Respiratory health hazard assessment of ash from the 2010 eruption of Eyjafjallajökull volcano, Iceland. A summary of initial findings from a multi-centre laboratory study

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Summary

- 14 samples were analysed from the ash fallout on Iceland from Eyjafjallajökull volcano. 12 samples were from ash erupted 15-19 April during the phreatomagmatic phase (when glacial meltwater interacted with the magma, 14-17 April) and the following 2 days. Two samples were from ash erupted 6-9 May in the drier phase (4-22 May).
- The samples range from basaltic trachy-andesite to trachy-andesite.
- The grain size pertinent to respiratory health of fine samples was variable: 2-13 vol. % < 4 μm and 4-26 vol. % < 10 μm. The finest samples were all erupted during the phreatomagmatic phase, but as we only obtained 2 samples from the drier phase they may not be representative.
- Very dark grey/black ash and lighter grey ash were both visible in the plume as it was being erupted. The darkest ash samples were, in general, coarser than the lighter ash samples, independent of the eruptive phase.
- The crystalline silica content in all ash samples was negligible (within the 1-3 wt. % error of the technique).
- Morphology showed mainly angular, glassy particles, typical of volcanic ash. Occasional fibre-like particles in one sample from the dry phase were either feldspar, glass, gypsum or a Fe/Mg silicate and were unlikely to be of health concern.
- Surface area varied substantially from 0.3-7.7 m^2g^{-1}, showing that some samples have high available surface for reactions in the lung.
- Leachate analysis showed low release of trace elements relevant to respiratory health, with the exception of one sample.
- *In vitro* screening tests for potential bio-reactivity of the ash particles showed low hydroxyl free radical generation in comparison to ash samples from other volcanoes (except for one sample with iron-related reactivity akin to basaltic ash); and low values for oxidative potential (ascorbic acid oxidative capacity). Measurement of haemolysis (quartz-like behaviour), cytotoxicity and inflammatory markers also revealed low activity.
- **Conclusion:** The ash fallout examined contains a substantial fraction of fine-grained material which could generate elevated levels of $PM_{2.5}$ and PM_{10} in the ambient air when re-suspended by dry, windy conditions, by traffic and by those working in the ash. Average outdoor air concentrations in the ashfall area can be expected to regularly exceed World Health Organisation (WHO) 24-hour guideline levels for particles in the ambient air until the ash is incorporated into the environment with repeated rainfall. The *in vitro* toxicity tests suggest that the potential for the ash to trigger acute pulmonary inflammation at ambient levels of exposure is low. Persistence of deposited ash in the soils and environment would not present a significant silicosis hazard, e.g. to outdoor workers, as crystalline silica content is negligible.

Introduction

The explosive eruption of Eyjafjallajökull volcano, Iceland during April - May 2010, produced plumes of ash which were blown, at times, across Europe, the Atlantic and northern Africa, causing severe air traffic disruption. Closure of parts of European air space for up to six days highlighted the widespread dispersal of ash, and countries were concerned about the potential impacts of ashfall on agriculture and the respiratory health hazard of the associated particulate air pollution. Here we present a brief summary of the initial results on a suite of tests using a protocol specifically developed for the assessment of the hazards to human health of ash from volcanic eruptions (Fig. 1). All samples were obtained on Iceland (Fig. 2). A full report will be published separately.

Health-pertinent volcanic ash characteristics

A detailed overview is given by Horwell & Baxter (2006)[1] along with a description of the mechanisms of pathogenicity in the lungs and a review of mineralogical, toxicological and

medical studies at previous volcanic eruptions up to 2006. The protocol used here (Fig. 1) has been developed in the light of this global experience[2].

