The Icelandic volcano Eyjafjallajökull caused major disruption in European airspace last year. According to his co-author, Freysteinn Sigmundsson, the reconstruction published in Nature six months later by aerospace engineering researcher, Dr Andy Hooper, opens up a new direction in volcanology. “We want to see how the magma moves inside the volcano.”

When the confusingly-named Icelandic volcano erupted in late March, geophysicist Dr Andy Hooper rushed to book a flight to Iceland. This was just before parts of the European airspace were closed to traffic, owing to the Eyjafjallajökull volcano’s huge ash clouds. “It’s great to see such an eruption up close,” Hooper recounts. “Our pilot made a special detour to give us a view of the volcano.” But Dr Hooper, who has worked in the faculty of Aerospace Engineering’s remote sensing department since 2008, was looking for more than sensation alone. This kind of eruption is certainly exciting - his grinning face on the accompanying photograph, taken on the volcano, leaves little doubt that Dr Hooper enjoys the sensation of feeling -15 °C on his face and 30 °C on his back. His primary objective however was to gather as much data as possible during the eruption. “This is a fascinating volcano because it erupts only occasionally [four times in the last 1,000 years, ed.]. In recent times, Hekla [a neighbouring volcano – ed.] has erupted..."
every ten years. As pressure builds, the volcano rises a few centimetres before sinking again after an eruption. But in the case of Eyjafjallajökull - the name literally means 'island-mountain-ice cap' - the pattern is far more complicated.

In order to acquire data at the site, Dr Hooper contacted the Nordic Volcanological Centre, which is now part of the University of Iceland. The centre's director, Dr Freysteinn Sigmundsson, was a familiar face from his time as a postdoc at TU Delft, from 2006 to 2008. “If you want to study volcanoes, there's no better place than Iceland,” Dr Sigmundsson says, and it was this that prompted his move there. He and his team have been observing the volcano for 18 years now. As recently as the summer of 2009 there was just a single GPS station on the volcano's flanks, but as its activity increased, this was quickly extended to three. The fixed GPS stations have an accuracy of 2 mm per year, explains Dr Sigmundsson, before adding: “Just before it erupted, the volcano was moving 5 mm a day!”

Dr Hooper had also secured additional data from the German operator of the TerraSAR-X radar satellite, which orbits the Earth at a distance 500 km, passing over each area every 11 days. The satellite, which emits microwave radiation and then records its reflection, uses the phase differences between the emitted and reflected waves to calculate the distance to the Earth's surface. By comparing the figures to its previous orbits, it becomes possible to record movements in the Earth's surface down to the level of a millimetre. This meant that Dr Hooper had a secure supply of data when the eruption started, but he never could have imagined that this minor eruption on the volcano's flank, which lasted from 20 March to 12 April, would be followed just two days later by a sudden explosive eruption from the volcano's summit, or that the volcano would remain active for an entire month. As much of Europe groaned under the ash cloud, data continued to flow into the aerospace faculty.

Reconstruction

Six months later, on 17 November 2010, Dr Sigmundsson, Dr Hooper and a dozen other researchers published a reconstruction of the eruption in the scientific journal Nature (*).

Although Dr Sigmundsson was the primary author, he was full of praise for Dr Hooper in our telephone interview: “Andy combined the interferometric data with the GPS data. He was also responsible for much of the modelling. The work he did was extremely significant.” Dr Hooper is equally complimentary about his Icelandic colleague: “Freysteinn has pioneered the measurement of volcanic deformations in Iceland and has amassed years of experience in this field.”

In the article, the co-authors reveal the complicated pattern of magma flows beneath the volcano: as early as 1994, magma was already spreading in a horizontal sill beneath the volcano at a depth of 5 km. A second sill developed a kilometre deeper some five years later. Then, 11 years later, in 2010, the magma forced its way upwards and spread into horizontal, 4 to 5 km deep sills and into a vertical dike reaching just beneath the volcano’s surface. The GPS stations recorded a movement of 6 cm.

On 20 March 2010, the magma broke through the volcano’s flank, spewing lava downwards over a three-week period. Strangely, two of the three GPS stations did not return to their pre-eruption values, indicating that the residual pressure remained undiminished. On 14 April 2010, after two days of calm, a further explosive eruption came from the volcano’s snow-covered crater. According to the analysis, this was because, at a depth of 4 km, the magma had come into contact with an older magma sill. Dr Hooper: “This magma had been there for some time, which meant it had increased in viscosity and also contained lots of gas. The gas caused an explosive eruption, and the denser magma produced smaller ash particles that reached higher into the atmosphere, from where they spread further.”

The article presents a fascinating picture of the course of the eruption, and, according to Dr Sigmundsson, this is just a foretaste of future developments in volcanology. The ultimate aim is to provide a comprehensive picture of the magma flows within the volcano. “We intend to engage in volcanic anatomy,” he explains. The reconstruction results from a type of reverse design. In this, Dr Hooper assumes that there is an 'elastic' substrate or sections of earth where the deformations reflect the build-up of pressure in the magma flow. He then calculates the deformation on the Earth's surface as the magma forces its way through a vent around 20 cm in width. He then compares these calculations with the measurements in order to make adjustments to his reconstruction. After repeating the process a number of times, Dr Hopper reached a result that effectively corresponded with the measurement data.

