Ice-volcano interactions during the 2010 Eyjafjallajökull eruption, as revealed by airborne imaging radar

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[1] During the eruption of the ice-covered Eyjafjallajökull volcano, a series of images from an airborne Synthetic Aperture Radar (SAR) were obtained by the Icelandic Coast Guard. Cloud obscured the summit from view during the first three days of the eruption, making the weather-independent SAR a valuable monitoring resource. Radar images revealed the development of ice cauldrons in a 200 m thick ice cover within the summit caldera, as well as the formation of cauldrons to the immediate south of the caldera. Additionally, radar images were used to document the subglacial and supraglacial passage of floodwater to the north and south of the eruption site. The eruption breached the ice surface about four hours after its onset at about 01:30 UTC on 14 April 2010. The first SAR images, obtained between 08:55 and 10:42 UTC, show signs of limited supraglacial drainage from the eruption site. Floodwater began to drain from the ice cap almost 5.5 h after the beginning of the eruption, implying storage of meltwater at the eruption site due to initially constricted subglacial drainage from the caldera. Heat transfer rates from magma to ice during early stages of cauldron formation were about 1 MW m⁻² in the radial direction and about 4 MW m⁻² vertically. Meltwater release was characterized by accumulation and drainage with most of the volcanic material in the ice cauldrons being drained in hyperconcentrated floods. After the third day of the eruption, meltwater generation at the eruption site diminished due to an insulating lag of tephra.


1. Introduction

[2] Eruptions of ice-covered volcanoes often result in interaction of magma with ice and snow, and associated meltwater formation, jökulhlaups and lahars. Such flooding is a highly significant hazard in some volcanic areas, including Iceland, Alaska, the northwest USA and parts of the Andes [e.g., Major and Newhall, 1989; Pierson et al., 1990; Trabant et al., 1994]. Jökulhlaups caused by volcanic and geothermal activity have been identified as the most frequently occurring volcanic hazard in Iceland [Gudmundsson et al., 2008]. Most of these are relatively small, caused by semi-periodic accumulation or drainage of geothermally sustained subglacial lakes while major events with peak discharges of order 10,000–100,000 m³ s⁻¹ are much less frequent. These major jökulhlaups are often associated with large eruptions under glaciers [e.g., Björnsson, 2002; Tómasson, 1996].

[3] The interaction of volcanic eruptions with an overlying and surrounding glacier has been studied in recent eruptions in Iceland, notably the eruptions at Gjálp in 1996, Grímsvötn in 1998 and 2004 and relatively small events that may have been minor subglacial eruptions in the Katla caldera [Gudmundsson et al., 1997, 2004, 2007; Björnsson et al., 2001; Gudmundsson et al., 2002; Gudmundsson, 2003; Jarosch and Gudmundsson, 2007; Jarosch et al., 2008]. These studies have provided information on glacier response to rapid melting for ice thicknesses ranging from 50 to 200 m in Grímsvötn to 600–750 m in Gjálp. For the thick ice found at Gjálp, rapid ice flow toward ice depressions, formed over the erupting subglacial vents, was observed and explained by the nonlinear deformation of ice in response to applied stress. In contrast, under the thin ice conditions at Grímsvötn, ice flow is slow and plays a relatively minor role. Geological analyses of products of Pleistocene subglacial eruptions [e.g., Jones, 1968; Tuffen et al., 2002; Smellie, 2006; Schopka et al., 2006] and theoretical models [e.g., Höskuldsson and Sparks, 1997; Gudmundsson et al., 1997, 2004; Wilson and Head, 2002; Gudmundsson, 2003;
Tuffen, 2007], have shown that during the subglacial stage of an eruption, highly efficient heat transfer from magma to ice takes place, leading to rapid melting of the overlying ice. The instantaneous efficiency of heat transfer from magma to ice melting during fragmentation may be in the range 50–80% [Gudmundsson, 2003; Gudmundsson et al., 2004; Tuffen, 2007]. However, when an eruption emerges through the ice cover and forms a volcanic plume, the eruption’s thermal energy will be partly dissipated in the atmosphere. The Eyjafjallajökull eruption is an example of this, since major magma-ice interaction at the vents was mainly confined to the first two of the 39 days of continuous eruption.

[4] Remote sensing techniques such as Synthetic Aperture Radar (SAR) and Interferometric SAR (InSAR) have been used to study ice surface changes in relation to geothermal and volcanic activity under ice [Jónsson et al., 1998; Björnsson et al., 2001; Gudmundsson et al., 2002; Magnússon et al., 2005, 2010; Scharrer et al., 2007], as well as airborne radar elevation profiling [Gudmundsson et al., 2007] and infrared cameras applied to map temperatures of ice-free spots such as water surfaces, tephra patches and domes [e.g., Stewart et al., 2008].

[5] The ice covered Eyjafjallajökull volcano on the south coast of Iceland rises to 1640 m above sea level (Figure 1). During the summit eruption of Eyjafjallajökull, 14 April – 22 May 2010, intensive volcano-ice interaction occurred in the first few days. Rapid melting of ice, formation of ice cauldrons and sediment-laden outburst floods occurred during April 14–16. Some melting occurred later in the eruption, but in comparison to the first three days the melting rates were low and significant flooding did not occur. Although clouds obscured the craters during these first three days, an airborne SAR on-board the Dash 9 aircraft of the Icelandic Coast Guard, TF-SIF, was used to study the formation and development of ice cauldrons in near-real-time and unprecedented detail.

[6] In this paper we describe the volcano-ice interactions observed at Eyjafjallajökull on 14–16 April 2010. The ice melting rates are inferred from SAR-derived temporal changes in cauldron sizes. These data are then used to: (i) constrain heat transfer rates from magma to ice; (ii) develop conceptual models of cauldron formation; (iii) constrain sediment loads of floods issuing from the summit ice cauldrons; and (iv) consider implications for subglacial hydrology and the controls it imposes on drainage of meltwater from subglacial eruption sites.

2. Data Acquisition

[7] The observations presented in this study are mostly based on high resolution radar images from an airborne SAR (Elachi [1987] for details on SAR techniques), a part of an X-band (~10 GHz) radar system on-board the aircraft, TF-SIF. A key feature of SAR is that images can be obtained through clouds and ash plumes. As a side-looking radar, the incidence angle $\theta$ (relative to vertical axis) is large, commonly 65–85°. The distance to imaged targets, which can vary from 15 to 90 km, is therefore much larger than typical flight altitudes for operating the SAR (~7,000 m a.s.l.). In general this distance was 20–30 km ($\theta$ of 70–76°) during the first days of the Eyjafjallajökull eruption, making it possible to obtain images of the eruption from a safe distance. The large $\theta$ produces significant data gaps in the SAR data and resulting images contain extensive shadows on the far side of steep hills and mountains and made it impossible to look into the ice cauldrons formed during the first days of the eruption.