The 2010 eruption of Eyjafjallajökull volcano

After an initial effusive eruption on the northeast flank, an explosive, phreatomagmatic eruption began beneath the central vent of Eyjafjallajökull volcano on 14 April 2010 as glacial meltwater from the icecap interacted with erupting magma. Fine ash and gases from Eyjafjallajökull were ejected up to 11 km into the atmosphere, with high intensity eruptive activity continuing until 18 April[3]. By 21 April, the eruption explosivity had decreased due to both a reduction in magma supply and reduced interaction with meltwater. Lava flows began on 21 April and activity continued with minor explosions. Between 4-6 May, explosive activity increased and effusive activity decreased again, resulting in increased tephra fallout. From 7-17 May, activity reduced but there was still considerable tephra fallout. On 18 May there was significant explosive activity with widespread ashfall across Iceland, but activity then decreased again and by 22 May the plume was ash-free[4]. Later, widespread drifting and remobilisation of ash deposits was reported in the vicinity of the volcano, indicating an ongoing respiratory hazard despite the cessation of ashfall.

Methods

- *Samples:* 14 samples were obtained, mainly from the phreatomagmatic stage (15-19 April), with 2 samples from the later, drier stage of the eruption (6-9 May)(Tab. 1, Fig. 2).
- *Bulk compositional analysis:* The major elemental composition of the ash was determined by X-ray fluorescence to categorise the magmatic composition of the bulk ash samples.
- *Grain-size analysis:* The grain-size distribution (0.02-2000 μm) was measured by laser diffraction to determine whether there was a significant proportion of 'respirable' (< 4 μm) and 'thoracic' (< 10 μm) material in the samples.
- *Crystalline silica quantification:* The quantities of cristobalite and quartz in the samples were determined using X-ray Diffraction with static position-sensitive detection[5].
- *Particle morphology and composition*: Images of the ash were obtained by Scanning Electron Microscopy and Transmission Electron Microscopy. The composition of fibre-like particles was determined from their elemental assemblage using energy dispersive spectroscopy and diffraction pattern indexing.
- *Sample appearance*: The colour of the samples was classified using the Munsell soil colour classification scheme (www.munsellstore.com).
- *Surface area*: The Brunauer Emmet Teller method with nitrogen adsorption was used to determine the specific surface area of the samples.
- *Leachate analysis*: The concentrations of water-soluble elements adsorbed on ash that may have potential relevance to ash toxicity were determined by shaking the ash in deionized water. The filtered solutions were acidified with HNO_3 and Cr, Fe, Ni, Cu, Zn, As and Cd were analysed by ICP-MS. The pH of the leachates was also measured.
- *Hydroxyl radical generation and iron release:* Electron paramagnetic resonance spectrometry was used to measure potentially deleterious hydroxyl radicals (HO•) released into solution from the samples through replication of the Fenton reaction[6]. UV-Visible spectrophotometry was used to estimate the amount of iron that could be released by chelators from the ash surface for participation in the Fenton reaction.
- *Particle oxidative capacity*: Ascorbate is an antioxidant found in the fluid lining the surface of the lungs, often referred to as the respiratory tract lining fluid (RTLF). Oxidising species on the surface of inhaled particles may cause changes in the natural balance of protective antioxidants found in RTLF, which may have an impact on cellular redox states, and hence may lead to airway irritation and oxidative stress. The depletion of antioxidants in the presence of ash particles might have significance for the health of asthma sufferers.

- *Haemolysis*: The propensity for the particles to display quartz-like toxic activity in the lung was examined by the Erythrocyte Lysis Assay.
- *Cytotoxicity and inflammation:* One sample (EYJ_10_13) was tested for its cytotoxicity against human lung epithelial type-1 cells as well as measuring induction of acute markers of inflammation: release of interleukin-6 (IL-6), interleukin-8 (IL-8) and monocyte chemotactic protein-1 (MCP-1).

