Recent Interdisciplinary Research in the Neovolcanic Zone of Iceland using SAR Data.

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Abstract

The ESA project "Monitoring of Natural Land Surface Change in Iceland using ERS-1/ERS-2 and Other Remote Sensing Systems" was initiated to investigate the possibilities of radar remote sensing to observe glaciers and volcanic areas in Iceland. In this context, the ERS-1/2 Tandem Missions (August 17, 1995 - May 16, 1996, and October 21-24, 1996) offered a unique opportunity to employ interferometric methods. In 1995/96 an international team of scientists carried out a preparatory work, marking test sites in Iceland with corner reflectors, obtaining GPS and soil moisture measurements, and determining surface roughness. Radar data processing, interferometric software development and processing were undertaken. The importance to explore the limitations of the technique as well as the advantages was demonstrated in autumn of 1996 when a volcanic eruption took place within the Vatnajökull glacier in Iceland. The usefulness of the Tandem data is presented by one example where a cm-scale uplift is observed in two surface depressions within the Vatnajökull glacier. The depressions are due to subglacial geothermal activity and the uplift is a result of an iceflow into the depressions.

Keywords: ERS, SAR, Iceland, volcanism, glaciers, disaster monitoring, interferometry.

Introduction

Iceland is located on the Mid-Atlantic ridge where the plates of North America and Eurasia spread apart. Volcanic and seismic zones form the plate boundary in Iceland (Figure 1). Glaciers presently cover about 11 200 km^2 of Iceland, or about 10.8% of the country (Björnsson, 1988). They are mainly in the southern part of the island where precipitation is considerably higher than in the northern part. Some of the volcanoes and geothermal areas in south Iceland are covered by glaciers that makes Iceland interesting for studies of glacier-heat and glacier-volcanic interactions.

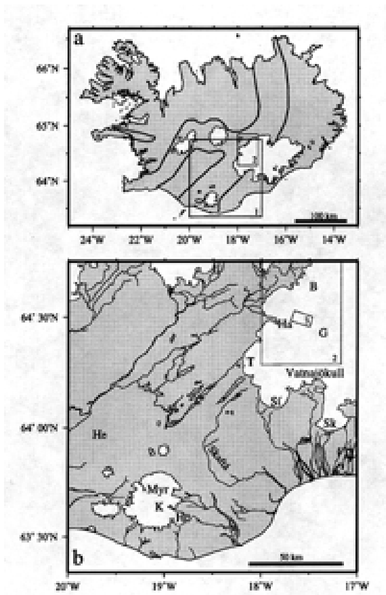

Figure 1. a) Map of Iceland showing the location of volcanic zones as well as the specified test area of the ESA project (frame 1). b) A map of the test area in central south Iceland where the volcanic zone is partly covered by the glaciers of Mýrdalsjökull (Myr) and Vatnajökull. Frames 2 and 3 mark the areas covered in figures 2 and 3, respectively. Central volcanoes: Katla (K), Hekla (He), Bárðarbunga (B), Hamarinn (Ha), Grímsvötn (G). Glacier tongues: Tungnaárjökull (T), Síðujökull (Sí), Skeiðarárjökull (Sk), Höfðabrekkujökull (Hö).

Several of the sub-glacial geothermal areas cause a sudden burst of water from the glacier on a regular basis, a phenomenon that is called jökulhlaup (an Icelandic term to express the phenomenon). Ice melts continuously within the geothermal areas and a reservoir of the meltwater is formed underneath the glacier. When the waterlevel within the reservoir has reached a certain level, high enough to overwin the overburden ice pressure around the reservoir, the water rushes out and a jökulhlaup starts. Jökulhlaups can also occur from a drainage of meltwater from subglacial eruptions and from marginal ice-damed lakes (Björnsson, 1992).

Jökulhlaups can be large and very destructive and can have a major effect on the landscape. They have destroyed large vegetated areas, formed canyons, and they transport huge amounts of sediments. They have caused loss of lives, ruined farms and farmlands in Iceland. Jökulhlaups also threaten electrical power plants, roads, bridges, electrical transmission lines, and other constructions (Björnsson, 1992).

It is therefore of considerable interest that the ESA project no. AO.2 D116 "Monitoring of Natural Land Surface Change in Iceland using ERS-1/ERS-2 and Other Remote Sensing Systems" (Principal Investigator U. Münzer) was initiated to investigate the possibilities of radar remote sensing to observe the ongoing dynamical processes, to detect changes on glaciers due to subglacial geothermal areas and due to volcanic activity, and to observe geomorphological effects of the jökulhlaups as well as changes at the fore-fields of retreating, advancing, and surging outlet glaciers. The project will help to understand further the ongoing processes and will be a demonstration of how the SAR technique can be used in other areas where similar processes are at work.