[8] Spatial resolution corresponding to image cell size of one meter is achievable with the SAR on-board TF-SIF, but at the time of the Eyjafjallajökull eruption, it had not been fully optimized for high resolution image acquisitions. The actual cell size for most of the images presented here is therefore around three meters. The acquired images were only saved on jpeg-format with high compression, hence the quality of the images were further reduced. Reprocessing the SAR images is not possible since the raw radar data were not saved. Despite these drawbacks the SAR-images obtained during the first hours and days of the eruption helped immensely in monitoring the eruption, both from a scientific and civil protection perspective. An example of the details detectable from the SAR images is shown by comparison with a photograph (Figure 2) obtained on 17 April, the first day of cloud free view to the eruption site. The main advantage of the SAR operated by the Icelandic Coast Guard compared to equivalent spaceborne systems is its flexibility. The first images of the eruption site were acquired within eight hours from the start of the eruption and a unique series of images was acquired over the first day at a temporal resolution presently not possible with available spaceborne radar systems, which also obtained images of the Eyjafjallajökull eruption site during the eruption [Münzer et al., 2010].

[9] Aerial photographs, observations of plume heights, hydrological measurements and other flood observations (Table 1) were used to constrain key stages in the course of the eruption.

3. Geological Setting

[10] Eyjafjallajökull is a central volcano, rising from sea level to an elevation of about 1640 m, built over the last 800 thousand years through numerous eruptions with varying degree of volcano-ice interaction [Loughlin, 2002]. Above 1000 m elevation the volcano, is covered by an 80 km² ice cap that is typically less than 100 m thick on the slopes. Thicker ice is confined to the 2–3 km wide summit caldera, where ice thicknesses varies from ~200 m in the west part of the caldera [Strachan, 2001] (pre-eruption conditions) up to 400 m in the east part (Institute of Earth Sciences, University of Iceland, unpublished data, May 2011). Before the 2010 eruption, the total volume of ice within the caldera was ~0.8 km³. Ice from the summit caldera flows northward, down the 4 km long Gigjökull glacier (Figure 1). Before the 2010 eruption, Gigjökull terminated in a ~1 km long and ~0.6 km wide proglacial lake, known as Gigjökulsln, enclosed by 50–100 m high lateral moraines.

[11] Before 2010, Eyjafjallajökull is known to have erupted on four occasions in the past 1500 years [Gudmundsson et al., 2005]. These eruptions were relatively modest, smaller than the eruption in 2010. The most recent eruption prior to 2010 occurred in 1821–23, lasting for about 14 months, although long intervals of little or no activity occurred during that period [Larsen, 1999]. The products of these eruptions were tephra layers and lava flows of mostly
Figure 1. (a) The study area of Eyjafjallajökull and its surroundings. The shaded relief image and the 100 m contours (only shown for the Eyjafjallajökull ice cap) are based on a digital elevation model (DEM) measured with airborne LiDAR in the summer 2010 [Jóhannesson et al., 2011] after the eruptions on Fimmvörðuháls and at the Eyjafjallajökull summit (summit caldera outlined with broken red line). Yellow lines and polygons show eruption fissures and vents and red areas indicate visible lava and cinder cones produced during the eruptions. The cyan arrow lines and the area outlined with broken blue line show the path of the floods and light blue areas outlined with broken blue line show flooded areas. Red triangles show locations of the river level gauge at a bridge over the river Markarfljót and lake level gauge in the lake Gígjökulslon. The corner inlet shows the geographical location of the area (red box) within the volcanic zones (gray) of Iceland. (b) Eyjafjallajökull from northwest, 19 March, 2010. Gígjökull outlet glacier and Gígjökulsón proglacial lake in the foreground. (c) Gígjökulsón from north, 14 April, 2010 at 9:44 (picture taken by Þórdís Högnadóttir) when the first flood was near peak flow at Gígjökull. It shows the flood bursting out from the glacier at the south side of the lake.
intermediate to silicic composition [Larsen et al., 1999; Óskarsson, 2008]. The 1821–23 eruption caused at least one sizable flood that issued from Gígjökull in the summer of 1822 [Gröndal and Elefsen, 2005].

4. Course of Events

[12] The timeline of events during the first three days of the summit eruption is given in Table 1. The table includes all events discussed in the following section but it documents the timing and nature of events in more detail. Events are grouped into three types; A: ash plume, C: cauldron development and F: flood.

[13] The eruption in Eyjafjallajökull was preceded by intense ground inflation and seismicity from January to March 2010 [Sigmundsson et al., 2010], leading to a small basaltic flank eruption on Fimmvörðuháls east of Eyjafjallajökull (Figure 1) from 20 March to 12 April. In the evening of 13 April an intense three-hour-long earthquake swarm led to an eruption within the summit caldera, beginning at about 1:30 (this and all subsequent times are UTC) 14 April. The summit eruption produced benmorite and trachyte [Keiding and Sigmarsson, 2012]. Aircraft pilots were the first to report the appearance of a weak eruption plume just before 6:00, and by 6:50 the level of Gígjökulsþón had begun to rise [Roberts et al., 2011].

[14] At 9:58 the lake level gauge at Gígjökulsþón was swept away by the first and most voluminous flood, when it was probably near peak flow at Gígjökull [Roberts et al., 2011]. A peak flow of ~2700 m³ s⁻¹ was observed around two hours later [Roberts et al., 2011] in the river Markarfljót (Figure 5a) 16 km east of Gígjökulsþón. A small flood occurred in the evening of 14 April but the following night the drainage from Gígjökull reached a fairly stable discharge of 20–30 m³ s⁻¹ [Roberts et al., 2011], an order of magnitude higher than normal in late winter. It remained at this level until the following evening. Limited observation of plume heights indicated significantly weaker plume in the afternoon of 15 April than had been observed from 9:00 the previous day and until the morning of 15 April (Table 1). A new SAR image series obtained 17:00–18:10, 15 April, showed a new cauldron within the summit caldera, west of the previous ice cauldrons (Figure 6a). Images of the north side of Eyjafjallajökull showed that the lake Gígjökulsþón had by the afternoon of 15 April been filled with volcaniclastic material transported during the floods, an observation confirmed by eye-witness accounts (B. Sigurbjörnsson,
Table 1. Timeline of Events During the First Three Days of the Summit Eruption in Eyjafjallajökull