Results

- *Bulk Composition:* The samples range from basaltic trachy-andesite to trachy-andesite (53 – 59 wt. % SiO_2). There was no obvious change in erupted composition with time.
- *Grain-size:* Respirable ash (< 4 μm diameter) varied from ~ 2-13 vol. %. Certain conditions during the phreatomagmatic stages produced significant quantities (> 10 vol. %) of respirable ash. This can be compared to phreatomagmatic ash from Vesuvius, Italy (≤ 17 vol. % < 4 μm material[7]). The two samples collected during the drier phase (1.96 and 5.09 vol. % < 4 μm material) are comparable to ash from other mildly-explosive eruptions (e.g. 5.9 vol. % for vulcanian explosions at the Soufrière Hills volcano, Montserrat[8]).
- *Crystalline silica content:* Total crystalline silica content (1.4-3.2 wt. %) was approximately within the 1-3 wt. % error for the technique. Tridymite was not identified. The samples were mostly amorphous, visible as a high background hump in the XRD patterns. It can be concluded with confidence that there is little to no crystalline silica in any of the samples analysed.
- *Particle morphology*: Morphology was typical of volcanic ash (blocky and angular). Some respirable, fibre-like particles were identified but were extremely rare and found only in sample EYJ_10_13.
- *Particle composition*: The fibre-like particles were either glass, feldspar, gypsum or a Mg/Fe rich mineral which could not be classified but was not related to asbestos minerals.
- *Surface area*: The BET specific surface area for the samples ranged between 0.29 – 7.67 $m^2\ g^{-1}$, with the higher values considered unusually high for volcanic ash.
- *Leachates*: Among the 8 elements measured, Fe was the most concentrated in the ash extracts (<1-26 mg kg^{-1}). Except for Zn in EYJ_10_13, the concentrations of all the other elements were less than 1 mg kg^{-1} and were low compared to ash from other volcanoes[9]. Some samples produced alkaline pH values (7.9-9.1) in the leachates, whilst others gave pH values < 6 with EYJ_10_13 being the most acidic (pH 4.4).
- *Hydroxyl radical generation*: The number of hydroxyl radicals released by all samples was very low (< 0.5 μmol m^{-2}) in comparison to a suite of standard ash samples analysed concurrently, with the exception of EYJ_10_13 which generated radicals and released iron on a scale akin to iron-rich basaltic samples. There was an excellent linear correlation (R^2 = 0.99) between iron release and HO• generation.
- *Haemolysis and oxidative capacity:* The propensity for haemolysis was low for all samples (< 5 %). No evidence of oxidative activity was observed for any samples. Positive and negative controls demonstrated expected results.
- *Cytotoxicity and inflammation:* EYJ_10_13 showed some cytotoxicity, being slightly higher than a sample from Soufrière Hills volcano, Montserrat. There was no change in release of IL-6, IL-8 or MCP-1 following exposure to either of these samples, indicating that the particles have little acute reactivity at physiologically-realistic exposure levels.

Discussion and health message

The ash fallout from Eyjafjallajökull volcano was variable in terms of grain size, most probably controlled by factors such as fragmentation mechanism and efficiency as well as location of fallout with respect to distance from the volcano and plume axis. According to Óskarsson (personal communication), the colour of the ash is related to oxidation of Fe in the glass during interaction with steam in the erupting plume. Darker samples were, in general,

coarser, although this was not always the case; furthermore no relationship was found between sample colour and surface iron availability (neither Fe^{2+} nor Fe^{3+}).

Other health-pertinent mineralogical characteristics, such as crystalline silica content and particle morphology, gave no specific cause for concern; bio-reactivity screening was also negative. One sample (EYJ_10_13) generated substantial hydroxyl radicals, was the most acidic, had the lowest surface area, contained fibre-like particles and leached more trace elements of relevance to ash toxicity in comparison to the low levels measured in all the other samples. This sample was erupted in the drier phase but otherwise has no distinguishable differences from the other samples except that it was collected dry, during the ashfall itself. It is possible that its pristine condition may have preserved leachable and reactive surface elements. However, the other samples are likely to be more representative of particulate in Iceland which is likely to be rapidly exposed to rainwater following deposition.

The substantial fraction of fine-grained material could generate elevated levels of airborne particulate matter < 2.5 μm and 10 μm in diameter ($PM_{2.5}$ and PM_{10}) when the deposits are re-suspended under dry, windy conditions or by outdoor human activity (outdoor workers in particular can be heavily exposed). As a result, average outdoor air concentrations can be expected to regularly exceed WHO 24-hour health guideline levels for particles after ashfalls until the ash is incorporated into the environment with repeated rainfall. Elevated ambient levels of respirable ash particles are known to exacerbate the symptoms of people with chronic respiratory conditions such as asthma and chronic bronchitis[1] who may need to adjust their medication and obtain medical advice if the dusty conditions persist. The results also indicate that the potential of the ash to cause long-term respiratory effects in healthy adults and children is low.

