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ENLARGEMENT OF THE ACTIVE RIFT DURING GLACIATIONS

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Abstract

During the last glaciation, an ice sheet covered Iceland approximately 1000 m thick. A reconstruction of the ice flow lines shows that the ice sheet was partly drained through fast-flowing streams. The major drainage routes correlate with locations of geothermal anomalies, suggesting that ice stream activity was favoured by water produced in regions of high geothermal heat flux. A widening of active rift zone was also deduced revealing a coupling between deep and surface processes.

Introduction

By its location both on a hot spot and on the Mid-Atlantic Ridge, Iceland has a specific rheological structure (thin lithosphere with low viscosity at shallow depth), which controls the deformation processes on lithospheric scale. Furthermore, its position in the middle of the North Atlantic Ocean makes it highly sensitive to climate fluctuations due to oceanic and atmospheric circulations changes. Iceland is therefore subject to several deformation processes (magmatic, tectonic, and glacial) having their own wavelength and time response.

The dynamics of ice sheets depends on internal parameters, such as the mechanical and thermal properties of the ice, and on external boundary conditions. The external conditions are (1) the topography, (2) the nature of the bed, (3) the distribution of accumulation, ablation and temperature at the surface and (4) the géothermal heat flux at the base. When past and present ice sheets are studied or modelled, proper attention is given to the topography, to the nature of the bed and to the atmospheric conditions. In contrast, because the geothermal heat flux is measured with difficulty in glaciated regions, its effect on glacial flow is poorly known and is rarely taken into account. In tectonically and volcanically quiet regions, such as the Greenland and East Antarctica cratons, variations of geothermal heat flux in space and time are small and probably do not significantly affect glacial flow. However, there are major glaciated regions of the world that are also tectonically or volcanically active: tectonic control on glacier dynamics has been suggested in West Antarctica, East Antarctica, North America and South America. In Iceland, tectonics and volcanism, due to lithospheric spreading at the Mid-Atlantic Ridge, occurred during the last glaciation beneath an ice sheet approximately 1000 m thick. From a reconstruction of the flow patterns of this ice sheet, and from simple calculations, we illustrate how ice dynamics can be controlled by the geothermal heat flux associated with tectonic and volcanic activity.

Geological framework

Iceland is a young island, created by the interactions between the Mid-Atlantic Ridge and a mantle plume, 50 Ma ago. This specific context explains the anomalously thickness of the crust and the intense tectonic and magmatism of the island. The spreading rate of the Mid-Atlantic Ridge is about 2 cm/yr (DeMetz *et al.* 1994). Consequently, Iceland is crossed by a series of faults and volcanoes forming the Icelandic rift system at the junction between the Reykjanes Ridge at south and the Kolbeinsey Ridge at north. Three active zones composed of central volcanoes, rifts and fissure swarms accommodate the spreading and magmatism (Fig 1). The West Volcanic Zone (WVZ) in the southwest is linked to the East Volcanic Zone (EWZ) by transform fault systems, the South Iceland Seismic Zone (SISZ) and the Mid Iceland Belt (MIB). The North Volcanic Zone (NVZ) extends towards the north to the Tjörnes Fracture Zone (TFZ).

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The Icelandic mantle plume enhances melt production under Iceland, generating an anomalously thick igneous crust. The crust is the thickest (40-41 km) above the centre of the plume, at the north-western part of the Vatnajökull icecap. It thins away from the plume centre and the thinnest crust (< 20 km) is found in the active rift zone such as the northern part of the NVZ and the southwest of the WVZ (Darbyshire *et al.*, 2000). Therefore the Icelandic lithosphere differs drastically by its thickness and its rheology from “classical” oceanic lithosphere.

