regions.

## 32 Oral

### Large explosive volcanic eruptions: completeness of the Holocene record and application of extreme value statistics

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A rating system, the Volcanic Record Index (VRI), is developed to indicate how far back continuous knowledge of a volcanos eruptive history extends. Both how the knowledge of (1) when eruptions occurred and (2) the quantification of eruption size of eruptions are considered when assessing a volcanos VRI. Volcanoes with the potential for large explosive eruptions of a Volcanic Explosivity Index 4 or greater are rated according to the VRI scale. Analysis of global and regional trends indicate that the eruptive history for a third of the volcanoes considered is poorly understood and only a quarter of volcanoes eruptive histories are known from some point in the first half of the Holocene. There is a strong regional bias for how well a volcanos eruptive history is understood. Most volcanoes in developing countries have records extending only to when written records were introduced to the region, while volcanoes situated in developed countries or those that have had notable activity in the past few decades are typically extensively geologically studied. We have applied value statistical methods to evaluate the extent of under-reporting back in time for explosive eruptions of different magnitude. For magnitudes above VEI 4 the under-reporting ranges form 60 to 80% before 0 AD, with larger magnitude ereuptions having a better record than smaller eruptions. We have also applied extreme values statistics to the global record corrected for under-reporting to investigate magnitude frequency relationships and recurrence rates of eruptions of different magnitude.

## 33 Oral

### First 12-month of high-term resolution $SO_2$ flux measurements using an automated UV scanner array on Mt. Etna (Italy)

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Five automatic ultraviolet scanners were installed on the southern and eastern flanks of Mt. Etna in October 2004. Each scanner measures a horizon-to-horizon profile of $SO_2$ amount every 5 minutes. These profiles are transmitted via GSM modem to a base station where plume height is calculated, allowing geometric correction of profiles and derivation of the plume cross-section. Spectral evaluation is performed by non-linearly fitting a forward model to the observed spectrum, after removal of a dark spectrum which is collected a new for each profile. Combining the $SO_2$ cross-section with wind speed (obtained from a high resolution meteorological model) we derive the flux of $SO_2$.

Here we present the first 12-month results of $SO_2$ flux data (January–December 2005) from a Flame (FLux Automatic MEasurements) UV scanning array, together with a critical evaluation of errors and limits of the automatic analysis system. Plume height is a fundamental parameter to obtain low-error measurements of flux. With the current spacing of the stations and average plume height of ~ 1500m a.s.l, plume heights can be constrained ~ 40% of the time. For other measurements, we can calculate a flux assuming an average plume-height or using a wind speed-calibrated plume height. Moreover, it is the case that a scanner captures more than half but not a complete profile. Therefore, according these two parameters we have developed a quality evaluation of the flux measurements discriminating between four quality classes of $SO_2$ flux; (i) $SO_2$ flux derived from a profile with a complete plume and precise plume height; (ii) $SO_2$ flux value from precise plume height but incomplete plume profile; (iii) $SO_2$ flux derived from data with complete profile but without precise height and (iv) $SO_2$ flux from incomplete plume profile and without a precise height. High temporal resolution $SO_2$ flux data represents an important forward improvement in volcanic surveillance that provides real-time information of volcanic dynamics. Timesteps typical of the geophysical datastreams gain the opportunity of enquiring, in short-term and long-term, evidences of magma supply rates of volcanoes. Furthermore, real-time daylight volcanic plume scanning could provide an extremely useful tool for volcanic ash-cloud hazard assessments, essential for aircraft safety.

## 34 Oral

### Column collapse and pyroclastic flow dynamics by using 3D multiphase flow simulations

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In the last two decades both simple 1D (energy-line type) and more complex 2D (based on homogeneous or multiphase flow formulations) models were developed and applied to the modelling of volcanic column collapse and pyroclastic flow propagation. However, in both cases, the application of these models to real volcanoes was strongly limited by the neglection of important three dimensional effects that control the dynamics of these phenomena. In fact, both the complex fluid-dynamics of the processes and the system boundary conditions as the volcanic topography and atmospheric conditions introduce important 3D effects.

In this study, carried out in the ambience of the EU-funded EXPLORIS project, we have simulated the collapse of the volcanic column and propagation of associated pyroclastic flows in fully 3D conditions. This was done extending the transient 2D multiphase flow model PDAC2D (Neri et al., JGR 2003) to the third dimension. Such an objective has required a major development of the simulation software. The code was first re-engineered and translated in a modular format by using the FORTRAN 90 language. At the same time the code was parallelized by a domain-decomposition technique in order to properly cope the heavy computational demand required by the simulations. The code accuracy was also improved by implementing third-order numerical schemes and an immersed boundary technique for a better representation of the propagation of the flow. First simulations aimed to analyze the dynamics of column collapse and the control of the 3D topography on the propagation of the flows will be presented. Simulations refer to column collapse scenarios associated to a sub-Plinian eruption at Vesuvius. The eruptive mixture was represented by a continuous gas phase of water vapour and two classes of pyroclasts of 30 and 500 microns. Conditions of the eruptive mixture at the crater rim were computed by simulating the decompression of the flow in a 2D crater and adopting conduit exit conditions from previous studies. The simulations lasted for about 20 minutes of eruption time requiring few days of computational time by using 500 processors on a IBM SP5 supercomputer. Simulation results show the transient and chaotic dynamics of the fountain and allow to quantify the different collapsing regimes of the column as a function of the percentage of mass collapsed. Simulations also describe the major effect produced by the relief of Mount Somma, on the northern slope of Vesuvius, on the propagation of flows and areas invaded.

## 35 Oral

### Listening to fire fountains at Etna volcano (Italy)

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Eruptive episodes from the 2001 eruption of Etna volcano show a series of Strombolian explosions, which may lead to a fire fountain at the vent. Insights into fire fountain formation is provided by a close comparison between episodes leading to fire fountains (13/07/2001) and those solely with Strombolian explosions (4/07/2001). Because visual observation shows that Strombolian explosions are the consequence of bursting large bubbles at the top of the magma column, the measured sound wave for each explosion is modelled by the bubble vibration at the surface. The best fit between measured and synthetic waveforms gives the bubble radius (5 m), length (8 m) and overpressure (0.39 MPa). The time sequence of each episode show the evolution of the number of bubbles, their gas volume and overpressure, giving a total gas volume of $7.4 \times 10^{7}$ $m^3$ per episode.

Such large bubbles fill most of the space available in the conduit, hence are slugs. The thickness of the lateral film around a bubble is estimated at 0.5 m for a magma viscosity of 30 Pa.s, giving a conduit radius of 5.5 m and an upwards velocity of 3.7 m/s. The Reynolds number, based of the bubble nose, is around 3000. Therefore a bubble develops a long turbulent wake, whose maximum length is 20 times the slug length. Such long wakes are not steady and periodically form and detach from the slug bottom. Small bubbles accumulate into the wake as the bubble rises upwards from the depth of the reservoir towards the surface.

Comparing the intermittency between explosions (several tens of seconds) with the combined length of a slug and its wake suggests that fire fountains results from merging several slugs and their wake together just below the surface. This is in excellent agreement with videos from fire fountains at Etna.

Although not all the eruptive episodes show a transition from Strombolian explosions to fire fountains, each episode can be interprated as resulting from the withdrawing, by coalescence, of a foam layer accumulated in the reservoir. The few days intermittency between eruptive episodes results in re-building the foam to its maximum stable height, giving a gas flux in the reservoir of $2.7 \times 10^{-2}$ $m^3/s$. Such a gas flux is obtained by rising small bubbles with diameters between 0.2 and 0.7 mm, gas volume fractions between 0.1 and 1 % and assuming a reservoir area of $10^6$ $m^2$.

# 3.2 – Experiments

## 36 Oral

### The influence of laboratory experiments in volcanology

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The role of laboratory experiments in recent developments of volcanology will be discussed. Some comments on the (few) experiments carried out by George Walker will be made. We will then concentrate on a description of the exchange flow of relatively dense, viscous fluid in a container connected by a vertical pipe to a container beneath it, initially full of relatively light fluid. A non-dimensional value for the flux of dense fluid down the tube can be determined as a function of the ratio of the two viscosities and the Reynolds number by using dimensional analysis and balancing buoyancy, inertial and viscous forces as appropriate. We will then discuss quantitative applications of these results to the movement of magma in volcanic conduits. The concepts indicate how bi-directional convection in the conduit between a lava lake and a magma reservoir deep in the crust is the essential ingredient in the explanation of the long standing problem that the amount of degassing of sulphur dioxide from a lava lake in a volcanic crater can exceed by many orders of magnitude that consistent with the amount of lava solidified in the crater.

## 37 Oral

### Experimental fracture and flow of rhyolitic magma in shear triaxial deformation experiments on obsidian

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Knowledge of the conditions required for shear fracture and flow of rhyolitic magma is essential for modelling magma deformation in conduits, domes and lava flows. We have used a triaxial high-temperature deformation apparatus at University College London to investigate the brittle-ductile behaviour of calc-alkaline rhyolitic obsidian from Hrafntinnuhryggur, Krafla, Iceland. These are the first measurements of the shear strength and brittle-ductile behaviour of rhyolitic obsidian at simulated volcanic conditions.

The experiments were carried out at confining pressures up to 50 MPa, temperatures of 600–750 C and strain rates of $10^{-4}$->$10^{-5}$ $s^{-1}$. This P-T-e' range corresponds to magma in the glass transition interval at depths of <2 km and is relevant to shallow conduits, domes and lava flows. The results of our experiments indicate the shear strength, brittle-ductile threshold and post-failure frictional behaviour of rhyolitic magma. Preliminary analysis of the textures generated by brittle-ductile deformation of obsidian is also presented.

The acoustic emissions (AE) were recorded during each experiment and provide information on the mechanics of failure and post-failure frictional slip. The presence of AE supports the hypothesis that shear fracture of rhyolitic magma may trigger volcano-seismic events[1]. This research provides useful inputs for modelling of brittle-ductile magma deformation, as well as constraints on the temperatures and strain rates at which distinctive brittle-ductile textures are generated in glassy lavas.

[1] Tuffen H, Dingwell DB & Pinkerton H (2003) Geology 31:1089–1092.

## 38 Oral

### Topographic and Structural Effects on Dike Propagation and Eruption

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We have modelled magma flow in a dike rising in a crack whose strike runs from a highland or ridge to an adjacent lowland to determine the effect of topography on the flow, using FLAC3D. The aperture, a, is calculated as a variable in a sheet of zones of fixed width, d, during the simulation as a function of model deformation. The permeability tensor of each zone is adjusted at each time step in response to the pressure in the cell according to the relationship

k_ij=delta_ij*a^3/(12*µ*d)

which is obtained by equating the flow through the layer of permeable zones from Darcy's law with the flow of a fluid with viscosity in a crack of width a from the Poiseuille law under the same gradient. We found a distinct tendency for the flow to be diverted away from the highland end of the strike toward the lowland. For the 4-km long strike length we modelled, eruption was offset between 500 and 1250 m toward the lowland from the center of the strike length. Separation of the geometric effect of the topography from the topographic overburden effect on lateral confining stresses at the crack indicates that both contribute to the effect. Although this analysis explains a tendency for volcanic eruptions to occur in low lands, it does not preclude eruptions on highlands. If the strike on the dike is parallel to the length of a ridge, the effect described here will not operate. Another possibility is that the strike length of a dike may be so short that its strike does not extend far beyond the edge of the ridge. A separate simulation used UDEC to investigate the interaction of magma in a vertical dike with normal faults and stratigraphy. We found that steeper faults are more easily intruded and that, as the magma rises to within a few hundred meters of the surface, sills are intruded into stratigraphic discontinuities in the hanging wall but not into the foot wall. The particular configurations modelled mimic topography and structure around the proposed nuclear waste repository at Yucca Mountain, Nevada, USA, so that the results relate to the volcanic hazard at the site. Field observations at nearby Paiute Ridge indicate behavior of Tertiary basalts intruding rhyolite tuffs similar to that in our UDEC models.

## 39 Oral

### Investigating the dynamics of Vulcanian explosions: scaled laboratory experiments of particle-laden puffs

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Scaled laboratory experiments analogous to Vulcanian eruptions were conducted, producing particle-laden jets, plumes and thermals. A reservoir of a mixture of water and methanol plus solid particles (kaolin or Ballotini glass spheres) was pressurized and suddenly released via a rapid-release valve into a 2 ft by 2 ft by 4 ft plexiglass tank containing fresh water. The duration of the subsequent flow was not pre-determined but was limited by the potential energy associated with the pressurized fluid rather than by the volume of available fluid. Experimental conditions were varied in a number of ways. Particle size (~4 microns & ~45 microns) and concentration (2-5vol%) were varied in order to change particle settling characteristics and control bulk mixture density. Water and methanol in varying proportions created a light interstitial fluid to simulate buoyant volcanic gases in erupted mixtures. Variations in reservoir pressure and vent size allowed exploration of controlling source parameters, buoyancy flux and momentum flux. Mass flux at the vent was measured by an in-line Coriolis flowmeter sampling at 100 Hz, allowing rapidly varying buoyancy and momentum fluxes to be recorded. The velocity-height relationship of each experiment was measured from high-speed video footage, permitting classification into the following groups: long continuously accelerating jets; accelerating jets transitioning to plumes; low-energy thermals; collapsing fountains which generated density currents. Field-documented Vulcanian explosions exhibit this same wide range of behavior (Self et al. 1979; Sparks & Wilson 1982; Clarke et al. 2002a,b; Druitt et al. 2002), demonstrating that regimes obtained in the laboratory are relevant to natural systems. A generalized framework of results was defined as follows. Increasing Mo/Bo for small particles (4 microns; settling time>>experiment duration) pushes the system from low-energy thermals toward high-energy, continuously accelerating jets; increasing Mo/Bo for large particles (=45 microns; settling time < experiment duration) pushes the system from a low collapsing fountain to a high collapsing fountain; and increasing particle size for collapsing fountains decreases runout distance of gravity currents and increases production of current-generated plumes.