Measures to minimise individual exposure to fine ash are generally recommended after volcanic eruptions (e.g. wearing light weight, high efficiency masks outdoors, staying indoors during periods of raised re-suspension of ash and wetting down ash in school playgrounds and before remediation efforts), together with clean-up operations to remove ash from roofs and outside homes, along roads and other public places.

Further Information

All data (as tables and figures) are available upon request and will be published in an academic journal shortly. Further information on preparedness for ashfalls and the health hazards of volcanic ash can be found in the pamphlets available on the International Volcanic Health Hazard Network website (www.ivhhn.org) as well as a library of literature relating to the health hazards of volcanic emissions, including key references on the methods used in the protocol.

A separate study is being carried out on ash that fell over the UK and Europe. Please contact Claire Horwell for further information.

Fluoride analysis is not included in this study as it has been extensively studied by the Nordic Volcanological Center, Iceland (by Níels Óskarsson) and by Pierre Delmelle (York University, UK) and its relevance to respiratory health hazards is unclear.

Acknowledgements

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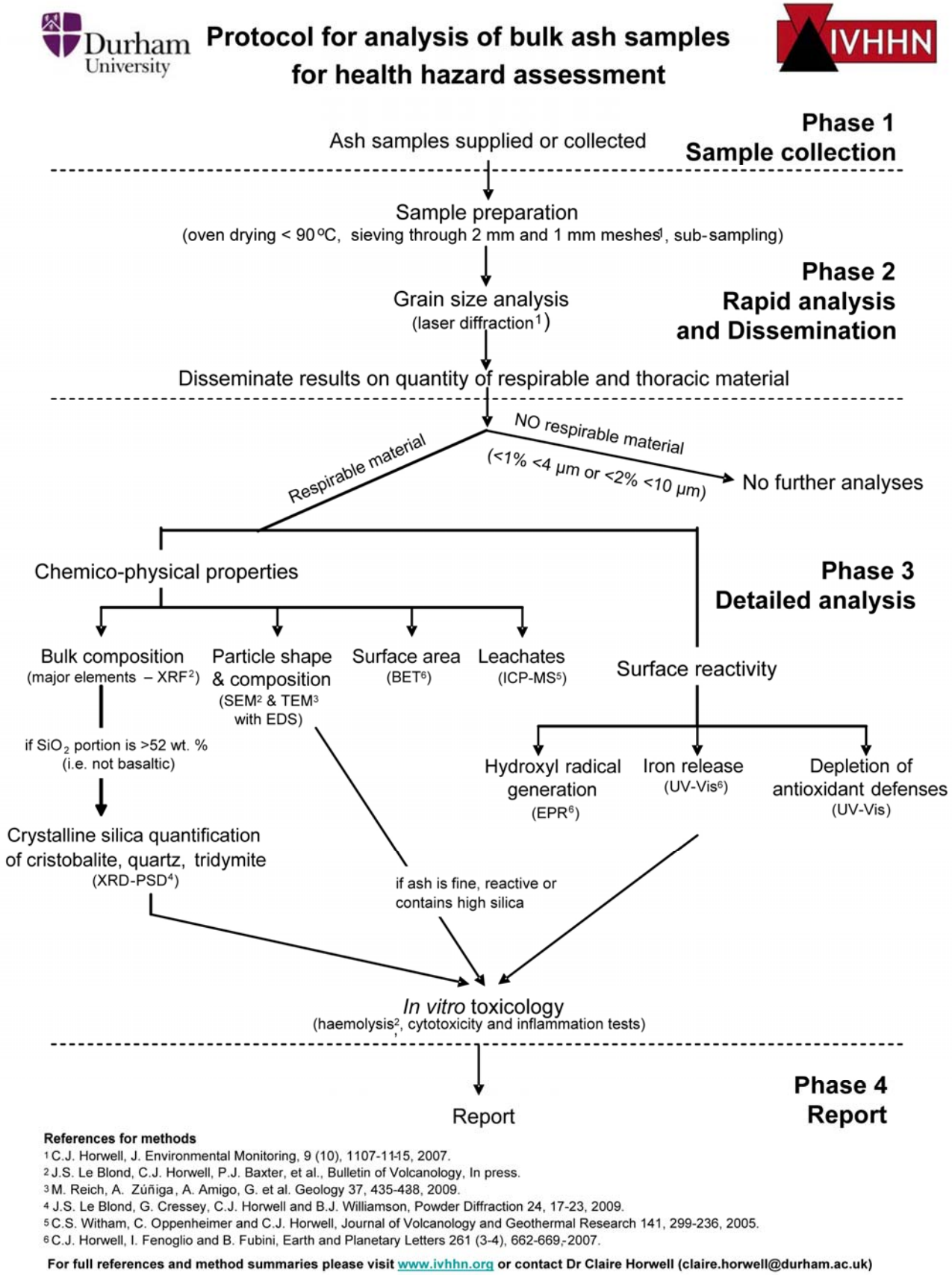
Figure 1. Protocol used for analysis of ash samples. Adapted from Le Blond et al. (2010[2]).



