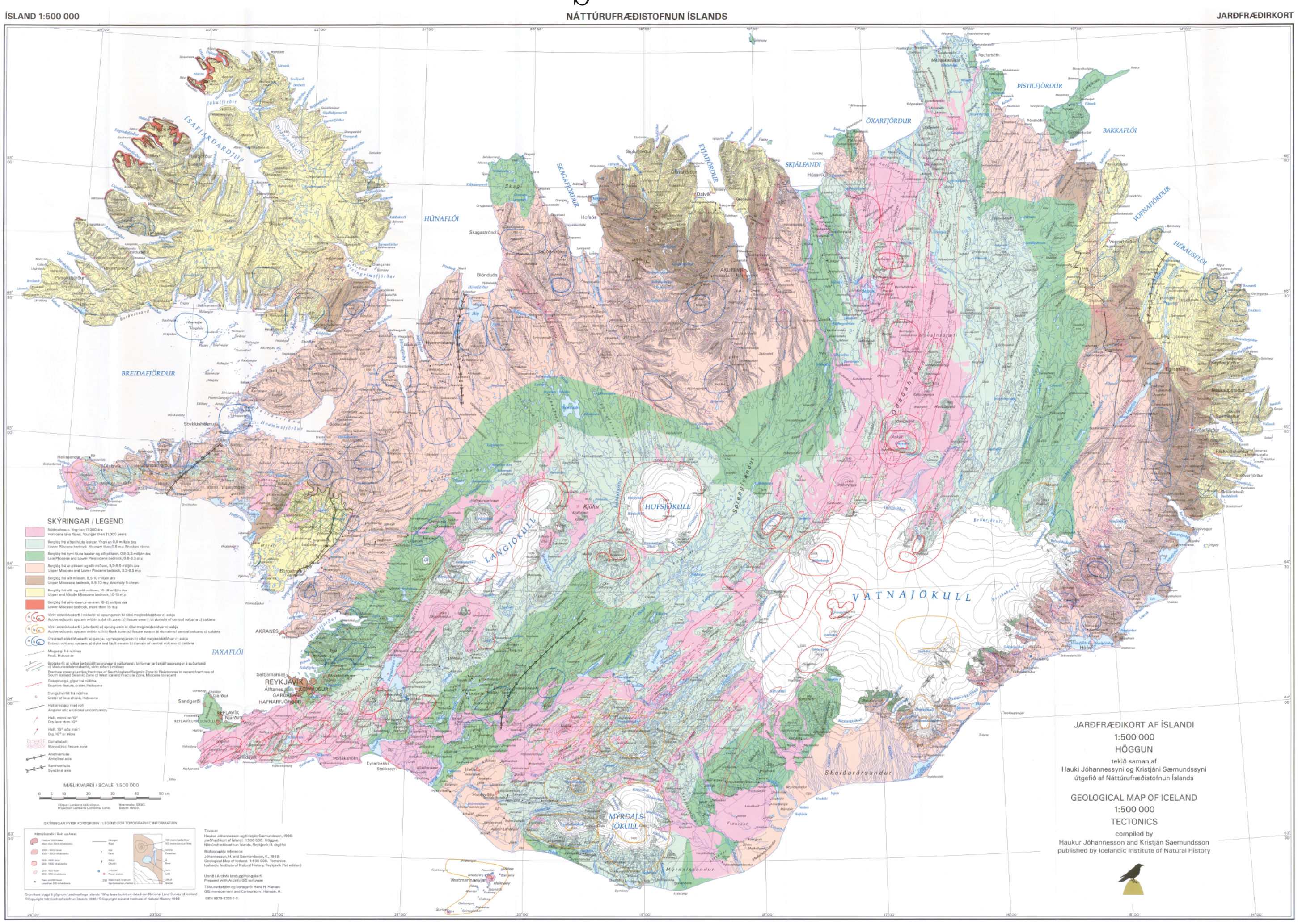
Iceland Spring Fling

May 26th-June 4th, 2011

California State University, Northridge

Geological Sciences



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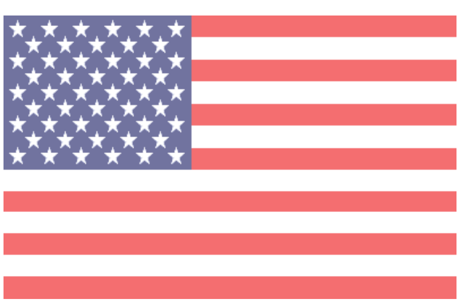

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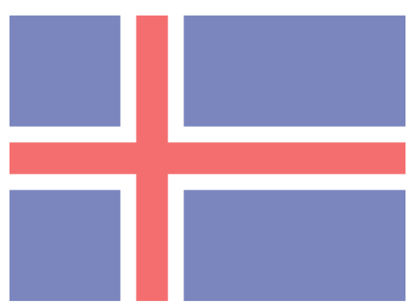

Iceland Geology Overview

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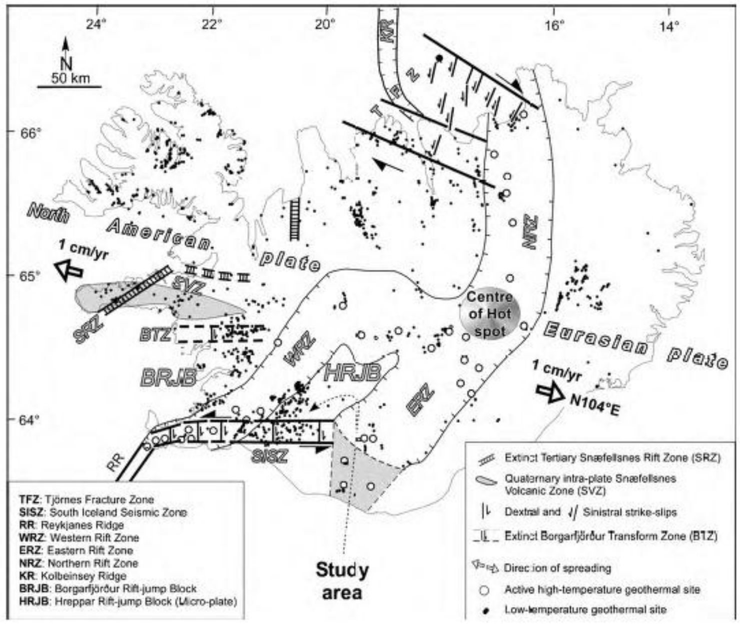


Iceland is primarily created by the interaction of a localized deep-seated mantle plume mixing with the asthenosphere under the northeast Atlantic and European plate margin. This plate boundary has migrated at a velocity of approximately 1-3cm/yr to the northwest for the last 60ma. The current mantle plume is situated underneath the Vatnajokull glacier which is located approximately 240km east of the Reykjanes and Kolbeinsey Ridges. The age of Iceland is oldest in the northwest, at about 20ma, with continuing younger strata heading southeast until the recent Vatnajokull area.

During the opening of the Atlantic seaway, around 60ma, the Icelandic plume was situated underneath Greenland. Flood basalts, hyaloclasites, and coinciding motion of other continental systems may show that the Iceland plume has been active as far back as 130ma. The rifting of the Atlantic first occurred on the extinct Aegir Ridge located east of Iceland. This now extinct ridge connects with the Reykjanes Ridge and was active until 25ma. Both the Aegir and Kolbeinsey Ridge occurred simultaneously after 36ma until the extinction of the Aegir Ridge. At that time the Iceland plume began to 'capture' and interact more heavily with the now current Mid-Atlantic Ridge (MAR). The Reykjanes and Kobeinsey Ridges passed over the top of the hotspot about 20ma. Since that time the Icelandic plume has created successive jumps in ridge migration on the Iceland continent which has essentially captured the mid-ocean ridge (MOR) as it moves its position in direct correlation with the plume location. Rift-jump ridges have occurred at roughly 24, 15, 7, and 3ma as the MOR propagates northwestward. Rift zones are approximately 50km wide and contain echelon arrays of volcanoes typically with 3 to 4 subparrellel fissure swarms within each rift zone. Fissure swarms feed central volcanic systems but do not always lead to such a system. Fissure swarms also inhibit extensional crustal deformation inside rift zones.

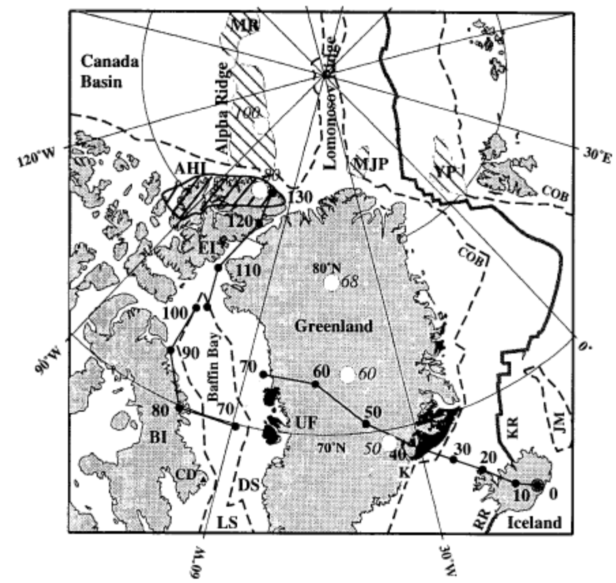


Figure 1. Synthetic hotspot track (North American plate fixed through time). Solid dots show paleoposition of hotspot every 10 m.y. AHI—Axel Heiberg Island; BI—Baffin Island; CD—Cape Dyer; DS—Davis Strait; EI—Ellesmere Island; JM—Jan Mayen; K—Kangerlussuaq, East Greenland; KR—Kolbeinsey Ridge; LS—Labrador Sea; MJP—Morris Jessop Plateau; MR—Mendeleyev Ridge; RR—Reykjanes Ridge; UF—Umanak Fjord, West Greenland; YP—Yermak Plateau; COB—continent-ocean boundary based on bathymetry. Dotted track between 70 Ma positions indicates that new sea floor was created after passage over hotspot. All ages referred to are based on time scale of Kent and Gradstein (1986). Open circles indicate plume positions proposed by Forsyth et al. (1986).

Tectonic activity in Iceland is focused mainly in transform seismic zones that link the Reykjanes and Kolbeisney Ridges to central volcanic rifting systems. The main transform zones include the South Iceland Seismic Zone (SISZ) located in southern Iceland and the Tjornes Fracture Zone (TFZ) located in northern Iceland. The SISZ is mainly a left-lateral transform zone comprised of bookshelf type tectonic motion. No discreet left-lateral fault has been located in southern Iceland linking the Reykjanes Ridge with the Eastern Volcanic Zone (EVZ). Instead the SISZ absorbs the movement within a broad area of north/south striking fault systems. The

TFZ has 3 discreet right-lateral transform zones that link the Kolbeinsey Ridge with the Northern Volcanic Zone (NVZ). The TFZ consists of the Grimsey Seismic Zone, Husavik-Flately Fault and the Dalvik Lineament. Both zones, the SISZ and TFZ, are active and have had damaging earthquake events within recorded historical times. The Hengill Triple Junction is a ridge-ridge-transform located where the Western Rift Zone, Reykjanes Ridge, and SISZ meet in southwestern Iceland which also creates large volcanic ruptures.

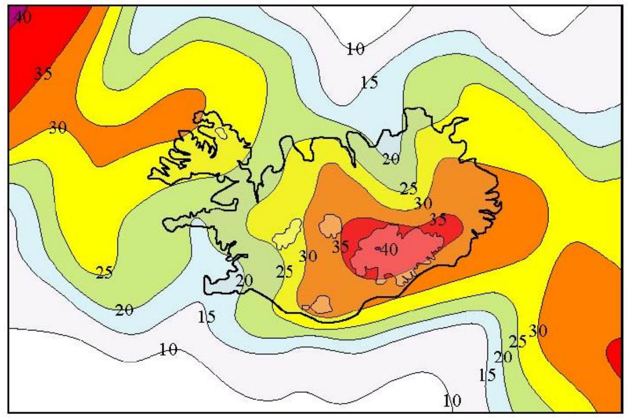
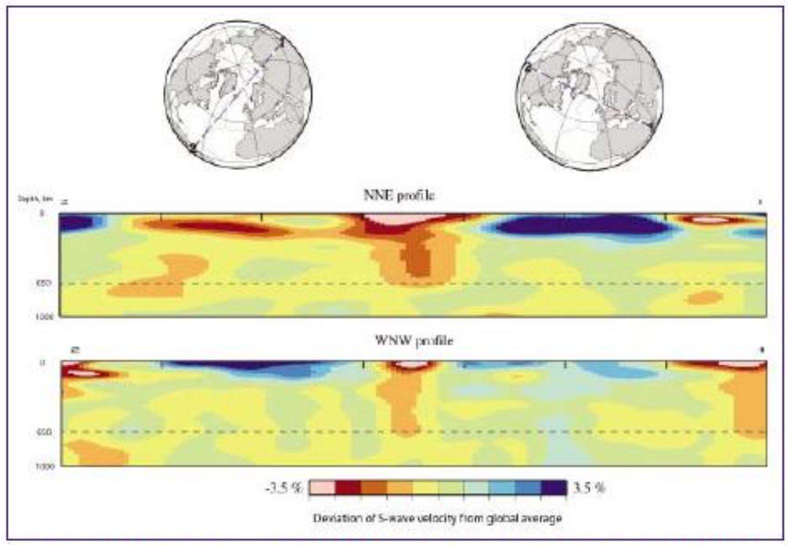


Fig. 5. Crustal thickness (km) variations across Iceland and the adjacent parts of the Greenland-Færöe Ridge (simplified after Kaban et al. 2002).

Eruptive volcanic activity in Iceland consists of both subaerial and subglacial eruptions. Subaerial eruptions can produce extensive shield volcanism and large sheet flows of basaltic and, less common, rhyolitic material. Subglacial eruptions are very efficient heat transfer systems that produce pillow lavas and hyalocalstic material. In the last 3ma Iceland has experienced major glaciations that encompassed the entire continent to a maximum of 100km continuation of glaciers offshore. These glaciation periods carved large fjords and erosional periods that can be seen in the Tertiary uncomformity. Subglacial eruptions can lead to a jokulhlaups, which are large outflows of material caused by melting glacial ice combined with clastic particles.



4: Cross sections through a whole-mantle tomography model (Ritsema *et al.* 1999) showing structure in the top 1000 km of the mantle at Iceland. (Courtesy of J Ritsema.)

Anomalously high crustal thickness occurs within the Iceland Plateau due to high magma production of the Icelandic plume. Low viscosity values occur with a diffuse Moho in direct relation to the plume underneath Iceland. The crustal thickness varies from 40km under the most recent location of the plume to 20km in rifting zones. Post glacial isostatic rebound studies constrain viscosity values to be less than 10^{19}Pas whereas averaged mantle viscosities range around 3 X 10^{20}Pas showing the presence of the Iceland plume.

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Blue Lagoon

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The Blue Lagoon is a geothermal spa and tourist site that has become one of Iceland's most visited spots, attracting over 400,000 people annually. It is located 50km southwest of Reykjavik on the Reykjanes peninsula just north of the town of Grindavik. Its Icelandic name is Bláa lónið. It was named "The Blue Lagoon" in 1980 shortly after the release and success of the Brooke Shields movie of the same name. It is 100m wide and 200m long at a depth between 1 and 3 meters.

The lagoon itself is a totally man made feature dug out of a lava field when the Svartsengi (Black Meadow) geothermal power plant was built in 1976. The Svartsengi power station and 4 others, Nesjavellir, Krafla, Hellisheioi and Reykjanes produce about 24% of the nation's energy. The remaining 75.9% of Iceland's energy comes from hydro electric sources and a mere 0.1% is obtained from fossil fuels.

Most of the water in the Blue Lagoon is runoff water from the geothermal plant at Svartsengi. The superheated water comes from the Svartsengi geothermal aquifer some 2000 meters underground via boreholes. In the aquifer, it is about 240°C and is a mix of 65% sea water and 35% fresh water. In the power plant, the pressurized water is first used to run turbines to generate electricity and then run through heat exchangers which provide heating for local cities. Outflow rate from the plant is about 900m^3 per hour. As it leaves the power plant on its way to the Blue Lagoon its temperature has dropped to around 70°C. Just recently the Blue Lagoon Spa and Resort drilled some of their own boreholes to better regulate the temperature, mineral and salt content of the lagoon. The pH level is 7.5 and salinity is at 2.5%. The operators strive to keep the salinity of the water the same as seawater which helps to reduce the "eggy" smell typical of water from geothermal sources.

The water averages 38°C or 100°F and is rich in silica and sulphur (a full analysis can be seen in Table 1. below). Along with algae growing in the lake this combination produces a beautiful pearly-blue color. The predominate algae is a type called *Leptolyngbya ereby var. thermalis*, which is part of the Cyanobacteria species. When the algae bloom is at its peak in the summer months the water takes on a more greenish color. The water is continually circulating and being replenished with a complete replacement cycle of 40 hours.

The lagoon is adjacent and to the west of the power plant. In the past, the stacks and buildings of the power plant were visible to bathers, however a large wall of lava boulders was added to the east end of the lagoon to block the view of the power plant and also to provide shelter from winds.

The Blue Lagoon is quite frequently used for filming; most recently the Amazing Race used it as a pit stop in the first leg of their 6th season. Additionally, the Hostel: Part II, the Incubus documentary *Look Alive* and Britain's

Next Top Model have filmed here. There is currently an ad campaign running on US television using it as a backdrop and the subject of a startup business for cosmetic mud facials.

The silicic mineral content of the water in the lagoon has proven medical benefits for psoriasis skin disease sufferers. A 1996 study found the Psoriasis Area and Severity Index decreasing from 21 to 3 (about 86%) in a study group of 23 patients who used tri-daily lagoon bathings combined with UVB treatments.

The mud in the lagoon is silica saturated and is continually precipitating out in the lake forming the sediment on the lake bottom. As the water temperature decreases on its way to the lagoon the water becomes supersaturated with silica and then precipitates out as a white mud. This unique ecosystem is home to several specialized microorganisms, with an average bacterial colony count of around 1.3×10^5 /ml. There are numerous other claims to the medicinal benefits of the lagoon's water and mud such as curing arthritis, baldness, bad karma as well as other similar maladies. But in reality the most common ailments that the Blue Lagoon is used to treat are hangovers and jet lag. There is a man made waterfall that many use for an invigorating massage.

Table 1. Composition (mg/kg fluid) of the fluid in the Blue Lagoon

pH/temp°C	7.7/24°	
SiO	137	Silica
Na	9280	Sodium
K	1560	Potassium
Ca	1450	Calcium
Mg	1.4	Magnesium
CO_2	16.5	Carbon Dioxide
SO_4	38.6	Sulfate
H_2S	0.0	Hydrogen Sulfide
Cl	18500	Chlorine
F	0.14	Fluorine

Total dissolved solids mg/kg fluid: 31900.

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Fjords in Iceland 

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Overview

A fjord (fjordhur) is a deep, U shaped valley carved into the landscape by a glacier (jok ull) and later filled with seawater. They typically trend in a straight line, have steep mountainous sides and are very deep. They form along the coasts where there is a large amount of relief and have been subjected to Pleistocene glaciation (2.5 Ma to 12,000 years BP).

There are over 70 major fjords in Iceland with several smaller tributary fjords (Figure 1.). ***The two that we will see on the early part of our trip are Borgarfjordhur and Hvalfjordhur***. Borgarfjordhur is just 18 kilometers north of Reykjavik (pop. 200,000) and Borarfjordhur is another 20 kilometers to the north. Hvalfjordur is 30 km from head to end and averages 3.5 km wide. Borgarfjordhur is slightly smaller at 14 km long and 3 km wide. In contrast, the largest Icelandic fjord, Eyjafjordur, is 60 km long and 25 km wide. It is located in central northern iceland and at its southern end is Iceland's second largest city, Akureyri (pop. 17,304).

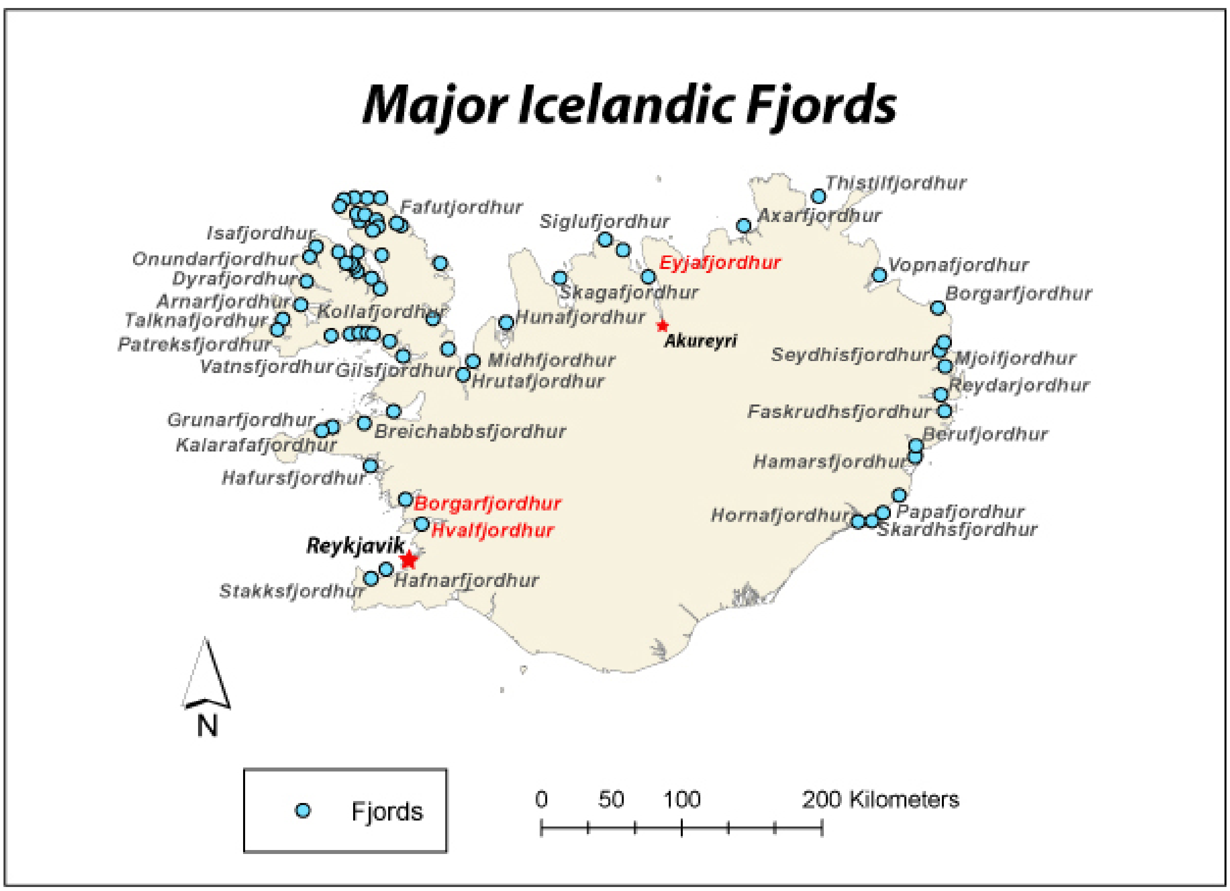

Figure 1.

Coastline Enhancement

A crudely drawn polygon around the coast of Iceland shown in figure 2 to the right, yields a circumference of approximately 1,872 km. However, Iceland has a total coast line length of 4,970 km. While this latter figure includes many islands, the majority of the 3,100 km of additional coastline is attributable to the distance added by all of the many fjords that are carved into the coastline.

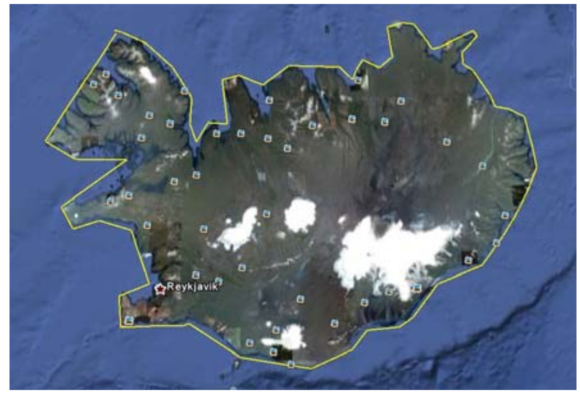

Figure 2.

Structure

In figure 3 below you can see a cross section and a longitudinal profile of a typical fjord. The cross section at the lower left depicts the classic "U" shaped valley remaining after the glacier receded. In the main profile you can see a dashed line which indicates the probable shape of the pre-glaciated valley floor. In the far wall you can see a hanging fjord on the right and a partially submerged fjord near the center. These are formed from tributary glaciers that were smaller than the main glacier and did not erode as deeply. After the main glacier reached its maximum extent and began to recede, it left a large terminal moraine represented by the strandflat area. Towards the head of the fjord on the right you can see a lake that has been formed from a dam created by a recessional moraine dump. The area depicted on the far right shows 3 different slope variants that form the transition from the present sea level to the level of the original pre-glaciated valley floor.

At the time of fjord creation, sea level was lower because much of the earth's water was retained in glaciers and ice caps. The scouring of the fjords by glaciation occured below present day sea level. When the glacial period began to wane, heavily ice covered areas such as Iceland then rose up in elevation from isostatic rebound but not significantly enough to bring the floor of the fjord above present day sea level. They still remain very deep.