<table>
<thead>
<tr>
<th>Day</th>
<th>Time (UTC)</th>
<th>Event Type</th>
<th>Event</th>
<th>SAR</th>
<th>Photos</th>
<th>Weather</th>
<th>Hydro</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>14 Apr.</td>
<td>1:30</td>
<td>Summit eruption starts</td>
<td>x</td>
<td></td>
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<tr>
<td></td>
<td>~6:00</td>
<td>A</td>
<td>Weak eruption plumes reported by airplanes</td>
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<tr>
<td></td>
<td>6:50</td>
<td>F</td>
<td>Gígjökulsókn lake level starts rising</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>8:27</td>
<td>F</td>
<td>Flood observed propagating from Gígjökulsókn</td>
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<tr>
<td></td>
<td>8:45</td>
<td>A</td>
<td>Ash plume rising above cloud cover</td>
<td>x</td>
<td>x</td>
<td></td>
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<tr>
<td></td>
<td>8:55</td>
<td>C</td>
<td>An open ice cauldron observed within the summit caldera</td>
<td>x</td>
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<tr>
<td></td>
<td>9:01–9:18</td>
<td>C</td>
<td>Two open cauldrons within the summit caldera</td>
<td>x</td>
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<tr>
<td></td>
<td>9:18</td>
<td>C</td>
<td>Third cauldron opens within the summit caldera</td>
<td>x</td>
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<tr>
<td></td>
<td>11:00</td>
<td>F</td>
<td>Lake level gauge at Gígjökulsókn swept away by the flood</td>
<td>x</td>
<td>x</td>
<td></td>
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<td></td>
<td>9:30–16:20</td>
<td>A</td>
<td>Ash plume pulsating up to ~9 km a.s.l.</td>
<td>x</td>
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<tr>
<td></td>
<td>10:18–10:42</td>
<td>C</td>
<td>Four open cauldrons within the summit caldera</td>
<td>x</td>
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<tr>
<td></td>
<td>10:23</td>
<td>F</td>
<td>A supraglacial flood channel evident on the glacier south side</td>
<td>x</td>
<td></td>
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<tr>
<td></td>
<td>10:24</td>
<td>C</td>
<td>Cauldron opens south of Eyjafjallajökull summit caldera</td>
<td>x</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>10:32</td>
<td>A</td>
<td>Small ash plume observed rising south of the main plume</td>
<td>x</td>
<td></td>
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<tr>
<td></td>
<td>11:00</td>
<td>F</td>
<td>The flood draining south reaches bridge 10 km from its origin</td>
<td>x</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>12:00</td>
<td>F</td>
<td>Peak flow of ~2700 m³ s⁻¹ at the Markarfljót gauge (Figure 1)</td>
<td>x</td>
<td>x</td>
<td></td>
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<tr>
<td></td>
<td>14:47–15:22</td>
<td>C</td>
<td>Three cauldrons within the summit caldera have merged</td>
<td>x</td>
<td></td>
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<tr>
<td></td>
<td>14:53</td>
<td>C</td>
<td>Small open cauldron observed at the rim of the summit caldera</td>
<td>x</td>
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<tr>
<td></td>
<td>15:22</td>
<td>C</td>
<td>A linear cauldron detected slightly south of the summit caldera</td>
<td>x</td>
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<tr>
<td></td>
<td>16:20</td>
<td>A</td>
<td>Small ash plumes still observed south of the main plume</td>
<td>x</td>
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<tr>
<td></td>
<td>~16:00–18:30</td>
<td>F</td>
<td>The flood draining south into the river Svadbælisá ceased</td>
<td>x</td>
<td></td>
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<tr>
<td>14/15 Apr.</td>
<td>16:20–10:10³</td>
<td>A</td>
<td>Ash plume relatively stable reaching 5–6 km a.s.l.</td>
<td>x</td>
<td></td>
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<tr>
<td>15 Apr.</td>
<td>~1:00–18:30</td>
<td>F</td>
<td>20–30 m³ s⁻¹ stable drainage from Gígjökull</td>
<td>x</td>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td>16:00–18:10³</td>
<td>A</td>
<td>Discrete observation of plume height show it at ≤5.4 km a.s.l.</td>
<td>x</td>
<td></td>
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<tr>
<td></td>
<td>17:00–18:10</td>
<td>A</td>
<td>Ash plume not reaching through cloud cover at ~5.5 km a.s.l.</td>
<td>x</td>
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<tr>
<td></td>
<td>~18:18</td>
<td>F</td>
<td>A new cauldron observed west of the previous ice cauldrons</td>
<td>x</td>
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<tr>
<td></td>
<td>~18:21</td>
<td>F</td>
<td>The lake Gígjökulsókn already filled with flood sediments</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td>x</td>
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<tr>
<td></td>
<td>~18:37</td>
<td>F</td>
<td>Evidence of supraglacial slurry flow observed on Gígjökull</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
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<tr>
<td></td>
<td>~19:55–20:07</td>
<td>F</td>
<td>An opening detected above flood subglacial flood channel</td>
<td>x</td>
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<tr>
<td></td>
<td>~19:55</td>
<td>F</td>
<td>A load roaring sound heard from the volcano</td>
<td>x</td>
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<td></td>
<td>~18:37</td>
<td>F</td>
<td>Flood water observed bursting out from Gígjökull</td>
<td>x</td>
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<td></td>
<td>~18:50</td>
<td>F</td>
<td>Thick slurry flow observed pouring down east of Gígjökull</td>
<td>x</td>
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<tr>
<td></td>
<td>~19:55–20:07</td>
<td>C</td>
<td>Westernmost summit cauldron grown slightly</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>~19:55</td>
<td>F</td>
<td>Five new openings observed above flood channels</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>~19:55</td>
<td>F</td>
<td>Origin of a slurry flow observed on Gígjökull at 1200 m a.s.l.</td>
<td>x</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>~19:55</td>
<td>A</td>
<td>Ash plume rising up to ~6 km a.s.l.</td>
<td>x</td>
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<td></td>
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<tr>
<td></td>
<td>~19:55</td>
<td>F</td>
<td>Peak flow of ~1400 m³ s⁻¹ at the Markarfljót gauge (Figure 1)</td>
<td>x</td>
<td>x</td>
<td></td>
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<tr>
<td>15/16 Apr.</td>
<td>Evening/night</td>
<td>F</td>
<td>Pulsating floods</td>
<td>x</td>
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<tr>
<td>16 Apr.</td>
<td>from 2:10²</td>
<td>A</td>
<td>Ash plume pulsating between 3 and 8 km a.s.l.</td>
<td>x</td>
<td></td>
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<tr>
<td></td>
<td>16:04–17:07</td>
<td>C</td>
<td>Only the westernmost summit cauldron grown from 15 April</td>
<td>x</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>~17:00</td>
<td>F</td>
<td>Openings above flood channels grown and new ones appeared</td>
<td>x</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>~17:00</td>
<td>A</td>
<td>The last flood related to the formation of summit cauldrons</td>
<td>x</td>
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</tbody>
</table>