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For full references and method summaries please visit www.ivhhn.org or contact Dr Claire Horwell (claire.horwell@durham.ac.uk)

Figure 2. Map of sample collection locations in relation to Eyjafjallajökull and surrounding landmarks.

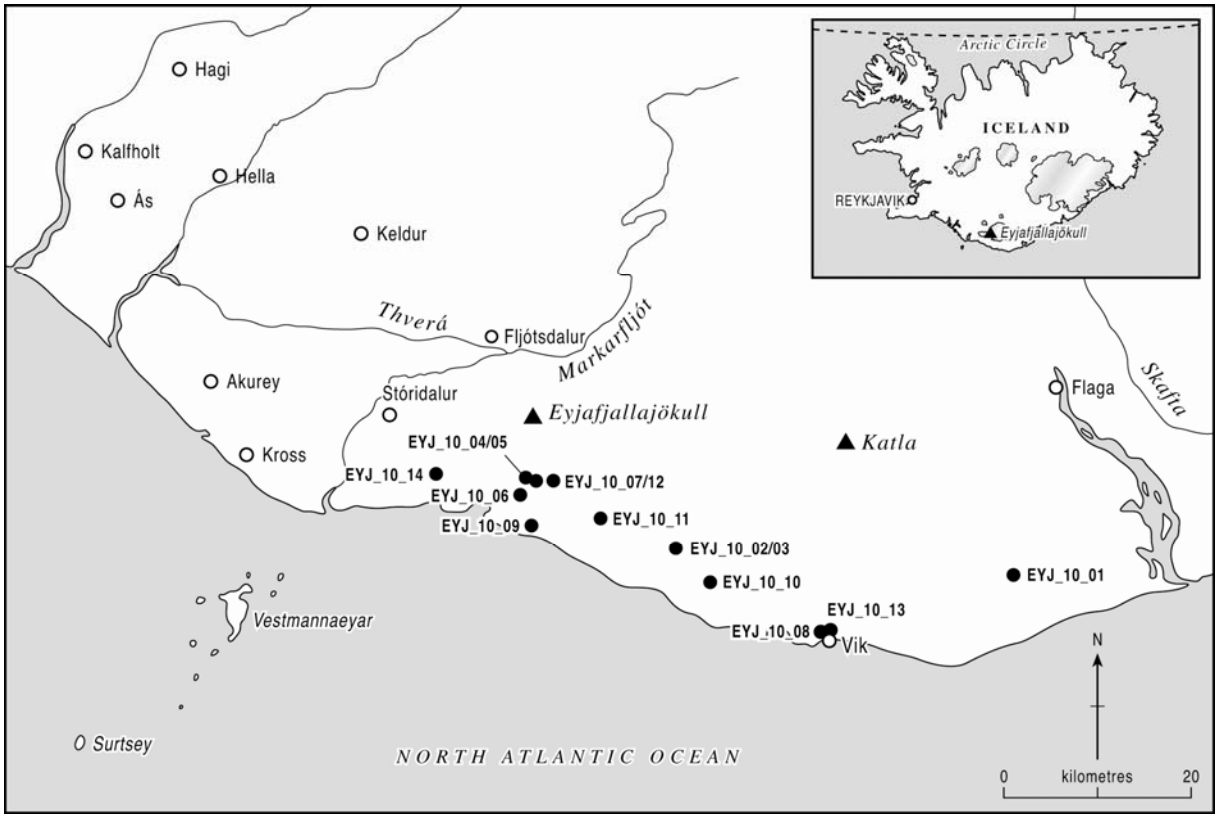

Table 1. Sample information

Sample I.D.	Original sample I.D.	Date erupted	Date collected	Location	GPS Co-ordinates	Distance from source (km)	Ash Colour (Munsell classfication)	Collected by	Collection information	State of sample
EYJ_10_01	15.04.10-2b	15.4.10	15.4.10	Myrdalssandur	N63°28.019' W18°35.939'	58	Dark/Very dark grey (5Y 3.5/1)	Gislason	All samples dried at 40 °C in Iceland. All samples in field for several hours up to 2 days before collection	Not known
EYJ_10_02	17.04.10-3	16-17.4.10	17.4.10	Solheimakot	N63°29.694' W019°19.727'	20	Dark/Very dark grey (5Y 3.5/1)	Larson & Höskuldsson		Dry
EYJ_10_03	18.04.10-4	17.4.10	18.4.10	Solheimakot	N63°29.694' W019°19.727'	20	Dark/Olive grey (5Y 4/1.5)	Larson & Höskuldsson		Damp
EYJ_10_04	18.04.10-18a	17.4.10	18.4.10	Thorvaldseyri power station	N63°33.643' W019°38.602'	8	Dark/Olive grey (5Y 4/1.5)	Larson & Höskuldsson		Wet