## 40 Oral

### An experimental investigation of sill formation and propagation in layered elastic media

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A series of experiments are described where dyed water (a magma analogue) was intruded into solid gelatine (a crustal analogue) to investigate the formation of sills. We considered a layered gelatine system with contrasting adjacent layers. By varying the density and rigidity of the gelatine we found that sills form when the upper layer is more rigid than the lower layer, with intrusion occurring in a plane directly below the interface. Dykes were observed to propagate to the surface when the Youngs Modulus ratio of upper to lower gelatine layers was less than one. Dyke arrest occurred when the upper layer was more rigid and the interface was strong. Two varieties of sill formed when the upper layer is more rigid than the lower layer and the interface was sufficiently weak. The form of the intrusion depends on the balance of driving pressures and the Youngs Modulus ratio of contrasting adjacent layers. When the rigidity ratio is high and there is a large driving pressure the feeder dyke completely converts to propagate as a sill. However, when the rigidity ratio and driving pressure are both close to one a dyke-sill hybrid forms. Under these conditions the sill formation is accompanied by contemporaneous dyke intrusion into the overlying more rigid layer. During sill propagation deformation structures such as faults and en echelon fractures are formed into the lower layer. Sill propagation dynamics are controlled by viscous dissipation along the length of the sill; causing acceleration with increasing length. Our study suggests that rigidity contrasts may play a major role in the location of sills and development of igneous complexes. In ancient cratonic areas the moho is a suitable site for the preferential formation of sills with higher rigidity continental crust overlying weaker mantle. Mantle plumes impacting ancient continents provide a situation in which large sills can form to fractionate prior to eruption on flood basalts. The boundary between the upper and lower crust (Conrad discontinuity) may provide a preferential focus for the emplacement of sheets of silicic magma at continental arcs where the lower crust is weakened by prolonged heating and possible hydration.

# 3.3 – Deformation

## 41 Oral

### Plate boundary deformation in Iceland observed by GPS

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Iceland provides a unique area to study a multitude of geodynamic phenomena due to its location astride a divergent plate boundary influenced by an active mantle plume. The biggest effort to measure crustal deformation in Iceland was undertaken in two nationwide GPS campaigns (termed ISNET) in 1993 and 2004. The network consists of about 120 campaign sites evenly distributed over the whole country. The data provide the first velocity and deformation rate maps of the whole country. Several M>5 earthquakes, volcanic intrusions and eruptions occurred during the time spanned by the two surveys. The southern part of the plate boundary was affected by the June 2000 earthquake sequence, when two Mw=6.5 earthquakes occurred in the South Iceland Seismic Zone (SISZ) and three M~5.5 earthquakes were triggered on the Reykjanes Peninsula. We correct the station displacements for the June 2000 earthquake sequence in SW Iceland and exclude data from a station on Grimsfjall that is affected by several eruptions, to generate a continuous velocity field for the strain rate calculations.

The horizontal velocities show spatial variation in the spreading rate across the active volcanic zones, with slightly elevated spreading rates in northern Iceland, following the 1975–1984 rifting episode in Krafla. The map of vertical velocities shows significant uplift rates over a large part of central Iceland, with a localized maximum of 2 cm/yr west of the center of the Iceland mantle plume. The large extent of the area of significan uplift (~1 cm/yr) is rather surprising. The cause of the high uplift rate is unknown, but glacial rebound due to the thinning of the Vatnajökull ice cap since 1890 is likely to contribute. Possible deep magmatic activity or increased pressure in the mantle plume could also explain the long wavelength uplift signal.

The main feature of the strain rate field is the extension across the active rift zones, with the highest dilatation rate (~0.15 ppm/yr) in the Northern Volcanic Zone, decreasing to about 0.1 ppm/yr in south Iceland. The maximum shear strain rate is highest along the Reykjanes Peninsula (~0.02–0.04 ppm/yr) and in the northern part of the Northern Volcanic Zone (~0.03 ppm/yr), but lower in the SISZ (~0.02 ppm/yr). The high maximum shear strain rate in the Reykjanes Peninsula is due to thinner (~7 km) elastic brittle crust there than in the other shear zones (~15 km).

## 42 Oral

### Excess drift in Iceland

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In 1975 G.P.L. Walker wrote an article in Nature on excess spreading axes and spreading rate in Iceland. His opinion 'that the spreading rate is several times greater in part of Iceland than elsewere on the Mid-Atlantic Ridge' was immediately opposed in the magazine. Walker answered the critics in a quick response article, after that the matter became silent. The problem of excess spreading in Iceland has however been mentioned once in a while since, Plmason e.g. regarded in 1981 the inconsistency between spreading and rock ages as an unsolved problem in Icelandic geology. This inconsistency surely exists and it has appeared in various ways in the geological data through the time. Its simplest manifestation is that the country is too wide from east to west compared to its age. Iceland is spreading away from rifting axes crossing the country where new crust is constantly produced. Consequently the oldest rocks, which date from roughly 14 million years, are found on the east and west coasts, 480 km apart. This indicates a spreading rate of 3.4 cm/yr, which differs widely from the generally accepted N-Atlantic rate of 1.8 cm/yr.

Magnetic anomalies have been studied to find out the behaviour of the drift on the ocean floor. On dry land they are not as convenient for this purpose, there the most representative formations are central volcanoes. They have local origin, limited extent and are usually formed near to the rift axis. In this paper the trajectories of 25 Icelandic central volcanoes away from the rift zones are tested. All of them have one thing in common; they seem to be drifting faster than the accepted drift rate in the N-Atlantic. The mean drift rate is 70% higher than on the adjacent ocean floor. This excess is far too high to be explained with some errors or uncertainties in the ages or distances. The enhanced drift seems to evince a steady and long-lasting geological process because young and ancient volcanoes show similar behaviour. The drift also seems to have been symmetric at the axis with fairly similar rate towards east and west through the time.

It is concluded that there is a discrepancy between the dates and rates in Iceland. The long time drift rate seems to be higher than has been suggested by using general models for plate velocities and it is higher than on the ocean floor around the island.

## 43 Oral

### Current Plate Boundary Deformation and the State of Stress on the Reykjanes Peninsula, South Iceland

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The Mid-Atlantic Ridge comes onshore on the Reykjanes Peninsula where it forms a complex and highly oblique left-lateral spreading zone between the North American and the Eurasian Plates. The NUVEL-1A predicted spreading rate across the Reykjanes Peninsula is 19 mm/yr in the direction of N103E. The plate boundary on the Reykjanes Peninsula has an overall orientation of N79E and is expressed at the surface as five NE-striking volcanic fissure swarms and a series of NS-oriented strike-slip faults. Seismicity along the plate boundary shows both spatial and temporal variation and earthquakes tend to occur in distinct clusters separated by areas of low seismicity.

Annual GPS campaigns have been conducted on the Reykjanes Peninsula since 2000, when two M6.5 earthquakes and several triggered events occurred in southwest Iceland. Using the geodetic data collected since 2000, we study the spatial and temporal variation of the crustal deformation. We model the postseismic velocity field assuming left-lateral motion along the Reykjanes Peninsula and opening across the Western Volcanic Zone. Preliminary results for a locking depth of 7–8 km indicates deep-slip rates of 20–24 mm/yr parallel motion and up to 10 mm/yr of extension across the peninsula.

We investigate the state of stress at seismogenic depths along the Reykjanes Peninsula using earthquake focal mechanisms from the SIL network. The large seismic data set allows us to estimate a large number of stress tensors, providing high stress resolution in both space and time. We study how the stress estimates compare to the surface deformation inferred from the GPS data and how to integrate the data sets to constrain our models.

## 44 Oral

### What controls the level of earthquake activity associated with magmatic intrusions?

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The currently two most important surveying tools in volcano monitoring are observations of seismicity and surface deformation. Magma migration within the Earth's crust is frequently associated with seismic activity, occurring often as distinct earthquake swarms. Understanding the exact nature and significance of these swarms is important when evaluating volcanic crisis situations. There seems, however, to be no general correlation between the amount of seismic energy release, and the rate and volume of magma on the move, which may complicate immediate risk evaluation.

It has previously been shown that stressing rate appears as the controlling factor on the occurrence of seismicity during intrusion. However, we emphasize that this is only true under specific circumstances. Other factors influence the evolution and resulting seismic energy release of a magmatically induced seismic swarm, and each intrusion scenario needs to be evaluated separately.

Based on three case studies, where seismic swarm activities have been confirmed through deformation measurements to be related to magmatic movements, we attempt to evaluate potential controlling factors on earthquake swarm activity. All case examples are located within Iceland, but in different tectonic settings.

1. The Hengill triple junction, situated where two extensional plate boundaries join a transform zone. The area experienced a period of unusually persistent earthquake activity from 1994 to 1999, contemporaneously with ground uplift at a rate of 1–2 cm/yr.
2. The Eyjafjallajökull volcano, situated in a volcanic flank zone where extensional fractures are only poorly developed. Two minor earthquake swarms, in 1994 and 1999 were associated with a cumulative surface uplift of more than 35 cm.
3. The Krafla rift segment, forming part of an extensional plate boundary. The area experienced an active rifting period with numerous intrusive and extrusive events during 1975 to 1984. The cumulative horizontal expansion was up to 9 meters.

The relationship between the volume change and the associated cumulative seismic energy release is strikingly different for these three cases. We suggest that, in a general approach, the most important factor governing the level of seismic energy release is the background stress state, whereas the stressing rate only plays a dominant role when either a) stress in the intruded area is close to the yield strength before intrusion or b) when the intrusion is extraordinarily voluminous and rapid.

## 45 Oral

### Present-day volcano deformation in Iceland

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Here we review the geodynamic signals detected by volcano geodesy during the last 15 years in Iceland. Extensive measurements of crustal deformation have been conducted using a variety of geodetic techniques. They include levelling, electronic distance measurements, campaign and continuous Global Positioning System (GPS) geodesy, and interferometric analysis of synthetic aperture radar images (InSAR). Results from these measurements provide a comprehensive view of the behaviour of Icelandic volcanoes. Between inflation, intrusion, and eruption episodes, volcanoes are likely to deflate or show no sign of seismic activity. Subsidence rates are often in the range of a few millimeters to a few centimeters a year, reducing progressively with time since the last eruption or intrusion at the volcano. Cooling and contraction of magma, outflow of magma, can cause subsidence or it can relate to plate spreading. Volcano subsidence or lack of deformation is often interrupted by episodic magma flow towards near-surface locations. Such magma recharge has been observed geodetically at Hengill, Hekla, Eyjafjallajökull, Katla, Grímsvötn, and Krafla volcanoes, with inflow inferred to last from a few months up to two decades. In the last 15 years, four volcanic eruptions, three intrusive events and two >M6 earthquakes have occurred. In recent years, the Grímsvötn and Katla volcanoes have exhibited annual, centimeter-scale inflation, while the Hekla and Torfajökull volcanoes have inflated at rates an order-of-magnitude less. Subsidence is occurring presently at the Askja and Krafla volcanoes. Within the period of geodetic measurement, signals consistent with no deformation are typical for most of the 35 active volcanoes in Iceland.

# 4.1 – Dikes

## 46 Oral

### Geometry and emplacement of dykes in composite volcanoes and rift zones

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Among George Walkers many outstanding contributions were his studies of dykes for understanding the mechanisms of rift-zone spreading and volcanic eruptions. His dyke studies in East Iceland and in Hawaii formed the basis of much subsequent work in this field. Walkers conceptual models of dyke swarms and dyke emplacement were based on meticulous field studies. Recent work combines detailed field studies with numerical modelling, focusing on the effects of mechanical layering and local stresses on dyke emplacement.

Field studies show that most dykes (including inclined sheets) are extension fractures that propagate only if the local stresses in the volcano are favourable to fluid-driven extension fractures. No dyke-fed eruption can thus occur unless the local stress in each rock unit through which the dyke must pass on its way to the surface favours extension fractures; any rock unit with an unfavourable local stress would tend to arrest the dyke and prevent the eruption.

Most volcanic eruptions are fed by dykes. It follows that in order to make reliable forecasting of eruptions we must understand dyke propagation, and thus the local stresses, in volcanoes. The local stresses are determined by the loading conditions (the tectonic regime, the magma-chamber geometry and its excess pressure) and, in particular, the mechanical properties of the rock units that constitute the volcano. Composite volcanoes and rift zones are composed of numerous layers (strata) many of which have contrasting mechanical properties, particularly at shallow depths. Some lava flows, welded pyroclastic units, and intrusions, for example, may be very stiff (with a high Youngs modulus), whereas young and non-welded pyroclastic and sedimentary units are often very soft (with a low Youngs modulus).

Field studies indicate that most dykes never reach the surface; most potential feeder-dykes become arrested in some rock units. Here I present field data and numerical stress-field models explaining, first, how the local stress fields ahead of a dyke tip are largely determined by the mechanical layering, and, second, why most dykes injected during unrest periods become arrested and the potential eruptions prevented.