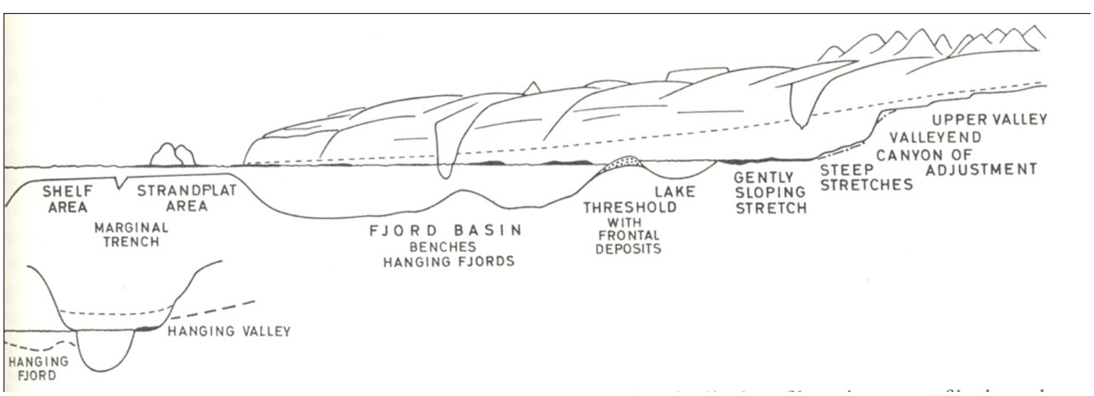

Figure 3.

Formation

In the past 5 million years Iceland has had about 20 glaciations. The earlier glaciations did not create significant glacial erosion and fjord creation. It was not until about 2.5 million years ago when substantial volcanism began and created greater topographic relief, that glaciation had the opportunity to begin fjord creation. The geologic maps below in figures 4 and 5 show a simplified view of Icelandic regional aging. From these maps and the one in figure 1 you can clearly see that the more heavily fjorded areas correspond to the oldest Tertiary basalt formations in the northwest, central north and east coasts. The Plio-Pleistocence formations have some fjording, but nowhere close to the numbers in the older formations but they do have more than the upper Pleistocene and Holocene formations which have but a few.

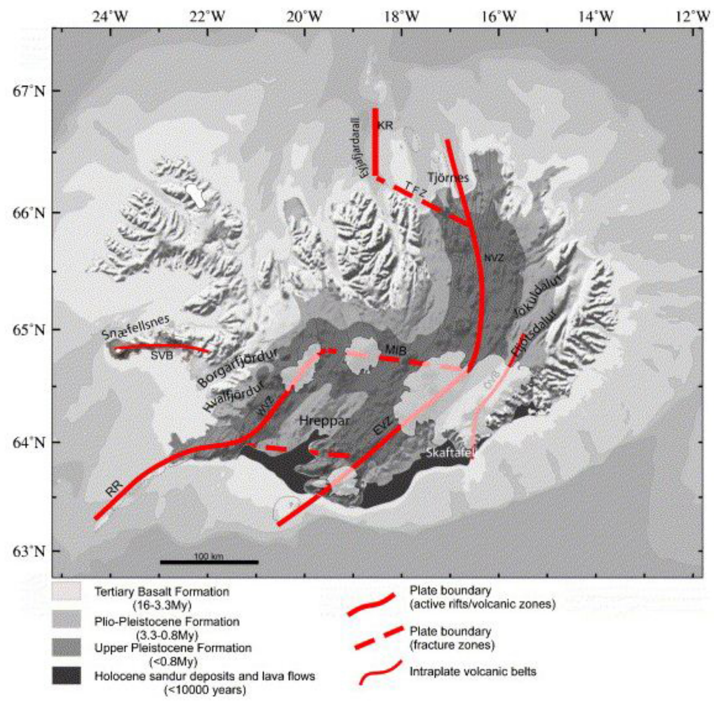

Figure 4.

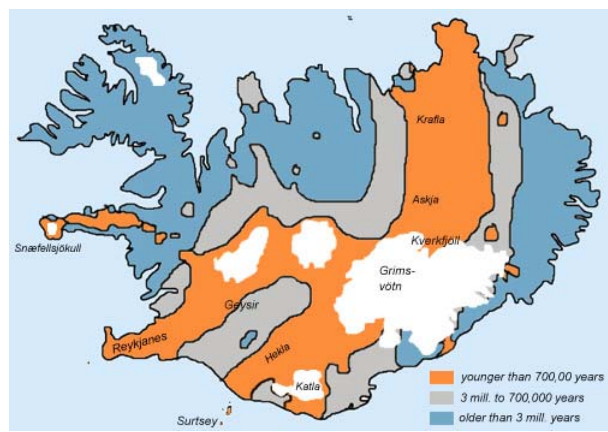

Figure 5.

The combined effects of increased topographic relief and several cycles of glaciation are responsible for the creation of the fjords that we will see. As late as 1913 British geologist J. W. Gregory believed that fjords were of tectonic origin and that the influence of glaciers on their development was minimal. In 1927 he attributed the Hebridean fjords in Britain to "rending of the crust during and after the Alpine earth movements and to the subsequent gaping of fissures during the Pliocene uplift of the British area." Today the cause and effect of topographic relief and glacial scouring is universally accepted.

The dating of glacial effects over several glacial cycles is somewhat problematic. Land-based evidence is not complete because each glaciation may wipe out evidence of its predecessors. However the marine record preserves all the past glaciations even when land evidence is removed. For example, in the past half million years there have been five Pleistocene glacial/interglacial cycles recorded in marine sediment but only three of those have been recorded on land see figure 7.

Speculation

If you look closely at the area of the two fjords we will visit, Borgarfjordhur and Hvalfjordhur on the geologic map below in figure 6, you will notice that the center line of each fjord appears to define a contact between different geologic units. Hvalfjordhur is bounded to the south by the late Pliocene and lower Pleistocene bedrock of 3.3-0.8my. To the north it is bounded by a unit of upper Miocene and lower Pliocene bedrock of 8.5-3.3my. Borgarfjordhur is bounded to the south by the same unit north of Hvalfjordhur and to the north it is bounded by upper and middle Miocene bedrock 15-10 my.

These zones of contact suggest a pre-fjord created valley or zone of weakness which subsequently allowed a tongue of glacial ice to begin flowing in the direction that was directly along the contact of the units.

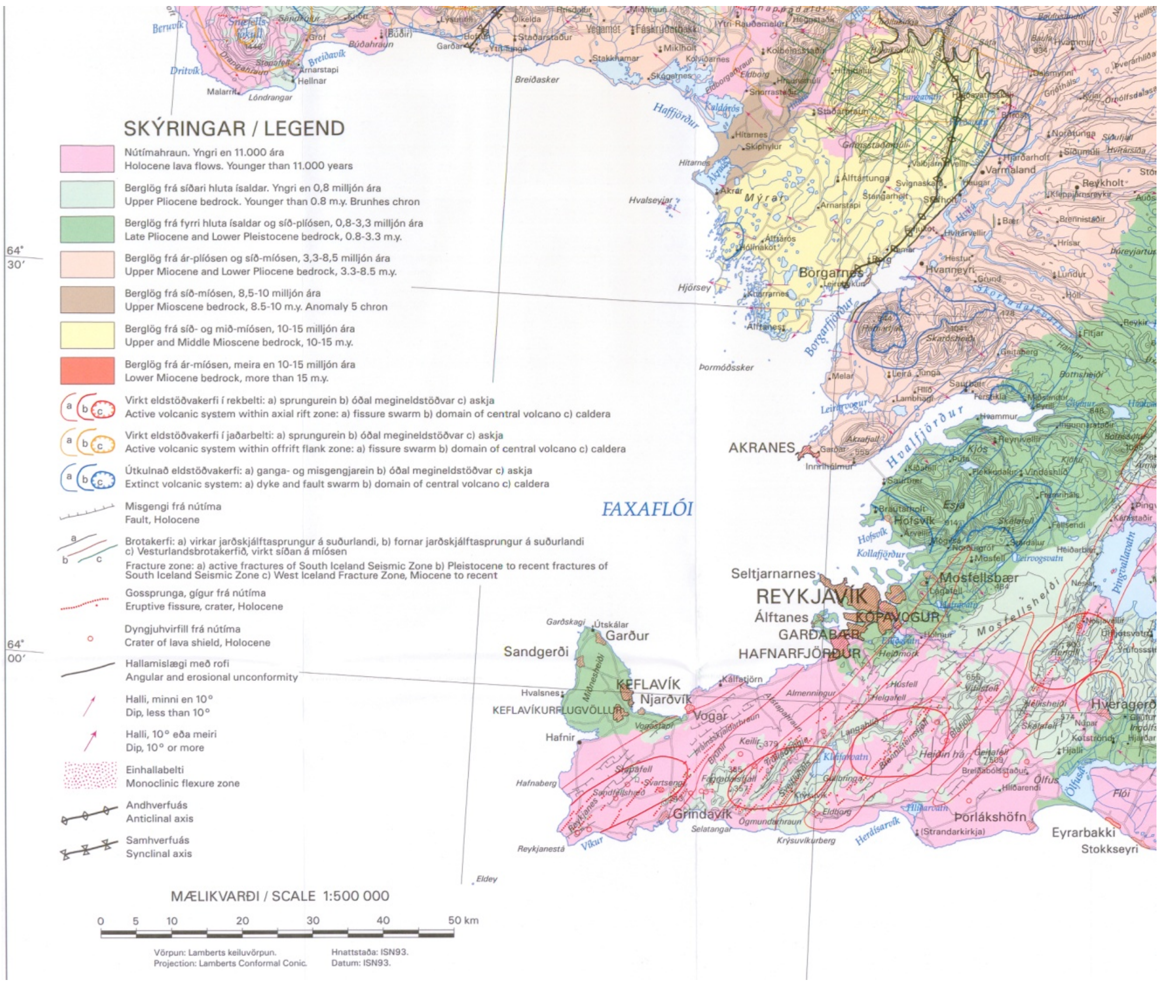

Figure 6.

Backwards Glacial Index	Names					Inter/Glacial	Period (ka)	MIS	Epoch
	Alpine	N. American	N. European	Great Britain	S. American				
				Flandrian		interglacial	present – 12	1	Holocene
1st	Würm	Wisconsin	Weichselian or Vistulian	Devensian	Llanquihue	glacial period	12 – 110	2-4 & 5a-d	
	Riss-Würm	Sangamonian	Eemian	Ipswichian	Valdivia	interglacial	110 – 130	5e (7, 9?)	
2nd	Riss	Illinoian	Saalian	Wolstonian or Gipping	Santa María	glacial period	130 – 200	6	
	Mindel-Riss	Pre-Illinoian	Holstein	Hoxnian		interglacial(s)	200 – 300/380	11 [verification needed]	Pleistocene
3rd – 5th	Mindel	Pre-Illinoian	Elsterian	Anglian	Río Llico	glacial period (s)	300/380 – 455	12 [verification needed]	
	Günz-Mindel	Pre-Illinoian		Cromerian*		interglacial(s)	455 – 620	13-15	
7th	Günz	Pre-Illinoian	Menapian	Beestonian	Caracol	glacial period	620 – 680	16	

Older periods of the Quaternary

Name	Inter/Glacial	Period (ka)	MIS	Epoch
Pastonian Stage	interglacial	600 – 800		
Pre-Pastonian Stage	glacial period	800 – 1300		
Bramertonian Stage	interglacial	1300 – 1550		

Figure 7.

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RIFT-JUMPS AND TECTONIC HISTORY

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Iceland's unique position astride the Mid-Atlantic Ridge (MAR) and above an active plume system has shown subsequent movements or 'jumps' of rifting zones beginning in the northwest and progressively shifting to the southeast. As the MAR continues a northwestward movement over the relative stable Iceland hotspot, subsequent development of new rifting zones are created and abandoned. Abandonment of one rift zone and creation of another have been shown to occur simultaneously. While one rift segment may be dying out the new rift segment is developing and accreting. Both old and new zones will continue volcanic activity overlapping in sequence. As the older rift is progressively abandoned the eruptive material becomes more silicic in composition due to depleting source magmas as the plate boundary continues to migrate. Fraction crystallization then occurs causing late eruptive cycles of volcanic activity that show a more silicic component. Velocities of migrating rift-jumps vary due to active volcanic activity burying newly created rifts and fault segments, and the jump system differential behavior in the north and south sections of Iceland. Velocities range from 12.5km/Myr to 3.7km/Myr.

For the last 15ma rift-jumps have occurred about every 1-2ma with movement of central volcanic systems shifting southeast 20-40km or every 6-8ma with a central volcanic zone moving 100-200km. The Snaellsnes Rift Zone (SRZ) was active from 15-6ma at which time the Reykjanes-Langjokull Rift Zone (RLRZ) became active about 6ma and is still active today. The shift in rift zone moved southeast ~120km. The most recent jump occurred about 3ma to the Eastern Rift Zone (ERZ) which is also active today.

Jumps can leave micro-plates between the old and new rift zones. The Northwestern Paleo-Rift (NPR) is a rift zone that was abandoned about 14.9ma when the SRZ subsequently became dominantly

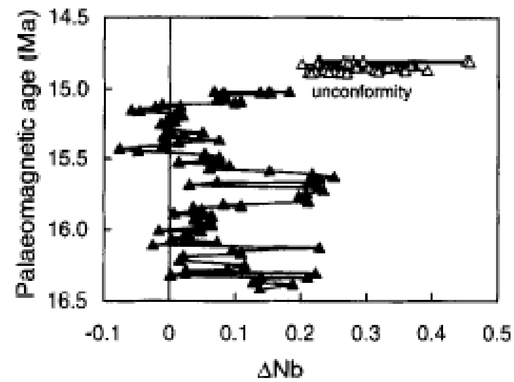

Fig. 8. ΔNb plotted against palaeomagnetic age across the unconformity in northwest Iceland. ΔNb is the deviation, in log units, from the lower bound of the Iceland array (Fig. 7). Positive values of ΔNb indicate an Icelandic mantle source and negative values an N-MORB mantle source [13,39].

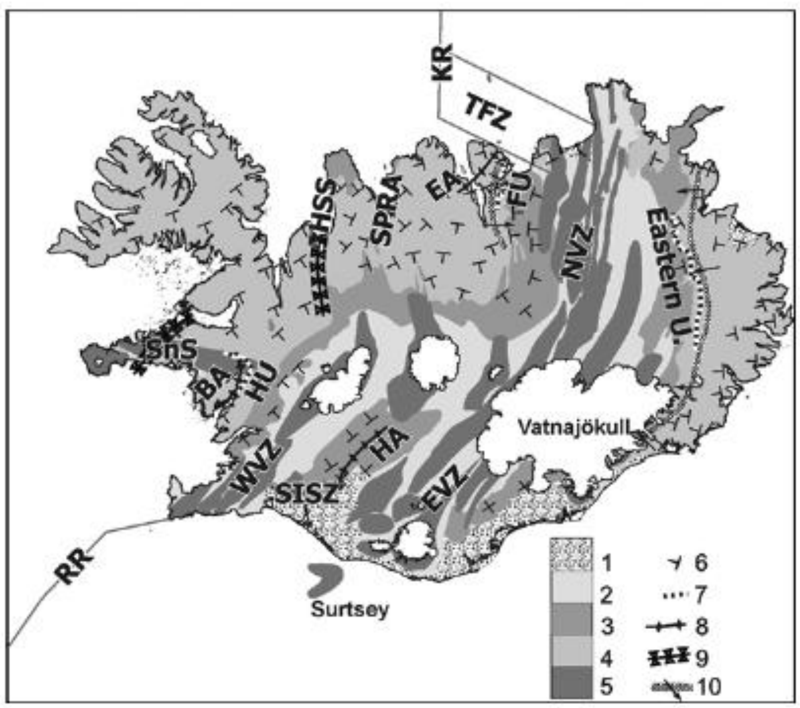

Figure 1: Structural map of Iceland: main active structures or resulting from rift jump process. 1: Holocene sediments; 2: Upper Pleistocene-Holocene lava flows (<0.8 Ma); 3: Plio-Pleistocene lava flows (<3.3 Ma and >0.8 Ma); 4: Tertiary lava flows (>3.3 Ma); 5: Active volcanic system; 6: Dip of lava flows; 7: Angular unconformity; 8: Axis of antiform-like structure; 9: Axis of synform-likestructure; 10: Flexure zone with sense of lava flows dip. BA: Borganes Antiform; EA: Eyjafjördur Antiform; EVZ: Eastern Volcanic Zone; FU: Flateyjarskagi Unconformity; HA: Hreppar Antiform; HSS: Húnaflói-Skagi Synform; HU: Hredavatn Unconformity; KR: Kolbeinsey Ridge; NVZ: Northern Volcanic Zone; RR: Reykjanes Ridge; SISZ: South Iceland Seismic Zone; SnS: Snaefellsnes; SPRA: Skagafjördur Paleo-Rift Axis; TFZ: Tjörnes Fracture Zone; U: Unconformity; WVZ: Western Volcanic Zone. Modified from Johannesson and Saemundsson [1998] and Kristjansson et al. [1992]

active. The SNZ then became abandoned about 6ma, but both rift zones were concurrently active for about 7ma. A major uncomformity exist between the deposition of NPR lavas and SRZ material. Below the uncomformity lava beds dip towards the NPR due to loading of eruptive material in the rifting zone whereas above the uncomformity lava beds dip towards the SRZ.

The anticlinal and synclinal features of rifting, deposition, and loading show paleo-rift zone locations and stable micro-plate blocks that have been unaffected by rifting processes. The Hreppar block and the Borgarfjordur block are two micro-plates located in southern Iceland. The Borgarfjordur block is a rift-jump block located between the SRZ and the Western Rift Zone (WRZ). The Hreppar block in a rift-jump block located between the WRZ and the ERZ. Both micro-plates express anticlinal structures that exhibit the rift loading of sediment dipping towards the production source of the material. Syncline structures can then be used to determine extinct paleo-rift locations such as the NPR.

The most recent analogue for rift-jump process is occurring along the ERZ. Currently the ERZ is taking up about 85% of the total plate movement whereas the WRZ is taking up 15% of the total motion. In a modern day analogue, the WRZ is becoming extinct while the ERZ is beginning to increase its capture of the total movement or the MAR as determined by geodetic data and sill and dike measurements. Volcanic and seismic activity are also less frequent in the WRZ than in the current ERZ. Displacement of the South Iceland Seismic Zone southward also shows the bypassing of WRZ with the direct linking of the ERZ with the Reykjanes Ridge.

S. Garcia et al. / Earth and Planetary Science Letters 214 (2003) 529–544 539

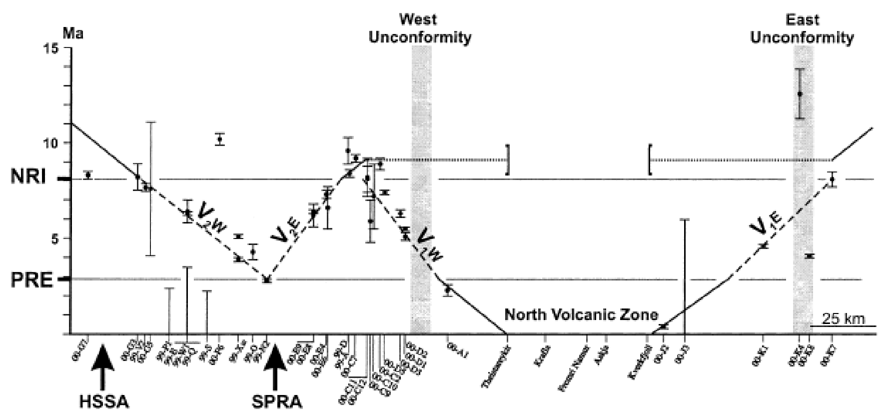

Fig. 5. Dyke ages inferred from $^{40}Ar/^{39}Ar$ radiochronology plotted on N106°E cross-section. Error bars on ages are indicated. Continuous and dashed lines indicate fitted segments for time periods with one or two active rifts, respectively. The values of half-velocities V_{2W}, V_{2E}, V_{1W} and V_{1E} (corresponding to the time period of coeval accretion along the 'old' and the new rift) are given in the text. NRI: New Rift Initiation time; PRE: Paleo-Rift Extinction time. The arrows indicate the Húnaflói-Skagi Synform Axis location (HSSA) and the Skagafjördur Paleo-Rift Axis location (SPRA). Grey bars indicate locations of west and east unconformities. See the text for further explanations. See Fig. 2 for cross-section position and dyke locations.

LAFEMINA ET AL.: GPS IN SOUTH ICELAND

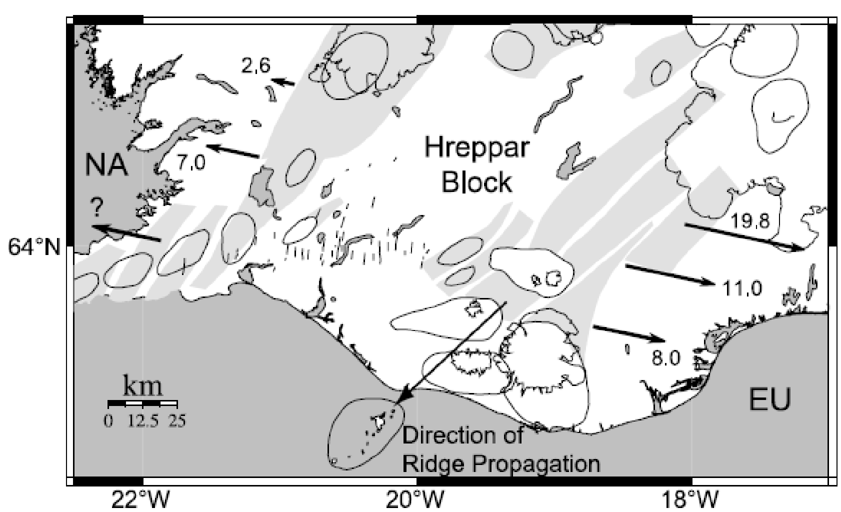

Figure 17. Map of spreading rates estimated with our elastic half-space models for profiles 1, 2, and 3. The along-strike variations in spreading rate match a propagating ridge model, where the WVZ is deactivating and EVZ is activating toward the southwest, the direction of ridge propagation.

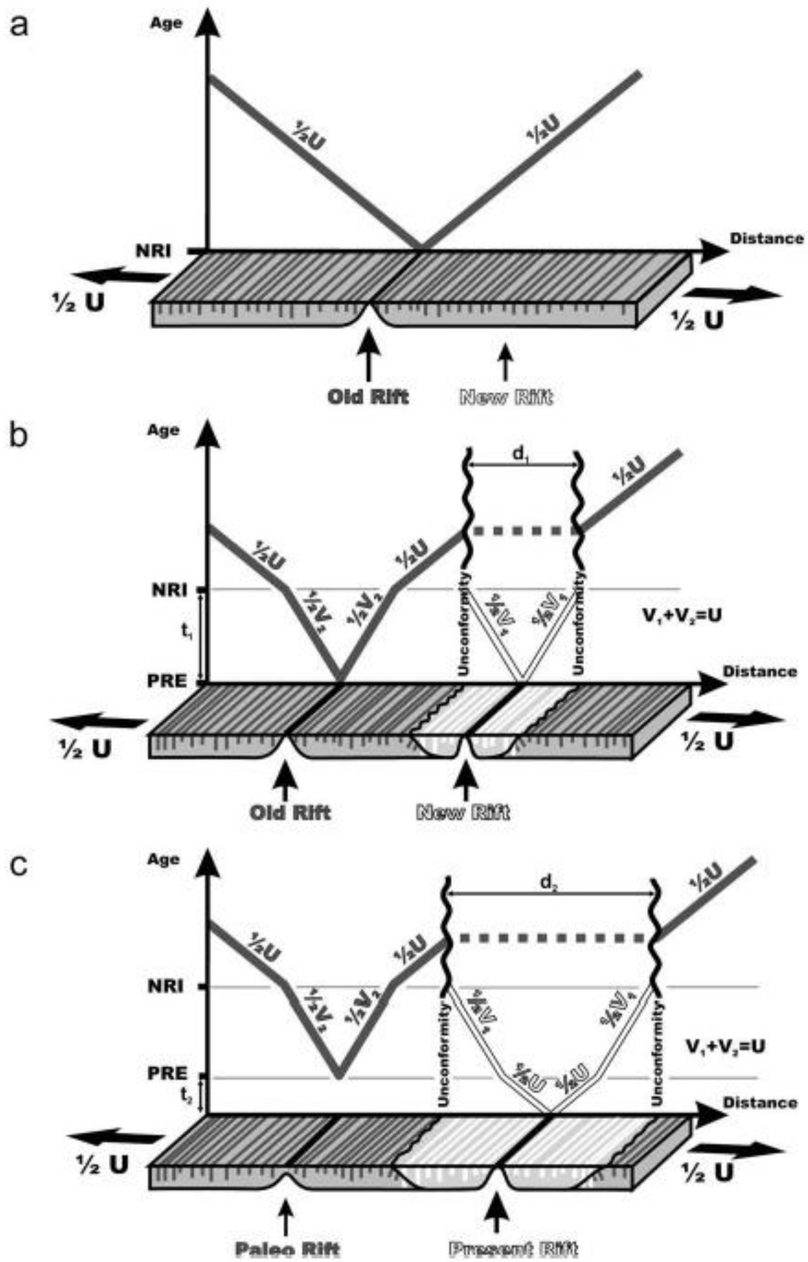

Fig. 4. Theoretical velocity model of a rift jump. The three stages are (a) before the new rift initiation, when only the 'old' rift accretes, (b) when the 'old' rift and the new rift accrete both at the same time, and (c) after the 'old' rift extinction, when only the new rift accretes. Block diagrams show positions of dykes with corresponding ages indicated in ordinate. Dykes on block diagrams and in graphs are in grey when issued from the paleo-rift ('old' rift) and in white when issued from the present rift (new rift). The values of the slope (i.e., the accretion rates) are indicated with the same colour codes. *U*: velocity of divergent plate motion. NRI: New Rift Initiation time; PRE: Paleo-Rift Extinction time. Unconformities are shown as waved lines and rift axes as black thick lines. See the text for further explanations.