Does this new understanding also help to predict future eruptions? “In Iceland, you never know which volcano will be the next one to erupt,” Dr Sigmundsson says. “It's impossible to make predictions,” Dr Hooper adds, “but you can more effectively forecast the progress in the course of eruptions. This is something that will certainly interest the world of aviation.”

(*) Dr Freysteinn Sigmundsson, Sigrún Hreinsdóttir, Dr Andy Hooper, et al.: ‘Intrusion triggering of the 2010 Eyjafjallajökull explosive triggering’, Nature, 17 November 2010.

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Land of volcanoes
Iceland is situated on the Mid-Atlantic Ridge. Every year, the North American and Eurasian plates shift away from each other by almost 2 cm. It is these plate movements that cause volcanic activity.

25 km

Eyjafjallajökull
Very little is known about the behaviour of less active volcanoes, such as Eyjafjallajökull (the Icelandic word for ‘island-mountain glacier’), which is not situated above the Mid-Atlantic Ridge. What does the magma chamber of a less active volcano look like and how does it behave?

Big neighbour
Next to Eyjafjallajökull (surface area 50 km²), is its bigger neighbour Kétla (surface area 600 km²). In the past, these two volcanoes were often active at the same time. Magma flows in the earth close to one of the volcanoes can cause the other to erupt. The most recent eruption of Kétla, in 1918, was larger than that of Eyjafjallajökull in 2010. Although there are no concrete indications that would suggest an eruption, volcanologists expect Kétla to erupt in the coming years. The volcano has a history of erupting every 40 to 80 years and is therefore already overdue.

REMARKABLE OBSERVATION
No subsidence after eruption
Usually, after an eruption, the Earth's crust subsides as the magma chamber empties. However, when the flank expanded after the eruption in 2010, this did not happen. This means that the magma from the flank eruption did not originate from the magma chamber under the flank but rather was fed directly from a source deep in the Earth’s crust. The crustal expansions continue to exist, even today, and the magma chambers therefore remain under pressure.

Classic volcano
The classic image of an active volcano is of a cone-shaped mountain with one large magma chamber. Before an eruption, magma flows into the chamber, the pressure increases and the chamber gradually expands. During an eruption, magma flows away, reducing the pressure and causing the chamber to contract again. The expansion and contraction of the magma chamber can be measured through satellite monitoring of the shape of the volcano (GPS and radar interferometry). Before the eruption in 2010, there were five GPS receivers around Eyjafjallajökull. These receivers measure 3D displacements semi-continuously.

Earth simulation
In the TU Delft computer model, the earth of the volcano is comprised of an elastic material that can develop fractures under the pressure of magma flows, which then fill with magma. The model attempts to simulate the movements measured on the surface by assuming that one or more (expanding or contracting) magma chambers are present underneath the volcano.

In 1994, major earth deformations (more than 18 cm) were measured. In the computer model simulation, the magma flows penetrate the earth, creating a horizontal magma chamber.

Magma flows form a second horizontal magma chamber.

There are one to four earthquakes per month.

There are earthquakes on a daily basis. Major earth deformations are being measured. The computer model calculates the formation of a horizontal magma chamber.
movements that cause volcanic activity. And Eurasian plates shift away from each other. Every year, the North American plate is situated on the Mid-Atlantic Ridge. Major earth deformations are semi-continuously recorded on Eyjafjallajökull. By comparing consecutive images (the satellite orbits every 11 days), it is possible to relate the measurements to each other and to use them to predict eruptions. This has formed a basis for predicting eruptions in the future.

Magma speed 30-60 m/s

Magma volume Approximately 100-200 million m³

Small ash cloud
Because the 'young' magma in the flank eruption was less viscous, the gases were able to escape from the magma before it was ejected. This meant that the flank eruption was less explosive and produced no large ash cloud.

Large ash cloud
Starting on 14 April, a small section of 'evolved' magma is released, a remnant from an old magma chamber from previous eruptions. This 'old' magma is more able to hold gases than the 'young' magma (which originates directly from a deep magma source). As the magma is ejected, the gases make the magma explode into very fine ash particles which rise high into the air. Interaction between the magma and the ice cap causes more gas to form, making the ash cloud even more explosive and the particles even finer. The result was an ash cloud reaching a height of 10 km and closing European airspace for days on end. Once the evolved magma had been spewed out of the old magma chamber, the ash cloud dissipated.

Conclusion
The explosive eruption of Eyjafjallajökull on 14 April 2010 was the result of 18 years of volcanic activity in which several flat horizontal and vertical magma chambers had formed above and alongside each other. This cumulative behaviour makes it difficult to detect warning signs in less active volcanoes and to use them to predict eruptions.