

Extreme Value laws), and a suitable multivariate *copula* (or *dependence function*)  $C$  satisfying the Max-Stable property, i.e.,  $C(u_1^t, \dots, u_d^t) = C^t(u_1, \dots, u_d)$  for all  $t > 0$  and  $u_i \in [0, 1]$ . In fact, for all  $x_i \in \mathfrak{R}$ , it holds  $F(x_1, \dots, x_d) = C(F_1(x_1), \dots, F_d(x_d))$ .

The Extreme Value Theory is a fundamental tool in applications, since it provides the theoretical framework for performing risk assessment and rational decision-making in all areas of geophysics.

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## Cross-references

Biblical Events  
 Disaster  
 Frequency and Magnitude of Events  
 Hazard  
 Models of Hazard and Disaster  
 Prediction of Hazards  
 Risk

## CASE STUDY

### EYJAFJALLAJÖKULL ERUPTIONS 2010

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#### Definition

*Eyjafjallajökull*. An ice-capped volcano in South Iceland that erupted in 2010 and disrupted air traffic. The ice cap covering the volcano has the same name as the volcano itself.

*Eyjafjallajökull eruptions 2010*. Two eruptions at Eyjafjallajökull in 2010. An explosive summit eruption beginning 14 April, with sustained activity until 22 May. Ash transported toward mainland Europe led to closure of large part of European airspace for many days, with global disruption of air traffic and economic influence at an unprecedented scale. A preceding effusive eruption occurred 20 March–12 April at the eastern flank of the volcano, in the Fimmvörðuháls area just east of the Eyjafjallajökull ice cap. The effusive eruption is also referred to as the Fimmvörðuháls eruption and the explosive summit eruption as the Eyjafjallajökull eruption of 2010. The two eruptions are also sometimes referred to as a single eruption with different phases of activity.