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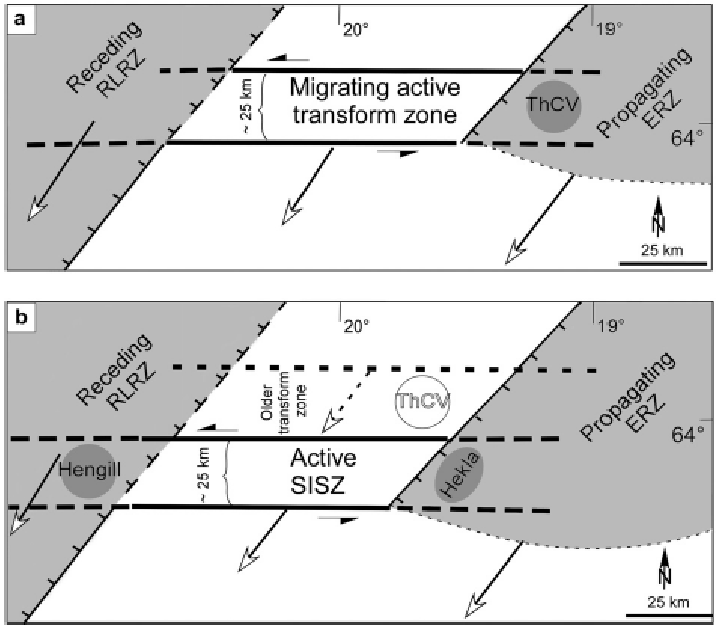

Fig. 13. (a) Schematic sketch showing the initial position of the Thjórsárdalur central volcano (ThCV) at the plate boundary. (b) Position of the volcano after it shifted away from the rift zone, and after the transform zone migrated southward by a distance equivalent to the current width of the SISZ. The dashed white arrows indicate the direction of propagation of the ERZ, the recession of the RLRZ, and the migration of the active transform zone.

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VOLCANOES IN SOUTHERN ICELAND AND GENERAL OVERVIEW OF ICELANDIC VOLCANISM

Margaret Banda Compton, *Department of Geological Sciences, California State University, Northridge*

Figure 1. Regional map of Iceland showing major volcanoes. Last know eruption of Grímsvötn just started in May 2011. Note positions of Helka, Katla, Eyjafjallajökull and Grímsvötn, which will be discussed in further detail in this trip guide.

Background

Iceland was created by combined volcanic activity from the Atlantic Mid-Ocean Ridge and the Iceland Mantle Plume (Andrew and Gudmundsson, 2008). This anomalous juxtaposition has permitted a higher flow rate of lava than most mid-ocean ridge settings, resulting in Iceland's much "more substantial size and topography" in comparison to the Azores, Ascension and other Atlantic Mid-Ocean Ridge islands which are not situated above a hot spot (Lopes, 2005).

Modern-day volcanism in Iceland is largely confined to a volcanic belt which Andrews and Gudmundsson define as the Neovolcanic Zone. The Neovolcanic Zone is sub-divided into three regions: the North Volcanic Zone (NVZ), West Volcanic Zone (WVZ) and East Volcanic Zone (EVZ) (Fig. 2). There are approximately thirty volcanic systems within the Neovolcanic Zone, which are comprised of central volcanoes, basalt volcanoes, large fissure and fault swarms, in addition to dikes and inclined sheets. Most systems have one central volcano, with a few having more than one central volcano (Andrew and Gudmundsson, 2008, Gudmundsson, 2000).

Volcanic systems within the active volcanic belt tend to be associated with “well-defined tension fractures, normal faults and volcanic fissures.” In contrast, volcanic systems outside of the Neovolcanic Zone are linked with regional dikes and normal faults (Gudmundsson, 2000).

The WVZ and EVZ are parallel rift segments which are connected by a 70-80 km long transform fault zone known as the South Iceland Seismic Zone (SISZ) (Fig. 3). The SISZ is covered by another author in greater detail in this guide. The EVZ is thought to be a rift which is propagating into the Eurasian plate. The volcanoes north of the transform are characterized by divergent zone features such as fissure eruptions, normal faults and fissures. In contrast, volcanoes south of the transform tend to be larger, rifting structures are not as apparent, and they exhibit Fe-Ti volcanism, which is characteristic of propagating rifts (Sturkell, et al. 2003).

During the course of this trip to southern Iceland, our primary focus will be on volcanoes in the EVZ, which are more active than those found in the other two volcanic zones. The Icelandic mantle plume is believed to be located under the EVZ, under Vatnajökull glacier, helping to explain why the EVZ is the most historically active of the three volcanic zone (Gudmundsson, 2000). The EVZ includes four volcanoes I will discuss in further detail in this guide: Kalta, Hekla and Eyjafjallajökull and Grímsvötn (Fig. 1).

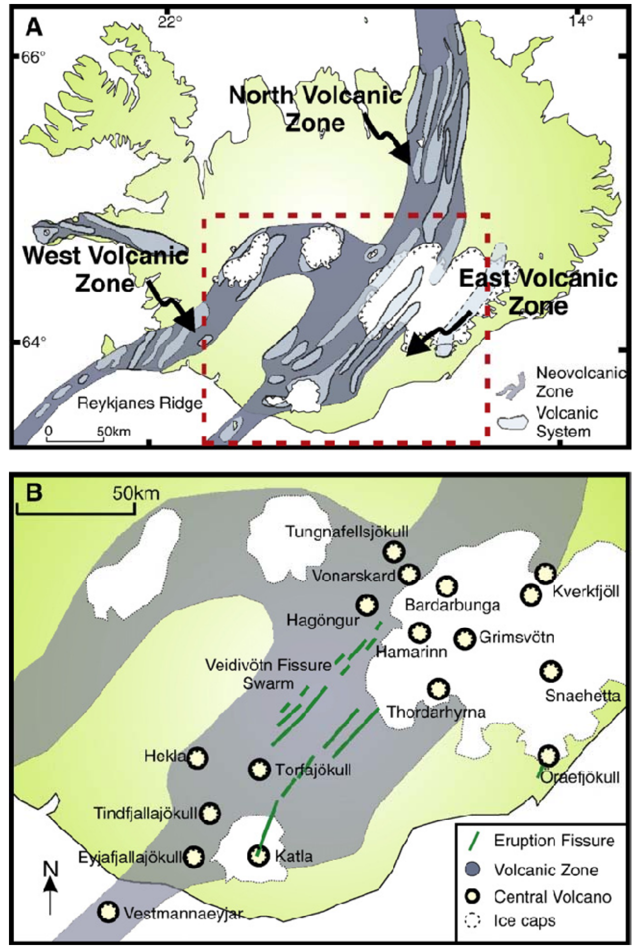

Figure 2. A: Map of Iceland showing Neovolcanic Zone and volcanic systems, with outline of bottom figure. Note N-S trend of volcanic belt in north Iceland and NE-SW trend in south Iceland. B: East Volcanic Zone with central volcanoes and select Holocene volcanic fissures. From Andrew and Gudmundsson, 2008.

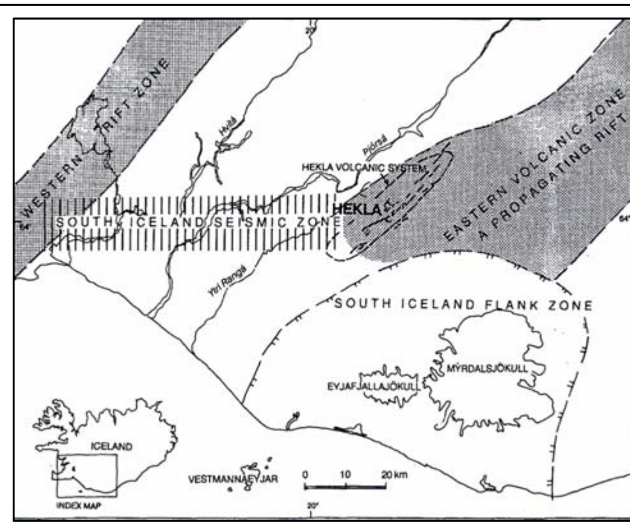

Figure 3. Map showing the SISZ, a transform fault zone, which connects the WVZ and EVZ in South Iceland. From Gudmundsson, et al. 1992.

Central Volcanoes

Central volcanoes are the largest structures in Icelandic volcanic systems and they are predominantly stratovolcanoes or collapse calderas. The average lifetime of a central volcano ranges from 0.5-1 Ma (Gudmundsson, 2000).

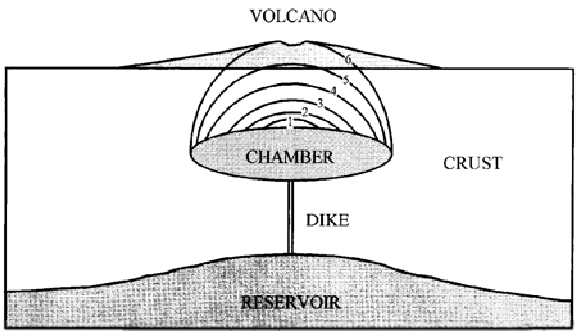

Figure 4. Depiction of double magma chamber consisting of deep-seated reservoir supplied by mantle plume, connected to shallow chamber below volcano. Numbers 1-6 represent succession of sheet injections that eventually created the volcano. From Gudmundsson, 2000.

Central volcanoes have frequent eruptions of basaltic, intermediate and acidic lavas and other volcanic ejecta; however, the most common rocks they produce are the intermediates (Andrew and Gudmundsson, 2008, Gudmundsson, 2000). In addition to erupting at the summit areas, shallow magma chambers under the central volcanoes also supply all of the magma to surrounding fissures. In turn, the Icelandic Plume provides most of the melt from its deep-seated reservoirs to the magma chambers (Fig. 4) (Gudmundsson, 2000). The central volcanoes tend to produce silicic magmas such as rhyolite and andesite, and their eruptions are predominately plinian in nature. This is generally more characteristic of subduction zone volcanism, however, the shallow portion of the double magma chamber underlying central volcanoes is thought to be responsible for producing these type of eruptions and lavas. Magma that is supplied to the shallow chamber from a deeper reservoir is simply more evolved or differentiated than magma that is supplied to an eruption directly from the deep reservoir. Magmas from shallow chambers are more silicic because they are also created by partial melting of basaltic crust due to heat from the hot spot (Bullard, 1976). In contrast, magma supplied directly from the deep reservoir to most fissures, dikes, sheets, crater rows and shield volcanoes, is primarily basaltic, implying that it's more primitive and undifferentiated, and those eruptions are predominantly effusive (Gudmundsson, 2000, Bullard, 1976).

Fissure Swarms, Fissure Eruptions and Fault Swarms

Elongated and well-defined fissure swarms, ranging from 40 to 150 km in length and 5 to 20 km in width, exhibit an en echelon pattern throughout the volcanic belt, with each swarm arranged around a central volcano (Lopes, 2005, Andrew, et al. 2008). Both the active volcanic belt and fissure swarms trend N-S north of Vatnajökull; while south of Vatnajökull, they trend NE-SW (Bullard, 1976) (Fig. 2).

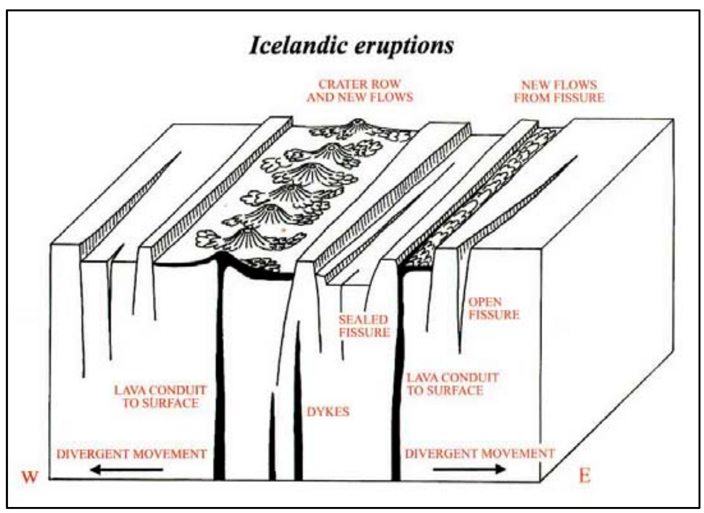

Figure 5. Diagram of fissures (open and sealed), dikes, crater rows and plate movement, illustrating their association with one another and respective locations. From Lopes, 2005.

Fissure eruptions are the archetypal eruptions in Iceland, especially within the Neovolcanic Zone. The fissures are tension fractures, which are a direct result of the North American and Eurasian plates moving away from one another. They are created as the plates pull apart and magma invades them, but it does not always reach the surface. These fissures turn into dikes when the magma solidifies (Fig. 5).

Normal faults also develop within the Neovolcanic Zone, offering further proof that the area is under tension caused by plate pull. Faulting is most apparent in the uppermost few hundred meters of the crust, while dikes are more common in the deeper parts of the crust in this region (Fig. 5).

Basalt Volcanoes

Basalt volcanoes supply most of the lava within the Neovolcanic Zone. The basalt is erupted subaerially from crater rows, shield volcanoes, and fissures, as well as from subglacial and submarine eruptions.

Shield volcanoes usually begin as fissure eruptions; once multiple fissures erupt close enough to one another, overlapping shields are built up, eventually producing a main shield and vent. Shield volcanoes dominate the NVZ and EVZ, while crater rows flourish in the EVZ.

Subglacial and submarine eruptions produce pillow lavas and table mountains, however, that topic will be covered by another author.

Dike Swarms and Sheets

Dike swarms and sheets are regional features that are mainly found at a distance from central volcanoes. They are usually inclined, subparallel and comprised of basalt (Gundmunsson, 2000). It is thought that these dikes are primarily created by horizontal/lateral migration of magma, as opposed to vertical movement (Lopes, 2005), and their movement has been “modeled as fluid flow in fractured media.”

Other Miscellaneous Interesting Notes Regarding Icelandic Volcanoes

- Volcanism in Iceland began in Early Tertiary (Eocene) time and it was related to flood basalts in Scotland, Ireland and Greenland. During this time period, it was profuse, whereas, modern volcanism in Iceland is much more restricted.
- Iceland uses volcanic geothermal energy to provide 85% of the heat in Iceland. There is very little use of fossil fuels in Iceland due to all the geothermal energy available.
- Iceland is the only place in modern time where flood basalts occur (Bullard, 1976).

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Snæfellsjökull

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Snæfellsjökull, Icelandic for "snow-fells glacier" or "snow-mountains glacier," is reasonably long-standing volcano (~1 Ma), which has erupted a diverse group of magmas (primitive basalts to evolved trachytes) over a prolonged time period following the last glaciation and gives a unique opportunity to study time scales of magma evolution. The volcano is located at the western tip of the Snaefellsnes Peninsula, marginal to the main rift zone of hot upwelling mantle beneath central Iceland (Figures 1 and 2).

Figure 1: View of Snæfellsjökull (Sissane, 2009)

The mountain is one of the most famous sites of Iceland, principally due to the novel *A Journey to the Center of the Earth* (1864) by Jules Verne in which the protagonists enter a passage leading to the center of the earth on Snæfellsjökull, and is located in the Snæfellsjökull National Park.

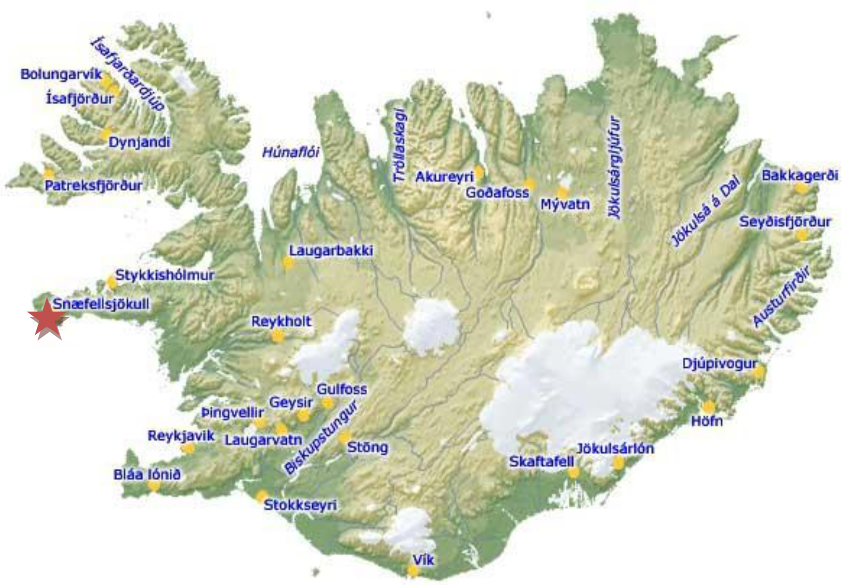

Figure 2: Location map of the Snæfellsjökull volcano in Iceland. Red star indicates Snæfellsjökull (reto.com).

The Snæfellsjökull volcano, situated at the westernmost point of the E–W trending Snaefellsnes Peninsula, is a stratovolcano that has produced a complete alkaline magma series, with three Plinian eruptions releasing trachytic tephra layers of postglacial age. To the east, the Ljósufjöll complex is principally composed of silicic extrusives with a few lavas of intermediate composition, all of which were formed in subglacial eruptions during the Pleistocene. The Ljósufjöll and Lysuskard volcanic systems lie to the east, arranged in a NW–SE en echelon fashion to each other (Figure 3a and b). The Snaefellsnes Peninsula is depicted as a trans-current fault-zone that was formed by differential spreading in north and south Iceland. According to this view, the Snaefellsnes Peninsula characterizes a somewhat superficial tectonic feature reflecting easy pathways for magma ascent rather than reflecting a deep-seated magma source, as is the case for the main rift zones.

Seismic data point to a crustal thickness between 20 km and 26 km for the western tip of the Snaefellsnes Peninsula. Owing to the recurring rift-relocations in Iceland, the Snaefellsnes Peninsula could become tectonically and magmatically inactive in the (geological) near future. The basaltic rocks of the Snæfellsjökull volcano are divided into early-, late- and post-glacial stages. The oldest dated rocks are 842 ± 10 kyr old but the earliest volcanism at Snæfellsjökull volcano probably predates this age. The majority of Snæfellsjökull volcano, particularly to the south and west, is covered by lava flows of post-glacial age (i.e. <10 kyr old), which erupted from dispersed peripheral vents (Figure 3c). Three larger tephra deposits (SN3–SN-1) have been dated by radiocarbon to ~7–9 kyr BP (SN-3), 3960 ± 150 BP (SN-2) and 1750 BP (SN-1) with SN-1 representing the most recent explosive volcanic activity.

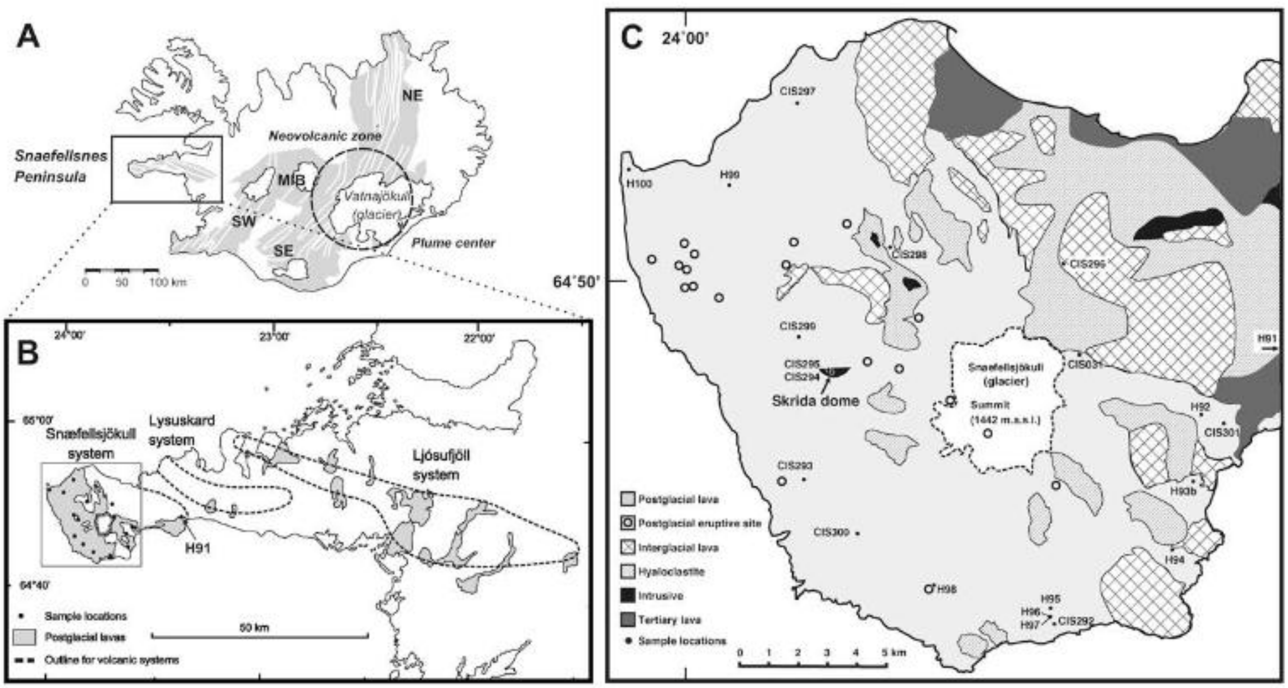

Figure 3: A. Overview of study area in relation to main rift zones on Iceland: Northeast (NE), Southeast (SE), Mid-Iceland Belt (MIB) and Southwest (SW) rift zones. Dashed circle shows the outline of the Iceland mantle plume at ~200 km depth. B. Map of Snaefellsnes Peninsula and the location of three adjacent sub-rift systems, Ljósufjöll, Lysuskard, and the Snæfellsjökull systems. C. Geological map of the Snæfellsjökull volcano. During post-glacial times, the Snæfellsjökull volcano erupted a lava suite ranging from olivine basalt (H91) to trachyte (H95, CIS292, CIS031), including the full range of intermediate compositions. Shown are the post-glacial volcanic centers and the sample locations (Kokfelt et al., 2009).

Kokfelt et al. (2009) interpret the evolution of Snæfellsjökull in this manner. Huge magma batches were trapped in the crust when the glacial lid was the thickest; only larger magma batches of 3–4 km^3 survived over 60-70 Ma, whereas smaller magma batches froze in the crust before the ice sheet melted. Once the lid started to melt, trapped magma batches escaped and new magmas, even small ones, were able to reach the surface without appreciable residence in the crust. Magma production appears to have increased slightly, further assisting the ascent of magma to the surface and also aiding the flushing out of the older evolved magma batches. Their conceptual scheme for explaining the Snæfellsjökull volcano lavas as the result of isolated magmatic events followed by closed system fractionation requires that different basaltic magma pulses remained unmixed. This model either involves a stratified magma chamber for which the successive introduction of new basaltic magma batches into the base of the magma chamber would leave the existing chemical layering intact, or several isolated magma bodies that developed parallel (Figure 4). Either way, the full range of compositions erupts simultaneously. These distinct compositional layers are consistent with the zoned magma reservoir having inclined chamber walls similar to the model proposed for Hekla volcano. The alternative model of parallel magma differentiation in separate reservoirs would require relatively large sizes for the reservoirs containing the oldest magma batches.

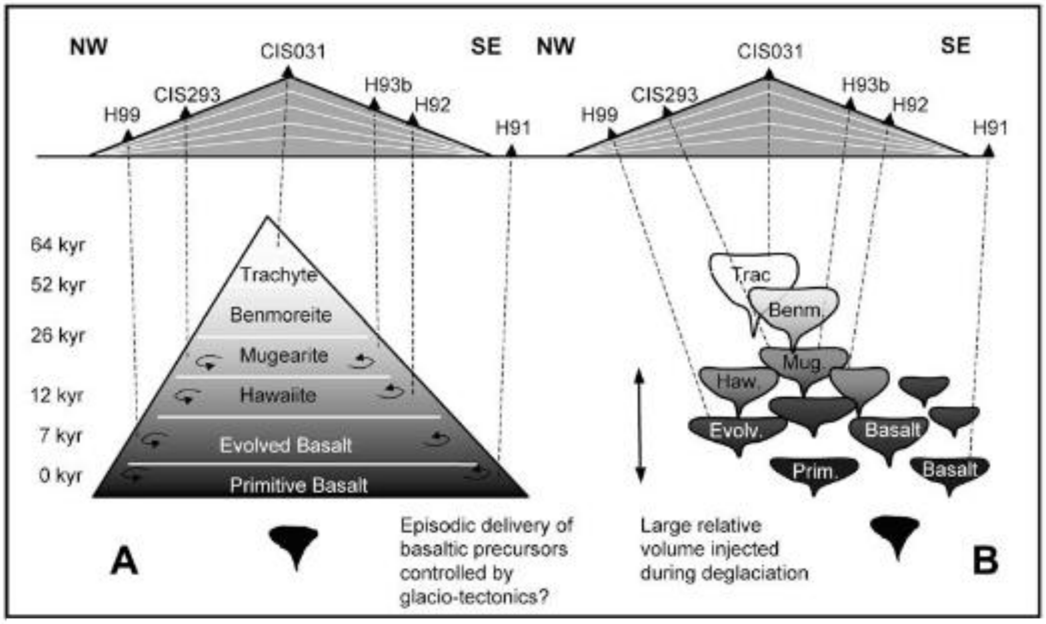

Figure 4: Sketch profile through the Snæfellsjökull volcano and underlying zoned magma chamber. (A) The preferred model includes a zoned magma chamber. Parental basaltic magma is periodically supplied to the base of the chamber from beneath, without disturbing the existing layering. A conical or bell-shaped magma chamber allows for the more primitive deeper levels of the chamber to be tapped and erupted away from the central part of the volcano, whereas the more evolved counterparts preferentially erupt towards the central summit. (B) An alternative model involves separate storage of individual magma batches. This model would require that the older magma batches were large enough to survive 'thermal death' during ~66 kyr ((Kokfelt et al., 2009).

In summary, Kokfelt et al. (2009) indicate that the dominance of post-glacial intermediate lava compositions (evolved basalt to trachybasalt/ hawaiite) at Snæfellsjökull volcano with short inferred differentiation times is consistent with the intrusion of their basaltic precursors into the shallow magmatic plumbing system over an extended time period corresponding to the final deglaciation in Iceland between 16 and 8 kyr BP.

Figure 5: Summit of Snæfellsjökull volcano (Snæfellsjökull.com)

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Birds in Iceland

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We will be seeing a great variety of birds in Iceland. They can be divided into the following categories: Seabirds, waterbirds, and landbirds. Iceland acts as a hub for several migratory routes and can host as many as 278 species. May and June are the primary months for presence, plumage and weather. Pictured below are just a few of what we might see.