¹Event types are: A: ash plume, C: cauldron formation, F: flood. Sources of data, shown on left, are SAR images, photos from aircraft, weather radar, records from hydrological gauging stations and other (seismic/tremor records, reports from local observers on ground or aircraft pilot reports).
²From Arason et al. [2011].
³From Roberts et al. [2011].
⁴From Sigurðsson et al. [2010].
⁵Only few discrete recording of plume heights available between 10:10, 15 April and 2:10, 16 April due to recording failure and thick precipitation clouds.

The images also revealed changes in the surface of Gígjökull from previous observation flights including collapse of a channel roof at 1380 m a.s.l. and remains of a 1300 m long supraglacial slurry flow (mixture of ice, snow and meltwater) starting at 1200 m a.s.l. extending down to 800 m a.s.l. (Figure 6a). At 18:21 (±2 min) on 15 April a load roaring sound was heard from the volcano at the farm Fljótsdalur, 10 km north of the eruption site (A. Runólsdóttir and the Icelandic Police, Civil Protection Department, personal communication, 2011); this sound was interpreted as a new flood draining from the eruption site. The resulting outburst displayed standing waves and reduced turbulence, and thus had the appearance of a hyperconcentrated flood (Figure 7). It was very swift, with most of its water (4–8 Gl estimated from Figure 5a) draining from Gígjökull in less than half an hour. The average discharge was therefore of order 4–8 Gl/1500 s ≈ 2500–5500 m³ s⁻¹, with a peak flow at Gígjökull lasting at most 5–10 min, being roughly two to three times the average, or 5000–15,000 m³ s⁻¹. The flood overtopped protection barriers on the north side of the sandur outwash plain opposite to Gígjökull; these barriers had withstood the main flood the day before. The peak flow was significantly damped while spreading over the wide river plain west of Gígjökull. As it reached the river level gauge 16 km west of Gígjökull (Figure 1), the peak flow was lower (~1400 m³ s⁻¹) than the one observed on 14 April (Table 1). Slightly east of Gígjökull an ice-laden slurry was observed pouring...
down the mountain side to an elevation of 250 m a.s.l. Lubricated by floodwater, the slurry comprised a mass of mechanically fragmented ice (80% by volume, derived from later field campaigns), sourced from both the collapse pits on Gígjökull, as well as snowpack from the upper part of the glacier.

While obtaining a new series SAR images between 19:55 and 20:07 the eruption plume rose above clouds to an

Figure 3. Series of geo-referenced SAR images obtained between 8:55 and 15:00 on the first day of the eruption. It shows the evolution of ice cauldrons and features formed by supraglacial flooding in the vicinity of the first cauldron (area outlined with broken cyan line) and on the south side of the glacier (single channel). Contour lines (50 m) are from SPIRIT DEM obtained in 2004 [Gudmundsson et al., 2011] and the glacier margin (blue line) is from the LiDAR DEM obtained in 2010. The red boxes in Figure 3a indicate the area covered by Figures 3b–3e.
elevation of ~6 km a.s.l. The SAR images (Figure 6b) showed some growth of the new ice cauldron. The most dramatic changes were observed on the surface of Gígjökull where, during the flood, five new openings were formed above the flood channels. The SAR images also revealed that the slurry flow, observed coming down the mountain side east of Gígjökull, issued from the largest of these new openings at an elevation of 1200 m a.s.l. Repeated floods came down from Gígjökull later in the evening and during the night but these floods ceased early next morning.

The final series of SAR images presented here were obtained around 16:20, 16 April (Figure 8a). It showed that only the westernmost cauldron was still growing, signifying that most of the heat flux was concentrated at this location. It also revealed further changes on the surface of Gígjökull (Table 1 and Figure 8). SAR images obtained in the following days show that the cauldrons did not expand much further (Figure 5) until the eruption became partly effusive on 21 April. The SAR onboard TF-SIF was used throughout the eruption at Eyjafjallajökull to monitor crater development and track advance of the lava flow down the outlet glacier Gígjökull, but analysis of these data is beyond the scope of this paper.

5. Discussion

The SAR images from the first day of the eruption show no evidence of the formation of system of concentric crevasses (Figure 3), as observed during drainage of subglacial geothermal areas or eruptions under thick ice like in Gjálp in 1996 [Gudmundsson et al., 1997]. This scarcity of crevasses on April 14 is not an artifact, since comparison of photos taken from aircraft on April 17 and SAR images from April 18 shows how crevasse patterns are well imaged with the SAR (Figure 2). Thus, the opening of the ice cauldrons seems to have taken place without significant subsidence of the ice; most likely through upwards melting of the ice, with sufficient pressures within the underlying cavity to prevent collapse. Moreover, the absence of concentric crevasses on 14–15 April indicates little inward flow of the ice.

The progressive ice cauldron widening and the estimated ice volume melted during the first days of the
eruption are shown for each of the three main cauldrons within the summit caldera in Figure 5. We assume vertical ice wall for open cauldrons. This may produce higher uncertainty than assumed below for the ice already melted in the morning 14 April, before and shortly after a new cauldron opens, while it is possible that for a short period a part of the cauldron roof remained intact and ice blocks from the roof floated within the cauldron before melting. It can be ruled out that a thick ice block compared to the total ice thickness prevailed within the cauldron since at the time of first SAR observation (8:55), considerable ash plume was rising from the eruption site. We do expect that as the cauldrons evolved the uncertainty related to the assumption of the cauldron morphology, is insignificant. Moreover, direct sighting of the cauldrons on April 17 (e.g., Figure 2) showed that the cauldron walls were vertical at that time and that negligible inward-directed ice flow had taken place at that time.