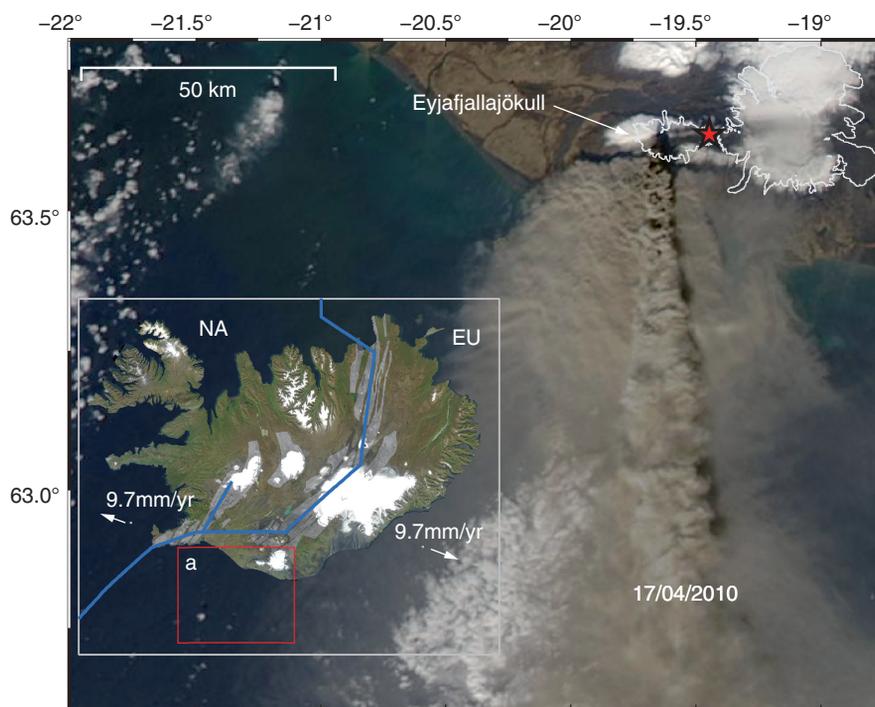
## Introduction

Iceland is a subaerial part of the divergent plate boundary between the North American and Eurasian plates, with over 30 active volcanic systems and eruptions occurring an average every 3–4 years (Thordarson and Larsen, 2007; Sigmundsson, 2006). Basaltic eruptions are common, but explosive eruptions of more evolved magma do also occur. Some of the most active volcanoes are subglacial, leading to generation of eruption plumes due to explosive phreatomagmatic fragmentation of magma even in basaltic eruptions that would, without ice cover in the source area, have generated lava flows. Although the effects of many eruptions in Iceland remain local, there is the potential for widespread influence from long-range transport of ash and gas from Icelandic eruptions. This was the case for the explosive eruption of Eyjafjallajökull volcano that began on 14 April 2010 and directly influenced more people on Earth than any preceding eruption. Advice of the Volcanic Ash Advisory Centre in London (London VAAC) formed the basis for closure of large part of European airspace 15–21 April, leading to cancellation of over 100,000 European flights (Oxford Economics, 2010). Additional airspace closure occurred in early May in a limited area.

## Tectonic setting and volcanic unrest

Mt. Eyjafjallajökull (~1,660 m.a.s.l.) is a moderately active ice-capped volcano with eruptive periods producing both tephra (airborne eruptive material) and lava, separated by hundreds of years of dormancy. The volcano is located south of the spreading part of the Eastern Volcanic Zone of Iceland and has a tectonic setting comparable to an intraplate volcano within the Eurasian Plate (Figure 1). The volcano is aligned in an east–west direction, with a shape intermediate between that of a stratovolcano and an elongated shield, with a small summit caldera. Its edifice links to the edifice of the neighboring Katla volcano, one of the most active volcanoes in Iceland that has had ten explosive eruptions breaking through the ice cover of the overlying Mýrdalsjökull since 1500 A.D. (Larsen, 2000; Eliasson et al., 2006). Volcanic hazards due to eruptions at Eyjafjallajökull include tephra fallout and short lava flows, but the main local threats of eruptions of Eyjafjallajökull are jökulhlaups, sudden glacial outburst floods that come swiftly down the slopes of the volcano when eruptions melt their way through overlying ice (Gudmundsson et al., 2008).

Eyjafjallajökull had a prolonged summit eruption 1821–1823, when a short phreatomagmatic phase in December 1821 was followed by a yearlong period of intermittent magmatic/phreatomagmatic activity and flooding (Larsen, 1999). After that, no activity is known at Eyjafjallajökull until unrest began in 1992 with increased seismicity. Intrusive episodes occurred in 1994 and 1999–2000, witnessed as ground deformation and seismicity interpreted in terms of  $\sim(10\text{--}30) \times 10^6 \text{ m}^3$  sill intrusions at 4.5–6.5 km depth (Sigmundsson et al., 2010;



**Eyjafjallajökull Eruptions 2010, Figure 1** Satellite image (MODIS) of the eruption plume emanating from Eyjafjallajökull main crater on 17 April 2010. Outline of ice caps shown with *gray line*. *Red star*, location of the preceding flank eruption. *Inset*, satellite image of Iceland overlain by fissure swarms in rift zones (*shaded grey*) and showing schematically in *blue* the main axes of the plate boundary between the North American (NA) and Eurasian (EU) plates. Half-spreading rate is 9.7 mm/year. (Modified from Sigmundsson et al., 2010). The MODIS image is courtesy of NASA/GSFC, MODIS Rapid Response (<http://rapidfire.sci.gsfc.nasa.gov/>).

Hjaltadóttir et al., 2009; Pedersen and Sigmundsson, 2004, 2006; Sturkell et al., 2003, 2010; Hooper et al., 2009). A peak in seismicity occurred also in 1996, without observed deformation. After 2000, no deformation was detected until mid-2009, when a period of elevated seismic activity was associated with 10–12-mm displacement at a continuously recording GPS geodetic station at the base of the volcano, related to minor intrusive activity.