Seabirds

Puffins

Black Guillemot

Gannet

Storm Petrels

Cormorant

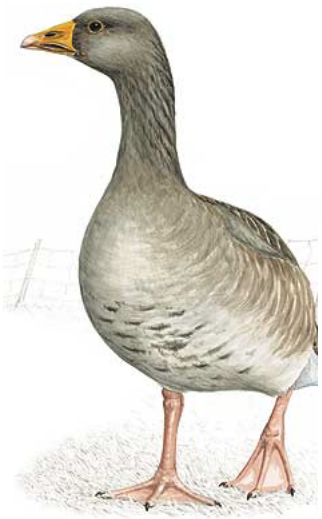
Great Skua

Black Tailed Godwit

Golden Plover

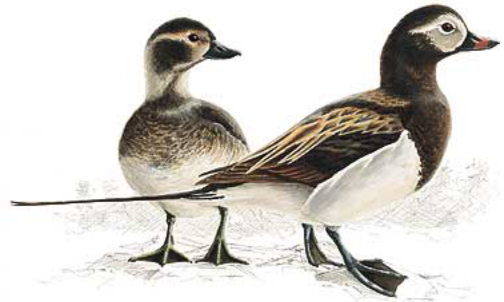
Birds in Iceland

Waterbirds



Graylag Goose

Harlequin Duck



Long Tailed Duck

Red-throated diver

Landbirds

Merlin

Ptarmigan

Gyrfalcon
Iceland's National Bird

Meadow Pipit

Icelandic Mantle Plume

Jenna Fleck *(California State University, Northridge-Department of Geological Sciences)*

Iceland has thick crust near the center and thinner crust towards the edges of the continent. The crustal thickness is about 40m beneath Vatnajokull and gets less than 20m in the Reykjanes Peninsula. The thick oceanic crust results from high magma production and a topographic and geoid anomaly coincide with the thickening of the crust with a diameter of 2000km. The crust can be a proxy for mantle temperature. Over the first 5 million years, after the continental breakup, the mantle plume temperature decreased over ~50C and oscillated by ~25C over 3 millon years, these sort of temperature variations have been since at least 49Ma. A mantle pulse of 25C thickened the crust in a linear pattern from 48-45Ma. There was a rapid decrease in the mantle temperature between 51 and 49 Ma from 120C to 70C.

V-shaped ridges can be used to determine the asthenospheric flow within the plume head. They are located on both sides of Iceland crossing the mid-ocean ridges and are generated by small changes in the temperature of the asthenospheric flow. Asthenospheric temperature fluctuates away from the plume's center. If it flows radially, the mass flux can be deduced to 1-3x10^{14}kg/yr over the past 17 million years. If the radius of the plume conduit was 150km, the upwelling rate would be 270mm/yr.

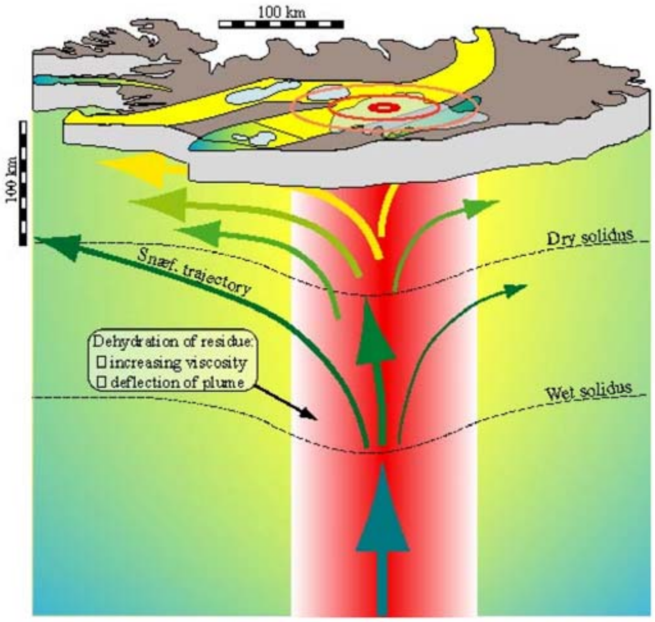


Fig. 1. Schematic illustration of flow trajectories and melting regime of the Iceland plume in relation to the volcanic rift zones (yellow) and off-rift zones (gradients from yellow via green towards blue). The degree of melt depletion of the mantle surrounding the axial plume stem is indicated schematically by colour shades from blue (least melt-depleted) to yellow (most melt-depleted). The same colour coding is used for the flow trajectories. The illustration is a combination of a three dimensional perspective and an east-west vertical cross section, with approximate plume location and dimensions based on Wolfe et al (1997), Shen et al. (2002) and Ito (2002). The crustal thicness is in accordance with Kaban et al. (2002). The initial lateral deflection of the plume flow near the wet solidus is caused by viscosity increase related to the initial dehydration melting (e.g. Ito et al. 1999). (Tronnes, 2002)

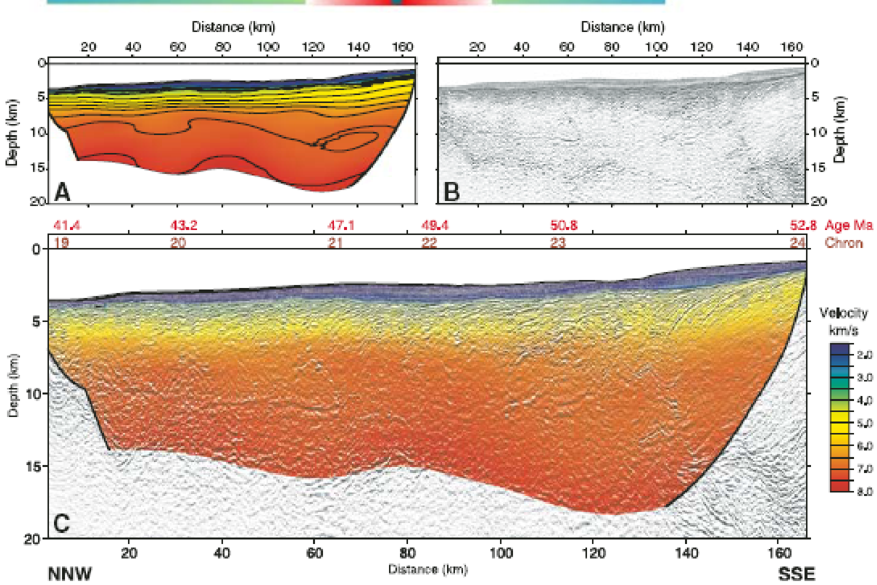


Fig. 2. Coincident profiles through oceanic crust of the Integrated Seismic Imaging & Modelling Project (iSIMM) profile from two seismic data sets. A: Crustal profile determined using ocean-bottom seismometer (OBS) wide-angle refractions and reflections. Solid black lines show lateral limit of velocity control; base of color transition is Moho. B: Reflection profile from 12 km streamer data with velocity model in A used for poststack time migration and depth conversion. Both A and B show reflections from Moho. C: Integrated model; color crustal OBS velocity model of A is illuminated by reflection streamer profile in B, giving detailed image of oceanic crust from seafloor to Moho. (Parkin et al., 2007)

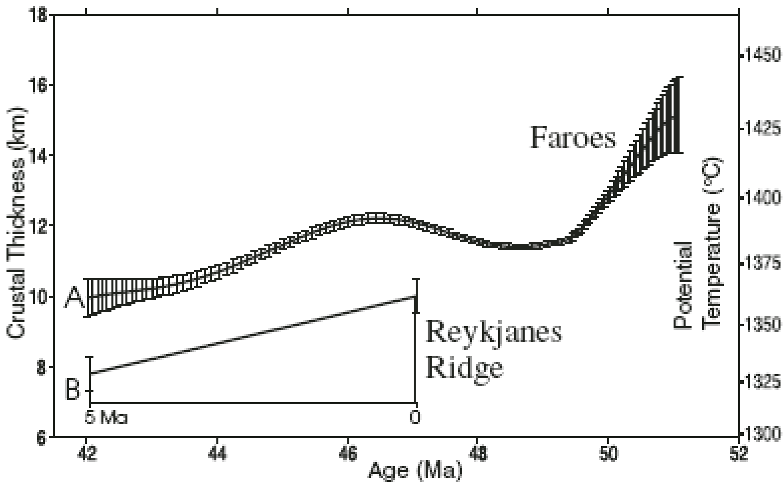


Fig. 3. Crustal thickness vs. age. A: Mantle potential temperature (right) assumes passive upwelling (Bown and White, 1994). Temperatures elevated by ~120 °C above normal immediately after seafloor spreading commenced at 55 Ma, decreasing to ~70 °C above normal at 49 Ma. From 48 to 45 Ma inferred ~25 °C pulse beneath Aegir Ridge generated extra 2 km of crust. Wavelength and amplitude of ridge of thickened oceanic crust are similar to those of more recent V-shaped ridges south of Iceland on Reykjanes Ridge. Uncertainty bars are from Monte Carlo analysis of crustal model. B: Results from previous work by Smallwood and White (1998) at Reykjanes Ridge across 0–5 Ma crust (see Fig. 1A for location). (Parkin et al., 2007)

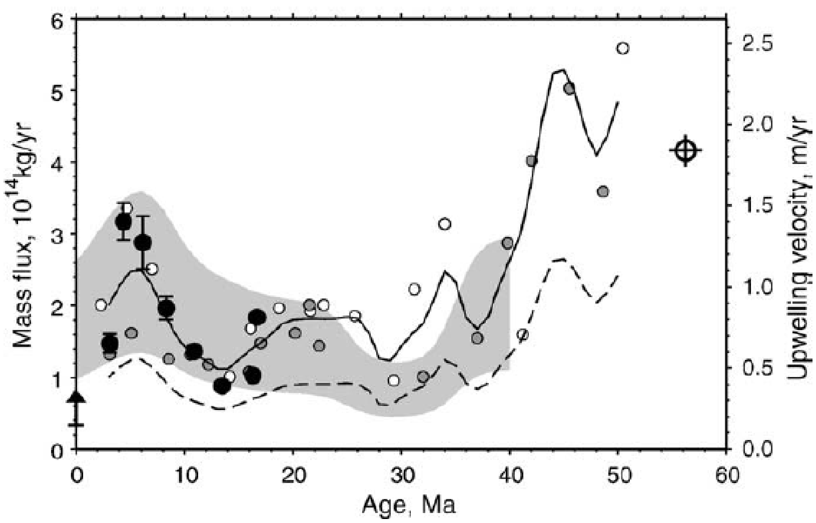


Fig. 4. Estimates of mass flux of Icelandic plume as a function of time. Solid black circles with error bars=mass fluxes calculated from velocities estimated from residual height picks; open and grey circles=mass fluxes, east and west of the spreading ridge respectively, calculated from velocities estimated from picked V-shaped ridges; solid line=line fitted to estimated fluxes using a Gaussian window of 8Ma; dashed line=estimate of mass flux from elliptical geometry and using a Gaussian window of 8Ma; grey band=mass fluxes calculated from locus of boundary between fractured and smooth oceanic crust which assumes that plume layer has a thickness of 75–200 km; arrow symbol=inferred upwelling velocity from Maclennan et al. (2001); crossed circle=Eocene mass flux of Icelandic plume calculated by Rudge et al. (2008). (Poore et al., 2009).

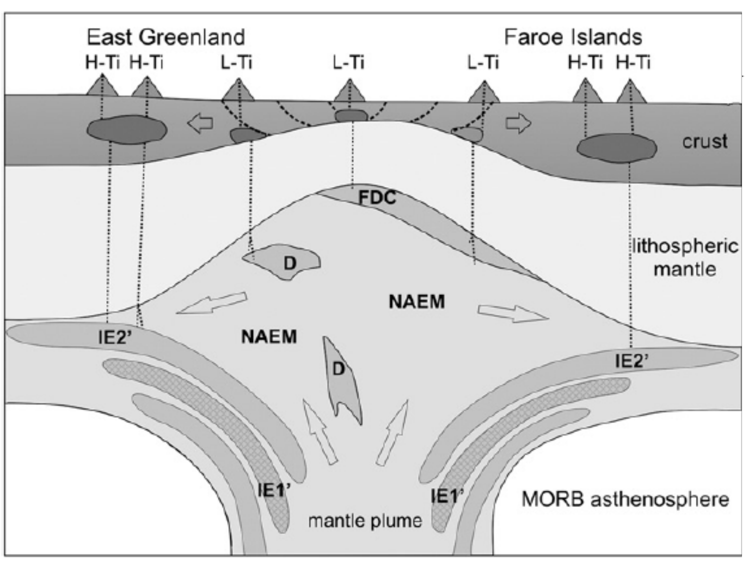


Fig. 5. A schematic model of the internal structure of the early Iceland plume. The enriched components IE1′ and IE2′ and the depleted component D are tentatively shown as blobs in a depleted plume matrix with NAEM composition (see text for discussion). The FDC forms a small body of local depleted upper mantle material left beneath the Faroe lithosphere. The enriched blobs are directed away from the rift zone and therefore only yield melts beneath the Faroese and East Greenland continental areas. Only depleted components are present in the melt zone beneath the rift zone area. (Soager and Holm, 2011)

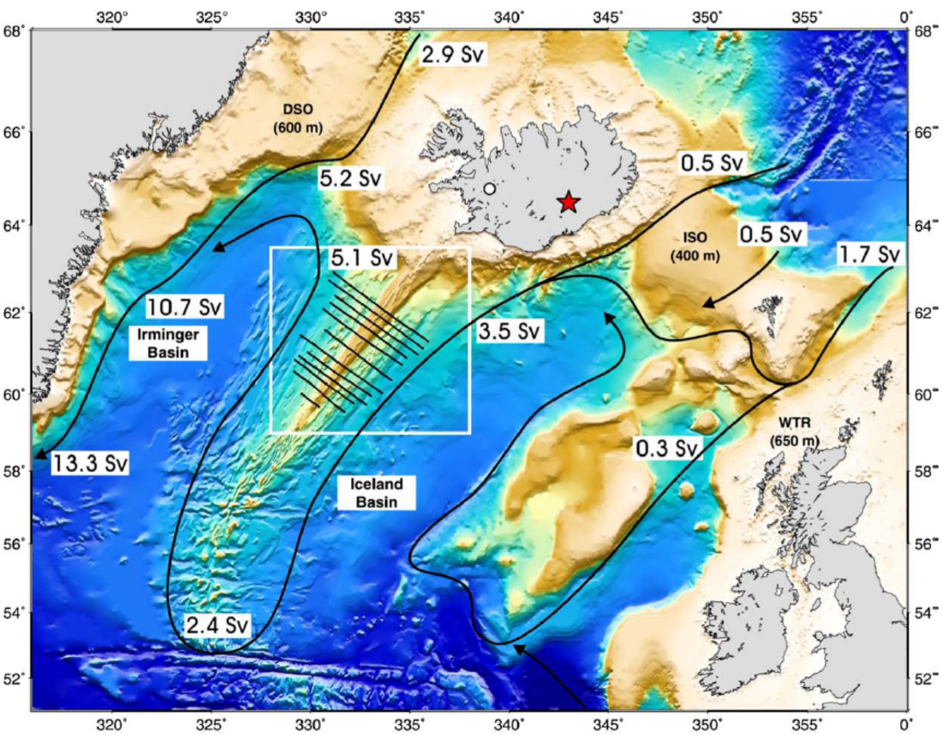


Fig. 6. Bathymetric map of the North Atlantic Ocean which shows the location of seismic reflection survey analyzed in text and principal pathways of deep-water overflow. White box=location of Fig. 2; grid of thin black lines=subset of seismic reflection profiles acquired by RV Vema (Talwani et al.,1971); labelled black sinuous lines=principal over flow positions of North Atlantic Deep Water with current flow given in Sverdrups (1Sv=106m3 s−1), after Schmitz Jr. and McCartney (1993) and Dickson and Brown (1994); DSO, ISO and WTR= Denmark Straits, Iceland Sea and Wyville–Thompson Ridge Over flows (sill depths in meters). Red star=centre of present-day Icelandic plume; white circle=intersection between Reykjanes Ridge and flowline through plume center. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.) (Poore et al., 2009)

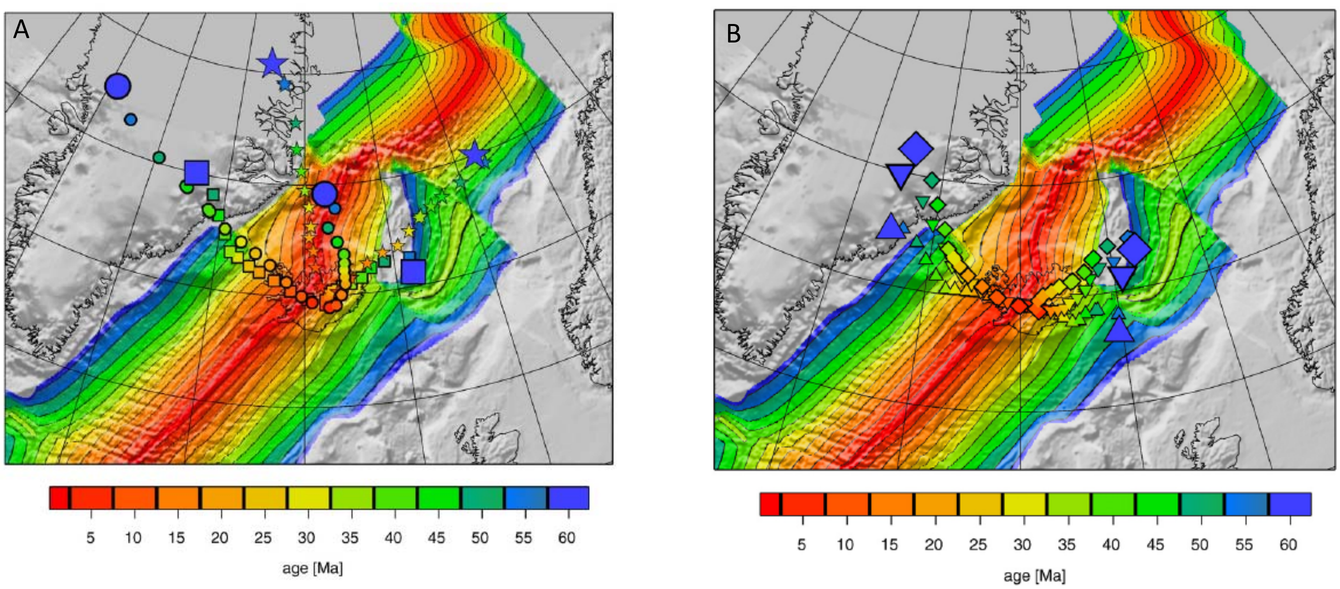


Fig. 7. A) Hotspot tracks relative to Greenland and Eurasia calculated with different reference frames. Circles are for model 1, squares for model 2 a. Note that the difference between models 1 and 2 a is due to both motion of the Iceland hotspot in model 2 a, and the different absolute plate motion reference frames (Müller et al., 1993 vs. Steinberger et al., 2004). Stars are for model 2 e, i.e. without net rotation of the lithosphere relative to the deep mantle. Big symbols are for initial time 60 Ma. On the same color scale, the seafloor age grid age_1.6 from Muller et al. (1997) is shown. Note that any segment of a computed track cannot correspond to an actual hotspot track if the age is older than the lithosphere age at the same location. Those segments are plotted for the assessment of possible plume–ridge interaction. The shaded relief shows the topography dataset topo_8.2 from Smith and Sandwell (1997).
B) Hotspot tracks relative to Greenland and Eurasia calculated with different tomography models. Inverted triangles are for model 2 b (S20RTS), diamonds for 2 c (TXBW), triangles for 2 d (SB4L18). Big symbols are for initial time 60 Ma. Different tomography models are used to calculate the motion of the Iceland hotspot, however, the same absolute plate motion model (Steinberger et al., 2004) is maintained in all cases. (Mihalffy et al., 2008)

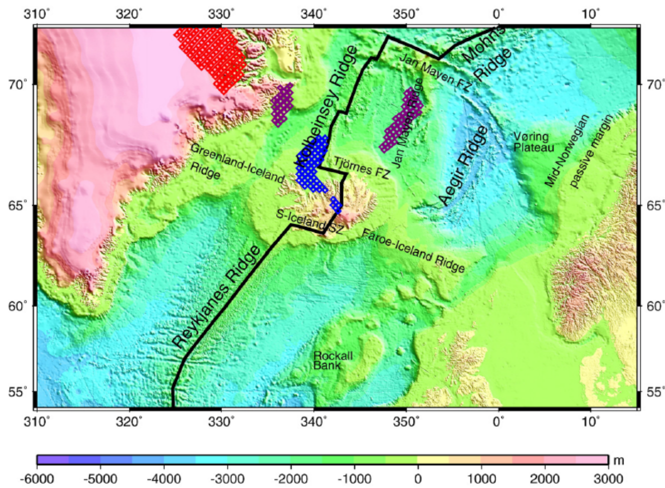


Fig. 8. Model 3 a (moving-source) plume head track for 40 Ma (red diamonds), 20 Ma (purple diamonds), and 0 Ma (blue diamonds), and bathymetry of the North Atlantic. (Mihalffy et al., 2008)

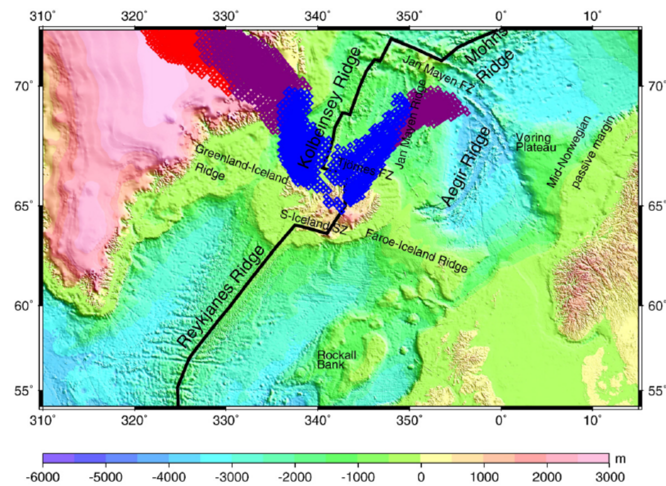


Fig. 9. Model 3 a (moving source) plume head track for 50 Ma–40Ma (red diamonds), 40 Ma–20 Ma (purple diamonds), and 20 Ma–0 Ma (blue diamonds), and bathymetry of the North Atlantic. (Mihalffy et al., 2008)

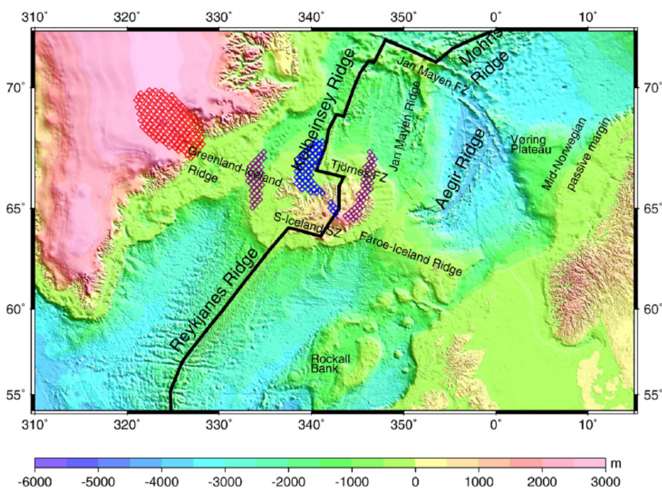


Fig. 10. Model 3 b (fixed source) plume head track for 40 Ma (red diamonds), 20 Ma (purple diamonds), and 0 Ma (blue diamonds) and bathymetry of the North Atlantic. (Mihalffy et al., 2008)

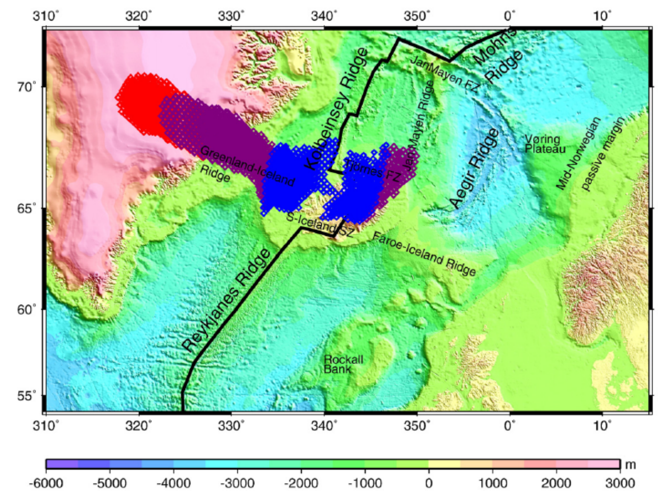


Fig. 11. Model 3 b (fixed source) plume head track for 50 Ma–40 Ma (red diamonds), 40 Ma–20 Ma (purple diamonds), and 20 Ma–0 Ma (blue diamonds) and bathymetry of the North Atlantic. (Mihalffy et al., 2008)

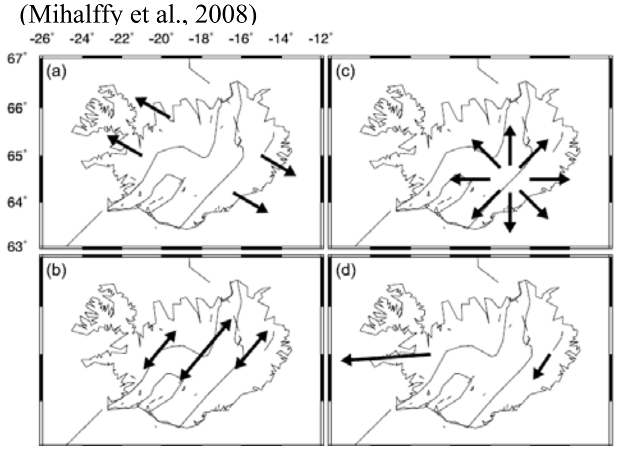


Fig. 12. Cartoon showing possible mantle £ow components beneath Iceland. (a) Mantle £ow in plate spreading direction. (b) Flow channeled along the Mid-Atlantic Ridge. (c) Radial £ow away from the plume center. (d) Flow related to absolute plate movement. Flow directions are schematic except the absolute plate motions in d, which are obtained from NUVEL-1. (Li and Detrick, 2003)

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Subglacial Eruptions

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Introduction

Eruptions that have occurred in Iceland have drawn attention to many scientists due to being a good area to study the influence that glaciers have on volcanic activity. The volcanic activity that is seen in Iceland occurs due to a mantle plume that lies beneath the Mid-Atlantic ridge. (Gronvold et al., 2002) The Icelandic rifts that occur in the mid Atlantic ridge have migrated stepwise towards the east in the last 20Ma in order to keep their position near the surface expression of the plume. This step wise movement is was leads to the rift and transform zones changing pattern. (Tronnes) In interest of subglacial eruptions the area of study is Hlooufell, it is in the South western part of Iceland and will be examined for the length of this paper.