The total volume of melted ice between 14 and 20 April, as derived from the SAR data, corresponds to ~0.08 km$^3$ or ~10% of the pre-eruption ice volume of the caldera. The cumulative drainage until 17 April, obtained from the river level data, is shown for comparison. The difference between the two estimates is insignificant considering the uncertainties in both methods. Inaccuracies in ice thickness at the eruption site produce the main uncertainty in the estimate derived from the SAR data, but based on measurements by Strachan [2001], we assume an average ice thickness of 210 m for the first cauldron (red, in Figure 5) and 180 m for the other two. The uncertainty in ice thicknesses derived from continuous radio echo sounding (RES) profiling in a temperate glacier with RES-system of similar frequency range has been considered ±15 m [Björnsson et al., 2000]. Since these ice thicknesses are derived from discrete RES-observations at and near the cauldron locations, which makes data interpretation more difficult than in case of RES-profiling, we assume a cautious error estimate of ±30 m for the above ice thicknesses. For the volumetric estimate of floodwater drainage, the error margin of 20% is based on the fraction of water that bypassed the bridge where gauging took place. During the height of the floods on 14 and 15 April an unknown volume of floodwater drained around the inundated gauging site. The figure of 20% takes into consideration visual estimates of maximum discharge. Before and after the peaks of the floods, water was confined to the span of the bridge, allowing more accurate measurements of floodwater discharge. It should be noted that some difference between the estimate of meltwater volume obtained from the size of the cauldrons and cumulated discharge obtained from the river level data is to be expected. First, an unknown but probably minor part of the meltwater was incorporated as water vapor into the eruption plume after the cauldrons opened, reducing the drainage in the river Markarfljót. Second, ice was also melted along the subglacial flood path, due to the thermal and frictional energy of the floodwater and additional water was added with the incorporation of the proglacial lake. This latter effect adds volume to the discharge in the river while not registering in the cauldron volumes. We estimate the water originating from Gígjökulsún (total volume of lake minus the water stored in the mud filling the lake) to be 9 ± 3 Gl, but the lake volume of 15 ± 4 Gl is obtained using 0.6 km$^2$ for the lake.
area (from SPOT 5 image in 2008) and an average depth of 20–30 m. The depth in the northern part of the lake is derived from discrete depth measurements [Rist, 1981]. The depth in the southern part is approximated from pictures taken in 2005 showing the height of the calving front and floating ice blocks above lake surface as well as radio echo sounding measurement carried out in 1999 [Strachan, 2001] while the southern part of the lake was still filled with

**Figure 6.** SAR images obtained (a) before and (b) after a short but intense flood (Figure 7) on the second day of the eruption. (c) The red boxes indicate the area covered by the two image mosaics.
Figure 7. Hyperconcentrated flood from Gígjökull shortly before 19:00 on 15 April. The width across the flooded area in Figure 7a is around 800 m. The protection barriers in the upper left corner of Figure 7b is at \( \sim 1.5 \) km distance from the airplane. Characteristic wavelength of standing waves is 20–30 m. Pictures taken by Þórdís Högnadóttir.

Figure 8. (a) A mosaic of SAR images (location shown with red box on inlet) obtained on the third day of the eruption around 16:20. New openings above flood channels as well as growth of old openings are observed within the area outlined the broken red line. (b) Photograph taken the same day showing ice columns jacked up by \( \sim 10 \) m indicating high water pressure during floods. (c) Photograph taken on the fourth eruption day showing one of these openings. Rough estimate of the width of the opening and the visible semi-cylindrical tunnel are shown. Both Figure 8b and 8c are taken from south.
The first two cauldrons formed within the summit caldera (red and green in Figure 5) stopped growing on the second day of the eruption, suggesting that significant activity was over at these vents, and that the eruption moved to the new cauldron west of the initial fissure (blue in Figure 5). This may have happened as early as noon on 15 April, when plume activity apparently decreased significantly. This new cauldron continued to grow during the third eruption day, reaching an area of 0.2 km². During the following days only a minor growth of the cauldron was observed (Figure 5), despite the eruption continuing at comparable rate. This indicates that in contrast to the first two days of the eruption, a very small proportion of the eruption’s thermal energy went into melting the cauldron walls after 16 April. Contributing to this development was probably the lack of water, minimizing heat transfer to the ice walls, and the accumulation of tephra within the cauldron, which helped to insulate the ice.

We see no evidence in the summit area of mechanical disruption of the ice playing a major role in forming the cauldrons containing the craters. Such evidence might, e.g., be a field of ice blocks adjacent to the cauldrons and possibly upwardly displaced ice blocks or cauldron sides. This contrasts with the path of the meltwater, where the outlet glacier is heavily disrupted by holes apparently formed by breakout of water with associated transport of ice blocks and rubble down the glacier. In all likelihood, ice blocks that fell into the growing cauldron are quickly melted. This conforms to limited observations in Grímsvötn eruptions [Gudmundsson, 2005; Jude-Eton et al., 2012].

Since there is no evidence to suggest significant mechanical removal of overlying ice, we assume that the growth rates observed for the cauldrons represent melting rates. The data allow both upwards (vertical) and horizontal (radial) melting rates to be estimated (Table 2). These in turn can be converted to heat transfer rates from magma to ice.

The values obtained are average values over periods of some hours but yield about 1 MW m⁻² for radial heat transfer and about 4 MW m⁻² for the vertical heat transfer. The radial rates are similar to the values that were obtained for Gjálp in 1996 by averaging the melting rates over the surface of the volcanic edifice [Gudmundsson et al., 2004]. However, the vertical heat transfer rates obtained here are considerably higher than the radial rates and the average Gjálp rates. This indicates that within a water-filled cavity where magma fragmentation takes place, upwards melting exceeds sideward melting. It remains to be seen how general this observation is, it needs not apply in different settings, e.g., at high pressures under very thick glaciers where explosivity may be highly suppressed [Zimanowski and Büttner, 2003].

5.1. Cauldron Formation and Flooding on 14–15 April

The efficiency of heat transfer from magma to ice is a key parameter for the study of ice melting and the relative proportions of volcanic material, meltwater and the volume of ice melted [e.g., Hóskuldsson and Sparks, 1997; Gudmundsson, 2003; Tuffen, 2007]. It can be calculated that unless the efficiency (\(f_i\)) is 90% or higher (assuming all magma is transformed to non-crystalline glass, ignoring any effects of magma vesicularity and using the magma temperature derived by Keiding and Sigmarsson [2012]), the net volume of erupted volcanic glass plus meltwater exceeds the volume of melted ice. The tephra erupted in the early phases of the Eyjafjallajökull eruption was mostly vesicle poor and very fine grained [Dellino et al., 2012]. Efficiency greater than 90% is, however, physically unrealistic, since it assumes that the meltwater, the main agent of heat transfer from magma to ice, is at zero degrees [e.g., Gudmundsson, 2003]. It is therefore likely that a volcanic eruption under ice always leads to a volume increase, i.e., that the combined volume of meltwater and volcanic material is greater than the ice melted. As a consequence, meltwater has a tendency to drain away from an eruption site under a glacier [Gudmundsson, 2003; Gudmundsson et al., 2004]. Next we apply these principles to the cauldron development observed.