### Activity in 2010

In January 2010, deformation and elevated seismicity indicated the beginning of a new intrusive episode in the roots of Eyjafjallajökull that escalated until 20 March when an eruptive fissure opened at the eastern slopes of the volcano. The unrest signals were stronger than in the earlier intrusion periods, in particular in the last 3 weeks preceding the flank eruption, with more than 100 earthquakes recorded on some days and observed deformation rates of more than 5 mm/day. The deformation was well mapped with both GPS geodesy and InSAR (interferometric analysis of satellite synthetic aperture radar images). Interpretation of these data suggests evolution of a complicated intrusion in the volcano roots, with magma flow rates into the intrusion of 30–40 m<sup>3</sup>/s after 4 March (Sigmundsson et al., 2010). Detailed seismic studies also reveal the evolution of the intrusive complex (Hjaltadóttir

and Vogfjord, 2010; Tarasewicz et al., 2012). The eruptive activity that began on 20 March ended 18 years of intermittent precursory activity of the volcano, associated with main intrusions formed in 1994 and 1999 in addition to the 2010 intrusion that evolved in the volcano roots for 3 months prior to delivering magma toward the surface.

From 20 March to 12 April, an effusive basaltic eruption at a short fissure complex at the eastern flank of the Eyjafjallajökull, just east of the ice cap, produced ~0.02-km<sup>3</sup> lava field (Edwards et al., 2012; Eyjólfur Magnússon, personal communication, 2012) (Figure 2). Activity on a short eruptive fissure focused quickly onto several craters; in early May, another short fissure opened up directly northwest of the initial one. During this eruption, lava flowed toward north into steep canyons producing lava falls and steam plumes originating at the lava fronts, as the advancing lava melted snow. Plume originating at the eruptive craters, and tephra produced, was miniscule. The volcano practically stopped deforming during this eruption, signifying magma drainage from a large depth through the intrusive complex formed in the preceding months, rather than draining and collapse of the intrusive complex (Sigmundsson et al., 2010). When the eruptive fissure opened in late evening of 20 March, the earthquake activity had been declining and the onset of eruption tremor was very gradual. Seismic signals of the immediate precursors in the preceding few hours and the



**Eyjafjallajökull Eruptions 2010, Figure 2** The Eyjafjallajökull flank eruption during its later stages in early April 2010 (Photo: Freysteinn Sigmundsson.).

eruption beginning were so minor that the exact timing of the eruption was not forecast; the eruption was visually confirmed before it was recognized on instrument recordings. The eruption attracted a large crowd of tourists who enjoyed spectacular lava fountaining at close distance, as well as the lava falls into canyons. Lava expelled during the eruption is olivine- and plagioclase-bearing mildly alkali basalt with  $\text{SiO}_2$  content about 46 wt% (Sigmarsson et al., 2011; Moune et al., 2012).

In late evening of 13 April, seismic activity renewed, this time under the ice-capped summit, signified new propagation of magma toward the surface (Tarasewicz et al., 2012). At about 1:30 h on 14 April, a new eruption broke out at the ice-capped summit of Eyjafjallajökull, with initial phase of the eruption (few hours) being fully subglacial. Ice cauldrons melted by heat of eruptive products, creating floods of meltwater rushing down the slopes of the volcano in jökulhlaups. The catastrophic explosive phase of the eruption began when the eruption had melted its way through the overlying ice cap. A complete cloud cover hindered initially visual observations in the summit region, but airborne SAR instrument on board an airplane of the Icelandic Coast Guard allowed mapping of the development of the ice cauldrons.

The height of the eruption plume was monitored throughout the eruption with weather radar at the Keflavik airport, at a distance of 155 km (Arason et al., 2011), as well as web cameras, and visual evaluations from ground and overview flights. The eruption was highly explosive on 14–18 April and again after 4 May, with



**Eyjafjallajökull Eruptions 2010, Figure 3** The Eyjafjallajökull explosive eruption on 17 April 2010 (Photo: Eyjólfur Magnússon.).