Geologic Setting

In the past 3Ma Iceland has been covered by large ice sheets and smaller ice caps. The volcanic plume that lies under the ice comes into contact with the ice and forms a subaqueous environment that will be in the form of a water filled ice cavity or ice damned lake. (Tronnes) As the lava is coming up the characteristics that it will exhibit depend on two variables, the hydrostatic pressure, and the internal volatile pressure in the magma chamber. (Tronnes) In a subglacial mountain the general stratigraphy of the cores consists of pillow lava, followed by pillow breccia, then hyaloclastite tuff. The stratigraphy that is seen demonstrates that as the lava rises and the mountain grows higher the hydrostatic pressure from the ice is decreasing. (Tronnes) The mountains that the subglacial eruptions produce are usually steep sided and lead to higher topography while sub aerial eruptions lead to more flat topography.

Hlooufell

In figure 1 the location of Hlooufell is seen to be contained within the south western part of Iceland. Hlooufell is located 80km northeast of Reykjavik, and 9km south of the Langkjokull ice cap. It is a tuya in the Western Volcanic Zone, research done has proven Hlooufell to well demonstrate the growth of ice confined basaltic volcanoes in sub glacial stage.

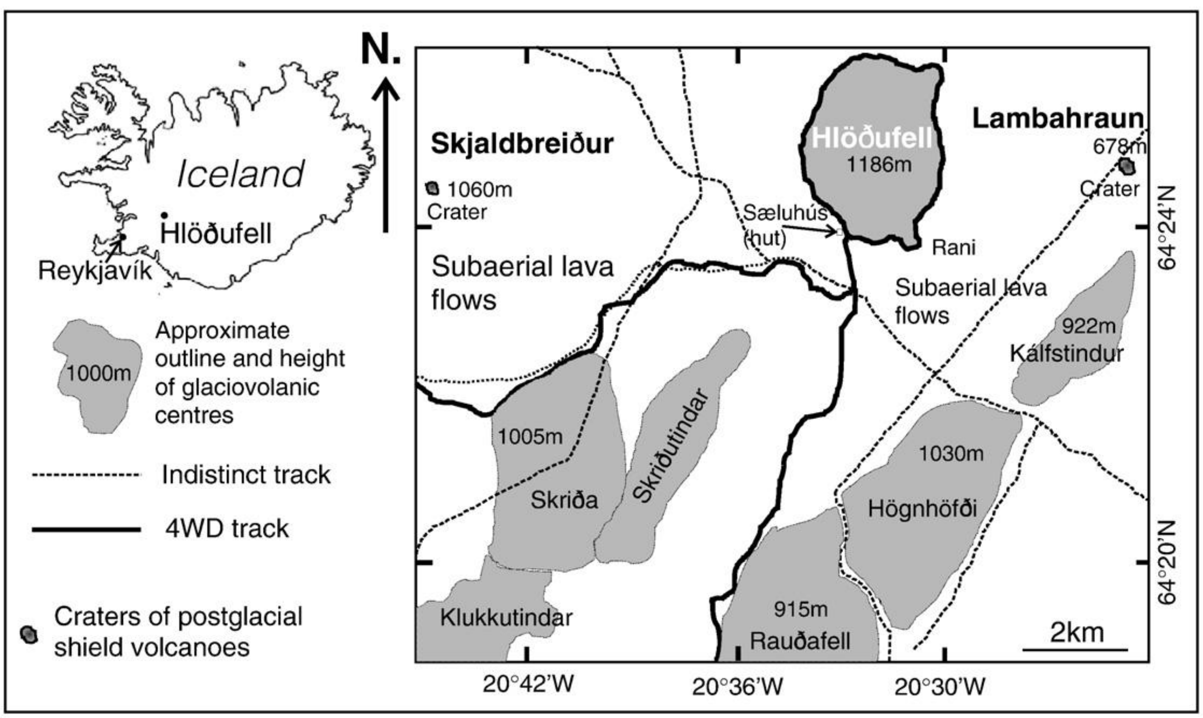


Figure 1 (Skilling, 2009)

Evolutionary stages

Research done in (Skilling, 2009) divided the evolution of Hlooufell into four stages. The division was done according to the facies architecture; these can be seen in figure 2.

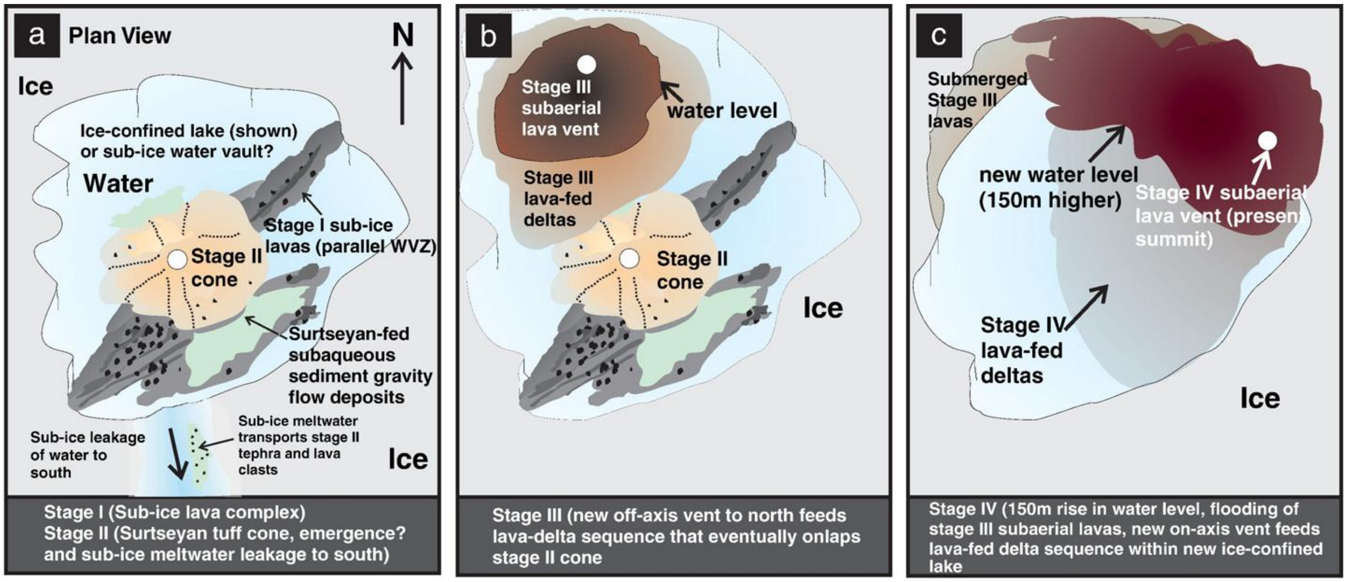
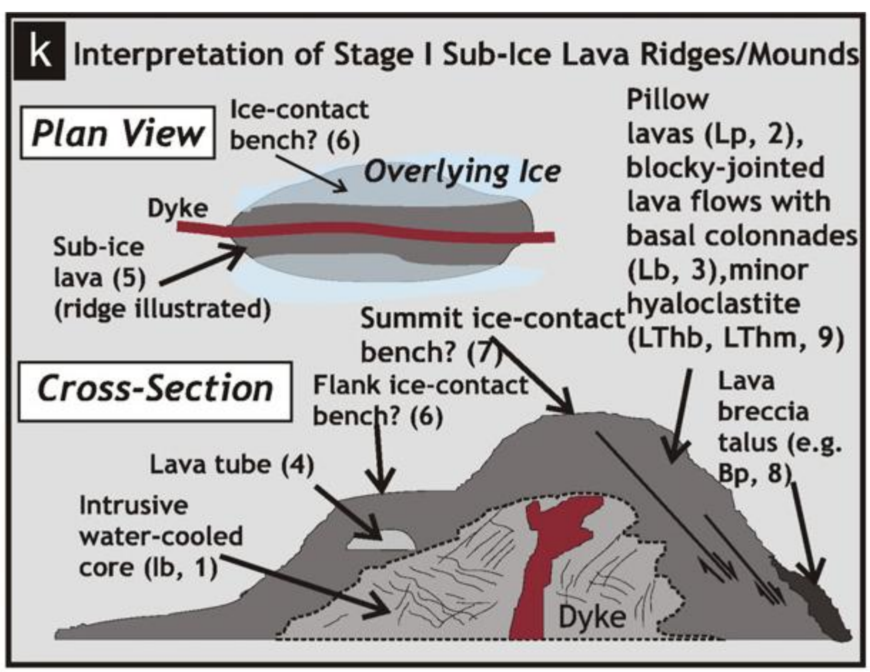


Figure 2 (Skilling, 2009)

Stage 1 facies is identified as the sub ice lava complex. These facies are exposed in many places adjacent to the base of the mountain, at higher topography where they are exposed from the talus slopes, most of the exposure though is seen in a step sided gully near the south east corner of Saelahus hut mountain. Stage 1 as seen in figure 3 consist of blocky jointed lavas, pillow lavas and water cooled jointed intrusions. These facies were erupted in a NNE-SSW trend of the fissures, and are up to 350m in length and up to 240m in height. There are a few of the exposures that have contacted ice and preserved structures that formed form the lava chilling, confinement of ice , ice melting and ice fracture. In these structures they display clusters of open meter sized cavities that occur in the areas where the margins of the lava body are defined by steep laterally extensive flat-bulbous glassy surfaces. (Skilling, 2009)

Figure 3 (Skilling, 2009)



Stage 2 is the subaqueous phreatomagmatic deposits, there are a water lain tephra sequence that is best exposed in cliffs around the southern third of the mountain. There is an exposure of part of the cone of stage 2 in the southern tip of the mountain; part of this exposure is overlain by stage 3. (Skilling, 2009) Stage 3 is the lowest sub aerial pahoehoe lava flow and cogentic lava fed delta sequence. The stage 3 contains mostly steeply dipping facies with overlying sub horizontal sun aerial lava flows. The passage zone is sub horizontal which indicates that there was a stable water level when the deltas were made. The sequences contain dikes that indicated that there was wet sediment. (Skilling, 2009) Stage 4 contains sub aerial lava fed delta sequence, this was fed form a will preserved vent that is now the summit of the mountain which can be seen in figure 4 number 3. The steep difference in the altitude of stage 3 and 4 indicates that there was a rapid rise in the melt water during the formation, approximately 150m of water. (Skilling, 2009)

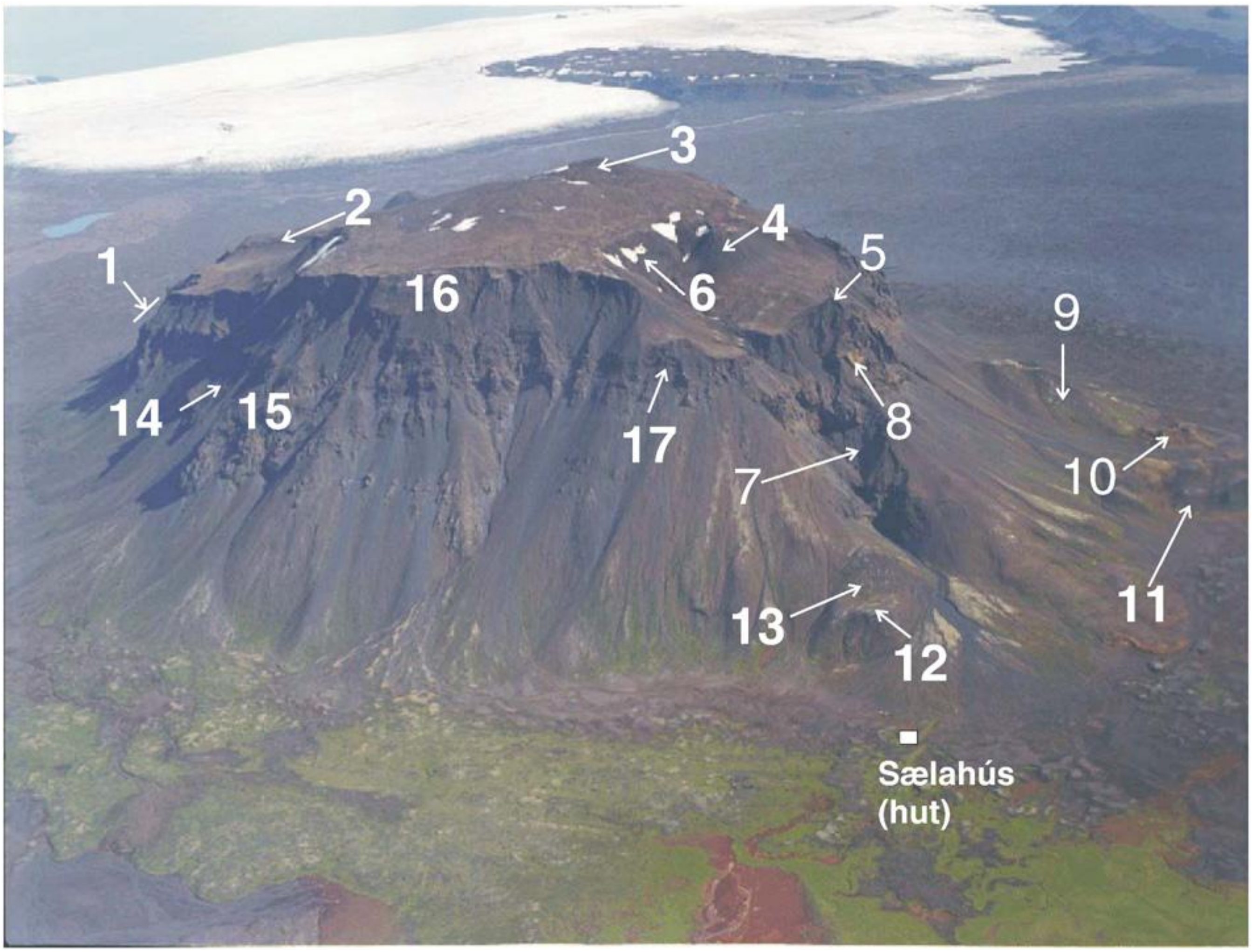


Figure 4**Oblique aerial photograph of the western side of Hlöðufell illustrating several features described in the text and illustrated on figures, including location of vents and the main area of outcrop of stage I sub-ice lavas on south and south-eastern side of mountain. Location of figures in this manuscript are also shown. (1): stage IV lava-fed deltas; (2): stage IV lava bench, discussed in text and see Fig. 8; (3): Main cone/vent for stage IV (summit of mountain); (4): stage IV Cone 2 vent; (5): stage II cone/vent, Fig. 7a; (6): stage IV lava-fed delta bench, discussed in text and see Fig. 8; (7): Deep gully with dissected stage I sub-ice lavas, Fig. 5a–c; (8): stage II tephra in steep chutes below cone, Fig. 7b; (9): stage I sub-ice lava ridges and mounds, Fig. 5g; (10): stage II tephra from stage II cone; (11): stage 1 sub-ice ridges and mounds (12): Bench or terrace on top of stage I sub-ice lava mound, Fig. 5e; (13): stage I sub-ice lava mound, Fig. 5e; (14): Location of Fig. 8b–d; (15): stage III lava-fed deltas; (16): stage IV subaerial lava flows; (17): stage III subaerial lava flows. (Skilling, 2009)**

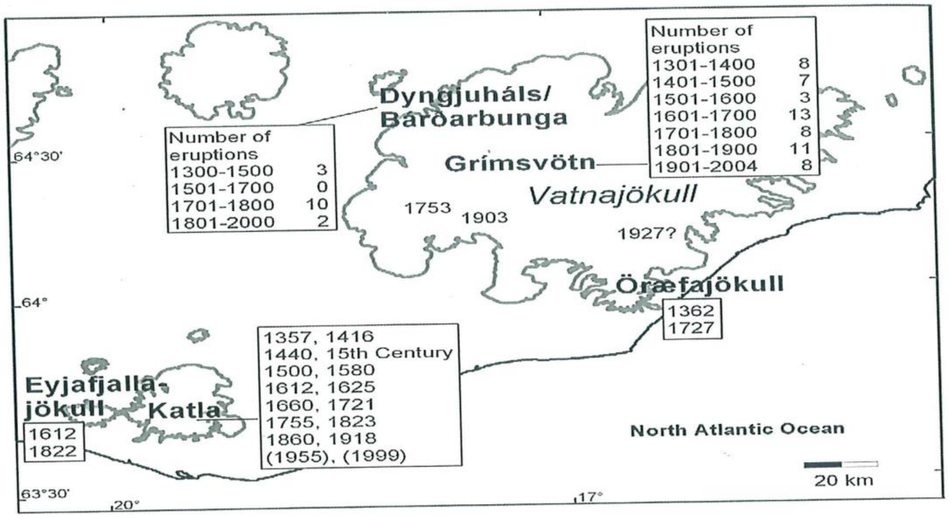


Figure 5 Known eruption sites in Icelandic glaciers since about 1300 AD. For Bárðarbunga and Grímsvötn the number of confirmed eruptions over intervals of 100 or 200 years is given while the eruption years are shown for other volcanoes (based on Thorarinsson, 1974; Larsen *et al.*, 1998 and Thordarson and Larsen, 2007). – *Eldgos sem kunnugt er um að hafi orðið í jökli hér á landi síðan um 1300. Byggt á ýmsum heimildum.*

Recent activity

Using soil samples found in sections of the glaciers **it** was found that 50% of eruptions since the settlement of Iceland have occurred within glaciers. As seen in figure 5 most of the eruptions have occurred in Varnajokull in the Grimsvotn central volcano. The Grimsvotn volcano has been recorded to erupt once every 10 years. The nature of the Vatnajokull region has activity that is periodic, having high activity intervals of 60-80 years then alternating with low activity levels for the same length. (Gudmundsson et al, 2008) Gjalp eruption occurred under 600-750 m thick ice with a 6km long fissure that erupted between the subglacial central volcano of Grimsvotn and Baroarbunga. It lasted 13 days, and melted 600 m of ice in 31 hours. This led to an eruption of tephra over north Iceland in the first 24 hours. (Gudmundsson et al, 2008) The more recent eruption was Eyjafjallajokull which was an icecap that overlaid the caldera of a volcano. The ash plume was not the largest there has ever been recorded however it led to problems for air travel.

Conclusion

The subglacial eruptions depend on factors that involve the hydrostatic pressure and the internal volatile pressure. The focus of the study was Hlooufell which is found in the south western part of Iceland, it is studied to have 4 evolutionary stages that make of the facies of the mountain. The first stage was sub ice lava complex, then stage 2 the subaqueous phreatomagmatic deposits, stage 3 lowest sub aerial pahoehoe lava flows and cogentic lava fed delta sequence, and stage 4 contains sub aerial lava fed delta sequence. The recent activity of the volcanoes of Iceland is also discussed to understand the activity level of the plumes in Iceland.

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MONOCLINES AND ECHELON FRACTURES IN NORMAL FAULT PROPAGATION

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Monoclinal structures accompany the normal fault propagation in the SISZ in southwest Iceland and have been used to demonstrate that faults develop at depth and advance upward. As fractures propagate from below to a depth of 250-500m, a monocline develops at the surface expression of the fault. This monoclinal structure has a maximum tensile surface stress at the upper hinge on the monocline. This maximum stress plus the angle and upward propagation of the fault from the subsurface encourages a vertical migration of the fault system which leaves the monocline intact with the hanging wall of the normal fault. Furthermore echelon fractures forming at the surface break in monocline show oblique motion and cause a more narrow monocline system whereas monocline lacking a dominant echelon fracture pattern tend to have a more broad area of deformation hinting at a pure dip-slip motion. Monoclinal structures can be viewed from the Thingvellir fissure swarm on the northwest side of Lake Thingvallavatn.

Fig. 3. Typical features along fracture zones in the Vogar fissure swarm. In this example, a surface monocline is breached by a fault along its upper hinge line. The fault displays both vertical and opening displacements and the fault scarp is vertical.

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Fig. 10. Surface monocline sloping towards Lake Thingvallavatn on the hanging wall side of Almannagjá in the Thingvellir fissure swarm (location of star in Fig. 8). View is towards the northeast. The upper hinge line of the monocline is breached by numerous right-stepping, échelon fractures. Note the summerhouses along the lakefront for scale.

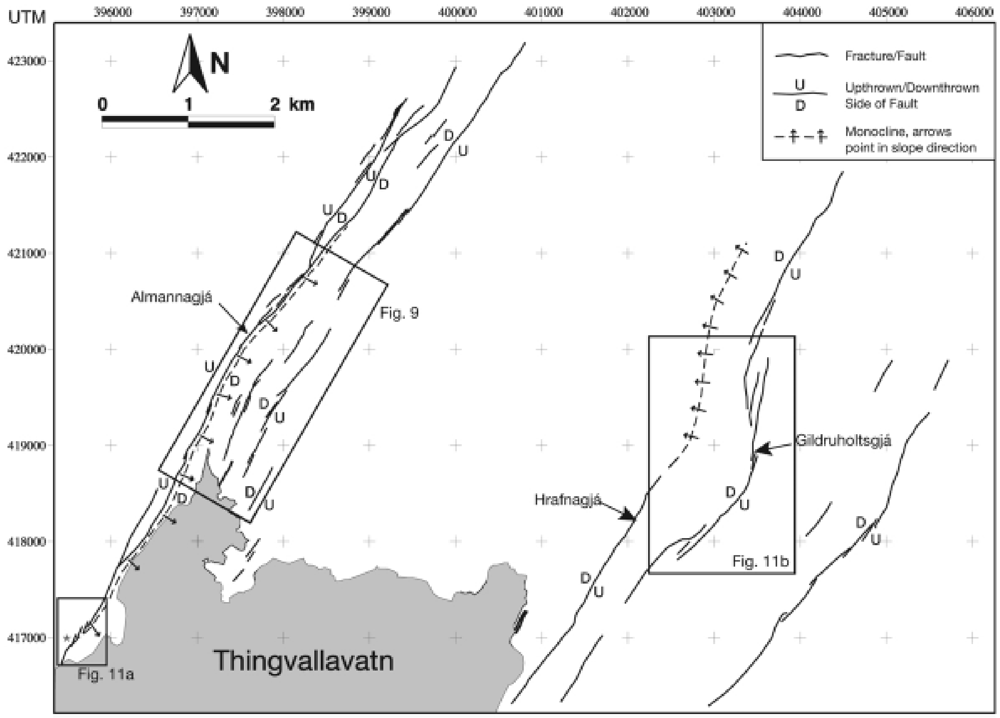

Fig. 8. Map of the Thingvellir fissure swarm (box B in Fig. 1), north of Lake Thingvallavatn, showing the orientations and locations of fractures, faults, and monoclines. Boxes show the locations of fracture maps in Figs. 9 and 11a and b. The star at the southern end of Almannagjá shows the location of the photograph in Fig. 10. Location grid is in UTM coordinates.

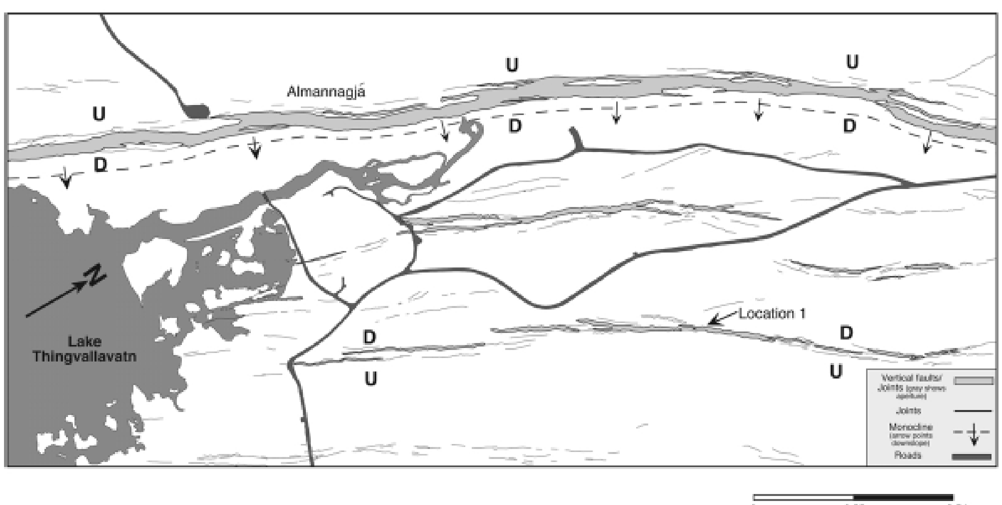

Fig. 9. Fracture map of vertical faults and joints in the Thingvellir fissure swarm (box in Fig. 8). Surface apertures are shown with light gray shading. The faults are segmented with individual segments oriented parallel to the overall trend of the fault trace except at bends in the faults, where en échelon patterns occur (Location 1 is referred to in the main text). Almannagjá is the most prominent fault and is associated with a hanging wall monocline that has been breached along its upper hinge line. Fracture zones in the hanging wall (southeast) of Almannagjá are antithetic to the main fault, which dips to the southeast in the subsurface.