Details in the SAR data help constrain the process of the ice-volcano interaction during the initial phase of the eruption and course of events. It is intriguing that more than five hours passed from the start of the eruption until water started to drain into the proglacial lake. We expect the temperature of the erupted magma \(T_m\), to be 1000–1060°C [Keiding and Sigmarsson, 2012] and the ice thickness to be 210 ± 30 m. In the absence of other observationally derived data constraining heat transfer efficiency, we use values between 50 and 61%, corresponding to the range of possible \(f_i\) in the first days of the Gjálp eruption in Vatnajökull [Gudmundsson et al., 2004], and a constant melt rate between the start of the eruption at 1:30 and 9:13 (the time of the first high resolution SAR observations) we obtain an eruption rate of 43–73 m³ s⁻¹ and an increase in the combined volume of meltwater and pyroclastic material (using particle density of 2400 kg m⁻³, obtained by assuming about 10% vesicularity of particles and the measured solid glass density of 2738 kg m⁻³ [Bonadonna et al., 2011]) relative to the volume of the ice of 14–37 m³ s⁻¹. Clearly, migration of water away from the eruption site was favored. However, since water accumulation in the proglacial lake was not observed until 6:50, we expect that an insignificant amount of meltwater had drained from the eruption site at 6:00. This
slow progression of meltwater was probably due to an inefficient (closed) subglacial drainage system [Paterson, 2006], largely being devoid of subglacial channels. This situation is to be expected during late winter in the accumulation area of a glacier [e.g., Paterson, 2006].

[26] By 6:00 on 14 April, around the time when the first cauldrons opened, the accumulated volume increase since 1:30 (assuming the volume increase rate of 14–37 m³ s⁻¹) corresponds to 1–3 m uplift of a 500 m wide ice plate (around twice the area of the cauldron at 9:13). Such uplift would have been caused by a negative effective pressure (ice overburden pressure minus basal water pressure). Two mechanisms may have been at work: Ice deformation (ductile) and elastic upwards flexure of the glacier. Ice deformation cannot explain all the uplift unless the effective pressure reached values significantly below ~0.21 MPa [Jóhannesson, 2002], the value that corresponds to the effective pressure assuming a water column equal the ~210 m ice thickness. It is therefore likely that, during the initial phase of the eruption, the water pressure within the cauldron exceeded this level meaning that the corresponding water head (level of the water column in a hypothetical vertical open pipe) was above the glacier surface, thus allowing artesian outpouring of floodwater. The observed signs of supraglacial flooding conform to such high water pressures (Figures 3b–3d) but it is also likely that the uplift was partly elastic and that the uplift extended over an area significantly larger than the cauldron. It is possible that fracturing of the ice occurred at the edges of the uplifted area.

**Figure 9.** Two schematic models (A versus B) for the formation of the first cauldrons during the initial phase of the eruption. Model A: (i) Subglacial eruption starts around 1:30, 14 April. The volume of meltwater and erupted material exceeds the volume of ice melted, hence excess water penetrates out of the cauldron. (ii-iii) The cauldron continues to develop and meltwater slowly forces its way from the eruption site. The drainage is however slow since there are no pre-existing drainage routes, hence water pressure significantly exceeding the ice overburden pressure is maintained. (iv) The uplift produced by deformation is slow due to the thin ice at the eruption site. The sudden relief in water pressure when the roof of the cauldron breaks therefore causes the counter level force from the sides of the stiff (on time scale of hours) ice cover to exceed the floatation force on the ice cover. The meltwater in the cauldron therefore swells above the edge of the cauldron, causing the supraglacial floods manifested in the SAR images (Figures 3b–3d). (v) The meltwater eventually penetrates out of the summit caldera toward the proglacial lake. The water in the cauldron level drops causing enhanced plume activity observed shortly before 9:00. Model B: (i) Same as A-i except the high water pressure causes hydraulic fracturing in pre-existing weaknesses in the ice allowing meltwater to penetrate upwards. (ii-iii) Meltwater penetrates to the surface producing fountains on the glacier surface until the water pressure has dropped to ~2.1 MPa corresponding a water column equal the ice thickness (~210 m). By then the water pressure is stable and the excess meltwater is tapped of through the crack causing supraglacial floods. The water pressure which still exceeds the ice over burden pressure causes uplift at the glacier bed but much less than in i). (iv) The collapse of the cauldron roof causes no significant relief in water pressure, hence the water level remains at the edge of the cauldron. (v) same as A-v.
Schematic model showing the formation of the main cauldron during the morning of 14 April. There the ice was of steam at the vents and thus increased gas thrust and confining pressure should have led to more rapid expansion of the water level in the cauldron. The resulting reduction in pressure at the eruption site before the meltwater cupola collapsed (Figure 9). The rise of a plume almost immediately after the roof collapsed also indicates that water level within the cauldron was at that time too low to prevent a relatively weak plume from rising from the vents.

A new cauldron (the west cauldron) within the summit caldera started to form between the afternoon of 14 April and noon on 15 April. From then on the main focus of the eruption was at this new vent, where plume formation was apparently restricted until late on 15 April, by overlying ice or a high water level in the cauldron. The discharge in the river Markarfljót (Figure 5a) indicates that most of the meltwater produced during the formation of this cauldron accumulated at the eruption site until shortly after 18:00, 15 April, when it was released in the swift flood that was observed emerging from Gígjökull at 18:37 (Table 1). It is expected that the volume of meltwater and tephra exceeded the volume of melted ice, as it did earlier in this eruption and in other known subglacial eruptions [Gudmundsson, 2003; Gudmundsson et al., 2004]. We suggest that the excess water, which the cauldron was unable to contain, drained over to the south cauldron formed on the first day (Figure 11). This allowed water to accumulate for longer time than during the formation of the first cauldrons. The water storage in the pre-existing cauldron also increased the ratio of the tephra to the total water volume accumulated within the new cauldron. The flood bursting out from Gígjökull after 18:30 on 15 April occurred as the west cauldron drained. If one cauldron is flushed down, it is likely that other nearby cauldrons are not able to respond on the very short time scale of several minutes, hence a flood originating from more than one cauldron would have produced at least two peaks in the water flow but not a single sharp peak as during this flood. The flood was particularly swift since the ice dam between the new cauldron and flood channels formed the day before was only several hundred meters wide. Thus, when the dam reached floatation, the water was flushed into the pre-existing flood channels. As the water reached the outlet glacier, the flood probably met significant constrictions in the partly open subglacial channels, producing very high water pressures and braking through the channel roof, leading in some cases to a supraglacial slurry flow (Figure 6b) with high concentrations of ice mechanically eroded from the flood path and surface snow. These openings continued to grow and new ones were formed by further floods in the following hours or simply due to collapse of weak channel roofs.