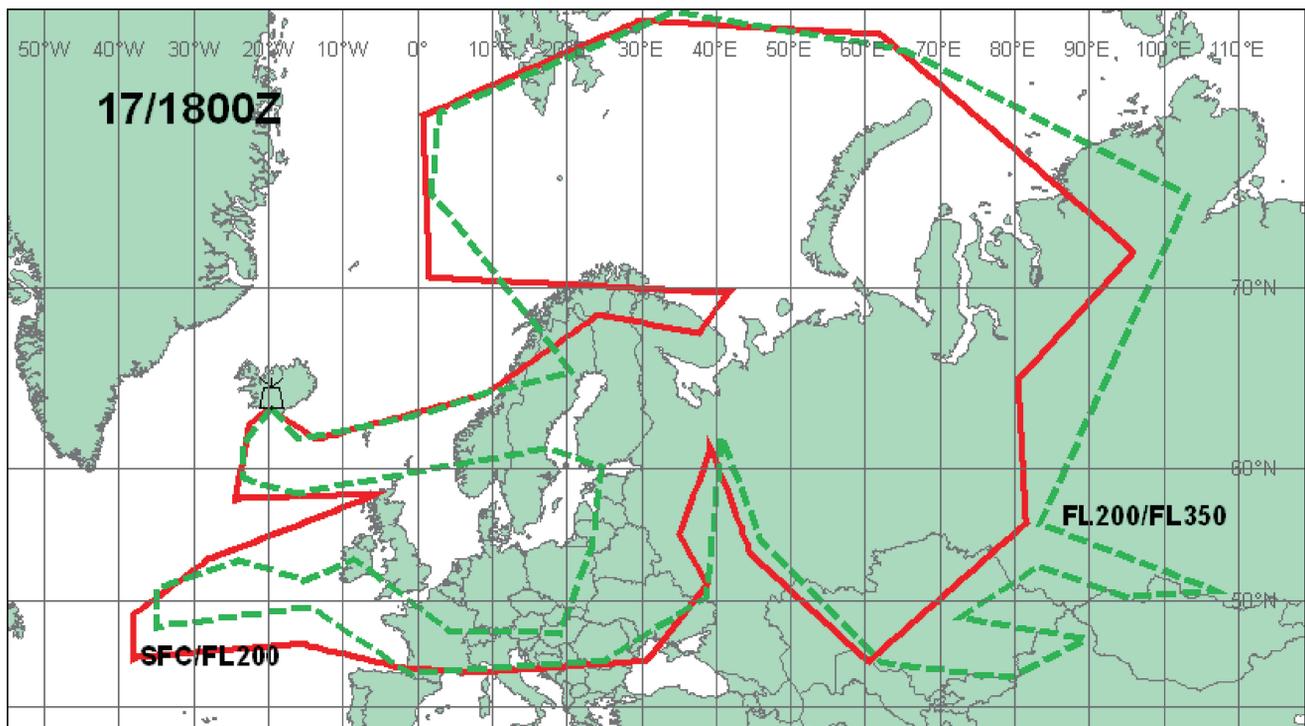
a 5–10-km-high eruption plume (Figure 3). In the intervening interval, the plume was mostly below 5 km height. During that interval, a narrow lava stream flowed northward from the crater area, at the Gígjökull outlet glacier. It produced a massive white steam plume due to ice melt, in addition to the ash-loaded eruption plume. Westerly and northerly winds prevailed during most of the eruption (Petersen et al., 2012), carrying ash quickly toward mainland Europe (Prata and Prata, 2012). The latter explosive phase followed renewed flow of basaltic magma from depth into the volcano as witnessed by seismicity and deformation. Intense ash fallout occurred in some inhabited areas in south Iceland both in the initial as well as the latter explosive phase of the eruption, associated with total darkness during the periods of most intense tephra fall.

This eruption was the first in Iceland to be monitored with web cameras. They provided valuable timely information on pulsating activity of the plume and allowed the general population easy access to monitor the progress of the eruption. A number of other techniques were also used for the first time to monitor Icelandic eruptive activity, including acoustic observations of infrasound and lidar measurements of the arrival of the ash cloud in Europe.

Magma erupted during the summit eruption was benmoreitic to trachytic in composition with  $\text{SiO}_2$  content in the range of 55–61 wt% (Sigmarsson et al., 2011).