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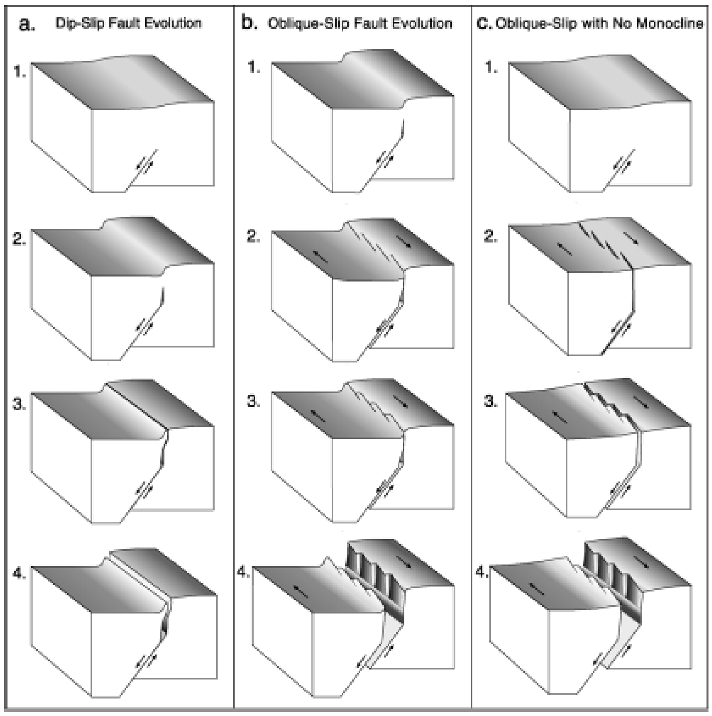

Fig. 15. 3-D block diagrams illustrating conceptual models for normal fault evolution in southwest Iceland. (a) Dip-slip normal faults. (1) A dipping normal fault initiates in the subsurface and propagates upwards. (2) A vertical fracture forms at the upper fault tip and a narrow monocline develops above it at the surface. (3) The joint propagates to the surface, curving slightly towards the footwall so that it breaches the monocline through the upper hinge. (4) Vertical and opening displacements develop and create a vertical fault scarp at the surface. (b) Oblique-slip normal faults. The sequence of events is similar to (a) except that left-stepping échelon fractures form along the upper tip of a vertical fracture in response to right-lateral oblique motion on the subsurface fault. The fractures breach the monocline upper hinge and link together, developing vertical and opening displacements along vertical, segmented fault scarps. (c) Oblique-slip normal faults with no monoclines form in a similar manner to (b) except that the developing vertical échelon fractures connect to the surface instantaneously by utilizing pre-existing joints in the basalt. The hanging wall and footwall can thus pull apart without a monocline forming.

References:

Grant, J.V., Kattenhorn, S.A., 2004; *"Evolution of vertical faults at an extensional plate boundary, southwest Iceland"*, Journal of Structural Geology, vol. 26, pp. 537-557

THE SOUTH ICELAND SEISMIC ZONE

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The South Iceland Seismic Zone (SISZ) is a broad zone, 20-30km wide and 80km long, of left lateral movement connecting the Reykjanes Peninsula (RP) with the Eastern Rift Zone (ERZ). Though sinistral displacement is shown by GPS and field observation methods, no defined left lateral fault exist. Instead, shear motion is taken up by north-south trending right lateral bookshelf faulting. In northern Iceland, the Kolbeinsey Ridge (KR) is a right lateral transform fault zone defined by 3 distinct faults though the 3 faults comprise the zone of faulting. Movement along these fault systems is more centralized and consists of acute mappable faults like the Husavik-Flatey Fault (HFF) in the Tjornes Fault Zone (TFZ). These two major transform zones encompass most of the seismicity in Iceland. The areas, though being primarily transform in nature, have significant extensional components and resemble overlapping spreading centers. The TFZ has been active since ~8ma and the SISZ ~3ma. This difference in age between the two zones has provided the northern section greater time lapse to mature to acute fault zones within a given stress field. The SISZ, however, is relatively new and lacks the fully developed transform fault development of the north.

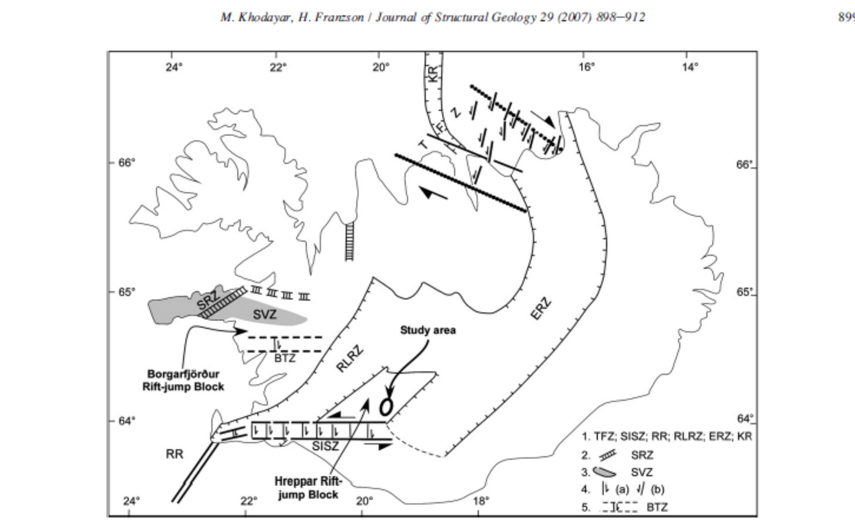

Fig. 1. Major tectonic elements in Iceland (modified from Khodayar and Einarsson, 2002a) and location of the study area. 1. TFZ: Tjörnes Fracture Zone; SISZ: South Iceland Seismic Zone (note that only the strike of the main earthquake fractures are shown within the SISZ); RR: Reykjanes Ridge; RLRZ: Reykjanes-Langjökull Rift Zone; ERZ: Eastern Rift Zone; KR: Kolbeinsey Ridge. 2. SRZ: Snæfellsnes Rift Zone (extinct Tertiary rift). 3. SVZ: Snæfellsnes Volcanic Zone. 4. (a) Dextral strike-slip fault; (b) sinistral strike-slip fault. 5. BTZ: Borgarfjörður Transform Zone.

The Hreppar Rift-Jump Block (HRJB) of southern Iceland is bordered by the Western Rift Zone (WRZ) the ERZ and the SISZ. Late Tertiary to Pleistocene basalts comprise the block that has been eroded and glacially smoothed down to a paleoburial of 500-700m. During the last jump phase, about 3ma, the SISZ was located about 12km to the north and parallel to its current location. A central volcanic system existed at this northern site, the Thjorsardalur volcano. The now central volcano systems are the Hekla and Hengill volcanos in the current SISZ. Dikes, fissure swarms, and fracture zones relate synonymously to the now active SISZ patterns exist throughout the HRJB. The SISZ once existed north of its current location and the jump must have moved southward at least as wide as the SISZ is currently (about 20-30km). This jump may, in part, be caused by the continued migration of the ERZ in relation to the RP. As the ERZ continues to propagate southward, future migrations of the SISZ may occur along with abandonment of the RP.

Lake Thingvallavatn in southwestern Iceland resides about 5km north of the Hengill triple junction and was significantly altered by an eruption at 1.9kyr creating two smaller islands in the lake named Sandey and Nesjaey. This flow is called the Nesjahraun lava.. The Thingvallvatn area is comprised of north-south trending right lateral bookshelf offsets of the SISZ. Two major faults occur on the west and east flanks of the lake, Almannagja and Hrafnagja faults respectively. Almannagja slips at 3mm/yr and and is the most impressive scarp. Hrafnagja has a minor thrown down to the west. Graben development allows water to pool from springs in the area. The lake is unique in that it is not fed by riparian systems but by rainfall and springs which limits sediment deposition within the lake. This allows sonar and seismic studies to be more readily utilized for more accurate and clearer pictures of lake bottom geolmorphology. The graben and extensional features of ground surface SISZ faulting continues on the lake bottom and events have been dated using lava flows primarily sourcing from Hengill that have also taken advantage of the low topography of the lake basin. These lava flows cause reflectors in seismic surveys that are used as markers for fault recognize on seismographs. No significant faulting has been recognized on the lake bottom since the Nesjahraun lava. Within the lake the maximum throw is 55m with displacements as small as 30cm, but the total displacement is ~110m. Within the SISZ this fault system takes up 17-43% of the extension and expanded the area by 30-75m. Most the recent extension, the last 25m of displacement, occurred during the Hengill event 1.9kyr which significantly displaced the northern portion of the lake. The total displacement is relatively the same throughout the area but with motion on the flanks of the lake to the north and within the lake to the south. Total extension is ~8mm/yr which shows movement must be being taken up elsewhere either along the SISZ or ERZ/WRZ or the time frame used is not representative of the SISZ over greater fluctuations of time.

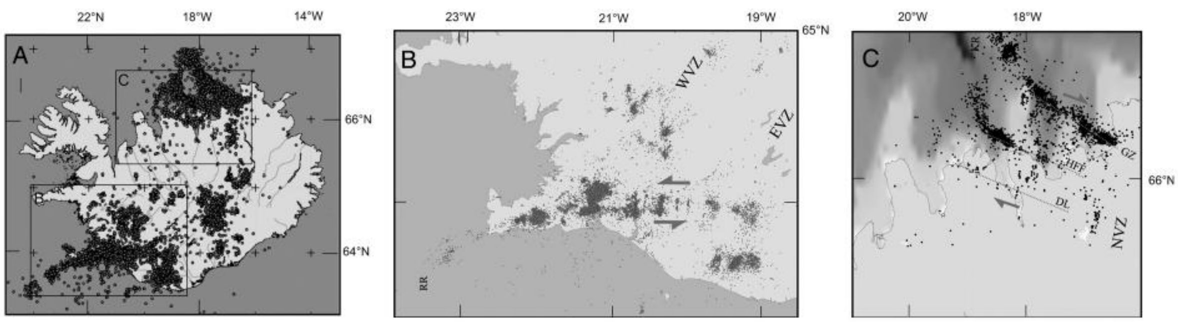

Fig. 2. Present day seismicity of Iceland (after Dauteuil and Bergerat, 2005). (A) earthquakes of magnitude equal or superior to 1 for the period 1994–2002 for the whole Iceland, (B) earthquakes of magnitude equal or superior to 0.5 for the year 1995, in the South Iceland Seismic Zone, (C) earthquakes of magnitude equal or superior to 1 for the period 1993–2002 in the Tjörnes Fracture Zone. Couple of arrows indicate sense of transform motion. KR: Kolbeinsey Ridge, RR: Reykjanes Ridge, GZ: Grimsey Seismic Zone, HFF: Húsavík–Flatey Fault, DL: Dalvik Lineament, NVZ: North Volcanic Zone, WVZ: West Volcanic Zone, EVZ: East Volcanic Zone.

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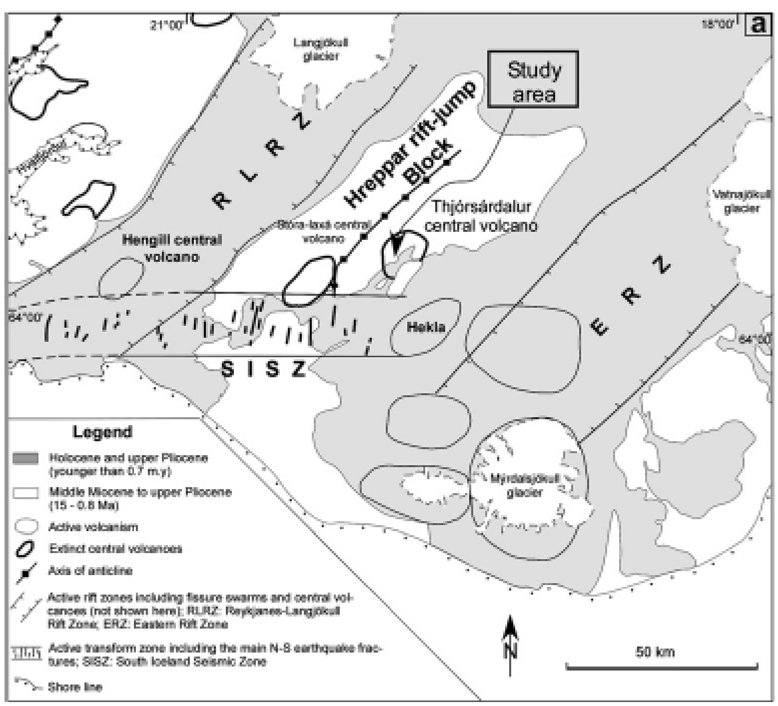

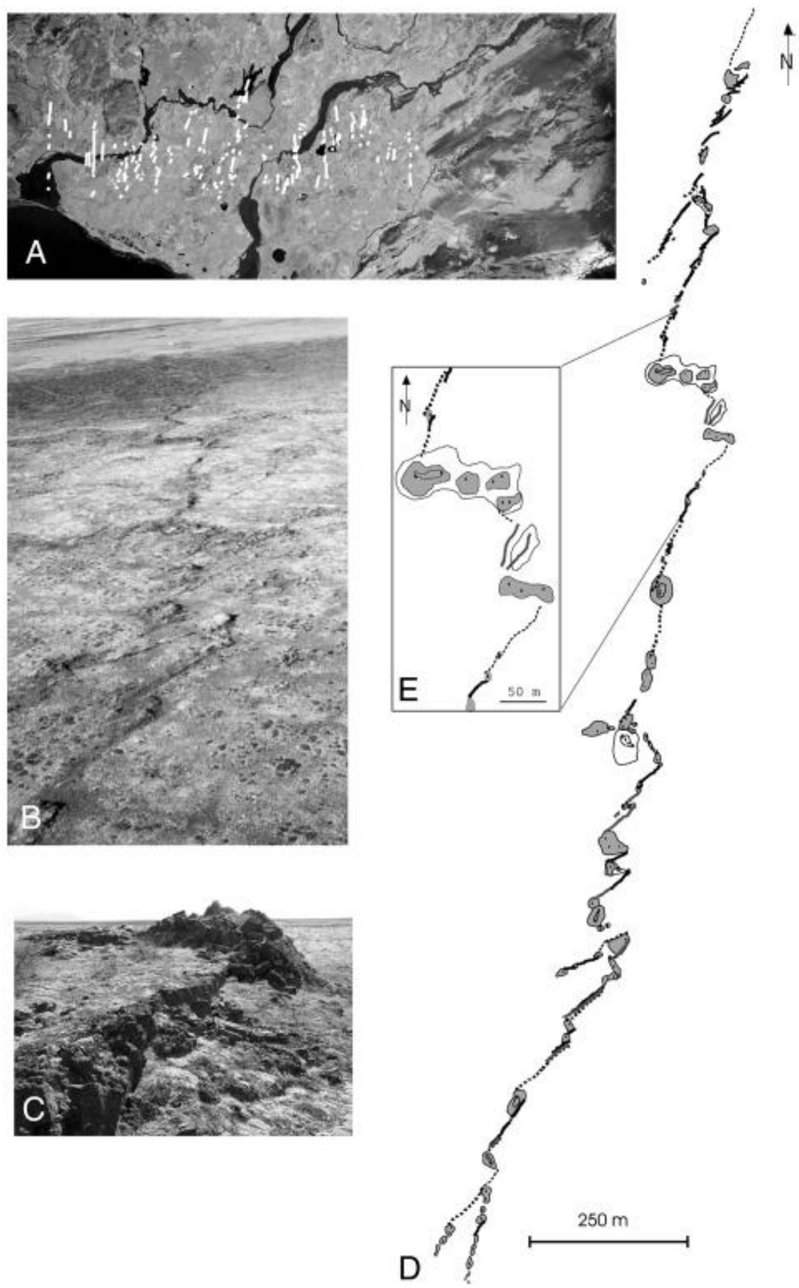

Fig. 3. Examples of post-glacial to present-day fault patterns in the SISZ, at regional and local scales. (A) fault map after Einarsson et al. (2005) showing the arrangement of N–S right-lateral faults in the E–W trending left-lateral SISZ. (B) oblique aerial photograph (courtesy from Agust Gudmundsson) of the Leirubakki Fault, a typical N–S trending right-lateral fault. (C) outcrop photograph showing a typical push-up structure and individual fracture. (D) GPS-based map of the Leirubakki fault from Bergerat et al. (2003) showing the segmentation and en-échelon pattern with push-up structures. (E) Detail of the Leirubakki map showing the junction of two fault segments.

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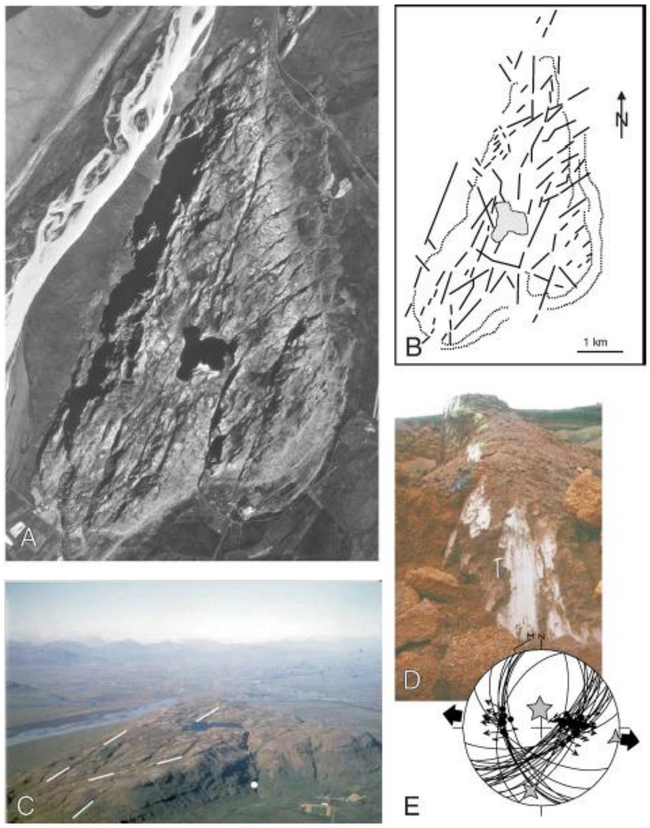

Fig. 4. Examples of Holocene fault patterns in the SISZ. (A) aerial photograph of the Vordufell area. (B) corresponding fault map showing the conjugate pattern of strike–slip faults in the Pleistocene lava pile (after Bergerat and Angelier, 2000). Dotted lines indicate cliffs (boundaries between volcanic formations). Straight continuous lines indicate main faults and dykes (C) oblique aerial photograph (courtesy from Agust Gudmundsson) of the Vördufell area. White lines on the picture underline some major faults; white dot indicates the site of Fig. 5. (D) outcrop photograph showing normal oblique-slip fault surfaces in scoriae of post-glacial volcano near Seydishólar. (E) Corresponding paleostress determination (after Bergerat et al., 1999). The method of inversion used is INVDIR (Angelier 1990). Stereoplots are Schmidt's projection, lower hemisphere (N is geographic north, and M is magnetic north). Fault planes are shown as thin lines, slikenside lineations (striae) are small dots with single or double thin arrows (mostly normal or strike slip, respectively). Three-, four-, and five-branched stars are computed axes σ_3, σ_2 and σ_1, respectively. Large solid arrows are directions of horizontal extension and compression.

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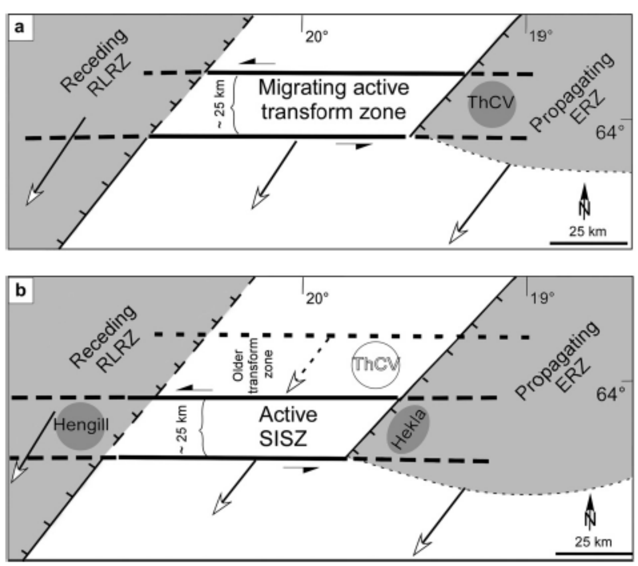

Fig. 13. (a) Schematic sketch showing the initial position of the Thjórsárdalur central volcano (ThCV) at the plate boundary. (b) Position of the volcano after it shifted away from the rift zone, and after the transform zone migrated southward by a distance equivalent to the current width of the SISZ. The dashed white arrows indicate the direction of propagation of the ERZ, the recession of the RLRZ, and the migration of the active transform zone.

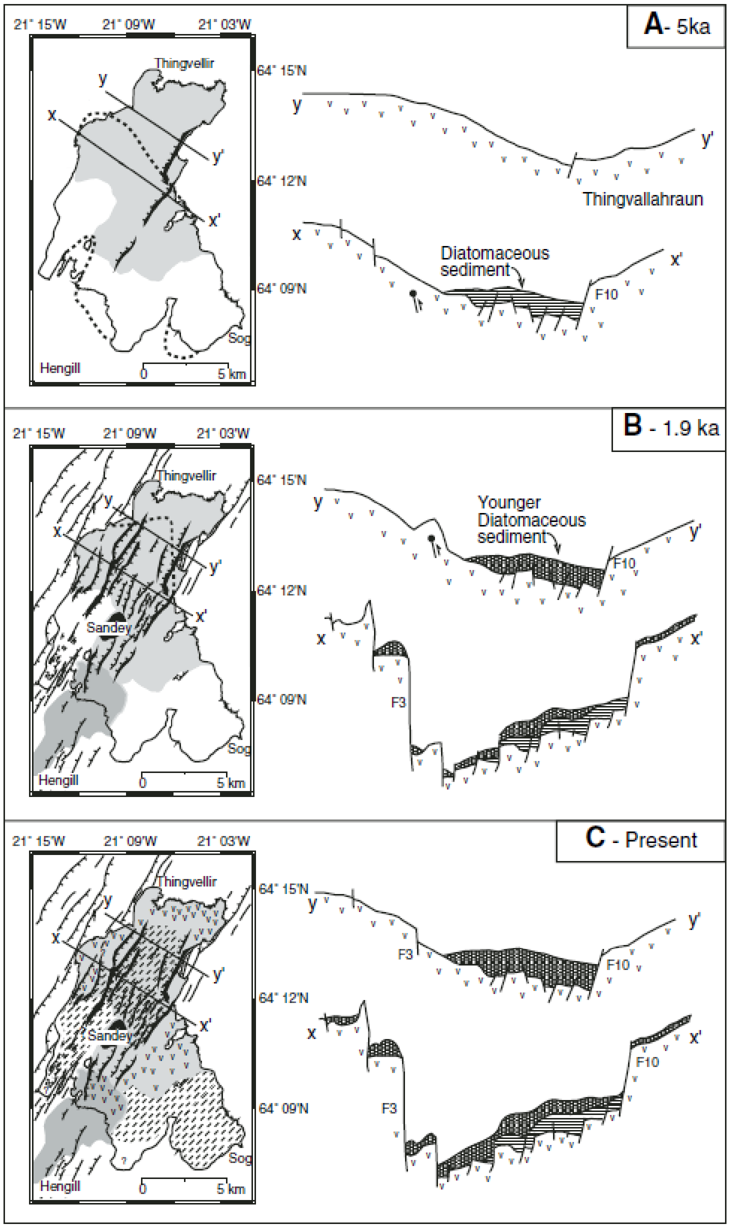

Figure 15. Interpreted evolution of the lake from 5 ka to present; ornamentation and annotation as in Figure 2. In the maps, the dark, dashed line shows where the position of the lake boundary differed from the present day (Saemundsson, 1992). In the cross sections, the v pattern is the top of the Thingvallahraun lava flow, while the layered hatching represents the infill of diatomaceous sediment. (A) Thingvallavatn at 5 ka. The map shows the lake 4 k.y. after the emplacement of the Thingvallahraun lava flow. The cross sections show that a modest graben existed, with the major faults occurring in the eastern part of the lake. (B) Thingvallavatn at 1.9 ka. This map shows the lake soon after the Hengill-Sandey event at 1.9 ka, when the Nesjahraun lava was emplaced, the Sandey scoria cone was formed, and major subsidence occurred in the northern part of the lake. The major western boundary faults formed at this time (cross section X–X′) and the lakebed subsided ~25 m. Note that the thickest sediment is now away from the deepest water depth. The tip of fault F3 is associated with a fault-tip fold on the more northerly section Y–Y′. (C) Thingvallavatn at present day. Sedimentation has continued covering the lakebed morphology that was formed at 1.9 ka.

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Hengill Triple Junction

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The Hengill triple junction is a ridge-ridge-transform triple junction. The ridges were Reykjanes Ridge and the Western Rift Zone. The transform branch us the EW trending SISZ. Seismicity occurs in infrequent intense crustal movement and continuous daily small magnitude quakes. The triple junction has high temperature (>2000C) and low temperature (<150C) geothermal resources. The largest feature in the Hengill area is the Hengill central volcano, towering 803m high. The volcano is cut by normal faults and fissures striking N25E.

Prior to 0.7My, there was a different active central volcano, Grensdalur, and a fissure swarm. When the ridge migrated to the west about 5km, the new volcano, Hengill, formed and Grensdalur became extinct. A geothermal area is beneath both volcanoes, but deeper under Hengill than Grensdalur.

Lateral extension of 0.3 cm/yr was evident in the fissure swarm lavas. Over the past 8000yrs, the subsidence rate in the Hengill area was 5-8mm/yr. Precision leveling over 5yrs showed a subsidence rate of 2.5mm/yr. In 1789, rifting caused 60cm of subsidence during an earthquake swarm.