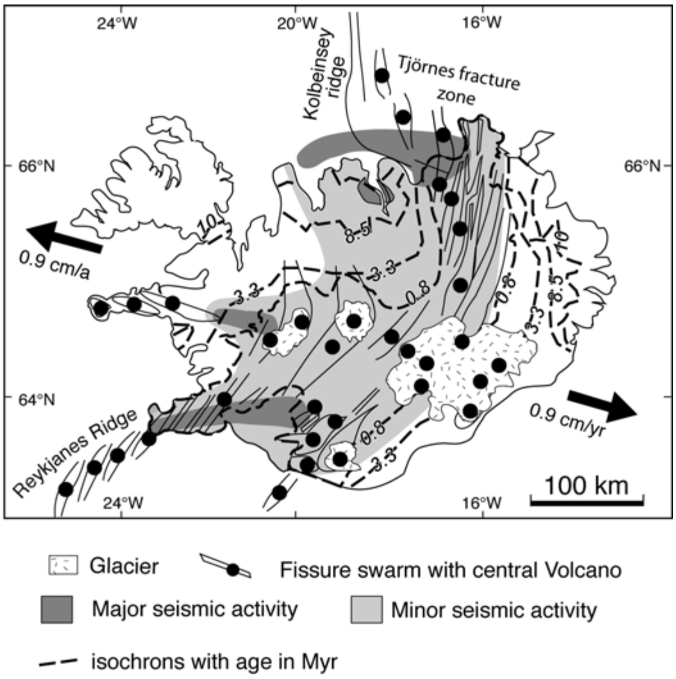

Figure 1 : Geological setting. Iceland lies at the junction between the Reykjanes Ridge to the southwest, and the Kolbeinsey Ridge to the north. Current tectono-volcanic activity occurs in the Neovolcanic Zone, composed of three main branches, the Northern (NVZ), Western (WVZ) and Eastern (EVZ) Volcanic Zones. The Saefellsnes peninsula, in western Iceland, is also active. Lithospheric spreading occurs in fissure swarms associated with central volcanoes (black dots). The dashed lines display the basalt ages. The light grey zone corresponds to the recent active while the dark grey one to the main seismic areas.

The location of Iceland in the middle of the North Atlantic Ocean makes the ice extents highly sensitive to climate changes and consequently to glacial stages. According to Einarsson & Albertsson (1988), 15-23 glaciations affected Iceland during the past three million years. The most recent glaciation, the Weichselian period, took place after the Eemian period, approximately between 120,000 and 10,000 yrs BP. The Last Glacial Maximum (LGM) in Iceland is estimated between 20,000 and 17,000 yrs BP (Van Vliet Lanöé *et al*., 2006) with an ice cap thickness up to 2000m in the centre of the island (Norddahl & Pétursson, 2005). The glacial extent during the LGM is still controversial. Some authors suggest an ice cap extent until the shelf break (Olafsdottir, 1975; Norddahl & Pétursson, 2005; Hubbard *et al.* 2007) and others authors (Van Vliet-Lanöé *et al*. 2006) suggest the ice cap was much less extended. Very abundant precipitation in the southern part of the island must have been responsible for the location in south Iceland of the thickest part of the ice sheet as it is nowadays (Bourgeois *et al*. 2000).

Flowing pattern of the ice cap

An ice cap flows both by internal creep and by sliding on its bed. After the ice cap has vanished, the sliding component is recorded in striaes, flutes and drumlins visible on the deglaciated bed. We used these geomorphic features to reconstruct the pattern of basal sliding of the Weichselian ice cap. Because the creep component has been neglected, the overall flow was probably slightly different from the proposed reconstruction. We used measured glacial striae described in the literature and observed in the field. These data have been combined with geomorphic features (glacial valleys, nunataks, flutes, drumlins, *roches moutonne´es*) observed in the field, on SPOT images, and on a digital elevation model. We assumed that all these features were Weichselian in age, i.e. that the last glaciation had obliterated older small-scale landforms. We also assumed that the landforms used in the reconstruction could be considered synchronous. This assumption is reasonable at our working scale. Indeed, the preserved moraines corresponding to the successive stages of déglaciation can be split into two consistent sets: successive end moraines at the front of the ice cap are concentric and nearly orthogonal to striae, whereas successive lateral moraines along the flanks of valleys formerly occupied by outlet glaciers are parallel to striae. This arrangement shows that no major changes in the

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ice flow lines occurred during the deglaciation.