This silicic magma was mingled with basalt, revealed by a variety of basaltic, intermediate, and silicic glass in the eruption fallout. The geochemical studies thus show that the summit eruption was triggered by injection of basalt into silicic magma. This was also suggested by Sigmundsson et al. (2010) based on the pattern of deformation associated with the eruptions and intrusions. The deflation source associated with the explosive eruption under the summit of the volcano had not inflated during the preceding unrest. Rather, the recharging of the volcano was associated with inflow of basaltic magma under its eastern flank into an intrusive complex that later started to “leak” magma toward the surface in the flank eruption. The meeting of the two different magmas, silicic magma residing under the summit area and newly arrived basaltic magma, was a key feature triggering the summit eruption.

Ash generated in the explosive eruption was unusually fine grained, fragmented by two processes. Purely brittle magmatic fragmentation due to gas exsolution in the eruption conduit occurred throughout the eruption. This fragmentation process was augmented by fragmentation due to magma-water interaction at least in the initial phase of the eruption; the eruption plume was rich in water vapor during the initial explosive phase but dry during the later one (Dellino et al., 2012). A study using nanotechniques demonstrated that ash particles from the initial explosive phase were especially sharp and abrasive over their entire size range from submillimeter to tens of nanometers



Eyjafjallajökull Eruptions 2010, Figure 4 Graphical display of volcanic ash advisory on 17 April 2010 at 18:00 GMT from the London VAAC. Red and green outlines delimit airspace with predicted contamination of ash. Red outline from the Earth's surface to flight levels (FL) 200, corresponding to about 20,000 ft. Dashed line for FL200-350, or from about 20,000 to 35,000 ft.

(Gislason et al., 2011). Long-range ash transport was facilitated by the fine-grained ash, but aggregation of ash particles was an important process contributing to the fallout (Taddeucci et al., 2011). The amount of erupted material during the summit eruption is estimated to corresponding to dense rock equivalent of  $0.18 \pm 0.05 \text{ km}^3$  (Gudmundsson et al., submitted manuscript).

### Eruption response and impact

Monitoring of eruptive activity was led by the Icelandic Meteorological Office and the Institute of Earth Sciences at University of Iceland (Gudmundsson et al., 2010) that provided advice to civil protection authorities. A National Crisis Coordination Centre operated by Icelandic civil protection authorities, hosted by the National Commissioner of the Icelandic Police, coordinated communication with the public, local, national, and international authorities; scientists; and the media and was the hub for emergency operations. Good response plans were in place at a local level because of prior evaluation of the volcanic hazards and training of population in the area. During the 2010 eruptions, the area surrounding the volcano was temporarily evacuated for short periods during times of uncertain development of eruptive activity and jökulhlaups.

The catastrophic effect of the explosive eruption was the closure of large part of European airspace for many days, based on the guidance of the International Civil Aviation Organization (ICAO) that ash in the atmosphere should be avoided by aircraft. Information on eruption plume height, translated into estimates of mass eruption rate using an empirical relation, was used by the London VAAC to run models of transport and dispersion of the eruption cloud that formed the basis for their advisories of regions where ash was forecasted to be present (Webster et al., 2012). With this approach, a large part of European airspace became closed (Figure 4). During the eruption, a revised procedure was, however, agreed on in Europe, allowing aircraft to fly within the predicted volcanic ash cloud in regions with low levels of ash. The new limits are organized into three levels with a “no fly” high contamination zone for concentrations greater than  $4 \text{ mg/m}^3$  (see, e.g., London VAAC, 2011; Hooper et al., in press). These zones apply in European airspace and have not been accepted for global use. These new rules imply that ash concentrations can both be measured, e.g., by using multispectral satellite measurements (Prata and Prata, 2012) and forecast, a major challenge for the response to future volcanic eruptions.

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### Cross-references

Aviation, Hazards to  
 Caldera  
 Emergency Management  
 Eruption Types (volcanic)  
 Galeras Volcano, Colombia  
 Jökulhlaup  
 Karakatoa (Krakatau)  
 Lava  
 Magma  
 Montserrat Eruptions  
 Nevado del Ruiz, Colombia  
 Plate Tectonics  
 Remote Sensing of Natural Hazards and Disasters  
 Santorini  
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