5.2. Mass Removal From Cauldrons

As confirmed by the eyewitness account the SAR images show that lake Gígjökulsþón (pre-eruption size 0.6 km²) had disappeared and filled with water-transported...
tephra in the afternoon of 15 April (Figure 6a). This information can be used to put constraints on the solid mass transport of the floods down Gígjökull on 14 April, and by using water gauge data, to estimate the solid concentration in the floods.

[31] The porous, water-saturated fill of volcaniclastics that had formed by the afternoon of 15 April in Gígjökulsión had a volume of 15 ± 4 Gl. The bulk density of the Eyjafjallajökull tephra of 1400 kg m⁻³ (M. T. Gudmundsson et al., Ash generation and distribution from the April-May 2010 eruption of Eyjafjallajökull, Iceland, submitted to Scientific Reports, 2012) is used together with previously estimated particle density of 2400 kg m⁻³ to find that the tephra displaced 9 ± 3 Gl of water with another 6 ± 2 Gl left as pore water. The mass of the solids left deposited in the lake is therefore 2.2 ± 0.7 × 10¹⁴ kg. For magma at temperature of 1000–1060°C, specific heat capacity of 1100 J kg⁻¹°C⁻¹, around 55% of the total thermal energy of this mass of magma would be needed to produce ~40 Gl of meltwater. This volume of water corresponds to the volume of ice melted in the first 24 h of the eruption (Figure 5a). The question arises how large a fraction of the volcaniclastics was deposited in the lake and how much accumulated in the cauldrons in the first 24 h. However, if an equal amount remained within the cauldrons in the summit area as was deposited in the lake and all this material gave away heat to a thermal efficiency of less than 30% results. Since the resulting efficiency is below 30%, much less than inferred for Gjálp [Gudmundsson et al., 2004], we find this value implausible given the fine-grained character of the Eyjafjallajökull tephra. We therefore expect that the majority of the volcaniclastics settling in the cauldrons and releasing heat for ice melting were washed out during the floods.

[32] The accumulated drainage at the Markarljót bridge (Figure 1), 16 km down-river from the proglacial lake, during the floods on 14 April and the night of 15 April was 35 ± 7 Gl. This includes 9 ± 3 Gl water volume originated.

Figure 11. Suggested procedure for the formation of the last cauldron within the summit caldera. (a) A new cauldron starts to form when an eruption vents opens slightly west of the first ice cauldron, sometimes between the afternoon 14 April and noon 15 April. The cauldron cannot hold all the meltwater since the volume of meltwater and erupted material exceeds the volume of ice melted. Excess water escapes to the surroundings. The water flow from the old cauldron is blocked by accumulated tephra and/or collapsed channels. (b) The new cauldron soon becomes hydrologically connected with the main cauldron formed the first eruption day due the short distance between the two cauldrons and weakness at the ice-bedrock interface created during the formation of the pre-existing cauldron. The water pressure in the new cauldron consequently drops; hence penetration of flood water out of the eruption site is halted. (c) The leakage of flood water in to the pre-existing cauldron delays the flotation of the glacier allowing longer time for tephra accumulation. Shortly after 18:00 the water level reaches flotation level of the ice next to the west cauldron. The ice dam between the new cauldron and the flood channels formed the day before is jacked up producing a swift hyperconcentrated flood. (d) When most of the water in the new cauldron mixed with the accumulated tephra has drained out the water route is blocked again. Plume activity increases and water drains back from the old cauldron, which in addition to meltwater produced by further melting of the ice cauldron cause more floods during the evening 15 April and following night.
from the Gígjökulslón. However, this water volume was replaced by equal volume of solid volcanic material; hence 35 ± 7 Gl correspond to the total volume of the mixture flowing from the eruption site. We therefore obtain sediment concentration of 9 ± 3 Gl/35 ± 7 Gl = 26 ± 10 volume percentage (vol%) for the floods down Gígjökull, corresponding to solid mass concentration of 45 ± 13 weight percentage (wt%) using densities of 1000 kg m⁻³ and 2400 kg m⁻³ respectively for water and volcaniclastic particles. This value may even be slightly higher, since our estimate does not take into account any sediment deposited on the sandur plain between Gígjökull and the gauge at the Markarfljót bridge (Figure 1). Discrete measurements of suspended sediments however indicate that <1 vol% of the 35 ± 7 Gl draining under the bridge was solid matter.

The flood bursting out around 18:30 on the 15 April (Figure 7) showed all the characteristics of being hyperconcentrated (i.e., indicating solid concentration of 20–60% vol% [Vaillance, 2000; Pierson, 2005]). It appeared even more loaded with sediment than previous floods, which would be in agreement with leakage of meltwater to the south cauldron during the formation of the west cauldron (Figure 11), as proposed in Section 5.1. Sediment concentration higher than derived above is therefore likely. The only measurement of suspended sediment concentration for this flood, obtained after the flow had declined to half of its peak flow, indicated ~3 vol% sediment concentration at the Markarfljót bridge (Figure 1). Most of the sediments transported by this flood were therefore deposited on the sandur upstream from the bridge.

5.3. Implications for Ice Cap Response and Subglacial Hydrology

The Eyjafjallajökull eruption occurred at the end of winter when the preexisting drainage system is probably very inefficient (no channel flow). Thus, new subglacial water routes relieving the pressure of the system can only be formed by uplift of the ice. Whether this uplift is elastic or caused by ductile ice deformation, must depends on the effective pressure at the bottom of the ice and the ice thickness but exactly how is beyond the scope of this paper. However, it is clear that during the ~4 h period of subglacial eruption at the first cauldron of Eyjafjallajökull, little or no meltwater managed to escape the summit caldera. This suggests that the environment controlling the subglacial water pressure was different than at the Gjálp eruption underneath Vatnajökull glacier in 1996 [Guðmundsson et al., 1997, 2004]. At Gjálp meltwater drained into the subglacial lake Grímsvötn throughout most of its subglacial eruption period. Importantly, the Gjálp eruption occurred in the early autumn (starting at the end of September in 1996) when the subglacial water drainage system was fully developed.