First, the divides of the main ice cap were drawn from the directions of glacial striae in central Iceland. Second, a series of sliding lines were drawn at regular intervals from the ice divides towards the sea, following the directions of striae. These lines represent ice flow trajectories, but they do not reflect the amount of ice flowing at each place because the distribution of precipitation has not been taken into account in the reconstruction. In coastal areas, the ice cap was assumed to divide into outlet glaciers flowing between nunataks that behaved as emerging obstacles. We considered the flow of glaciers on the nunataks independently from the flow of the main ice cap: we assumed that valley glaciers flowed radially away from nunatak summits, either up to the sea, or until they joined outlet glaciers of the main ice cap.

Results

This reconstruction outlines a four ice divides (Fig. 2): a first one extending from Reykjanes to Langjokull, a second one from Myrdalsjokull to Melrakkasletta, at North with and branch and a fourth one extending from Hofsjokull to Trollaskagi. Other ice divides were located on Vestfirdir and Snaefellsnes peninsulas. Between the ice divides, the flow was channelled into streams. Between ID1 and ID3, an ice Stream flowed southwestwards along the eastern flank of the WVZ. Between ID2 and ID4, two ice streams flowed northwards along the NVZ. Flow lines converging towards these ice streams show that they drained the major part of the ice cap and imply higher velocities relative to the surrounding ice.

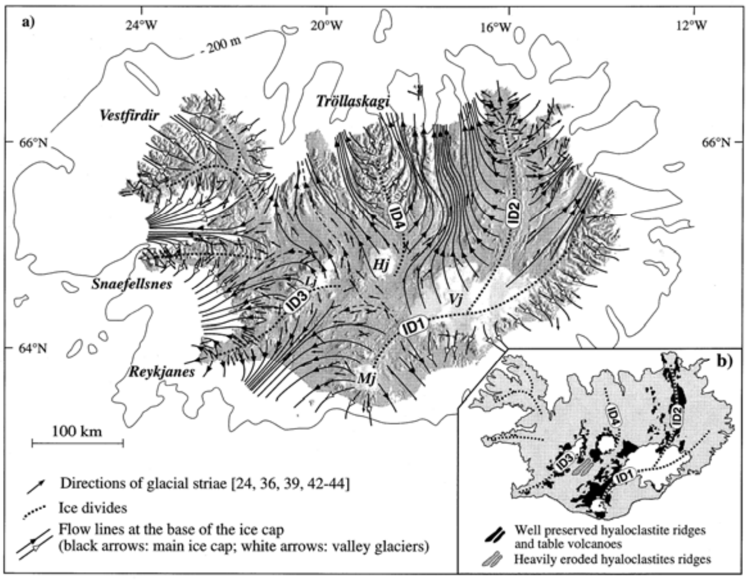

Figure 2: Reconstruction of the pattern of basal sliding of the ice cap. The main ice cap (black arrows) has been separated from the valley glaciers flowing through coastal mountains (white arrows). In addition to the two ice divides formerly recognised on the eastern flank of the Neovolcanic Zone (ID1 and ID2), two other ice divides lying on its western flank are shown (ID3 and ID4). Between the ice divides, the flow is channelled into streams. Two of them are located in the NVZ, another one is located on the eastern flank of the WVZ. (b) Comparison of the location of preserved subglacial volcanic edifices with the location of the ice divides in the reconstruction. Subglacial volcanic edifices have been preserved preferentially beneath ice divides. They are either nearly absent, or heavily eroded in areas occupied by ice streams.

There is a striking correlation, everywhere in Iceland, between the location of well preserved subglacial hyaloclastite ridges and the location of the ice divides in the reconstruction (Fig. 2). On the other hand, in areas occupied by ice streams in the reconstruction, hyaloclastite ridges are either nearly absent in north volcanic zone or heavily eroded (Hreppar area). Ice flows away from the ice divide, leavingat its base a wedge of stagnant ice. If a subglacial eruption occurs within this preserved area, its products will stay in situ and will pile up from one eruption to another. On the other hand, extensively fragmented and unconsolidated products erupted subglacially in a site far away from the ice divide will be easily dislocated, incorporated to the moving ice, and continuously removed in the time lap between eruptions.