The test area covers the Eastern Volcanic Zone which is partly covered by the glaciers of Mýrdalsjökull and Vatnajökull (Figure 1). The central volcano of Katla, underneath the Mýrdalsjökull glacier, has erupted approximately every 50 years during last centuries. The eruptions have been accompanied by destructive jökulhlaups reaching peak discharge of 100 000 - 300 000 m^3/s (Thórarinsson 1957). The western part of the Vatnajökull glacier covers the central volcanoes of Bárðarbunga, Hamarinn and Grímsvötn (Björnsson and Einarsson, 1990). During the last decades jökulhlaups have occurred regularly from the caldera of Grímsvötn (Guðmundsson et al., 1995) and from two subglacial geothermal areas between Hamarinn and Grímsvötn (Björnsson, 1977).

A volcanic eruption started within the Vatnajökull glacier on September 30, 1996, several kilometers north of the Grímsvötn caldera (Figure 2) (Einarsson et al., 1997). The eruption lasted nearly two weeks. Huge amounts of meltwater drained into the caldera were it accumulated in a subglacial lake. On November 5-6, 1996, the water rushed out to the south coast, forming the century's most destructive jökulhlaup from the Grímsvötn caldera. The consequences were serious. Several bridges and more than 10 km of the ring road were destroyed, electrical transmission lines and communication cables broke.

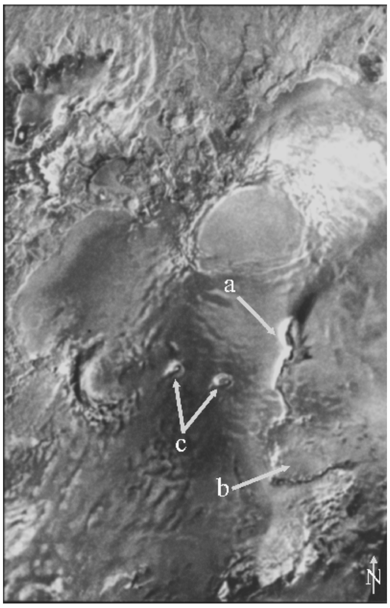

Figure 2. ERS-2 subscene of the western part of the Vatnajökull glacier from October 6, 1996, about one week after the volcanic eruption started. The eruption fissure within the glacier is clearly visible (a). The subglacial tunnel where the melt-water drained south from the eruption site to the caldera of Grímsvötn (b) can also be detected. The two round features (c) are surface depressions in the ice cap due to subglacial geothermal activity. (c)ESA 1996

Disaster Monitoring - a Research Project in Progress

The ESA project referred to above was initiated in 1995. Participants are from institutions in Germany, Iceland, Austria and Poland. Difficulties in funding have had a restraining effect on the project, so the joint effort had to be carried out on a smaller scale than previously planned.

Much of the preparatory work was carried out in 1995. 20 corner reflectors were established in the field, specifically designed to withstand Iceland's climate. The corner reflectors are mainly situated around the Mýrdalsjökull glacier and the Hekla volcano. They have played an important role in geocoding radar images of the area. During the scheduled acquisition times of the Tandem Mission in August and September 1995, soil moisture measurements were made at the reflector sites at depths of 0-2 cm, 2.5 cm and 5-10 cm. In addition, surface roughness was determined in the vicinity of the reflectors. The corner reflectors were located with accuracy better than 2 cm using Global Positioning System (GPS) receivers, a work carried out by co-investigators of the Nordic Volcanological Institute, Reykjavík, the Iceland Geodetic Survey (IGS), and the Institute of Applied Geodesy, Germany (IfAG). The corner reflectors will be in use during the whole time of the project. Co-investigators from the Institute of Geography of the Nicholas Copernicus University in Torun, Poland, made geomorphological field investigations at the fore-fields of the outlet glaciers of Síðujökull, Tungnaárjökull, and Skeiðarárjökull (Figure 1).

The following year, 1996, was dedicated to in-situ research in Iceland as well as to data processing and interpretation of the first results. The geomorphological mapping was continued at the western margin of the Vatnajökull glacier and east of the Mýrdalsjökull glacier. A detailed map of the Skeiðarárjökull glacier fore-field was completed before the catastrophic flood occurred in November 1996 (Wisniewski et al., an unpublished map), and will serve as an invaluable reference for future studies of the changes that occurred during the jökulhlaup. Aerial photography, with a Wild RC 10 metric camera, of the eruption site and the flooded areas was carried out by the IGS in November.

Most of the radar data processing and interferometric software development has been in the hands of co-investigator German Aerospace Research Establishment (DLR), Oberpfaffenhofen, Germany. A Digital Elevation Model (DEM) of the test area was generated for geocoding of radar images and for differential interferometry, using topographic maps (1:50 000) from the IGS. The co-investigator from the Institute of Meteorology and Geophysics at University of Innsbruck, Austria, has investigated backscatter patterns of the glaciers, soil moisture, and surface roughness, as well as analysed the coherence of interferograms.