## 47 Oral

### An experimental investigation of the emplacement and dynamics of sills in layered elastic media

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Sill formation has been investigated experimentally by intruding dyed water (a magma analogue) into solidified gelatine (a crustal analogue). The aims were to identify potential controls on sill emplacement and to characterise sill propagation dynamics. We considered a layered gelatine system set under hydrostatic conditions with adjacent layers having contrasting properties. Sills were found to form when feeder dykes intersected the boundary between a more rigid (stronger) layer overlying a less rigid (weaker) layer and sill intrusions occurred at the layer interface. Conversely, dykes were unaltered by the layer interface and propagated to the surface when the rigidity ratio of upper to lower layers was less than unity, that is when the upper layer was weaker than the lower layer. Two varieties of sills were observed depending on the balance of driving and fracture pressures and on the rigidity ratio of contrasting adjacent layers. For large rigidity ratios and large driving pressures, the feeder dyke completely converts to propagate as a sill. However, when the rigidity ratio and the ratio of driving to fracture pressure are both close to but greater than unity, a dyke-sill hybrid forms. Under these conditions, the sill formation is accompanied by contemporaneous dyke intrusion into the overlying more rigid layer. During sill propagation, deformation structures were also observed to form into the lower layer. Also, these experiments show that sill propagation dynamics are controlled by viscous dissipation along the length of the sill, causing acceleration with increasing length. This contrasts with the dynamics of basaltic dykes, which are controlled by the time-dependent failure of solid rock at the dyke tip, and has implications for the geometry and size of sills, which are commonly thicker than dykes of identical magmas. This study suggests that rigidity contrasts may play a major role in the location of sills and development of igneous complexes. In ancient cratonic areas the moho is a suitable site for the preferential formation of sills with higher rigidity continental crust overlying weaker mantle. Mantle plumes impacting ancient continents provide a situation in which large sills can form to fractionate prior to eruption on flood basalts. The boundary between the upper and lower crust (Conrad discontinuity) may provide a preferential focus for the emplacement of granite sills and sheets at continental arcs where the lower crust is weakened by prolonged heating and possible hydration.

## 48 Oral

### Theoretical aspects of particle movement in flowing magma: implications for the anisotropy of magnetic susceptibility of dykes

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Following a seminal paper on the anisotropy of magnetic susceptibility (AMS) of dykes in the Ko'olau dykes, O'ahu, most studies of this type assumed that the axes of maximum susceptibility (kmax) should define an opposed imbrication pointing along the direction of magma flow, and that this orientation should be preserved along the dyke. This assumption is partially based in a model predicting a cyclic movement of the particles that is overlooked in most AMS studies without further justification. The consequences of considering the full rotation of the ellipsoidal particles, as actually predicted by the theory, in the expected AMS of dykes are examined in this work. The complete version of the motion of ellipsoidal particles is then incorporated in a model of magma movement that takes into consideration the distribution of shear deformation within the dyke as predicted from the velocity gradient of the moving magma. Although based in an idealized scenario of magma movement within a dyke, the model developed here explains satisfactorily the sometimes observed variation of AMS along flow direction in one dyke, and provides a simple explanation for many of the 'abnormal' magnetic fabrics that have been reported in dyke swarms around the world, including the Koolau dykes. Furthermore, it is possible to take advantage of the systematic variations of the AMS predicted by the theory to devise sampling schemes that can be used to add more confidence to the interpretation of the AMS measurements.

## 49 Oral

### Emplacement of shallow dikes and sills beneath a small basaltic volcanic center – the role of pre-existing structure (Paiute Ridge, southern Nevada, USA)

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Late Miocene sills and dikes in the Paiute Ridge area of southern Nevada were emplaced in an extensional setting beneath a small volume, alkali basaltic volcanic center. Dikes (400–5000 m long, 1.2–9 m wide) mostly occupy pre-existing E-dipping normal faults. Elastic deformation of the wall rocks alone cannot explain dike dimensions; inelastic deformation, wall rock erosion by flowing magma, and syn-emplacement extension of the host structural system also contributed to dike widths. After primarily subvertical emplacement, flow focused toward the southern end of one of the dikes to form a volcanic conduit. This dike and a fault-hosted radial dike subsequently were subject to high pressures due to transient volcanic processes. Three small sills (extending laterally up to ~500 m into the hanging wall blocks, and 20–46 m thick) and two larger sills (each having lateral dimensions ~1 km) locally branch off some dikes within ~250 m of the paleosurface. Individual small sills extend only into the hanging wall blocks of the faults that host their parent dikes, and are connected to the dikes by stems that are only a few tens of meters wide; elsewhere along their strikes the parent dikes extend above the sills. This mode of sill emplacement was caused by local rotation of principal stresses related to the intersection of the dike-hosting fault planes with the complex contact between relatively strong Paleozoic carbonates and weak Tertiary tuffs. Orientation of bedding planes in the tuffs controlled the direction of sill propagation. The three most areally extensive sills formed lopoliths with sagging roofs, indicating interaction with the free surface.

## 50 Oral

### Conduit dike swarm in Unzen Volcano: Scientific drilling

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Unzen (Kyushu, Japan) is a composite volcano developed in the active graben under the NS extensional tectonic stress field, where magma is expected to intrude as dikes. Unzen Scientific drilling Project, aiming at penetration into the conduit and carried out during 1999–2005, brought the core samples and logging data that verified the conduit dikes including that of the last eruption. The target of the drilling was set into the hypocenter region of isolated volcanic tremors that had occurred in the depth between 0.5 to 1.5 km under the crater just before the dacite dome growth. Isolated tremors also occurred in the same region after the eruption ended, though shallow, low frequency earthquakes had taken place during dome growth. The conduit zone penetrated is about 1.5 km below the crater, and is occupied by homogenous volcanic breccia probably of the diatreme origin. The zone was as wide as 400 m, containing parallel (EW trending), multiple dikes and fuffisite veins. Dikes that is highly plausible of the last eruption is as thick as 40 m thick. Identification was based on chemical consistency between the sample and erupted dacite, including the Sr isotope ratios and on the temperature distribution. It is surprising that the formation temperature of the conduit was as low as about 180 deg C only 9 years after the eruption ended. Rock samples (dacite) even of the last eruption are highly altered hydrothermally; for example, hornblende phenocrysts were replaced by aggregation of chlorite, carbonate and rutile within the pyrite-bearing devitrified groundmass. These facts suggest continuous strong circulation of hydrothermal fluid soon since the end of the last eruption. Each dike is a composite dike, consisting of sub-dikes up to 7 m wide, which are sometimes characterized by chilled part and shear zones in the margins. Hydrothermal alteration sometimes develop from cracks or thin tuffisite veins. It is likely that tuffisite veins and central cracks or veins in hydrothermal alteration area represent isolated tremors before and after the dome growth, respectively. In contrast to the presence of quartz phenocryst in the erupted dacite, the conduit lavas lack quartz phenocryst except in chilled part, where partially resolved quartz survives. It is likely that slow cooling in the intrusive condition allowed its resorption in the dacite mixed magma, while not in quenched (erupted) phase.

# 4.2 – Modelling

## 51 Oral

### Long-term evolution of volcanic systems: Coupling between edifice growth, magma storage and transport at shallow crustal levels

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A large strato-volcano generates stresses in the upper crust whose magnitudes are comparable to those of tectonic stresses and fluid overpressures within magmatic feeding systems. This presentation will explain how this affects magma storage and eruption.

Three regimes may be defined for magma transport as a function of magma buoyancy, edifice size and density stratification in the upper crust: (1) eruption through the summit, (2) storage beneath the edifice, (3) horizontal propagation to feed a distal vent. As eruptive products build up a thick lava plateau or a stratocone, dense primitive magma can no longer erupt through the focal area. Large horizontal propagation distances can be achieved if magma is negatively buoyant at shallow depth. A horizontal dyke cannot extend in the vertical direction beneath an edifice and develops a 'hump' at some distance from the focal area, which may feed a distal eruptive center. With time, a laterally extensive volcanic field develops. As magmas evolve due to storage and differentiation, eruptive vents occur increasingly closer to the focal area.

A mature volcanic system eventually develops a shallow magma reservoir. Tensile failure of the walls occurs at the top of the reservoir beneath the edifice summit, implying the focussing of volcanic activity through a central vent system. Beneath a large strato-volcano, the magmatic overpressure at the onset of eruption increases as the edifice grows and decreases following edifice destruction.

During an eruption, the reservoir pressure is constrained to lie within a finite range: it cannot exceed the threshold value for reservoir failure, and cannot decrease below another threshold such that feeder dykes get closed due to magmatic underpressure. As long as the critical reservoir pressure for roof failure lies outside this operating range, caldera collapse cannot occur and the volcanic system can sustain repeated eruptions. With a large volcanic edifice, large tensile stresses develop in the roof region, whose magnitude increase as the reservoir deflates during an eruption. Failure of the roof region may occur before the end of eruption when the edifice exceeds a critical size.

## 52 Oral

### Cladistic analysis applied to the classification of volcanoes.

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Cladistics is a systematic method of classification that groups entities on the basis of sharing similar characteristics in the most parsimonious manner. Here cladistics is applied to the classification of volcanoes using a dataset of 59 Quaternary volcanoes and 129 volcanic edifices of the Tohoku region, North-East Japan. Volcano and edifice characteristics recorded in the database include attributes of volcano size, chemical composition, dominant eruptive products, volcano morphology, pre-dominant landforms, volcano age and eruptive history. Without characteristics related to time the volcanic edifices divide into two groups, with characters related to volcano size, dominant composition and edifice morphology being the most diagnostic. Analysis including time based characteristics yields four groups with a good correlation between these groups and the two groups from the analysis without time for 108 out of 129 volcanic edifices. Thus when characters are slightly changed the volcanoes still form similar groupings. Analysis of the volcanoes both with and without time yields three groups based on compositional, eruptive products and morphological characters. Spatial clusters of volcanic centres have been recognised in the Tohoku region by Tamura et al. (2002). The groups identified by cladistic analysis are distributed unevenly between the clusters, indicating a tendency for individual clusters to form similar kinds of volcanoes with distinctive but coherent styles of volcanism. Uneven distribution of volcano types between clusters also suggests distinctive evolution as magmatic systems. Cladistic analysis can be a useful tool for elucidating dynamic igneous processes that could be applied to other regions and globally. Our exploratory study indicates that cladistics has promise as a method for classifying volcanoes and potentially elucidating dynamic and evolutionary volcanic processes. Cladistics may also have utility in hazards assessment where spatial distributions and robust definitions of a volcano are important, as in locating sensitive facilities such as nuclear reactors and repositories.

## 53 Oral

### Application of granular column collapse physics for modelling pyroclastic flows.

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The majority of existing numerical pyroclastic flow models utilise the same governing equations and physics to describe the characteristics of the flow throughout its depth. High concentrations at the base of the flow result in a collapse of any dilute cloud assumptions, due to a change in the governing physics for this more granular regime. Thus uniform bulk continuum models can not accurately replicate this region. To answer this issue, we use a two layered approach to develop a model for the formation of a basal granular avalanche due to sedimentation from the ash cloud, as observed during an eruption column collapse. We describe the development and validation of a model for the formation, growth and subsequent collapse of a depth averaged granular avalanche. The governing physics is described by bulk continuum conservation equations, while the avalanche is assumed to be isothermal with a constant density. These equations are solved using the Finite Volume Method, with approximate Riemann solvers to first order accuracy utilising the Godunov method. The sedimenting source from the ash cloud is applied using a combined two stage Runge Kutta TRBDF2 method, maintaining stability in our results. Investigations into the effect of sedimentation on simple granular collapses will be discussed. Our model successfully illustrates the formation, growth and subsequent stopping phase of a granular avalanche, the first stage in construction of the full two layer pyroclastic flow model. Further simulations of the behaviour of the flows along slopes and over a change in gradient will be presented. These results are an important step in developing an accurate pyroclastic flow model, which replicates both the physics and run-out of the natural phenomena, vital for any hazard and risk assessment.

## 54 Oral

### The role of degassing and magma convection in magma chamber dynamics and the formation of igneous cumulate deposits.

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The mechanisms of passive volcanic degassing, and the speciation of released gases, have been studied extensively. In contrast, the impact of this process on magma chamber dynamics and the textures of cumulate rocks found in igneous complexes has received little attention. We have investigated this process using laboratory analogue experiments, analytical modelling, and field studies.

We have developed a model of how a plume of degassed, crystal rich magma, descending from an open conduit, interacts with the convection within a low viscosity magma chamber. While the turbulent plume entrains ambient material, the convecting ambient extrains material from the plume at a rate proportional to the mean convective velocity within the magma chamber. Thus, the plume will grow whilst entrainment dominates, but as the mean plume velocity decreases, extrainment by the convecting ambient can become dominant, eroding the plume away. Extrained crystals are released into the bulk of the magma chamber, and under favourable conditions, are seeds for further crystal nucleation and growth. Laboratory analogue experiments are used both to test assumptions on how the plume and convecting ambient surroundings interact, and to illustrate the end-member situations of plume-dominated and convection-dominated regimes.

The end-member regimes we identify are as follows. (1) Plume motion is strong c.f. convection. In this case the plume reaches the bottom of the magma chamber, and spreads as a density current. Most degassing-induced crystals are kept separate from the chamber interior. Crystal deposition is principally from gravity currents. (2) Plume motion is weak c.f. convection. The plume is fully incorporated into convection before reaching chamber floor. All degassing-induced crystals are released into chamber interior, possibly acting as seeds for nucleation and further crystal growth within the main body of the chamber. Strong deposition is expected from gravity-driven settling of crystals.