Another important difference between Eyjafjallajökull and Gjálp was that the initial ice thickness at Gjálp was 550–750 m [Guðmundsson et al., 2004] compared to ~200 m at the Eyjafjallajökull main eruption site. The relatively thin ice obviously shortens the time that the eruption can stay subglacial, assuming comparable melting rates. Another observed difference is the relative absence of ice flow into the cauldrons at Eyjafjallajökull compared to the fast ice flow observed at Gjálp [Guðmundsson et al., 1997, 2004; Jarosch et al., 2008], demonstrating the highly nonlinear dependence of ice deformation on ice thickness [e.g., Paterson, 2006].

5.4. Water Storage Potential, Sediment Loading and Terrain Slopes

The conditions allowing the water accumulation during the initial phase of the Eyjafjallajökull eruption and the formation of a new cauldron on the second day of the eruption along with the steep slope of water routes underneath the Gígjökull glacier outlet, cause a very different drainage pattern (periodic) from the eruption site than observed during the Gjálp eruption (apparently dominated by continuous drainage [Guðmundsson et al., 2004]). The steepness of the terrain and the high volume, short duration floods leads to a much higher sediment concentration in the flood water compared to an eruption like Gjálp that occurred within a large glacier. In Gjálp around 10% of the total material accumulated underneath the ice is considered to have been transported from the eruption site and deposited into the lake Grímsvötn, corresponding to drop in sediment concentration of the subglacial floods of 2.5–3 vol% [Guðmundsson et al., 2004]. Our results show that in Eyjafjallajökull the majority of the tephra accumulating in the cauldrons in the first two days was washed out during the flood resulting in order of magnitude higher sediment concentrations. This suggests that the preservation potential of fragmented material erupted in glaciers is very much dependent on the setting, with craters and mounds formed on stratovolcanoes where terrain is steep and ice thicknesses low may be flushed away with meltwater.

The first three days of the Eyjafjallajökull eruption in terms of meltwater drainage (water accumulation at eruption site, followed by swift flood) and sediment concentration show more similarities to Katla jökulhlaups than Gjálp, even though the magnitude of Katla jökulhlaups is much larger [Larsen, 2000]. In terms of swiftness and solid content, the floods released from Eyjafjallajökull on 14–15 April have some resemblance to lahars observed during eruptions of Redoubt in Alaska and other steep-sided ice covered stratovolcanoes [e.g., Major and Newhall, 1989; Thouret, 1990; Pierson et al., 1990; Trabant et al., 1994; Kilgour et al., 2010]. However, for the recorded events at stratovolcanoes, lahars were initiated by either dome collapses forming hot debris flows overriding snow and ice, or pyroclastic flows from collapsing eruption columns [Major and Newhall, 1989]. As shown above, melting at Eyjafjallajökull mostly occurred from below, within ice cauldrons, not on its surface; pyroclastic flows or debris avalanches were either absent or had very minor effects. What Eyjafjallajökull had in common with many of the stratovolcanoes listed by Major and Newhall [1989] is the limited but not negligible water storage potential at the vents and the rapid drainage down steep glaciers. The existence of the summit caldera on Eyjafjallajökull with considerably thicker ice and more gentle slopes than found on the flanks provided conditions for the limited storage of meltwater instrumental in initiating the floods on 14–16 April.

6. Conclusions

The airborne SAR made it possible to obtain frequent images of the Eyjafjallajökull eruption site during the first...
days of the eruption, despite the ash plume and cloud cover obscuring the view to the summit during the first three days of the eruption. Such frequent observations are impossible with current comparable spaceborne sensors. The SAR images combined with other data provided unique details on various eruption parameters and processes. The key observations are:

1. Around 0.08 km$^3$ of the ice was melted within the summit caldera of Eyjafjallajökull during the formation of ice cauldrons in the first few days of the eruption. This corresponds to $\sim$10% of the preexisting ice volume within the caldera.

2. The heat transfer rates from magma to ice can be estimated from the rate of widening of the cauldrons (horizontal or radial melting rate), and the rate at which the eruption melted through the glacier. The values range from about 1 MW m$^{-2}$ (radial) to 4 MW m$^{-2}$ (vertical).

3. Subglacial water pressure at the eruption site developed to very high values during the first hours of the eruption, resulting in supraglacial floods in the vicinity of the first cauldron. The late arrival of meltwater into the lake Gígjökulsálon also indicates water accumulation at the eruption site leading to uplift of the glacier near the first ice cauldron. This uplift may have been on the order of meters over the first four hours of the eruption.

4. The first indication of new eruption vents on the south side of Eyjafjallajökull were revealed by a supraglacial flood channel, down-glacier from the vents, before the roof of an ice cauldron was observed collapsing. This indicates that much of the water had drained from the ice cauldron when it collapsed, in contrast to what happened during the formation of the first ice cauldron within the summit caldera underneath $\sim$200 m thick ice. The vents on the south side of Eyjafjallajökull were located at steep mountain slope underneath 50–100 m thick ice, explaining the different behavior.

5. A new cauldron was observed within the summit caldera on the second day of the eruption. Images obtained the following day show that most if not all the volcanic activity was constrained to this new vent by the end of the second eruption day. Meltwater and tephra accumulated in the cauldron and partly in the preexisting cauldrons until it was flushed out during a very swift flood in the evening 15 April, that flowed both subglacially and supraglacially down Gígjökull breaking up its surface in places.

6. Sediment concentrations in the floods down Gígjökull are estimated to have been $26 \pm 10$ vol% on 14 April and even higher during the flood from the cauldron that formed on 15 April. Thus, the floods classify as hyper-concentrated. The Gígjökull lake acted as a sediment trap during 14 April but had been filled in the afternoon on April 15. Apparently, majority of the fragmented volcanic material that accumulated in the cauldrons during the early, subglacial phases was flushed down Gígjökull with the meltwater.

7. The data presented allow melting rates, accumulation rates of meltwater and sediment concentrations in volcanogenic floods from a steep stratovolcano to be derived. This is achieved from the temporal and spatial resolution of ice surface changes provided by the airborne SAR radar in combination with other data. The findings in particular throw new light on the volcano-ice interaction processes in explosive eruptions producing fine grained tephra. They should have relevance for planning of effective monitoring and hazard assessment at ice covered volcanoes in a variety of settings.

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