EYJ_10_05	18.04.10-18d	17.4.10	18.4.10	Thorvaldseyri power station	N63°33.643' W019°38.602'	8	Dark grey (5Y 4/1)	Larson & Höskuldsson		Wet
EYJ_10_06	20.04.10-1a	19.4.10	20.4.10	Thorvaldseyri	N63°32.757' W019°39.595'	9-10	Very dark grey (5Y 3/1)	Larson & Sverrisdóttir		Dry
EYJ_10_07	EYJ-A3	14-18.4.10	22.4.10	Seljavellir	N63°33.537' W19°37.322'	~6.5	Dark grey (5Y 4/1)	Delmelle		Fresh?
EYJ_10_08	EYJ-A15	14-18.4.10	24.4.10	Vik	N63°25.070' W18°59.501'	~37.5	Grey/Dark/ Olive grey (5Y 4.5/1.5)	Delmelle		Snowed on
EYJ_10_09	EYJ-A16	14-18.4.10	23.4.10	Onundarhorn farm	N63°31.440' W19°38.092'	~13	Very dark grey (5Y 3/1)	Delmelle		Fresh?
EYJ_10_10	EYJ-A17	14-18.4.10	22.4.10	Klifandi	N63°27.710' W19°13.877'	27	Dark grey (5Y 4/1)	Delmelle		Snowed on
EYJ_10_11	EYJ-A18	14-18.4.10	22.4.10	Hotel Skogar	N63°31.568' W19°29.607'	~14	Dark/ Dark olive grey (5Y 4/1.5)	Delmelle		Rained on
EYJ_10_12	5V #1	9.5.10	9.5.10	Seljavellir	N63°33.544' W19°37.327'	7.9	Very dark grey/Black (5Y 2.75/1)	Baxter & Jenkins		Damp
EYJ_10_13	VIK #1	6-7.5.10	7.5.10	Vik	N63°25.136' W19°0.568'	38.3	Dark grey (2.5Y 4/1)	Baxter & Jenkins		Fresh/ dry
EYJ_10_14	Holtsa 2.1	17.4.10	17.4.10	Bridge over Holtsa river on highway 1	N63°33.879' W19°50.593'	~5	Grey/Dark/ Olive grey (5Y 4.5/1.5)	Ilyinskaya		Fresh