These end-member regimes form texturally and petrographically distinct cumulates, as have been observed in the Duke Island Intrusion, Alaska and Rhum Layered Intrusion, Scotland. We predict what textures and geochemical trends will occur in each regime, and compare these predictions to features observed in the Rhum Layered Intrusion. By bringing together field, analytical and experimental studies, we are able to explain how different cumulate textures can be formed, and the magma chamber conditions required to form them.

## 55 Oral

### Magma intrusion and deformation predictions: Sensitivities to homogeneous, isotropic, Poisson-solid, and half-space assumptions

*Timothy Masterlark*
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Expansion-source models can simulate static deformation caused by the intrusion of magma within a volcano. These models usually take the form of an expansion-source embedded in a homogeneous, isotropic, Poisson-solid half-space (HIPSHS). However, the widely accepted HIPSHS assumptions poorly approximate the structures typically expected for volcanoes. This study computes Greens functions for displacement due to an expansion-source at depth using a combination of analytical and finite element models (FEMs), for which HIPSHS assumptions are not required. Interferometric synthetic aperture radar (InSAR) imagery suggests that Okmok volcano, Alaska, subsided more than a meter due to lava extrusion during the 1997 eruption of the volcano. Formal inverse methods, which use an HIPSHS model, precisely locate an expansion-source of -270 MPa at a depth of 3100 meters beneath the center of the caldera. Both the analytical HIPSHS and verified FEM approximations of an HIPSHS expansion-source model serve as reference models. Other model configurations examined here relax the combined suite of HIPSHS assumptions and sequentially allow for topographic effects; higher values of Poissons ratio; transverse anisotropy; and material property configurations that simulate a layered elastic problem domain combined with a variety of weak caldera configurations. Differences between predictions obtained by loading a non-HIPSHS model with the expansion-source estimated for the HIPSHS model illustrate the sensitivity of predicted displacements to each of the HIPSHS assumptions. Forward model predictions are relatively insensitive to topographic effects and layered elastic properties; somewhat sensitive to anisotropic elastic properties and the choice of Poisson's ratio; and particularly sensitive to the presence of weak materials within a caldera. Interestingly, deformation predictions are least sensitive to the two deviations from the HIPSHS assumptions (layered elastic properties and topographic corrections) that are occasionally relaxed in analyses of volcano deformation. Additionally, both analytical and FEM-generated Greens functions isolate and reveal the influence of each HIPSHS assumption on estimations of the expansion-source depth and pressure that are determined from inverse methods. Inverse results are particularly sensitive to the model configuration simulating a weak caldera, which produces a deeper (4500 m) and lower magnitude (-220 MPa) expansion-source estimate. Although the RMSE misfits for all model configurations are similar because of the high radial symmetry in the InSAR image, the spatial characteristics of the residual deformation patterns contain systematic differences. This suggests that the common practice of correcting deformation data for expansion-source contributions may introduce prediction artifacts into the residual.

# 4.3 – Magmas

## 56 Oral

### Magma flow, storage and emplacement in the Icelandic crust: Constraints from space and terrestrial geodetic observations

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Extensive geodetic measurements have revealed variable deformation characteristics of Icelandic volcanoes. Combination of multiple geodetic techniques gives time-series of deformation as long as 40 years (levelling), three-dimensional displacement vectors (GPS) and spatial resolution exceeding one observation per hectare over large areas (InSAR). Interpretation of observed deformation gives constraints on mode of magma transfer, emplacement and storage in the crust, allowing quantitative estimates of volumes of sub-surface magma movements. The geodetic measurements show that volcano deformation is spatially and temporally episodic, with persistent deformation taking place at only few volcanoes. The geodetic data, interpreted in conjunction with other sources of information, conform to the idea that only some of the central volcanoes in Iceland have presently significant molten magma chambers in the crust. These include the Krafla, Askja, Bárðarbunga, Grímsvötn, Hekla, Katla and Torfajökull volcanoes. Out of these, multiple magma chambers identified as separate pressure sources are suggested at Krafla, Askja and Bárðarbunga volcanoes. Magma inflow to these systems has been documented at a rate of 0.1–20 $m^3/s$ over a period as long as 15 years, with volumes of up to 1 $km^3$. Other volcanoes do apparently not receive sufficient inflow of magma to sustain shallow magma chambers at present times. Intrusive episodes there are characterized by emplacement of magma that solidifies prior to the next magma injection, such as those that occurred in Hengill and Eyjafjallajökull last decade. Number of processes are observed to cause deformation, the rate of which decays in an exponential manner, with decay constants ranging from hours (eruptions, fast intrusions) to decades (gradual decay in volcano subsidence). One volcanic system in Iceland stands out for its high long-term rate of subsidence. Askja caldera has deflated at a rate of about 5 cm/yr since at least 1983. Reduction of pressure in lower crustal part of the magmatic system at Askja in response to plate spreading, and an open link from its 3 km deep magma chamber to this deeper source may provide the conditions needed to produce this behaviour.

## 57 Oral

### Magma dynamics revealed by SIMS depth-profiling of plagioclase from Soufrire Hills Volcano

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Secondary ion mass spectrometry (SIMS) is currently being developed as a means to determine compositional changes in the outer microns of igneous phenocrysts, and from these changes, resolve the physical conditions in the volcanic system prior to eruption. Previous experimental work performed on the magma composition of Soufrire Hills Volcano (SHV) found that the Anorthite (An) composition of plagioclase resulting from decompression-induced growth corresponds with the $H_2O$ pressure of the magma (i.e. a depth of formation). Other independent analyses suggest a correlation between Li contents of eruptive products and degassing conditions of the host magma. Elevated levels of Li are hypothesized to represent closed-system conditions and depleted levels are thought to indicate open-system degassing. Our previous work has shown that An and Li trends in the outer few microns of plagioclase are dependent upon the style of eruption that produced the crystals, with effusive and explosive samples displaying distinct trends. Here we present new data from depth-profiling analysis of plagioclase phenocrysts collected from the August 3rd, 1997 dome collapse of SHV. For the first time, we have achieved depths >25 microns into the crystal surface, allowing us to see continuous changes through multiple phases of growth. Given the approximate range of growth rates for plagioclase feldspar in an active volcanic system and the 1997 SHV effusion rate, this chemical profile could represent changes associated with magma ascent, as well as changes in magma chamber conditions. Anorthite contents show two increasing and decreasing trends, with one small An peak near15 microns depth and a large An peak close to the crystal surface. Li contents are low at depth but then rise to higher values near the crystal surface. Potassium is high at depth, possibly representing analysis of sieve textured plagioclase, but decreases by an order of magnitude near the crystal surface. Iron, titanium, and zirconium are low at depth, but increase by an order of magnitude near the crystal surface. The depth profile may record pressurization or depressurization events, changes in degassing state and/or reheating and mixing events associated with injection of a more mafic magma at depth. Additional phenocrysts from both explosive and effusive eruptions of SHV are currently under examination in order to better constrain the cause of the observed crystal zonation and determine if the transition from magma chamber crystal growth to conduit growth can be clearly identified.

## 58 Oral

### Tephra reveals Holocene magmatic evolution and eruption frequency of the subglacial Katla volcano, south Iceland

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Recent unrest at the subglacial Katla volcano, Iceland, has spurred a new interest in its prior behaviour. Its historical activity has been thoroughly studied as well as the chemical composition of the erupted products, which are of homogeneous FeTi basalt composition. However, it is not certain that the last 1000 years are representative for the entire Holocene concerning both eruption frequency of Katla and its magma composition. Therefore we have undertaken a study of the tephra stratigraphy in a composite soil section east of the volcano. The section records ~8400 years of explosive activity from Katla volcano in 208 tephra layers of which in total 111 samples were analysed for major-elements. An age was calculated for the Katla layers using soil accumulation rate (SAR) estimated from previously $^{14}C$-dated marker tephra layers. Given the assumption that wind directions were similar through the ~8400 years, the eruption frequency was twice as high as known for the last 1000 years or 4 eruptions per century. Temporal variations of major-element compositions of the basaltic tephra divide the ~8400 year record into eight intervals of 630–1750 year duration. These compositional variations are characterized by steady, irregular and increasing value of the incompatible element $K_2O$ correlated with changes in other major-element concentrations. The magmatic evolution is mainly controlled by fractional crystallisation although binary mixing between a basaltic component and a silicic one occurs in few cases. Silicic (SILK) eruptions do not affect the magmatic evolution of the basalts but high basaltic eruption frequency seems to trigger the SILK eruptions. The compositional variability of the tephra suggests different behaviour of the plumbing system beneath Katla volcano. Two cycles are observed each one beginning with a simple plumbing system, displayed by a steady composition of the major elements, followed by a sill and dike system, which is characterized by irregular major element composition vs. time leading to the formation of a magma chamber, represented by a regularly increasing $K_2O$ value. The eruption frequency of each period shows increasing value from a simple plumbing system to a sill and dike system, which drops again when a magma chamber has evolved. According to this model the Katla volcano is actually in a period of a simple plumbing system with a relatively low eruption frequency.

## 59 Oral

### Record of T-time-composition histories of magmas preserved in zircon zoning

*Calvin Miller, Vanderbilt University, NASHVILLE, United States of America*

A case study using the USGS/Stanford SHRIMP-RG demonstrates the potential of in situ elemental and isotopic analysis of zircon in elucidating complex histories of magmatic systems. The Spirit Mountain batholith is a large, subvolcanic intrusion in southernmost Nevada. Zircon ages document a 2 m.y. history (17.4-15.3 Ma), with common entrainment of older antecrysts in younger units. Field relations and elemental chemistry of rocks ranging from felsic cumulates to leucogranites demonstrate both fractionation and frequent recharging. Titanium concentration ranges from 2.5 to 27 ppm, and T(Ti-zrc; Watson & Harrison 2005) ranges from 680 to 880 C; in individual grains, T varies by as much as 170 C, and large fluctuations are evident from core to rim. Ti and other elements are correlated and document both extreme fractionation and dramatic reversals in melt evolution trends, which are also evident in cathodoluminescence images of zoning. Hf content triples (6000-19,000 ppm) and U and Th rise by a factor of 250 (20-5000, 50-13,000 ppm) from least to most evolved zones. Rims with extremely evolved compositions are common, but interiors also frequently record low T(Ti-zrc) and highly evolved compositions. REE patterns all show positive Ce and negative Eu anomalies and extreme HREE/LREE fractionation, as expected, but in detail they also show considerable variability (e.g. larger Ce/Ce* and lower LREE in 'cooler' zones); these changes are interpreted to reflect accessory mineral crystallization and perhaps presence of oxidizing fluids. As T(Ti-zrc) falls to ~680–720 C, rate of increase in U and Th rises dreamatically, consistent with extreme fraction near the solidus.

The fluctuations in T and melt chemistry indicated by zoning patterns in elemental concentrations are consistent with the complex sequence inferred from petrology and U-Pb analysis, but the frequency of events implied by zoning is beyond the resolution of U-Pb (~100–500 k,y.). To achieve higher time sensitivity and to compare the magmatic history preserved in erupted zircons to those in plutons, we plan further studies on very young volcanic rocks that will combine in situ U-series dating (uncertainties to <10 k.y.) with elemental analysis.

## 60 Oral

### Abstract withdrawn

# 4.4 – Iceland

## 61 Oral

### Notes on George Walkers contribution to the geology of Iceland. Controversies and a discovery of fundamental significance

*Kristján Sæmundsson, Iceland Geosurvey, Iceland*

Walkers research in the late fifties and early sixties put the geology of Iceland on a firm basis. The relevant papers are classics which ever since they appeared have been perused and built upon by everyone working in this field. Rather than reviewing the outcome of those highly productive years, two partly controversial issues are touched upon and an observation of major practical importance pointed out, which has apparently been overlooked by most. The relevant papers were all published in the mid seventies, ten years after Walkers main field of research shifted towards active volcanism.

In 1975 Walker published a paper entitled 'Excess spreading axes and spreading rate in Iceland'. Needless to say that the observations presented are good and solid and the discussion certainly stimulating. In this paper Walker showed his interpretation of the volcanic zones as being divided into discrete structural units, later referred to as volcanic systems. Icelandic geologists had come up with a very similar division for the Reykjanes Peninsula and the Northern Volcanic Zone where this is most obvious but also for the central and southern part of Iceland as well (Tryggvason 1973), where relationships are less clear and in fact not fully explained yet. Walkers main additions were the Hofsjökull volcano with its rift zones. He also defined here for the first time the mostly dormant Öræfajökull-Snæfell rift zone a part of which (Breiðabunga) he encountered as volcanic valley fillings in SE-Iceland.

As to the spreading rate Walker concluded “that the southern half of Iceland had a spreading rate several times greater than that of both the northern half and some submerged parts of the Mid-Atlantic Ridge. This would imply according to him that magma plays a very active role in creating and jacking open the fissures there, indeed, perhaps in causing crustal spreading to occur”. There is a different solution to the spreading rate problem. This involves lateral migration of the spreading zones which was well known at the time, and accommodation of the excess volcanic production by downflexuring due to excessive loading which was less known. As to the latter implication later discovered tectonic extension at magma-limited slow spreading midocean ridges argues against the active role of magma in driving crustal spreading.