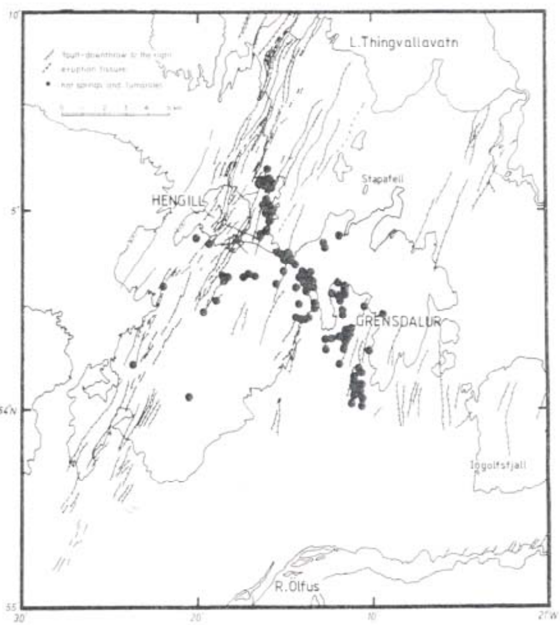

Fig. 2. Tectonic map of the Hengill area showing the 300- and 600-m contours, surface faulting, fissuring, hot springs, and fumaroles [from Saemundsson, 1967].

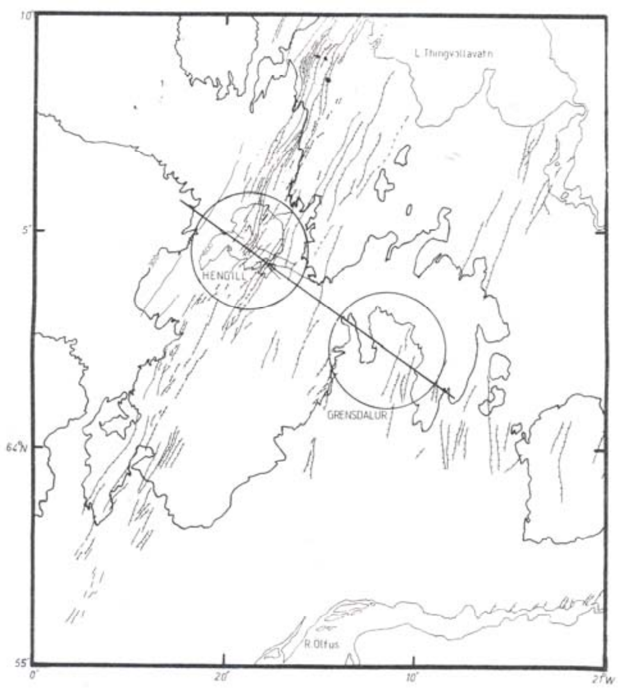

Fig. 4. Tectonic map of the Hengill area showing the proposed locations of the double volcanic system and the transverse structure.

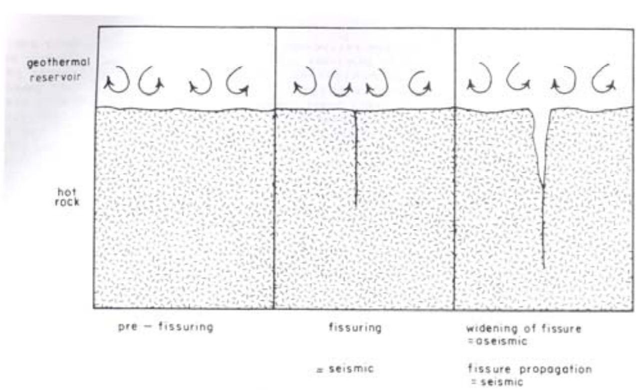

Fig. 10. Schematic illustration of the process of seismic fracture formation, aseismic widening, and seismic fracture propagation in a fluid cooled, hot rock environment.

TABLE 1. Comparison of the Hengill and Grensdalur Geothermal Systems

Hengill system	Grensdalur System
1. Hot, partially molten source	1. Hot, solidified source
2. Magma injections into system during periods of volcanic activity	2. No periodic magma injections; volcano extinct
3. Heat exchange maintained mainly from below by magmatic activity	3. Heat exchange maintained mainly from above by groundwater activity
4. Periodic tectonic rifting episodes forming fissures	4. No periodic rifting episodes
5. Reservoir relatively hot	5. Reservoir relatively cool
6. Well-sealed reservoir	6. Poorly sealed reservoir
7. Thick pile of rock over reservoir	7. Reservoir deeply eroded
8. Small surface heat loss relative to heat content of source	8. Large surface heat loss relative to heat content of source
9. Geothermal swarms and microearthquake activity continuous at a low rate	9. Geothermal swarms and microearthquake activity continuous at a high rate

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ICELAND'S WATERFALLS

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NORTHERN WATERFALLS

Dettifoss

Sellfoss

Aldeyjarfoss

Godafoss

Dettifoss is the most powerful waterfall in Iceland and is located in Vatnajokull National Park. It is located in a river (Jokulsa a Fjollum) running from Vatnajokull glacier at a rate of 193 m3/s, making it Europe's largest waterfall by volume discharge. It is 100m across and drops 45m. A human is in the picture for scale. Sellfoss is upstream of Dettifoss and is 11m high. Godafoss means waterfall of the gods and is located in North-Central Iceland. Aldeyjarfoss is located in northern highlands and drops 20m over basalt columns of the Frambruni or Suðurárhraun, hraun lava field.

SOUTHERN WATERFALLS

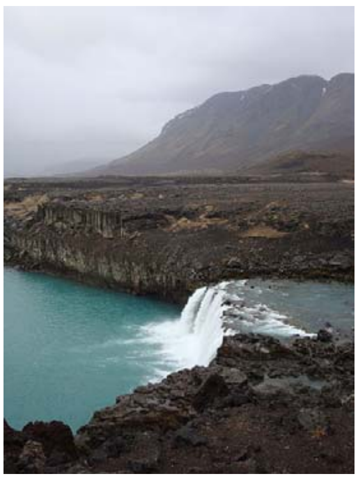
Gullfoss

Haifoss

Gullfoss means "Golden Falls". It has two drops, the first one being 11m and the second 21m. After the first drop the river makes a sharp right turn. Haifoss means "High Falls" is located near Hekla. It is the second highest waterfall in Iceland at 122m.

Skógafoss **Svartifoss**

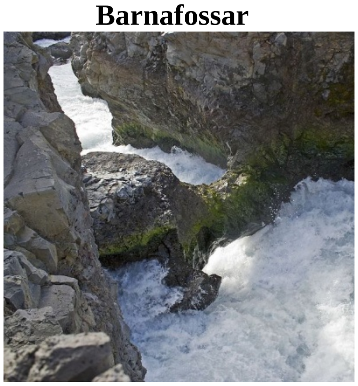
Þjófafoss **Öxaráfoss** **Ófærufoss**



Skogafoss means "Forest Falls" and is located along the south coastline. It is 25m wide and drops 60m. There is usually a rainbow visible when the sun is out, due to the intense amount of spray coming from the falls. Svartifoss means "Black Falls"and is located in Skaftafell National Park. It is surrounded by columnar basalts. Þjófafoss flows over the Merkurhraun lava fields. Öxaráfoss is in Þingvellir National Park, Iceland**.** Ófærufoss is located in the Eldgja chasm.

WESTERN WATERFALLS

Barnafossar **Glymur** **Hraunfossar**



Barnafossar, "The Children's Falls", is about 100km from Reykjavik. It is said that a mother but a curse on a natural bridge that her disobedient children went across, fell, and drowned. Anyone who were to cross the bridge would drown themselves and a few years later an earthquake occurred knocking down the bridge. Glymur is the highest waterfall in Iceland at 198m high. Hraunfossar is a 900m long stretch of waterfall flowing over the Hallmundarhraun lava field.

EARTHQUAKES AND RUPTURE PATTERNS OF SOUTHERN ICELAND

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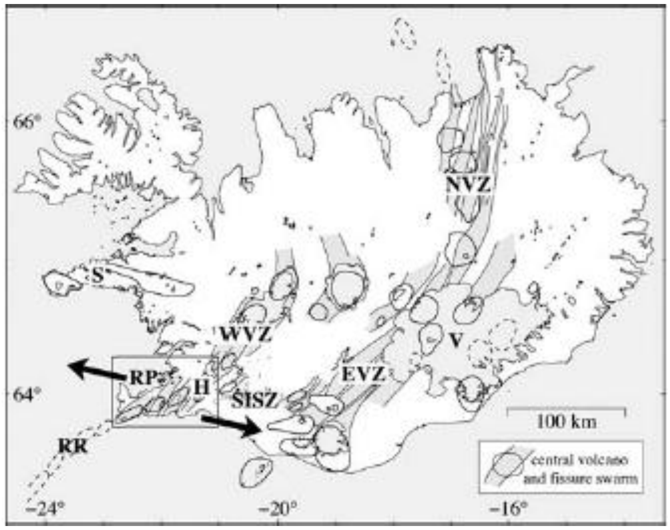
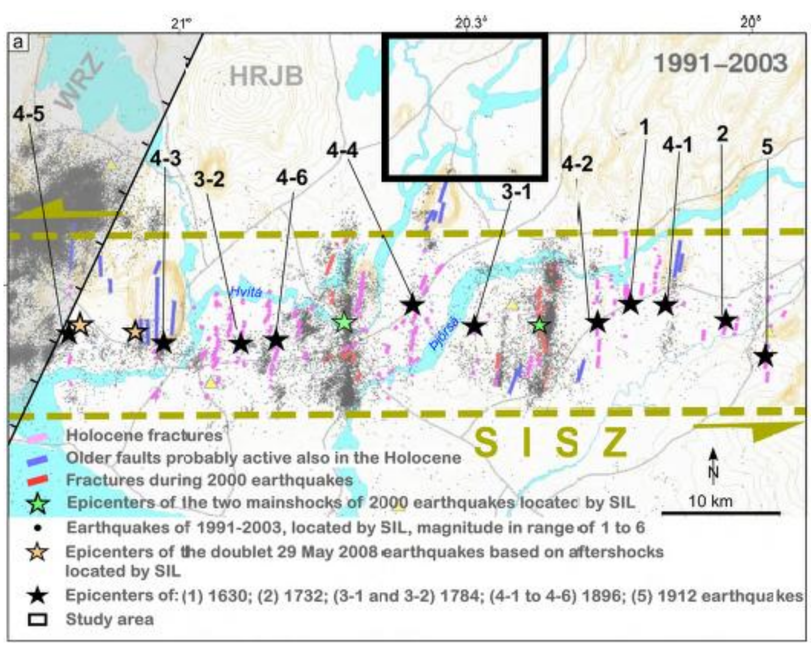


Seismicity in Iceland and is focused mainly in the south along the SISZ and the Reykjanes Peninsula. Both of these geographical areas have strong reoccurring earthquakes of magnitude 6 or larger events that occur within decades of each other. Single events within these zones can trigger secondary large events that propagate westward. 13 events of magnitude 6 or greater have occurred along this southern zone of seismicity since 1706. Seismicity tends to be stronger in the east and progressively weaken in the west. One such set of earthquakes occurred on June 17 and 21, 2000. Both events registered a M_s=6.6 with numerous aftershocks. The initial event occurred to the east of the secondary event but both earthquakes occurred on north-south striking faults in segments. Seismicity in Iceland is relatively shallow at depths of 1-8km with aftershocks fields commonly occurring below this depth. The base of the seismicity zone is between 8-11km. Both the depth of seismicity and base fluctuates along the zone from the RP moving east in the SISZ but relatively stays within this range.

Aftershock sequences can occur quite fast after a large event, sometimes within seconds of the main shock generally propagating westward. During the June event several strong M_s~5 occurred within this time frame. A strong component of aseismic activity was found to have occurred by fault movement and ground rupture in the RP. Though no instruments registered the events, which hints at aseismic activity, it is possible that the instrumentation was thoroughly flooded by the initial shock and hence unable to decipher the secondary events so close in timing to the initial rupture. Within the RP lake Kleifarvatn was affected by aseismic activity and subsequently suffered a 4m drop in water level triggered by an aseismic M_s=5.6 event. In a similar fashion, the southern Pula segment of the June 17th earthquake event the Pulutjorn pond began water level dropping soon after the earthquake and the 200m wide and 2m deep pond was fully dry as of 2003.



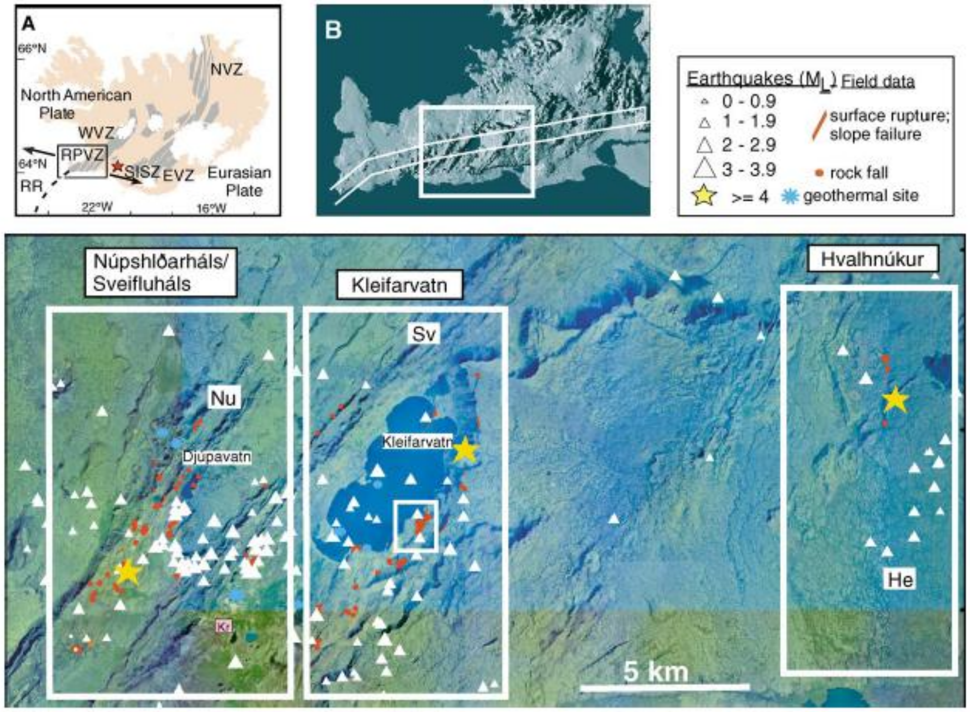


Fig. 1. The study area. White triangles: earthquakes that occurred in the 12-h period following the SISZ event; yellow stars: large triggered earthquakes. Red: location of mapped surface effects. Pink square: location of the Krísuvík SIL station. Blue stars: location of geothermal springs. Nu = Núpshliðarháls ridge. Sv = Sveifluháls ridge. He = Heiðin Há lava shield. Study areas enclosed in white boxes 1–3. Small white box in 2 shows area in Fig. 3. Color differences in the air photo are due to image processing and not an artefact of printing. Inset A: the plate boundary in Iceland (Einarsson and Saemundsson, 1992). RPVZ = Reykjanes Peninsula Volcanic Zone, SISZ = South Iceland Seismic Zone, WVZ = Western Volcanic Zone, EVZ = Eastern Volcanic Zone, NVZ = Northern Volcanic Zone. Arrows: direction of plate motion (DeMets et al., 1994). Red star: approximate location of the SISZ earthquake. Inset B: Reykjanes Peninsula, white box shows study area. White lines show the approximate location of the plate boundary zone.

References:

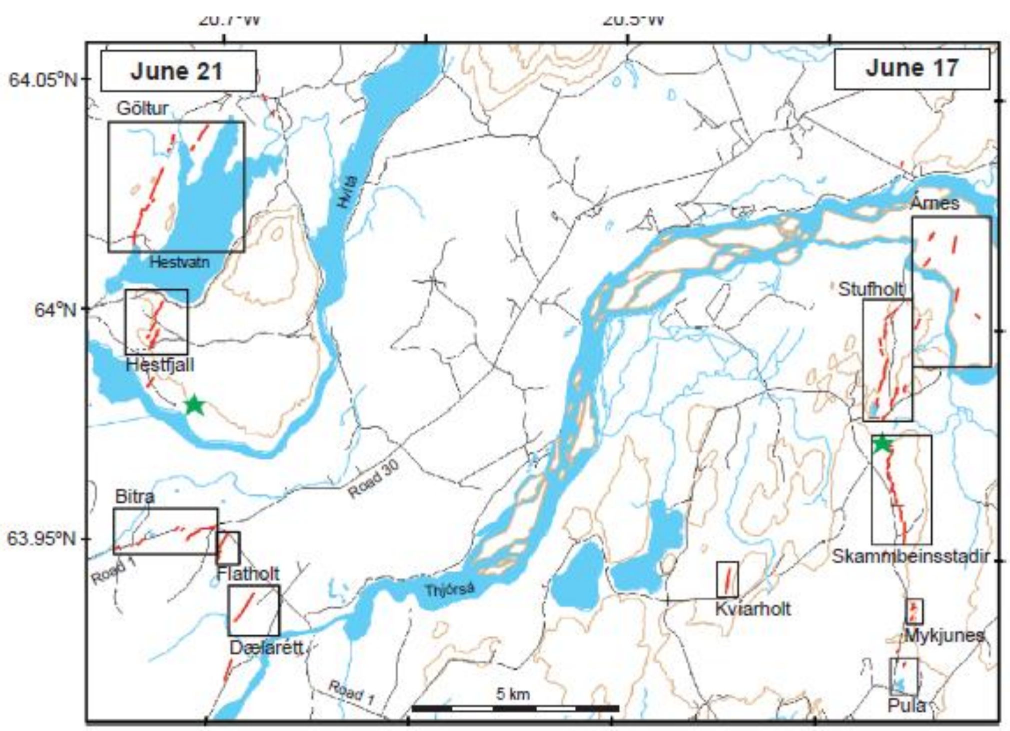


Fig. 2. Map of June 17 and June 21 earthquake areas. Mapped surface rupture shown in red. Green stars denote epicenter locations. Boxes outline rupture segments discussed in the text and shown in Figs. 3–12.

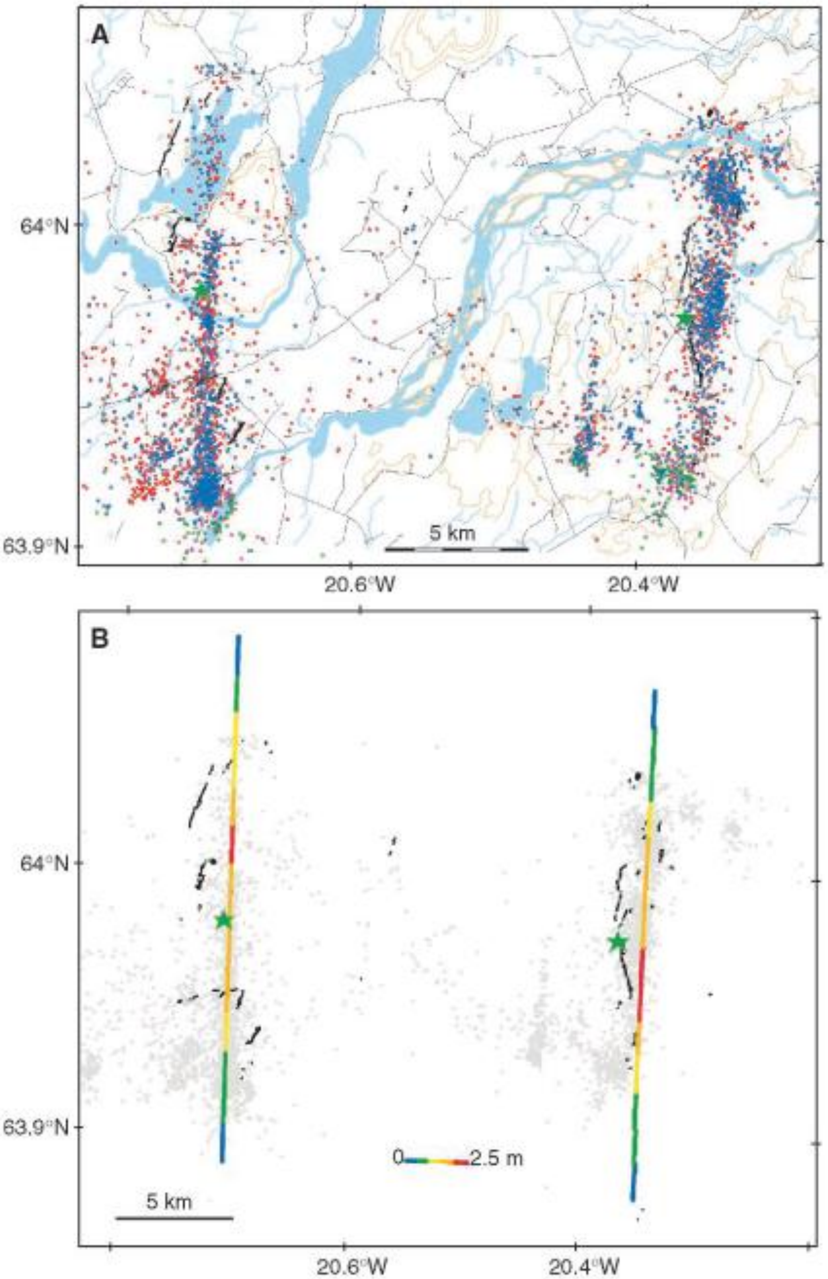


Fig. 13. (A) Aftershock hypocenters automatically located by the South Iceland Lowland network during the period June 17 to November 22 superimposed on map of surface rupture (shown in black). Aftershocks in red from June 17 to July 1. Aftershocks in blue from July 1 to November 22. (B) Surface projection of distributed fault slip model from combined inversion of GPS and InSAR data (Pedersen et al., 2003), normalized by slip area in a vertical column beneath the surface trace. Color scale shows slip distribution in 0.5 m increments. Aftershock hypocenters shown in grey. Surface rupture mapped during this study shown in black.

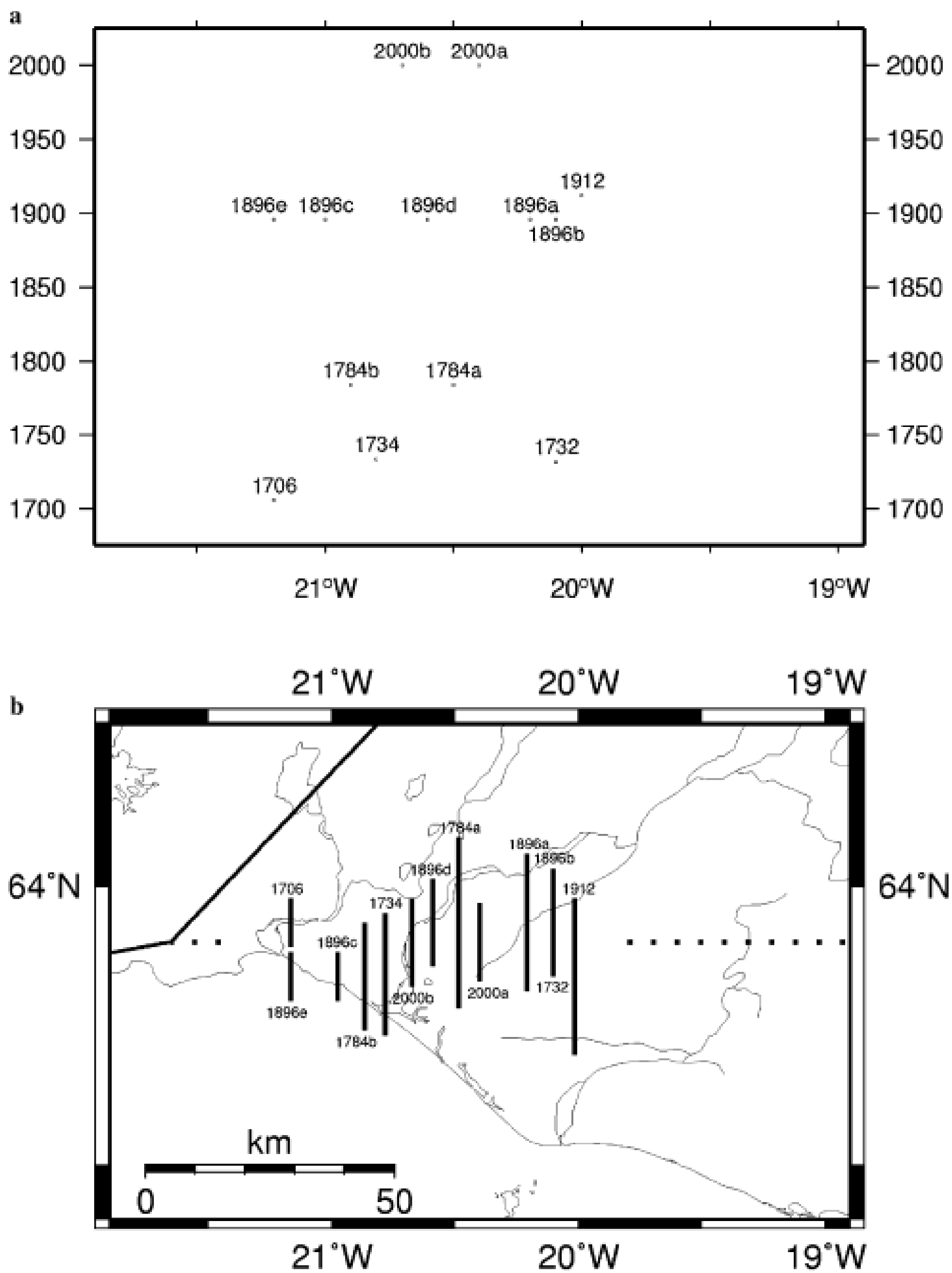


Figure 2
(a) Location of the earthquakes in space and time, cf. Table 1. As the events have been located on N-S trending faults in an E-W trending fault zone, their location is very accurately displayed in this graph. Events occurring in one year are numerated by letters a, ..., e. (b) The position of the rupture planes of the earthquake sequence as used in the models, cf. Table 1 and Figure 3.