Tectonic implications

Once the effect of glacial removal has been subtracted, the arrangement of subglacial volcanic edifices appears clearly. Similarly to post-glacial eruptive fissures, hyaloclastite ridges are gathered in

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swarms associated with central volcanoes located in the Neovolcanic Zone (Fig. 3). Because the North volcanic zone was occupied by an ice stream, subglacially erupted volcanics have been actively removed by fast ice flow. Few relics remain at the present time, except in table and central volcanoes where magmatic supply was sufficiently frequent to counteract removal by ice flow. Products of subglacial fissure eruptions have been preserved in the Fjallgardar Ridge, located beneath a former ice divide. The area where subglacial volcanic édifices have been preserved is 90 km wide, including table volcanoes of the NVZ and hyaloclastite ridges of the Fjallgardar Ridge. In contrast, the currently active NVZ in only 50 km wide (Fig. 3). In southern Iceland, present-day activity is restricted to the WVZ and EVZ, whereas hyaloclastite ridges give evidence of subglacial volcanic activity between them. Subglacial activity has been recorded in a 150 km wide zone, whereas the cumulative width of the WVZ and EVZ is only 100 km.

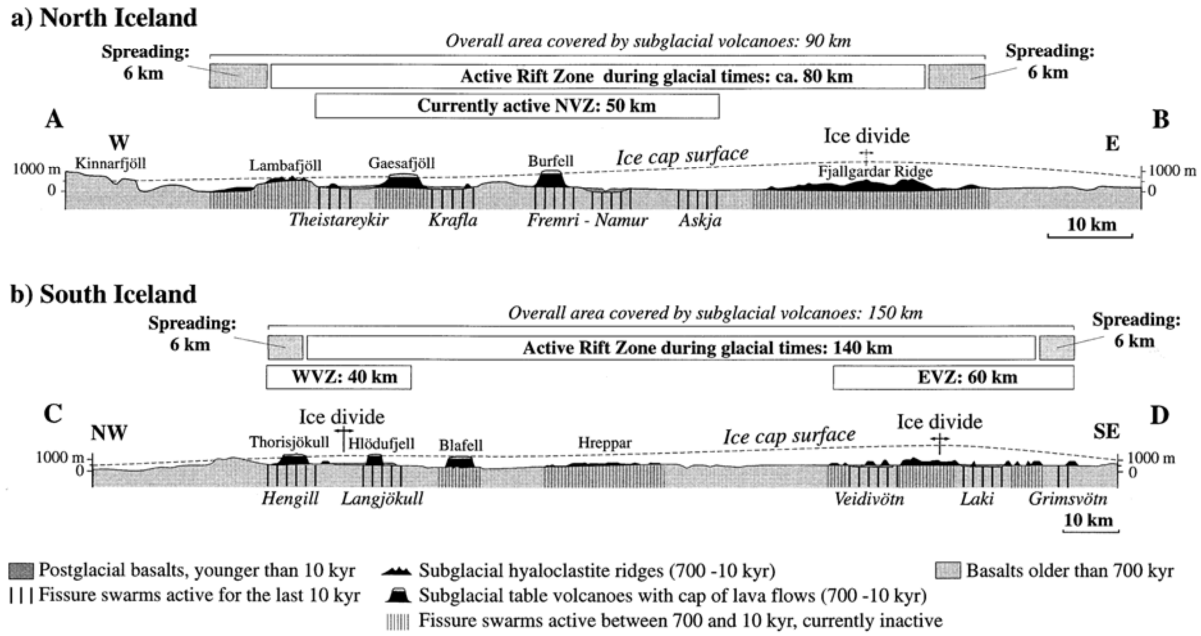

Figure 3: Cross-sections across the Neovolcanic Zone (Vertical exaggeration: 2). The surface of the former ice cap is drawn schematically. (a) Northern Iceland. Hyaloclastite ridges have been preserved beneath the Fjallgardar ice divide. Table volcanoes (Gaesafjoll, Burfell) have been preserved in the NVZ. Subglacial volcanic activity has been recorded in a 90 km wide region. The currently active fissure swarms (Theistareykir, Krafla, Fremri-Namur and Askja) affect a 50 km wide area only. (b) Southern Iceland. Subglacial volcanic edifices have been preserved beneath ice divides in the WVZ and EVZ. They have been eroded in the Hreppar area. Subglacial volcanic activity has been recorded in a 150 km wide area, whereas the cumulative width of the WVZ and EVZ is only 100km. Lithospheric spreading rate (1.8 cm=yr, full rate) can account for only 12 km of this width discrepancy. Either fissure swarms have wandered around their current location for 700 kyr, or the active rift zone has narrowed at the deglaciation.