In the seventies the nature of seismic layer 3 beneath Iceland (Vp ~6,35–6,5 km/s) was a major issue in Icelandic geology. It was apparent from Palmasons (1971) map showing the depth to this layer that it came closest to the surface underneath eroded central volcanic complexes. For us geologists it was thus rather clear that it was of intrusive origin. In 1975 Walker published a paper entitled 'Intrusive sheet swarms and the identity of Crustal Layer 3 in Iceland'. Here Walker concluded about the nature of crustal layer 3 from a basic, inclined sheet swarm of regional extent exposed in the deeply dissected part of SE-Iceland, where it forms locally up to 80% of the country rock. He pointed out also that sheet swarm cupolas occur in central volcanoes. The common explanation was that rocks of lower density captured the basic magma at a level now referred to as the level of neutral buoyancy. Walker showed the sheets as dipping downwards towards the spreading axis. A closer study of the sheet swarm in SE-Iceland has revealed that it is actually of the cupola type, split into several segments centered about central volcanic complexes with dips converging towards their roots. A regional Vp velocity of 6,35–6.5 km/s is reached about 2 km below sea level in SE-Iceland which supports Walkers interpretation. It is unlikely though that this is the lower limit of extrusives (2 km have been stripped off by erosion). Form thermal gradients Palmason suggested that Layer 3 might be amphibolite facies volcanics, whereas modern view sees it as grading from greenschist (of increasing dyke density) to amphibolite (of gabbroic intrusions).

In 1974 Walker published a paper entitled 'The structure of Eastern Iceland', a most clear and concise summary of his findings. One of his figures shows isochrons for lavas and dykes in the area. The angle between the two is about 30. The dyke swarms thus traverse from the volcanic centres 40–60 km into crust which is up to 3–4 M years older than the dykes themselves. The same relationship prevails in many other parts of Iceland including the present day spreading zones. Thus both on the Reykjanes Peninsula and in the Northern Volcanic Zone the fissure swarms diverge by about 30° from the strike of the spreading axis itself as defined by the row of the central volcanoes along it. This relationship is of major practical interest as regards many of the low temperature geothermal fields which occur in old crust on the distal parts of the fissure swarms. Perhaps the most spectacular case is Hofsjökull with its fissure swarms extending NW towards Skagafjörður and SW towards Hreppar and Skeið with ample geothermal activity on both branches. Walker in his 'Excess spreading . .' - paper of 1975 already showed both, however, only the proximal part of the southwestern one. In geothermal research this relationship has been one of the main criteria for evaluating geothermal resources and possibilities in an area extending far away from the volcanic zones of Iceland, where secondary permeability is a prereqiusite. It is tentatively concluded that dykes extend to the distal parts of the rift zones, but only rarely reach the surface.

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## 62 Oral

### Eruptive history of Ljósufjöll volcano, Iceland: mush, mixing and Milankovitch?

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Ljósufjöll volcano encompasses the largest outcrop of Quaternary silicic volcanics (rhyolite and trachyte) on the Snaefellsnes Peninsula, western Iceland. At least thirteen different silicic eruptive units have been identified at Ljósufjöll, spanning an age range of at least 500 ka. Older eruptive units have probably been eroded and / or buried by subsequent volcanism at the volcano.

The silicic volcanics range from trachytes through to peralkaline rhyolites. Magma mingling is ubiquitous, with mafic inclusions contributing <1%–15% of the rocks. Feldspar phenocrysts are common in most units. Feldspar glomerocrysts are also common in the trachytes, less so in the rhyolites, and exhibit complex growth histories. The major and trace element geochemistry of the rhyolites is consistent with fractional crystallisation of trachytic parent magma, crystallising an assemblage of over 80% alkali feldspar. The bulk major element chemistry of the modelled crystallising assemblage is similar to some of the trachyte units. It is suggested that the silicic volcanism at Ljósufjöll is due to the presence of a silicic mush chamber: the peralkaline rhyolites represent the interstitial melt, while the trachytes represent remelted mush.

Ar-Ar dating of feldspar crystals has revealed that inherited argon (i.e. when an eruption samples crystals (xenocrysts) that are older than the eruption itself) is a significant problem at this volcano. Many eruptive units for which inherited argon is a problem are effusive and incorporation of old xenocrysts from cold, solid material, without degassing of the xenocryst, seems unlikely. It is suggested that the source of the inherited argon bearing 'xenocrysts' is the mush chamber itself Comparing the Ljósufjöll data to published phase equilibria, petrographic and argon diffusion information and the local geothermal gradient gives mush temperature of 600–650°C and a depth of 6–7.5 km.

The Ar-Ar ages suggest that eruptions are most frequent during the onset of glaciation. These peaks in activity occur ~20 ka after a maximum in the obliquity of the Earths tilt which is associate with a glacial termination. It is suggested that unloading during a glacial termination increases basaltic activity in the area and replenishes the mush chamber. Crustal stresses due to compression during glacial loading result in filter pressing of the mush and rhyolite eruption.

## 63 Oral

### Abstract withdrawn

## 64 Oral

### Hydrothermal Heat Sources in Icelandic Central Volcanoes – Lesson learned from South Eastern Iceland –

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It has been assumed that hot magmas are the ultimate heat sources for the Icelandic high-temperature hydrothermal systems, while direct mineralogical evidence for the heat transfer processes from within the active systems has been meagre. This may change within the next few years in relation to the IDDP (Iceland Deep Drilling Project). IDDP's principal goal is to directly address the heat source question by drilling down into the heat transfer zones in order to extract hydrous fluid at supercritical conditions for energy production. Most likely will the first deep IDDP hole be within the Krafla Central Volcano. The Krafla Volcano involves a large magma chamber at shallow depths (3–7 km), reactivated during the Krafla eruptions in 1975–1984. The deepest drill holes a Krafla reach to some 2.2 km depth, and a dense intrusive rock complex, including sheeted dykes, granophyre- and gabbro intrusions, characterizes the drill field above the inferred magma chamber. The secondary mineralogy reaches lower greenschist facies and scattered evidence of contact metamorphic mineral assemblages are mentioned in drill hole reports. The fluid temperatures follow the boiling point with depth curve (BPD-curve) pretty closely for a large part of the drill fields above the magma chamber.

While the Krafla heat source(s) is inaccessible without drilling, former heat sources in many of the Tertiary central volcanoes are quite accessible, especially those in SE-Iceland, where the extent of erosion reaches deeper into the volcanoes than elsewhere in the island. In one of these, extensively studied by the author, clear mineralogical evidence for hot rock fluid interactions is found, both within and enveloping magmatic heat sources. In the case of large gabbro intrusions, inner aureoles of sandinite facies metamorphic rocks developed, enveloped by outer aureoles of hedenbergite-bearing skarn mineral assemblages in lava vesicles. These witness volatile reactions at temperatures from ca. 900°C downwards, via 600–400°C supercritical fluids into the hydrothermal system outside, controlled by the BPD-curve at much lower temperatures. Most likely will similar hydrothermal mineralogy be encountered at 3–5 km depth in the IDDP drill hole at Krafla, and ripe for detailed comparison. The major intrusions studied in SE-Iceland were emplaced at relatively shallow depths (1–2 km), but deeper level major intrusions are also exposed, involving aureoles which have not been studied in detail. The author likes to encourage students to pick up the flag and continue studies initiated by George P.L.Walker more that half a century ago in Eastern Iceland.

## 65 Oral

### Investigation of basalt-fluid interaction using stable isotopes in Reykjanes magma-hydrothermal system

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The Reykjanes geothermal field, located on the landward extension of the mid-Atlantic ridge, is the proposed location for a 5 km deep drill-hole being developed by the Iceland Deepcore Drilling Project to investigate supercritical fluids as a potential energy resource and to explore geologic processes in actively spreading margins, such as fluid-rock interactions. In order to evaluate the nature and extent of rock-fluid interactions and the applicability of Reykjanes as a proxy to oceanic spreading margins, it is necessary to understand the source and composition of hydrothermal fluids within the system. Previous studies have shown from elemental composition and salinity that Reykjanes geothermal fluids are likely hydrothermally modified seawater. However, hydrogen isotopes indicate a significant component of meteoric water, with dD values as low as -23‰. To evaluate the source of hydrothermal solutions we have analyzed hydrogen isotope compositions of geothermal epidote ($dD_{epidote}$) from wells RN-10 and RN-17 within the Reykjanes system at depths of 1–3 km. dD values of Reykjanes geothermal epidote from well RN-10 range from -64‰ to -70‰ between 1.0 and 2.1 km depths. dDepidote is -74.1‰ in well RN-17 at 3.0 km depth, and published dDepidote values from well RN-8 at 1.6 km depth are -48‰. dDepidote from Reykjanes systems are higher than the dDepidote value of -115 of the Nesjavellir geothermal system, which is dominated by meteoric water that has a dD composition of approximately -79‰. However, dDepidote values from the Svartsengi geothermal system of -68‰ are comparable to those from well RN-10, despite the fact that Svartsengi is a mixed meteoric-sea water system with a salinity of about two thirds that of Reykjanes. Hydrogen isotope compositions of geothermal fluids in equilibrium with Reykjanes epidotes are predicted using the temperature dependence of epidote-water H/D fractionations reported by Chacko et al. (1999) and measured downhole temperatures or temperatures approximated from the boiling point curve at depth. Results suggest that Reykjanes epidotes are not in equilibrium with present-day fluids (dDfluids ~ -20‰), but with fluids that more closely resemble modern meteoric water than hydrothermally altered seawater, with dDfluid values between -29‰ and -35‰. Additionally, spatial variability seen in the isotopic composition of Reykjanes epidotes indicates a more complex hydrothermal evolution than previously suggested. Further investigation of the relative importance of fluid mixing, rock-fluid interaction and evaporation is required before the hydrothermal fluids of the Reykjanes geothermal system can be accurately described.

# 5.1 Oral Poster Presentation

## 1 Poster

### Hiatus in the typical strombolian activity during the 2002–2003 Stromboli effusive eruption: $SO_2$ flux degassing and thermal release relationship as a marker of anomalous activity.

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For 2500 years, the typical activity of the Stromboli volcano (Aeolian Islands, Italy) has been characterised by regular small explosions (strombolian activity), which once or twice per year reach paroxystic levels. On 28 December 2002 a new effusive eruption started and continued until 21 July 2003. In May 2002 it was preceded by an increase in the intensity of strombolian activity and by a heightening of the magma level within the main conduit. In early December, both the intensity and the frequency of the explosions continued to increase, until the opening of a NE-SW eruptive fissure and the beginning of the effusive eruption on the afternoon of 28 December. After the onset of the 2002–03 Stromboli flank eruption, strombolian activity at the summit craters stopped. On 5 April a paroxysmal event occurred. This major explosion marked the decline of the effusive activity and the reopening of the summit crater conduits. Only on 1 June after seven months of effusion, did strombolian activity gradually resume becoming stable on 21 July after the cessation of the eruption. The 2002–2003 Stromboli eruption was a great opportunity to better our understanding of the connection between strombolian and effusive activity in relation to the feeder conduit processes. Here we describe the event through the correlation between COSPEC $SO_2$ flux measurements and FLIR thermal measurements carried out on the summit craters. The relationship between these data suggest three different stages of eruptive activity, and provide evidence of the fundamental role of 5 April paroxysmal explosion as a trigger for the re-establishment of typical strombolian activity at the summit craters. We also show how the relationship between $SO_2$ degassing and thermal release may play a prominent role in volcanic hazard assessment as a signal of anomalous activity at Stromboli.

## 2 Poster

### Vesiculation path of magma in the 1983 eruption of Miyakejima volcano, Japan

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The 1983 eruption of Miyakejima volcano, Japan, is one of the best documented mafic eruptions on the basis of direct observation, geophysical monitoring, and stratigraphical investigation (Aramaki et al. 1986). The eruption is characterized by simultaneous lava effusion and explosive sub-plinian (dry) eruptions with phreatomagmatic (wet) explosions. Here, the vesiculation of magma during the eruption is discussed based on systematic investigations of water content, vesicularity, and bubble size distribution for the products. The magmas are homogeneous in composition (basaltic andesite) and in initial water content ( $H_2O$=3.9±0.9 wt%), and residual groundmass water contents for all eruption styles are low ($H_2O$ <0.4 wt%) suggestive of extensive dehydration of magma.

For the scoria erupted during simultaneous dry and wet explosive eruptions, inverse correlation was observed between vesicularity and residual water content. This relation can be explained by equilibrium exsolution and expansion of ca. 0.3 wt% $H_2O$ at shallow level with different times of quenching, and suggests that each scoria with different vesicularity, which was quenched at a different time, provides a snapshot of the vesiculation process near the point of fragmentation. The bubble size distribution (BSD) varies systematically with vesicularity, and total bubble number density reaches a maximum value at vesicularity ~0.5. At vesicularity~0.5, a large number of bubbles are connected with each other, and the average thickness of bubble walls reaches the minimum value below which they would rupture. These facts suggest that vesiculation advanced by nucleation and growth of bubbles when vesicularity <0.5, and then by expansion of large bubbles with coalescence of small ones for vesicularity >0.5, when bubble connection becomes effective.

In addition, the presence of microlite may also be an important factor controlling the vesiculation path of magma. Microlite-poor melts in between bubbles are ruptured and thus these bubbles are connected easily, whereas microlite-rich melts persist in between bubbles because the microlites are bridging melt which would have been otherwise ruptured. This indicates that at least some types of microlites perform as inhibitors of bubble coalescence. Such an effect of small particles is well known in the foam industry and related fields, and is considered significantly to modify bulk mechanical properties such as the lifetime of foams. Some mafic sub-plinian scoria with different microlite contents show that the total number density ranges over as large as two orders in magnitude.

## 3 Poster

### Identification of Caldera Structure in Hong Kong

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Locating at the mouth of Pearl River Delta, Hong Kong shares high proximity with the maritime provinces of southern China in terms of geology. Igneous rocks in Hong Kong are regarded as part of the prominent magmatic belt of South China. Over 85% of land of Hong Kong is comprised of the Mesozoic granitic and volcanic rocks. The magmatic activities covered the period from mid-Jurassic to early-Cretaceous and were controlled by regional faults trending mainly towards NE. In the previous studies on structural control and tectonic setting of Mesozoic volcanism, a team of HK Geological Survey proposed that local volcanic activities were expressed in two forms: fissure type eruption and caldera-forming eruptions. However, the suggested location of calderas seems to lack field evidence.