SAR Interferometry of the Vatnajökull Glacier

The ERS-1/2 Tandem Missions (August 17, 1995 - May 16, 1996, and October 21-24, 1996) gave a unique opportunity to use SAR interferometry on areas where deformation rate is relatively high and where the coherence disappears quickly, like on glaciers. The Tandem Mission in October 1996, was especially valuable in observing the changes caused by the eruption site within the Vatnajökull glacier.

Among other interesting features on the Vatnajökull glacier that can be observed using SAR interferometry is uplift of two depressions in the ice-cap west of the Grímsvötn caldera (Figure 1-3). These two depressions are due to sub-glacial geothermal activity. Every few years the meltwater underneath the depressions reaches a level high enough to overcome the surrounding overburden pressure. When this happens, a jökulhlaup starts in river Skaftá (Figure 1). Therefore, these depressions have been called the western and the eastern Skaftá cauldrons (Skaftárkatlar). The ice surface in the depressions drops down by tens of meters following a jökulhlaup, but it is uplifted again in the following months and years, by the inflow of ice into the depression.

Several interferograms of this area, made out of Tandem data, were investigated. They show uplift of these depressions. The uplift rate depends on the surface slope into the depressions, or the time since the last jökulhlaup occurred (Jónsson et al., 1997). Figure 3 is a differential interferogram of the cauldrons showing the uplift during one day of October 21-22, 1996 (descending orbit). The topographical effect was removed using a DEM of the area, information about the satellite orbits, and the differential interferometry software of the DLR. One fringe in the interferogram represents a 2.8 cm change of distance in line of sight to the satellites. The western cauldron is uplifting more than 15 cm per day, but the rate of the deformation is too high in the center to quantify the uplift. The uplift rate of the eastern cauldron is estimated to be about 9 +/- 3 cm/day. The reason for higher uplift rate of the western cauldron is that a jökulhlaup occurred there in August 1996, only about two months before this observation. Therefore, the western cauldron is relatively deep with steep slopes, causing relatively fast inflow of ice and rapid uplift. The last jökulhlaup from the eastern cauldron occurred in July 1995. Hence, the eastern cauldron is closer to being full again than the western cauldron.

The estimated uplift rates are assumed to be accurate to about 3 cm. The altitude of ambiguity (Massonnet and Rabaute, 1993) of this interferogram is about 70 m. The accuracy of the DEM is not assumed to be better than several tens of meters in this area. Consequently, the errors in the DEM may account for up to one fringe in the differential interferogram. More detailed analysis of the ice-flow dynamics of these two depressions can be found in Jónsson et al. (in preparation 1997).

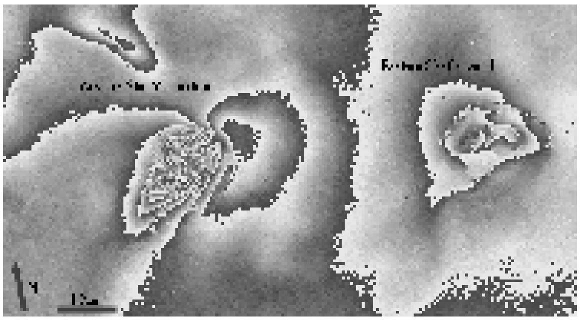

Figure 3. A differential interferogram of the Skaftá cauldrons in Vatnajökull from ERS-1/2 Tandem data of October 21-22, 1996. The rate of deformation in the western cauldron is too high to quantify the uplift, but it is more than 15 cm/day. The uplift of the eastern cauldron is estimated to be about 9 +/- 3 cm/day. (c)ESA 1996

Outlook

The status and the first results of the project, as well as future plans, were discussed at a Workshop in Reykjavík in August 1996, attended by all co-investigators. The importance of investigating the possibilities of the SAR technique to monitor glacier-volcanic interactions were clearly demonstrated by the volcanic eruption within the Vatnajökull glacier that started on September 30, 1996.

During the summer of 1997, several new corner reflectors near the western margin of the Vatnajökull glacier will be installed. Soil moisture measurements will be done near the new corner reflectors and repeated near the old reflectors. Field investigation and geomorphological mapping will be repeated in the fore-field of the Skeiðarárjökull glacier to detect the changes caused by the jökulhlaup in November 1996, based on multitemporal SAR data (Münzer et al., 1995). A continued geomorphological investigations will also be carried out of the Höfðabrekkujökull glacier, as well as in-situ investigations in the unstable, threatened Mýrdalsjökull area.

The data obtained from different radar imaging systems (ERS-1/2, JERS-1, and RADARSAT) will be compared and evaluated as to their suitability for disaster monitoring and hazard detection and prediction.

Acknowledgements

The research is now funded by DARA - German Space Agency, Bonn, No. 50EE9706. The Iceland Science Fund supported the work. Thanks are due to ESA, Frascati, for assistance in providing the required data, especially for repeating the ERS-1/2 Tandem Mission in October 1996 and in March 1997. We thank all participants of the project for their contribution.

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