DISCUSSION

External parameters controlling the direction and velocity of flow in an ice sheet are (1) the distribution of precipitation at the surface, (2) the bed topography, (3) the thermal conditions at the base and (4) the subglacial lithology. We now review these parameters in Iceland in order to determine how they can explain the reconstructed flow patterns and velocities.

Comparison of reconstructed ice flow lines with the map of geothermal heat flux shows that positions of main ice routes correlate with locations of geothermal anomalies (Fig. 4). The most probable ice streams (Skjalfandi, AxarfjoÈrdur and Hvita) were located in or close to the Neovolcanic Zone, where the geothermal heat flux reaches maximal values. A striking feature is the parallelism between the ice divides and the Neovolcanic Zone: ID1 and ID2 are on its eastern flank, ID3 and ID4 are on its western flank. This spatial correlation suggests that the dynamics of the ice sheet was partly controlled by the geothermal heat flux. Enhanced ice melting above geothermal anomalies probably involved intense water production at the base of the ice sheet, thus favouring lubrication of the bed

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and controlling the location of major ice routes and ice streams.

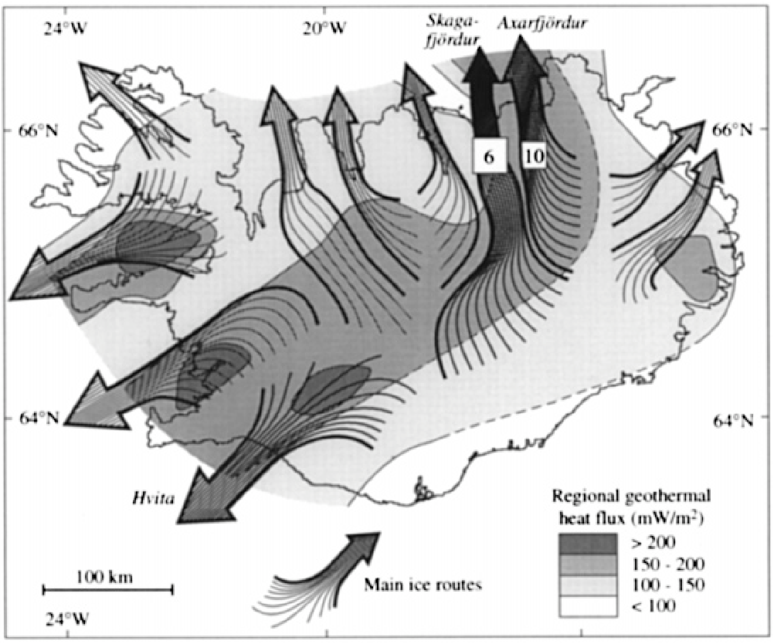

Figure 4: Correlation between flow patterns of ice sheet and geothermal heat flux. In order to avoid perturbations caused by circulation of warm water, the map of regional heat flux is based on values measured at carefully chosen sitesawayfrom hydrothermal areas (Flovenz and Saemundsson, 1993). The coincidence between location of main ice routes and location of thermal anomalies is striking.

CONCLUSIONS

Flow lines of the Weichselian ice sheet in Iceland have been reconstructed on the basis of glacial directional features. The reconstruction reveals the existence of channels of preferential flow and of fast-flowing ice streams. Mega-scale lineations and pervasively deformed subglacial till have been well preserved on the bed of some ice streams. Both in northern and in southern Iceland, the extent of the hyaloclastite ridges is greater than the extent of the currently active fissure swarms. This discrepancy suggests either continuous wandering of the volcanic activity from fissure swarm to fissure swarm for the last 700 kyr, or narrowing of the active rift zone and=or decrease of the length of the active part of the fissure swarms at the end of the last glaciation.

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