In our study, a lithology-facie-structure analysis is adopted, which has been used for the study of volcanic structures in other parts of South China. Under this approach, the spatial and temporal relationships between different volcanic facies were taken as the major tool in caldera identification. Also, the vertical and horizontal distribution and variation of volcanic facies together with the change in orientation of textural features are taken as concrete proofs for the collapse of volcano. A revived caldera structure covering most of the Hong Kong Island and Kowloon Peninsula is now revised base on the distribution of geological units with related radial and concentric faults of local scale. Our data from the fieldwork show that there were two volcanic Plinian-type eruption cycles. The first one clearly shows a complete cooling unit and forms the main part of the caldera structure. It is comprised of basal surge layer, volcanic breccia and welded crystal tuff. The second cycle is represented by welded tuff with increasing amount of clast towards the center. Since this overlying unit is with textural features dipping in a different direction, it is interpreted to be eruption product after the collapse. At the center of this caldera, all these units are intruded by a granite body. The result of electron microprobe analysis on the feldspars of the granite indicates a formation temperature below 650°C and a water pressure about 5kbar. As the granite shares similar age and chemistry with the volcanic units, it is quite possible that the doming represents a revival of the same magma source in a high $PH_2O$ environment.

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## 4 Poster

### A basaltic feeder dyke in the Northeast Rift Zone of Tenerife, Canary Islands: geometry, segmentation and magma transport

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For a volcanic eruption to occur, it is normally necessary that a magma chamber becomes ruptured and a magma-filled fracture, a dyke, forms and is able to propagate to the surface. In rift zones, when a dyke reaches the surface, it causes a fissure eruption. Normally, eruptive fissures contain from several to many tens of aligned vents. In active volcanic areas feeder dykes are usually cover with lava flows and other eruptive materials.

The Montaa Colmenas eruptive fissure, located in the Northeast Rift Zone of Tenerife (Canary Islands), is exceptional in that its feeder dyke is very well exposed. Here we report results on the geometry and segmentation of this feeder dyke and the associated volcanic fissure. In this study, special attention was given to the morphology, attitude, and flow indicators in the dyke-rock as well as the associated deposits. We also made detailed measurements of the sizes, geometries and distribution of vesicles, and other flow indicators, in the rocks.

The Montaa Colmenas eruptive fissure is 2.4 km long and contains some 15 vents with a general NE-SW trend. The main vent is a cinder cone where the eruption gradually became concentrated. The other vents are mostly spatter cones and chimneys. There are several outcrops along the eruptive fissure where one can observe the transition between the tabular dyke segments and the spatter cones, chimneys and lava flows.

In several ravines eroded into the phonolitic pyroclastics at the surface, there are good exposures of the near-surface part of the feeder dyke. In these exposures, the dyke has a mean dip direction of 318° and dips about 76°. The dyke thickness changes along its length, but ranges between 8 and 61 cm. It has chilled margins with flow indicators indicating subvertical to inclined magma-flow directions. Rounded vesicles fit with the low viscosity of the dyke magma and, in shape, indicate dominantly subvertical magma transport.

## 5 Poster

# A double magma chamber explains the high eruption frequency at Piton de la Fournaise Volcano (Runion Island)

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Piton de la Fournaise volcano is a highly active volcano located in Runion Island. The volcano has been monitored since 1980. Since then the Volcanological Observatory has registered 46 eruptions and 8 unrest periods without eruption. The 6 years from 1992–1998 was a period of rest, interrupted only by one seismic swarm but no eruption.

Previous studies on the magma supply at Piton de la Fournaise suggest a sill-like shallow magma chamber located at sea level. The eruptions are generated by the injections of dykes from this shallow chamber. The petrology of the lavas shows gradual differentiation of the magma in the chamber, indicating, as has been proposed, that the potential increase of fluid pressure in the chamber due to differentiation may trigger the eruptions. In this model, the shallow magma chamber is thought to be refilled from a deeper magma reservoir during short events at intervals of 15 to 30 years. Eruptions of oceanitic magma (with a high content of olivine crystals) are then thought to occur during those short events when the shallow chamber is being refilled.

Based on various observations and mechanical considerations, we propose that the high eruption frequency is unlikely to be satisfactorily explained in terms of the differentiation of the magma in an essentially closed (though occasionally refilled) shallow magma chamber. We rather suggest that the shallow magma chamber is being essentially continuously supplied with magma from a deeper reservoir, and that this additional magma volume generates the pressure that ruptures the shallow chamber and triggers eruptions. Thus, our model is a double magma chamber where the deeper chamber is much larger than the shallow chamber, and where a continues supply of magma from the deeper chamber, over many years or decades, frequently 'overfills' and ruptures the shallow chamber.

The high eruption frequency indicates that nearly all dykes injected from the shallow chamber reach the surface. This suggests that the state of stress in the volcano is essentially homogeneous and favourable to extension-fracture (dyke) propagation. Extension fractures are presumably favoured because of extension in the central part of the volcano, associated with the instability of its eastern flank. The stress-field homogenisation is primarily related to the absence of abrupt changes in mechanical properties between layers, partly because they are all basaltic and partly because the lava pile has been somewhat homogenised as a result of hydrothermal circulation.

## 6 Poster

### What controls the explosive-effusive transition during rhyolitic eruptions? Insight from a subglacial eruption at Torfajökull, Iceland

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The Quaternary subglacial rhyolite deposits in Iceland provide a unique 'natural lab' for physical volcanological studies. Preservation and exposure of pristine proximal deposits and dissected lava bodies is the norm rather than the exception. As a result, processes such as magma fragmentation and foam collapse are recorded in detail, shedding light on the behaviour of magma in shallow conduits and factors controlling the explosive-effusive transition.

Previous studies at Torfajökull volcano have documented the contrasting styles of large-volume (>1 km$^3$) tuya-building eruptions (with an initial explosive phreatomagmatic phase) and smaller-volume effusive eruptions (dominated by quench fragmentation). Here we focus on the products of a ~0.2 km$^3$ eruption at Dalakvísl, Torfajökull, where both styles of activity occurred beneath ice >150 m thick[1].

The deposits are dominated by massive, blocky fine-grained ash that was generated by low-explosivity magma-water interaction within subglacial cavities a typical deposit emplaced in an effusive subglacial eruption. However, this grades into a distinctive pumiceous pyroclastic deposit that contains deformed obsidian sheets metres in length. Textures in the sheets show that they represent the remnants of rising foam domains that were fragmenting around their margins (due to vesicle coalescence and shear strain) whilst their centres were collapsing and welding to form dense obsidian. It appears that the efficiency of fragmentation progressively decreased during emplacement of the deposit, and explosive activity gave way to intrusion of collapsed foam.

Surprisingly, the dissolved water contents of collapsed sheets are high (~0.5 wt %), suggesting that filling of the subglacial cavity with erupted debris, rather than exhaustion of magmatic volatiles, drove this change. We therefore infer that blockage of conduits by erupted debris may be an important factor in mediating the transition from explosive to effusive styles of eruption. This process may be especially relevant to subglacial eruptions, as melting is unlikely to be sufficiently rapid to accommodate growing pyroclastic deposits at the glacier base. It is also inferred that conduit closure[2] and the balance between fragmentation and welding are important factors controlling the explosivity of subaerial rhyolite eruptions.

[1] Tuffen H et al. (2006) An explosive-intrusive subglacial rhyolite eruption at Dalakvísl, Rauðufossafjöll, Iceland. Bulletin of Volcanology, in review.
[2] Wolff, J. A. 1986. Welded-tuff dykes, conduit closure, and lava dome growth at the end of explosive eruptions. Journal of Volcanology and Geothermal Research, 28, 379–384.

## 7 Poster

### Flood basalt eruptions: how much, how far, how fast, how often?

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Flood basalt volcanism is the extreme end-member of effusive volcanic activity (and, perhaps, of all activity) on Earth. Eruptions yielding > 1000 $km^3$ of basaltic magma appear to occur only during the peak period of continental flood basalt (CFB) magma output. Evidence from CFB provinces such as Columbia River Basalts (CRB) and Deccan are beginning to answer some basic questions about eruptive conditions, such as those listed below. George Walker provided some of the first evidence from the Deccan.

First, how much lava is produced in a flood basalt eruption? While smaller eruptive units do occur in CFB provinces, the lava piles appear to be dominated by the eruptive products of huge magma batches, up to 5000 $km^3$ in the CRB and even approaching 10,000 $km^3$ in the Deccan. These are almost always very widespread pahoehoe lava flow fields.

Second, how far do the lava units in such flow fields spread? Land-mass size appears to limit the lengths of CFB flows, because in both the Deccan and CRB provinces the longest flows reached the sea. Distances flowed are > 550 km for CRB and, arguably, > 1000 km for the Deccan.

Third, how fast is the magma erupted, or, in others words, how long do the eruptions last? Based on observations of the lack of thermal erosion at flow bases, the pahoehoe nature of the lavas, and temperature conservation constraints during emplacement from both measurement and modelling, eruptions must have lasted decades, or longer. New work by others on CRB dike longevity supports such durations. Time-averaged mass eruption rates implied by this conclusion give values in the same order ($10^4$ $m^3$ $s^{-1}$) as peak rates for recent flood lava events such as Eldgjá and Laki (Iceland).

Finally, how often does one of these huge eruptions take place during CFB formation? This important question will be difficult to answer quantitatively as eruptive peaks are known to be brief in flood basalt provinces. They are of similar duration, or perhaps shorter, than the resolution of presently attainable radiometric ages for CFB provinces (< 0.5 to 1 Ma). However, the number of eruptions occurring within such a period can be estimated, giving an idea of the average return period which is on the order of 1 per 5–10,000 yrs for both the Deccan and CRB provinces. Such intervals permit ample time for the formation of flow-top weathering/soil profiles and sediments observed between flow fields.

## 8 Poster

### The complexities of CFB province volcanic architecture

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The Deccan Traps continental flood basalt (CFB) province was formed ~65 Ma and occupies approximately 500,000 $km^3$, almost one quarter the area of peninsular India. Much of the previous work concentrated upon refining the well-known geochemical stratigraphy which is robust enough to trace formations from the western to the eastern-most boundaries of the province, a distance of ~500 km.

More recently, work has been undertaken to investigate the types of lava flows that form the Deccan Traps, but this has largely been confined to specific locations, and small-scale features (1-$10^2$ m). Here we present information, not only on the types of lava flows observed over a much wider area ($10^2$-$10^4$ km), but also on the volcanic architecture (i.e., the way the lava units are stacked together). By integrating detailed volcanostratigraphic logs with comprehensive palaeomagnetic and geochemical sampling of the classic area of Mahabaleshwar in the Western Ghats, a detailed picture of the architecture of the Deccan Traps may be investigated.

The Deccan lava pile is mainly formed of many 15–25 m thick (exceptionally 50 m) inflated pahoehoe sheet lobes which make-up lava flows and flow-fields. In detail they are as complex as the anastamosing flow lobes observed on the active Pu'u 'O'o flow-field of Hawaii. Unravelling the complexities of ancient volcanic architecture can be difficult due to limited exposure and also because individual sheet lobes have limited lateral continuity (i.e., on average they do not appear to be more than a few kilometres wide), and exposures are similarly spread. This problem is further compounded by the 95 m of topography which our work has demonstrated occurred on the active surface of the Deccan lava fields in the Mahabaleshwar area. This is most likely due to the emplacement of different numbers of lava units in varying locations across the study area and to a more minor extent by differential amounts of internal inflation (thickening) during sheet lobe emplacement.

## 9 Poster

### An ignimbrite cone-sheet feeder in The Hafnarfjall-Skarðsheiði central volcano W-Iceland

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A major central volcano in Hafnarfjall-Skarðsheiði was active from about 5,5 to 4 m.y. Four spatially distinct phases can be recognized; the first one in the Brekkufjall area, the second within the Hafnarfjall mountain complex, the third exposed in the lower northern slopes of Skardsheidi and the fourth one below Heidarhorn. Differentiated rocks are abundant within the central volcano, with relative abundance of intermediate rocks during the first and second phase while rhyolites predominate in the third an fourth phase. The ignimbrite under discussion here is the second youngest rhyolitic extrusion within the third volcanic phase. The eruption started with the extrusion of a viscous rhyolite lava dome of approximately 0.5 $km^3$ and up to 300 m elevation. A change to low-viscosity magma and ignimbrite formation took place in the later phase during the eruption. “Cupola-shaped” multiple cone-sheets intruded along the base of the rhyolite dome and represent the ignimbrite feeder conduits. The outer boundary of the cone-sheet swarm contains about 6 m thick pitchstone indicating rapid chilling against the country rock, while pitchstone is absent at the inner margin where it is in contact with the contemporaneous rhyolite. The total thickness of the cone-sheets is in the order of 100 m and divided into two groups: The outer group contains 30–40 1–4 m thick sheets, while the inner group contains similar number but much thinner ones. The radius of the sheetswarm is just over 500 m. Their dip in the outer perimeter rages from about 66 to 55°, while the inner ones have shallower dips in the order of 30–50°. This indicates that they coalesce into a central orifice at less than 300 m depth below surface. A series of approximately 40 ignimbrite flows lie adjacent to the feeder, and are considered their extrusive equivalent. Welding is pronounced in both the cone-sheets and the flows. The flattening of the fiammes is, however, rather extreme in the cone-sheets indicating their deformation due to the lithostatic pressure of the overburden during their ascent to surface. The change from viscous rhyolite to fluid “ignimbrite” magna is believed to be associated with an intrusion of basaltic magma into the rhyolitic magma chamber elevating the temperature, causing overheating and lowered viscosity of the latter.

## 10 Poster

### Violent Strombolian eruption at Vulcano Island: whichs the mechanism for magma fragmentation of the shoshonitic-basaltic magma?

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The island of Vulcano, (Aeolian Volcanic District, Italy) represents a composite volcanic structure formed between 130 ka and the present time, along a trans-tensional strike-slip fault NNW-SSE oriented. Vulcano magmas range in composition from mafic to silicic, with HKCA to SHO and KS affinities. Overall, potassium and incompatible element contents increase in the mafic melts during time, whereas mafic magma input into the volcanic system decreases in the last 15–20 ka (due to formation of small magma chambers and pockets at shallower levels). These poorly evolved silicate melts (SHO basalts), coming from reservoir(s) located between 21.5 and 17 km (0.56-0.45 GPa), generate different types of eruption ranging from effusive (Vulcanello lava platform) to explosive, with variably vesiculated scoria clasts. In the explosive products, we observe both fragmented clasts with moderate vesicularity (strombolian fall deposit from Vulcanello and Mt. Saraceno cones) and highly vesiculated scoriaceous lapilli with minor bomb-sized clasts, forming a fall tephra blanket, widely dispersed in the southern part of the island. According to the isopach and isopleths maps this tephra deposit could be associated to a fissural vent located with some uncertainty in the southern sector of La Fossa caldera. Multidisciplinary investigations on these basaltic pyroclasts, reveal chemical composition (major and trace elements) quite similar to those erupted from strombolian fall deposit, but several differences in terms of mineralogy and especially texture. Moreover, in the tephra blanket different types of lapilli can be recognized: a) dense; b) moderately vesicular; c) highly vesicular clasts. The various clast types contain abundant plagioclase and pyroxenes microlites, with minor microphenocrysts that suggest extensive degassing-induced crystallization during this eruption of 'violent strombolian' type. The viscosity of these melts under anhydrous conditions is in the order of $10^{2.5}$-$10^3$ Pa s at 1100°C. We suggest that the pre-erutive volatile content and temperature of the melts controls the fragmentation and explosivity of these magmas.

The presence of this eruptive style, together with higher hazard questions posed by eruptions involving pyroclastic density currents of phreatomagmatic origin or vulcanian fall deposit related to magma mixing, calls for a better understanding of mechanism of magma fragmentation and tephra dispersal during this type of activity

## 11 Poster

### The rapid ascent of magma through the lithosphere: An hydrostatic model of volcanism revisited

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A hydrostatic model of volcanism that is consistent with our current understanding of the nature of the regions of partial melting is developed here aiming to increase our understanding of some aspects related with the rapid ascent of magma from their source. In particular the questions of why magma remains temporarily trapped at the regions of partial melting before rapidly ascending to the surface, and why magmas either stop during their ascent or manage to move all the way to the surface are shown to be easily answered by using this model. Results of the calculations allow us to predict the minimum thickness of the zone of partial melting in the mantle (or seismically defined Low Velocity Zone) that is required to feed volcanic activity, ranging from 5 to over 100 km depending on the exact value of the strength of the overlying rock and on the overall magma composition. Additionally, it is also shown that under certain circumstances a rock strength < 200 MPa may suffice to keep magma trapped at depth whereas in other cases a strength > 600 MPa will not suffice to stop magma ascent resulting in volcanic activity at the surface. Consequently, the model of volcanism developed here shows why is that a given LVZ may lead to volcanic activity in some places whereas a completely identical LVZ may not result in volcanic activity in a different location. The agreement with observations made in two specific regions (Western USA and the Japanese arc) validate the model in a general context. Furthermore, the characteristics of this model make it an attractive alternative to address some aspects of the currently held volcano-tectonic relationship that seem to be impossible to reconcile with observations without the need of using a large number of ad hoc adjustments.

## 12 Poster

### Stratigraphy and spatial distribution of rootless cones within the Raudholar group, southwest Iceland: a contribution to understanding explosive lava-water interactions

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Rootless cone groups result from explosive interactions between degassed lava and underlying near-surface water and thus are natural analogs to explosive fuel-coolant interactions. This process implies rapid heat transfer rates due to physical mixing of molten lava and water-bearing sediments. The resulting phreatomagmatic explosions eject a mixture of disintegrated lava and substrate material to form complex conical landforms that rise 1–35 m above their surroundings. The cones typical have basal diameters of 2–450 m and collectively form groups covering 0.5 to >100 $km^2$. Although conceptual models for the origin of rootless cones are well established, the detailed processes involved in their formation are not well constrained. To determine the physical mechanisms responsible for rootless cone formation this study examines the internal stratigraphy, morphology, and spatial distribution of cones within the Raudholar group, located in southwest Iceland near Reykjavik. The Raudholar cones have distinct layering and generally exhibit the following four-fold stratigraphy: 1) Basal unit (>1 m thick) featuring a crudely bedded sequence of alternating ash to lapilli-grade scoria layers with abundant clods of red-baked lacustrine mud and armored clasts with cores of lake sediment or crystalline lava. 2) Middle unit (1–3 m thick) with wavy bedding and inversely graded layers of fine to coarse lapilli scoria alternating with silt-grade layers that are rich in red-baked lacustrine mud. Clasts with 'bread-crust' surface textures are common in the coarser-grained layers. 3) Upper unit (5–10 m thick) exhibiting multiple layers of spatter, scoria, and bread-crust bombs and contain very low abundances of ash-grade material. Juvenile clasts have fluidal shapes and the layers often include thin horizons of densely welded spatter. 4) The cone sequence is typically capped by a 1–2 m thick apron of densely welded to rheomorphic spatter. In some instances the apron feds secondary lava flows that extend onto the surface of the host lava. The general upward increase in grain size within the succession is interpreted in terms of a decrease the efficiency of explosive fuel-coolant (lava-water) interactions due to a reduction in the availability of groundwater. The Raudholar cones exhibit a Poisson (random) spatial distribution. This implies that explosion centers formed independently of one another and that competition for water resources between simultaneously active explosion centers was not a significant factor in determining the overall spatial distribution of cones within this group.

# 5.2 – Oral Poster Presentation

## 13 Poster

### The Relationship Between Dome Morphology, Eruption Rate and the Generation of Pyroclastic Flows: Examples from the 1995 to 1998 Period of Dome Growth at the Soufrire Hills Volcano, Montserrat

*Robert Watts*
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Dome growth at the Soufrire Hills Volcano (SHV) between November 1995 and March 1998 produced ~0.3 km$^3$ of crystal-rich andesitic lava that constructed a Pelan dome which sporadically collapsed. The predominant structures extruded were broad shear lobes that developed over 5 to 8 weeks through a combination of exogenous and endogenous growth. Growth cycles were evident with the directed emplacement of a shear lobe constructing a steep flank on one sector of the dome by the gradual accumulation of rockfall debris and internal inflation of the shear lobe. The shear lobe was composed of a broad headwall of fractured, yet massive lava that spawned rockfalls across a wide sector of the flank. During such periods, the formation of pyroclastic flows was relatively rare. Growth spurts of rapidly extruded, vesicular blocky lava commonly triggered dome collapse and episodes of large-scale pyroclastic flow development. Such collapses produced a large spoon-shaped scar within the dome edifice and re-growth of the scar involved the rapid extrusion of more blocky lava that was relatively unstable. The directed extrusion of this lava triggered further pyroclastic flow development as rockfalls that were guided down the main trench carved out by the major collapse. The trench cut down to deeper, hotter parts of the dome and lava blocks channeled down the trench and commonly developed into pyroclastic flows. As extrusion waned the trench gradually filled and lava was emplaced across a broader zone of the growing shear lobe. This promoted the slow growth of a flank by predominant rockfall activity that did not develop into pyroclastic flow behaviour. A relationship between style of extrusion and the triggering of pyroclastic flows was evident during the entire period. Furthermore, a distinct relationship between the morphology of extruded features and the eruption rate (subsequently affecting the textural character of the erupting lava) was also apparent. These observations have important implications relating to the conditions required to cross the transition from rockfall to pyroclastic flow behaviour. Applying this knowledge to the mitigation of hazards around any dome-forming volcano, particularly in the ongoing eruption at SHV should be given a high priority and investigated further.

## 14 Poster

### Discrimination of fluvial and eolian features on large ignimbrite sheets around La Pacana Caldera, Chile, using Landsat and SRTM-derived data

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Satellite images and ground-based observations were used to investigate the morphology and origin of valleys and ridges across large ignimbrite provinces around La Pacana caldera, N. Chile. We studied 12 separate sites that included five different ignimbrite units that range in age from ~5.6±0.5 Ma to 1.35±0.15 Ma. Over 400 features from within these study sites were quantified. Study sites typically have dimensions of 25 x 35 km. Measurements were made using Landsat TM, ETM+, and SRTM-derived DEM and Shaded Relief images. Morphological measurements were made of the ridges and channels, including the direction of regional slope, length, orientation and gradient of each feature. A classification of the different ignimbrite erosion influences, resulting in varying landscape morphologies identified 4 landscape types; Fluvial, Eolian, Modified and Complex. We conclude that the most prevalent features are fluvial-derived channels but the most distinctive are linear, wind-derived ridges. The orientation of these ridges suggests that strong uni-directional winds from the northwest have been constant over a long period of time (<2 My).

## 15 Poster

### Tectonics of the Hengill area, Southwest Iceland

*Michael Krumbholz, N Friese, S Burchardt, A Gudmundsson*
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The Holocene Hengill Volcanic System is situated in the active West Volcanic Zone in Southwest Iceland. The Hengill System includes the Hengill Volcano, located south of Lake Thingvallavatn, a central volcano that is the site of one of the most powerful geothermal fields in Iceland. The current spreading rate in the West Volcanic Zone varies between 3–7 mm/a, whereas the subsidence rate is about 1 mm/a. The Hengill Volcanic System is 60–70 km long and 5–10 km wide. Structurally, it is dominated by large NNE-striking normal faults.

The Hengill area is one of the seismically most active regions in Iceland. Focal mechanisms suggest that many earthquakes are caused by slips on conjugate NNE-striking dextral and ENE-striking sinistral faults.

To improve our understanding of the structural geology of the Hengill area detailed field studies were made of several thousand fractures in the area. These studies include the measurements of the attitude, opening, and displacement of some 2000 joints, about 1000 mineral veins, and 29 large normal faults. In addition, careful quantitative studies of fractures from aerial photographs were made, focusing on the orientation of large normal faults and other lineaments.

The average strike of the 29 normal faults measured in the field, as well the 251 normal faults measured on aerial photographs, is 032°. Most of the faults dip steeply. Aerial-photograph studies show that the eastern and the western graben shoulders are differ in structure. The eastern shoulder is dissected almost entirely by NW-dipping normal faults. There are nearly twice as many normal faults dissecting the western shoulder; half of those are NW-dipping, (as on the eastern shoulder), the other half being SE-dipping. Also, the average throw of normal faults dissecting the shoulders differs; it is about 31 m for the faults dissecting the eastern shoulder, but 43 m for the faults dissecting the western shoulder. By contrast, the average trace length of normal faults dissecting the eastern shoulder is about 0.75 km and thus larger than the average trace length of faults dissecting the western shoulder, 0.55 km. Our field and remote-sensing studies indicate that the formation of joints and mineral veins is largely controlled by the regional plate-boundary stress field.

## 16 Poster

### Structure and Formation of Shield Volcanoes in Iceland

*Ruth Andrew, A Gudmundsson*
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Formation of shield volcanoes (lava shields) has occurred throughout the geological history of Iceland. The best-studied shield volcanoes in Iceland, however, are those formed during the early Holocene. The Holocene shield volcanoes are distinctive in both space and time. As regards space, Holocene shield volcanoes are confined to two marked areas, namely the West Volcanic Zone and North Volcanic Zone. Apart from the shield on top of the island of Surtsey, there are no shield volcanoes in the East Volcanic Zone. Furthermore, many large shields are not located at the centres of the volcanic systems to which they belong but rather at their margins. As regards time, most of the shields formed during early postglacial. In fact, during the past 3500 years, only one shield has formed in Iceland. This is the shield that forms the top of the island of Surtsey, off the south coast of Iceland. It was formed in an eruption that lasted from 1963 to 1967.

Periods of glaciation and deglaciation are known to have affected the volcanotectonic regimes of Iceland, temporarily changing the stress fields of the crust. Glaciation and downbending of the crust encouraged the formation of shallow crustal magma chambers but largely prevented eruptions. By contrast, deglaciation generated temporarily compressive and tensile regime in the crust that favoured the eruption of primitive basalts from mantle reservoirs at the margins of the volcanic systems. During the early stage of the last deglaciation (while there was still ice cover), these eruptions generated subglacial hyaloclastite mountains, whereas in the later stages (when the land was ice free) they generated picrite and olivine tholeiite shields, primarily at the margins of the volcanic systems. Subsequently, when the rebound stresses had relaxed and normal plate-pull stresses dominated again, fissure eruptions inside the volcanic systems and associated central volcanoes, commonly issuing evolved magmas, became the most common type of eruptions.

Our conceptual and numerical models make it possible to understand four related features and processes. First, how high-density magmas were able to reach the surface forming the shields. Second, why most of the shields formed in the early part of the postglacial period. Third, why many of the shields formed at the margins of the volcanic systems to which they are associated rather than at their centres. And, fourth, why the shields became confined to the West and North Volcanic Zones, with essentially no shields in the East Volcanic Zone.

## 17 Poster

### A temporally and spatially-resolved global database of volcanic sulphur dioxide emissions 1998–2005

*FCR Mansfield*
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We present an updated and refined global volcanic sulphur dioxide emissions inventory that is both temporally- and spatially-resolved for the period 1998–2005. We have compiled data on the patterns of emission behaviour from both the published literature and personal communication, and have extended this to make an assessment of the emissions from unmonitored volcanoes worldwide according to detection method (e.g. TOMS, COSPEC), activity type and tectonic setting (continuous vs sporadic; arc vs intra-plate), elevation and location. We shall compare the updated inventory with previous work, and illustrate the potential of the new inventory for evaluating the effects of emissions of volcanic sulphur on the troposphere.

## 18 Poster

### Propagation and linkage of normal faults in the Thingvellir Fissure Swarm: field studies and numerical models

*Nadine Friese, Agust Gudmundsson*
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The Thingvellir Fissure Swarm (TFS), of Holocene age, forms the northern continuation of the 60-km-long Hengill Fissure Swarm in the West Volcanic Zone (WVZ) of Iceland. The swarm, which dissects 9000 year old basaltic lavas and Pleistocene hyaloclastite rocks is marked by N29°E striking normal faults and tension fractures trending subparallel to the WVZ, reflecting an extension direction perpendicular to the rift zone axis.

Here we present new results as to the geometry and mechanical interaction of fractures in the TFS, as well as a new tectonic map of the swarm. In the numerical models, the fractures are modelled as elliptical holes with horizontal (plate-pull) tension of 5 MPa as the only loading. Based on static laboratory measurements, Youngs modulus (stiffness) of the Holocene basaltic lava flow hosting the fractures is taken as 20 GPa, and that of hyaloclastite as 4 GPa. For the basaltic lava flow as well as the hyaloclastite Poissons ratio is taken as 0.25.

Numerical models using the finite element program ANSYS focus on two well-known fracture patterns in the TFS: (1) the en echelon fractures close to the south end of the boundary fault Almannagja, and (2) fractures associated with the fault Heidargja close to the hyaloclastite mountain Hrafnabjörg. We mapped the fracture patterns in detail, using aerial photographs so as to be able to make realistic models. For Almannagja, the fracture pattern is such as to generate zones of high shear stress concentrations between the fracture tips. Many of these shear-stress concentration zones have already developed into transfer faults. For Heidargja the fracture propagation into the mountain Hrafnabjörg is clearly difficult and its comparatively soft hyaloclastite seems to have arrested some of the fractures. The arrest is, first, because of the low Youngs modulus and thus low magnitude stresses, and second, because hyaloclastite has a very low tensile strengths (as to other soft sedimentary rocks) and hence it is unlikely to fail in tension (develop tension fractures). That numerical results are supported by the absence of young tension fractures in the mountain Hrafnabjörg. A general result of the numerical models is that en echelon fractures with an underlap subject to tension favour shear stress zones and transfer-fault development between nearby tips of tension fractures and normal faults, whereas collinear fractures tend to growth a as tip-to-tip segments into larger tension fractures and normal faults.

## 19 Poster

### The environmental effect of the dissolution of pristine volcanic ash on surface waters

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The overall objective of this study is to investigate the dissolution of pristine volcanic ash from the Hekla volcano, Iceland, during the first hours and days of the 1991 and 2000 eruptions. River Ytri-Rangá, in the vicinity of Hekla, was monitored to detect changes in chemistry due to weathering of the ash. Ash was collected as snow/ash mixture from the initial sub-plinian phase (2000) and in the later stage of the eruption (1991). The pristine volcanic ash was quickly weathered when exposed to rain, so the concentrations of F and Al in the river exceed drinking water limits during rainy periods. The computer code PHREEQC was used to model the dilution of polluted snow with unpolluted River Ytri-Rangá and unpolluted precipitation. The results were then compared with the observed river water concentrations and calculated species concentrations. The results show that $AlF_3$ dominates in both solutions at low levels of dilution. $Al(OH)_{4-}$ is the main specie at high levels of dilution in the river, while $Al^{3+}$ is the dominating specie in the unpolluted precipitation at high levels of dilution. The pH increases faster in the river than in the precipitation due to the rivers high alkalinity (1.48mmol/kg). The lowest pH measured in the river during the monitoring was 7.1. Modelling shows that the ash has been diluted 62 times when pH reaches 7.1. This corresponds to 163 l/s of ash/snow-melt in a river discharge of 10 000l/s. The dominating Al specie at the maximum pH dip in the river was $AlF_3$, which is considered harmful for aquatic life.

## 20 Poster

### The Partitioning of Transition Metals Between Melts and Minerals in Natural Samples

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Despite the environmental impact and economic importance of transition metals in igneous environments many aspects of the geochemical behaviour of these trace elements within crystallising and degassing magmas is still unknown. Although the behaviour of some elements have been modeled experimentally, very little data exists on these elements particularly Cu and Zn within natural materials and this is of critical importance when looking at variable tectonic settings.

This study presents new constraints on the behaviour of the transition metals using direct analysis of mineral-melt pairs within natural samples from a variety of different tectonic settings using EMP analysis and 213nm UV laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). Using these techniques we have established that Cu, Zn and other transition elements can be measured at high spatial resolution in minerals and co existing melt inclusions and glasses, rapidly and with minimum sample preparation.

The preliminary study concentrates on the partitioning behaviour of the metals and compares the results to the predicted behaviour set by the parabolic {log (partition coefficient) ionic radius} trends expected from theory.

We speculate on the possible causes of the measured deviation from predicted partition coefficients, and explore the possible implications of this behaviour in different tectonic settings. The factors which control the concentration of the metals and the compositions of erupted magmas are analysed by considering the resulting chemical signature of crystallisation and degassing in a growing phenocryst.

## 21 Poster

### Dyke nucleation and earlier growth from pressurized magma chambers: Insights from analogue models

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Nucleation and dyke growth from magma chambers are important, yet poorly understood aspects of magma transport in the lithosphere. To tackle this issue, we conducted qualitative experiments using gelatin and silicone to simulate, respectively, country rock and magma. In our experiments the pressurization of the magma-filled reservoir was the main responsible for dyke formation rather than the density difference between magma and country rock. Our results show that an overpressurized magma chamber leads to simultaneous nucleation of dykes in different parts of the reservoir, especially at places with large angular irregularities where local perturbation of elastic stress occurs. Early propagation of the leading-edge of a dyke results in arc-shape tabular intrusions that are controlled by the stresses surrounding the overpressurized magma chamber. The overall process of earlier dyke formation reveals three stages: 1) very rapid increase of the fracture length at constant width, 2) arrest of the intrusion front and 3) thickening of the intrusion. These stages suggest that dyke propagation to the surface occurs through several steps separated by the time needed for the renewal of magma pressure in the reservoir. In consequence, our experiments suggest that overpressurization of a magma chamber is a necessary condition that must be met to explain why is that some magmas can reach the surface even when the reservoir is located in a region close to the neutral buoyancy, but that the distribution of such overpressure is a dynamic variable that requires further examination.

## 22 Poster

### Uses of anisotropy of magnetic susceptibility in the study of emplacement processes of lava flows

*Edgardo Canon-Tapia*
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The anisotropy of magnetic susceptibility (AMS) is a powerful technique that can be used to explore in detail the mineral fabric of many types of rocks. In particular, it is well suited to determine mineral fabric of massive, otherwise featureless rocks, like for example the internal parts of many lava flows and dykes. Although the AMS technique relies in the use of an external magnetic field for its measurement, the methodology and general assumptions behind the AMS technique are more akin to other traditional petrofabric tecniques than they are to paleomagnetic works. Furthermore, like most other mineral fabrics the AMS is mainly acquired at a stage when flow-related deformation promotes a mineral array within the liquid (albeit viscous and probably with a yield strength) lava. The effort required to obtain three-dimensional information of such mineral array using AMS, however, is less than the effort required by other more traditional methods of fabric analysis. It must be noted that due to differences in the shape of various minerals it is possible to find some differences between magnetic and optically determined mineral fabrics. When attention is given to the systematic variations of the AMS within a lava flow or dyke, however, the AMS method allows us to infer aspects of lava (magma) emplacement that are not easy to study through other traditional petrofabric techniques, like for instance in mapping the regions of a lava flow that experience late shearing during emplacement. A detailed knowledge of such deformation partition within a lava flow can be used in turn as an useful criteria to determine whether the flow grew by endogenous or exogenous processes. Also, in some circumstances it may be possible to delineate zones that experienced the same deformation regime (i.e., pure or simple shear) using the information provided by the AMS method alone, or in combination with other petrofabric techniques, therefore allowing us to have a detailed record of the internal deformation of one flow unit. For these reasons, the AMS method is an efficient means for collecting a large number of observations which, in turn, are required to fully characterize lava flow fabric and kinematics.

## 23 Poster

### Guidelines for interpretation of degree of magnetic anisotropy in lava flows Examples from the Tiretaine lava flows (Chane des Puys, France)

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Anisotropy of Magnetic Susceptibility (AMS) is a convenient method for finding strain and thus emplacement information on lava flows. However, interpretation of AMS parameters, such as degree of anisotropy, requires caution and several factors need verification to avoid misunderstandings. Verification can be divided into 2 groups: 1) what minerals create AMS? 2) how AMS behaves?

1) For the magnetic minerals, thin sections are needed for estimating concentrations, sizes, shapes and compositions. Then finding Curie temperatures will indicate if magnetites are the main AMS carrier. First Order Reversal Curves (FORCs) are performed to find the magnetic type: multi domain (MD) or single domain (SD).
2) To find AMS behaviour, a comparison between AMS ellipsoid and microlite fabric ellipsoid shows how AMS is acquired and if it is controlled by the silicate template.

Examples were taken on vertical profiles from lava flows of the Tiretaine valley, Chane des Puys, France. Results show that AMS is carried by interstitial titanomagnetite, with a 5 to 50 m size (average of 25 m). The FORCs show that AMS is mainly due to MD magnetites. The comparison between the magnetic and microlite fabric shows that AMS fabric is controlled by the silicate template. Magnetites are therefore late formed, i.e. during the late stages of emplacement/deformation when significant cooling had occurred. As MD magnetites (big) are also the largest population, they have better recorded these late stages of deformation than SD (small crystals).

The degree of anisotropy profiles could be seen as the record of the late stage of deformation of the lava flow, or more precisely to the last deformation event as that particular part of the lava flow cools. Direct link with the gradient of deformation can be done by making the assumption that ? < 8 and no complete particle rotation has occurred. Values of degree of anisotropy are slightly biased (decreased) on account of the low SD concentration. Finally from this profile of gradient of deformation, a qualitative velocity profile can be proposed in the studied lava flow.

The guidelines given here for interpretation of degree of magnetic anisotropy can be used in any lava flow, but also on intrusions. An interpretation can be used as long as several requirements are met: magnetites as carriers of AMS, equivalence between the AMS and microlite ellipsoid and MD magnetites in the majority.

## 24 Poster

### Xenoliths mobilized from a deep-seated pluton from Hrólfsvík, Reykjanes Peninsula, SW-Iceland

*Tanja Grandvuinet, Nordic Volcanological Center, REYKJAVK, Iceland*

The Reykjanes Peninsula is a leaky transform connecting the Reykjanes Ridge to the Western Rift-Zone of Iceland. Volcanism during late Glacial to Holocene time is confined to five en-chelon arranged fissure swarms superimposed above the plate boundary along the Peninsula. The host lava of the Hrólfsvík xenoliths defines the southern tip of the Grindavík fissure swarm that propagates several kilometres into the western plate margin. The south segment of the Grindavík fissure swarm has erupted a suite of primitive basalts, the earliest Holocene lavas being picrites (MgO about 9 wt.%).

Most xenoliths are 3 to 25 cm round edged and coarse to medium grained. Distinct reaction rim towards the host lava show various degree of disintegration, which is sometimes reddish oxidized.

Mineralogical composition of the xenoliths is 60–90% homogeneous plagioclase ($An_{91-88}$) and 10-30% olivine ($Fo_{88-86}$). Minor phases are Cr-diopside (up to 1.6 wt.% $Cr_2O_3$) and occasional chromite. The xenoliths can be described as troctolites of primitive origin based on their mineralogy which resembles pheoncrysts in the local picrites.

New oxygen isotope data on four plagioclase separates from Hrólfsvík gave a $d^{18}O$ average of 5.77 0.14, which corresponds to the oxygen composition of the Reykjanes picrites and the oxygen composition of the mantle beneath the Reykjanes Peninsula as inferred from isotope analysis of basaltic MORB glasses.

Xenoliths from Hrólfsvík reveal a complicated mobilization history, for the reason that they enclose pockets of groundmass that contains mostly the same minerals as the bulk of the xenoliths but generally with a more evolved composition.

The grains that are in contact with the groundmass pockets also show a more evolved outer rim similar to some of the secondary assemblages in the pockets themselves. In those pockets one can observe pseudomorphic shapes that seem to indicate an incongruent melting of preexisting clinopyroxene. The groundmass pockets are consequently interpreted as the result of crystallisation after partial melting. We conclude that the local abundance of xenoliths in the Hrólfsvík bay is the consequence of the partial disintegration of a plutonic body that suffered incongruent melting of clinopyroxene upon contact with slightly hotter host lava at the mantle/crust boundary.

# Authors Index


Photo: Freysteinn Sigmundsson

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