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HEKLA, "THE GATEWAY TO HELL"

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Quick Stats*

Subregion: Southern Iceland
Type: Stratovolcano
System/Sub-type: Fissure vents and crater rows
Elevation: 1491 m (4,892 feet)
Latitude: 63.98°N
Longitude: 19.70°W

Background

Hekla is otherwise known as the "Gateway to Hell" in Icelandic folklore (Fig. 1 and 2). During the Middle Ages, many Europeans mistook tremors that were often heard emanating from Hekla before and after an eruption for the screams of doomed souls, and thought that it was either the actual gateway to hell or hell itself. However, the actual meaning of the name "Hekla" is "short hooded cloak," which is a reference to the cloud cover that usually surrounds the summit.

Figure 1. Hekla's Gateway to Hell. Photo copyright by Michel Detay, taken on 8/17/80.

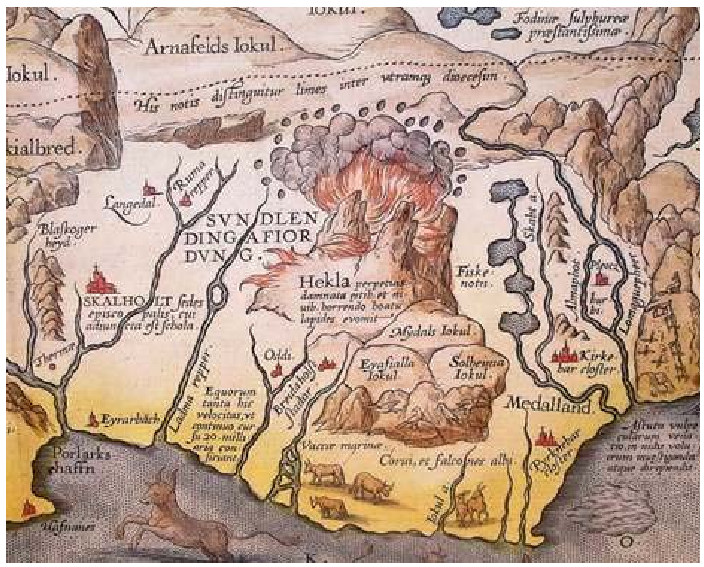

Figure 2. Hekla depicted as hell on an ancient map.

Hekla is one of Iceland's most famous and active volcanoes, with frequent eruptions occurring usually every 10 – 30 years; most recently in 1991 and 2000 (Gudmundsson, et al., 1992; Hoskuldsson, et al. 2007; Lopes, 2005). There have been a total of at least 17 documented eruptions in the past 1100 years (Gudmundsson, et al., 1992).

Volcanotectonic Background

It is situated in the SW Eastern Volcanic Zone (EVZ) (Hoskuldsson, et al. 2007), occupying a rift-transform junction. This rift-transform junction is where the EVZ (the rift) meets the South Iceland Seismic Zone (the transform zone) (Fig. 3). Hekla is the large central volcano of a volcanic system that is 40 km (25 miles) in length and 7 km (4.5 miles) in width (Gudmundsson, et al., 1992; Lopes, 2005). Hekla is somewhat unique due to the fact that stratovolcanoes are usually found in subduction zones, not at spreading ridges; however, in Iceland, most central volcanoes are either stratovolcanoes or collapse calderas.

Eruption Style

Hekla's eruptions are highly explosive, primarily Strombolian and Plinian in nature (Lopes, 2005). Hekla has high eruption plumes during the first stages of eruption, which are known to have reached altitudes of 12-36 km. These explosive phases produce massive quantities of tephra. Following the explosive phase, eruptions typically become more effusive (producing lava). The duration and intensity of the explosive phase has been linked to the frequency of eruptions, with more highly explosive eruptions occurring following longer periods of repose (Hoskuldsson, et al. 2007). The change in eruption style creates alternating layers of tephra and lava.

Lava flows are usually erupted from fissure vents such as Heklugjá, a 5.5 km long vent which cuts across Hekla and which has been usually very active along its entire length during recent major effusive episodes.

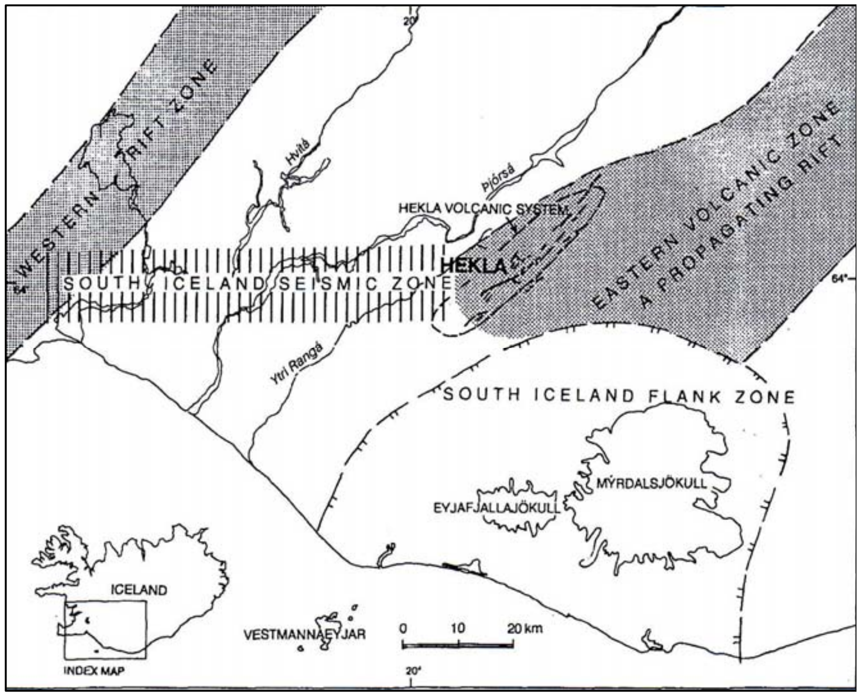

Figure 3. Hekla is situated at a rift-transform junction where the EVZ (the rift) meets the South Iceland Seismic Zone (the transform zone). From Gudmundsson, et al. 1992.

Petrology/Mineralogy

According to the Smithsonian Institute, the main types of lava erupted from Hekla are basaltic andesites, in contrast to tholeiitic basalts which are characteristic of most Icelandic volcanoes. Similarly, Hoskuldsson, et al. reports the two end-members of Hekla magmas as basaltic ferro-andesite and rhyodacite. Typically, eruptions following long periods of quiescence tend to be more silicic (rhyodacite), whereas, more recent or frequent eruptions (<30 years between eruptions) generate the more basaltic magmas (andesite to basaltic andesite). It is thought that the two end-members are produced by a “parent” basaltic magma at the base of the crust under Hekla feeding fissure eruptions. Following long periods of repose the basaltic magma functions as a heat source which melts silicic crust, producing more silicic magmas, by way of magma mixing of the two end-members and fractional crystallization (Hoskuldsson, et al. 2007; Lopes, 2005).

Hekla tephras, which are produced during the explosive phase, have a unique tendency to be rich in fluorine, which is extremely hazardous and even deadly for livestock. The fluorine contaminates groundwater and grassland, which in turn poisons grazing animals. In the 1970 eruption, over 7,500 sheep were killed due to fluorine contamination.

Hekla Center

The Hekla Center at Leirubakki is a small, but informative museum which exhibits contemporary, multimedia exhibition on Mount Hekla, such as eruption footage, a seismometer that keeps track of current grumblings, a screen saver-like software program artistically renders the seismometer its history, and its influence on human life in Iceland from the time of the island’s settlement until now.

Hekla Center strongly supports cooperation with scientists, organizing and sponsoring conferences and exhibitions where the latest scientific research and findings can be presented. In addition, the Center has special educational materials and it is also a working tourist information center, providing tourists advice about all of the surrounding area, including Mount Hekla.

To reach the exhibit, drive to the Leirubakki farm and service center via Route 26. You will find opposite an N1 gas station (Fig. 4). The Center is open every day from 10 am- 10 pm.

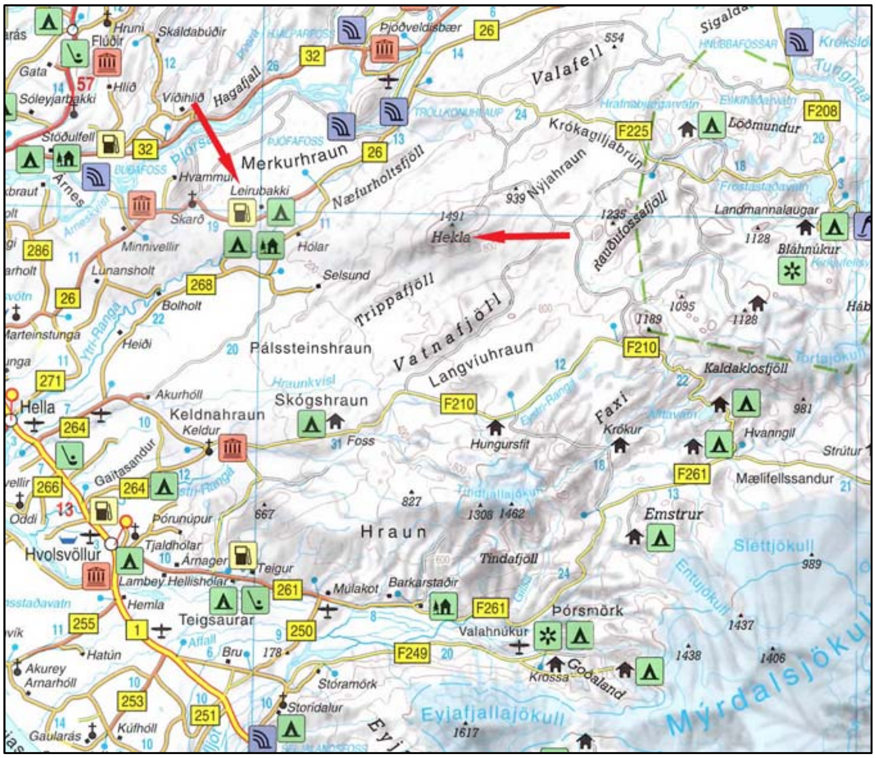

Figure 4. Road map of Hekla area. Bright red arrows point to Leirubakki and Hekla Volcano. From Freytag-Berndt Iceland Road Map, 2006.

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KATLA (MYRDALSJÖKULL)

Margaret Banda Compton, *Department of Geological Sciences, California State University, Northridge*

Quick Stats*

Subregion: Southern Iceland
Type: Subglacial Volcano
Elevation: 1512 m (4,961 feet)
Latitude: 63.63°N
Longitude: 19.05°W

Background

Katla volcano is located just 25 km east of Eyjafjallajökull (Fig. 1). It is a subglacial volcano that is covered by the 230 m thick Mýrdalsjökull ice cap (Fig. 2). Katla produces basaltic to rhyolitic magmas and tephra, and the resulting phreatomagmatic interactions during eruptions are highly explosive, with widespread tephra layers and severe jökulhlaups.

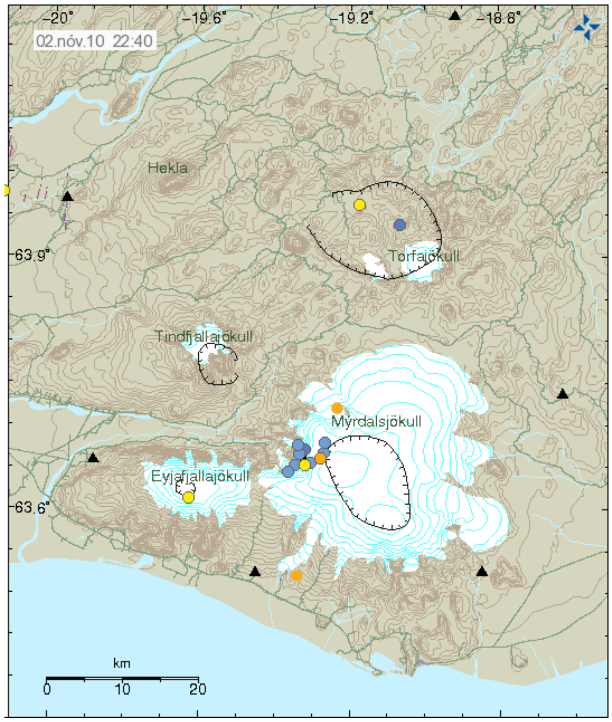

Figure 1. Topographic index map of Mýrdalsjökull ice cap and surrounding environs. Hatched spherical shape on Mýrdalsjökull represents outline of summit crater.

Katla is one of Iceland's most active volcanoes and studies have indicated that its volcanic system has produced the largest volume of erupted magma during historical time. Eruptions occur at Katla approximately every 40 - 80 years (Sturkell, et al. 2003). Eruptions at Eyjafjallajökull have historically been followed by eruptions at Katla within one year. Additionally, Katla has not had a significant eruption since 1918. Both of these things suggest that Katla is overdue for an eruption.

Figure 1. Katla volcano is overlain by the Mýrdalsjökull ice cap in the distance. Photo by Ignacio Izquierdo.

Volcanotectonic Background

Katla is the central volcano in an 80 km long volcanic system which features a 110 km^2 summit caldera and surrounding fissure swarm. Its Eldgjá fissure system (Fig. 3) extends N-W towards Grímsvötn volcano, for nearly 60 km, and it is a major source of eruptions. In 934 AD, Eldgjá produced approximately 18 km^2 of lava, making it one of the largest known Holocene flows.

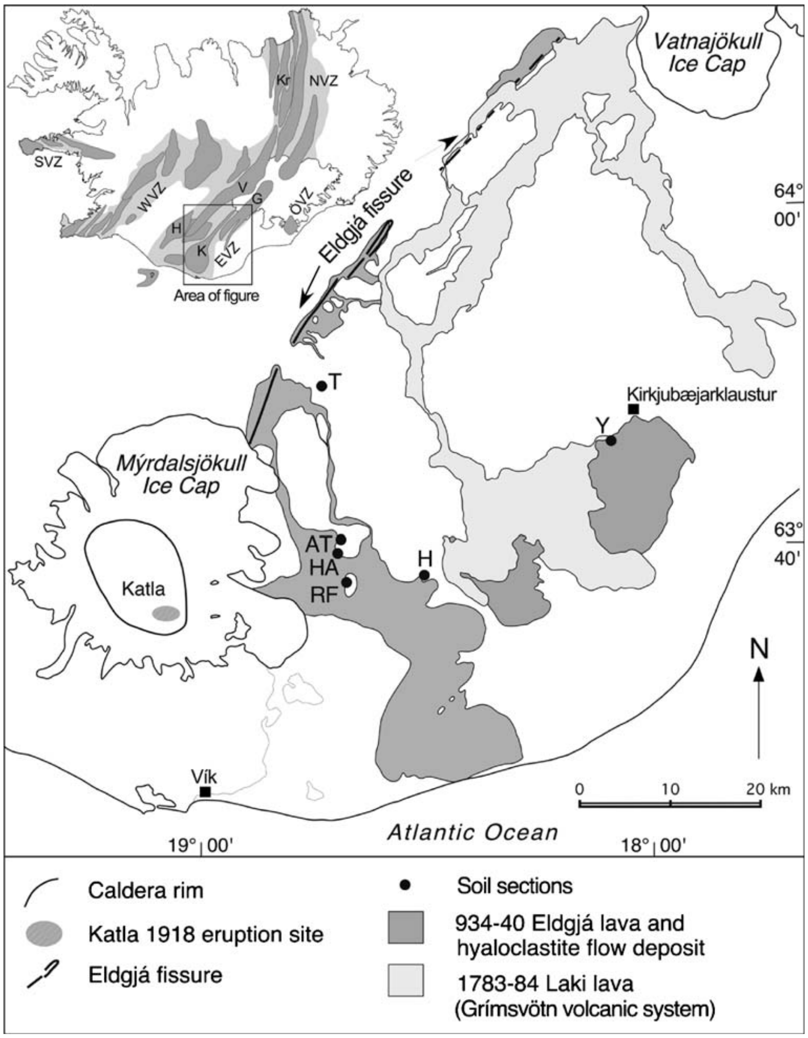

Figure 3. Map of Katla, Mýrdalsjökull ice cap, the Eldgjá Fissure System and other regional features. From Óladóttir, et al. 2007.

Katla, like Eyjafjallajökull, is located in the Neovolcanic Zone, south of the Eastern Volcanic Zone (EVZ), and South Iceland Seismic Zone (SISZ) transform system.

Petrology/Mineralogy

Katla is characterized by Fe-Ti basalts, which are usually associated with propagating rift zones. Although these basalts are principally tholeiitic, Katla also produces more alkali and transitional-alkali magmas as well. Magma evolution is thought to be primarily controlled by fractional crystallization.

Miscellaneous Notes:

Myrdalsjökull can be seen close to Skogafoss (before reaching Vik) and small detour can bring you relatively close.

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EYJAFJALLAJÖKULL (Pronounced "A-yuh-fyet-la-yo-kull")

Margaret Banda Compton, *Department of Geological Sciences, California State University, Northridge*

Volcanic Lightning during 2010 eruption. Photograph by Marco Fulle, Barcroft/Fame Pictures.

Quick Stats*

Subregion: Southern Iceland
Type: Stratovolcano
Elevation: 1,666 m (5,466 feet)
Latitude: 63.63°N
Longitude: 19.62°W

Background

Eyjafjallajökull is also known as Eyjafjöll, and it is located in South Iceland, just west of Katla (Fig. 1). Eyjafjallajökull is a relatively quiet and moderately active volcano, having had only five eruptions in the past 1,400 years. Three of those eruptions were followed by major eruptions at neighboring Katla within a year, and this has led to theories of mechanical coupling between the volcanic systems, however, there has been no strong scientific evidence presented to assert this (Pederson and Sigmundsson, 2006).

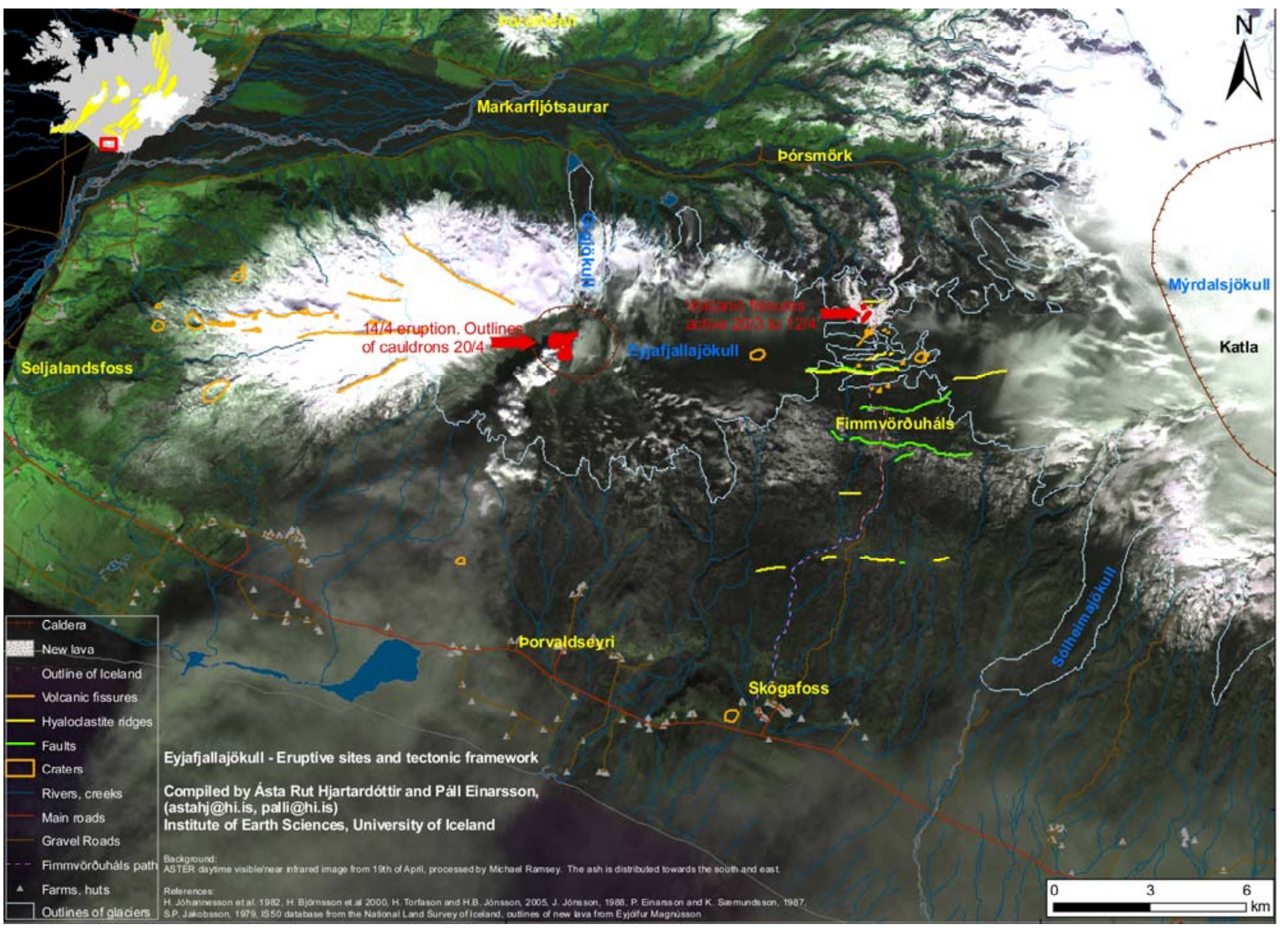

Figure 1. Regional satellite image of Eyjafjallajökull and surrounding areas, with highlighted volcanic features such as the caldera, lava flows, fissures, faults and craters from the 2010 eruption.

Volcanotectonic Background

Eyjafjallajökull is an E-W trending, ice-capped stratovolcano with a 2.5 km wide summit caldera. It is the central volcano in a volcanic system that includes eruptive fissures, a radial dike system and crater rows (Smithsonian Institute, 2011). Eyjafjallajökull is located in the Neovolcanic Zone, south of the Eastern Volcanic Zone (EVZ), and South Iceland Seismic Zone (SISZ) transform system. Fissure fed flows have been produced on both the east and west side of the volcano.

Petrology/Mineralogy

Rocks produced by Eyjafjallajökull have historically been alkalic, ranging from ankaramites to hawaiites, as well as other silicic varieties (Sturkell, et al. 2003). Similarly, the 2010 eruption, which is discussed in further detail below, produced trachyandesite.

2010 Eruption

The most recent eruption famously occurred last year, disrupting flights thoughout Europe. This eruption began as a 500 m long fissure eruption between Eyjafjallajökull and Katla, along Fimmvörðuháls Ridge, 9 km east-northeast of the summit area (Fig. 2). Prior to the eruption, there were warnings in the form of seismic tremors and surface deformation data collected by the Icelandic Meteorological Office (IMO) and the Institute of Earth Sciences (IES) at the University of Iceland. However, this data was not taken as seriously as perhaps it should have due to the fact that prior to the 2010 eruption, Eyjafjallajökull was known for sparse, episodic tremors which usually failed to produce an eruption (Pederson and Sigmundsson, 2006; Donovan and Oppenheimer, 2011; Venzke and Wunderman, 2010). Beginning in the early 1990s, there was an increase in seismic activity, with major earthquake swarms and sometimes associated crustal deformation occurring in 1994, 1996, 1999, 2000 and 2009 without a subsequent eruption (Sigmundsson, et al. 2011).

The initial eruption at Fimmvörðuháls began on March 20, 2010 and lasted until April 12, 2010. It produced basaltic lava that is believed to have been sourced from a deep magma reservoir. This effusive eruption was characterized by lava fountains and flows. From March 22 through March 21, 2010, there was an initially explosive eruption which produced trachyandesite from the summit crater (Venzke and Wunderman, 2010). Within a few days there was a decline in the explosivity, and then the summit eruption became effusive, producing lava fountains and flows similar to that produced during the Fimmvörðuháls fissure eruption (Donovan and Oppenheimer, 2011). Fissure eruptions (Fig. 3) on Fimmvörðuháls started up again in late March.

Figure 3. 2010 Eyjafjallajökull fissure eruption. Photo by Oddur Jóns.

On April 12, all volcanic activity temporarily ceased and there were minimal seismic tremors as well; however, a new explosive eruptive phase began on April 14 once again at the caldera. This new eruptive phase began as a subglacial eruption and when combined with the snowmelt, jökulhlaups began to flow into the lowlands (Venzke and Wunderman, 2010). On April 15, fissure eruptions were once again observed on the volcano. Localized volcanic activity was reported until it finally ceased in May 2010. The eruption was not officially declared over until October 2010, by Ármann Höskuldsson, an IES scientist.

In addition to major air travel disruption in Europe, this eruption was particularly damaging to Iceland's economy, specifically the tourism and agriculture industries. Heavy ash fall and dust suspension greatly affected air quality, and the ash from this eruption was high in fluoride which has proven deadly when ingested by grazing animals (Fig. 4).

Figure 4. Wild Icelandic horse during 2010 eruption. Photo taken by Kristjan Logason.

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Jökulhlaups

Martha Peggye Ahlstrom, *Department of Geological Sciences, California State University, Northridge*

A jökulhlaup (pronounced "yo-kul-h-loip") is a large, sudden and usually unwelcome increase in the rate of flow of a stream draining a basin in which there is an ice-dammed lake. The literal translation into English is a "glacier burst." Initially an Icelandic term referring to the subglacial outburst floods from Vatnajökull, Iceland, it has been adopted into the English language and it now describes any large and abrupt release of water from a subglacial or proglacial lake and/or reservoir. Jökulhlaups occur due to several geological events. However, the foremost origins of jökulhlaups in Iceland are from marginal or subglacial sources of water melted by atmospheric processes, permanent geothermal heat, or volcanic eruptions. Glacier-volcano interactions produce meltwater that either drains towards the glacier margin or accumulates in subglacial lakes. The accumulated meltwater drains intermittently in jökulhlaups from the subglacial lakes and occasionally during volcanic eruptions. Jökulhlaups have a significant potential impact on the landscape as they erode large canyons and transport (and deposit) gigantic quantities of sediment and icebergs over substantial outwash plains and sandur deltas (a glacial outwash plain formed of sediments deposited by meltwater at the terminus of a glacier).

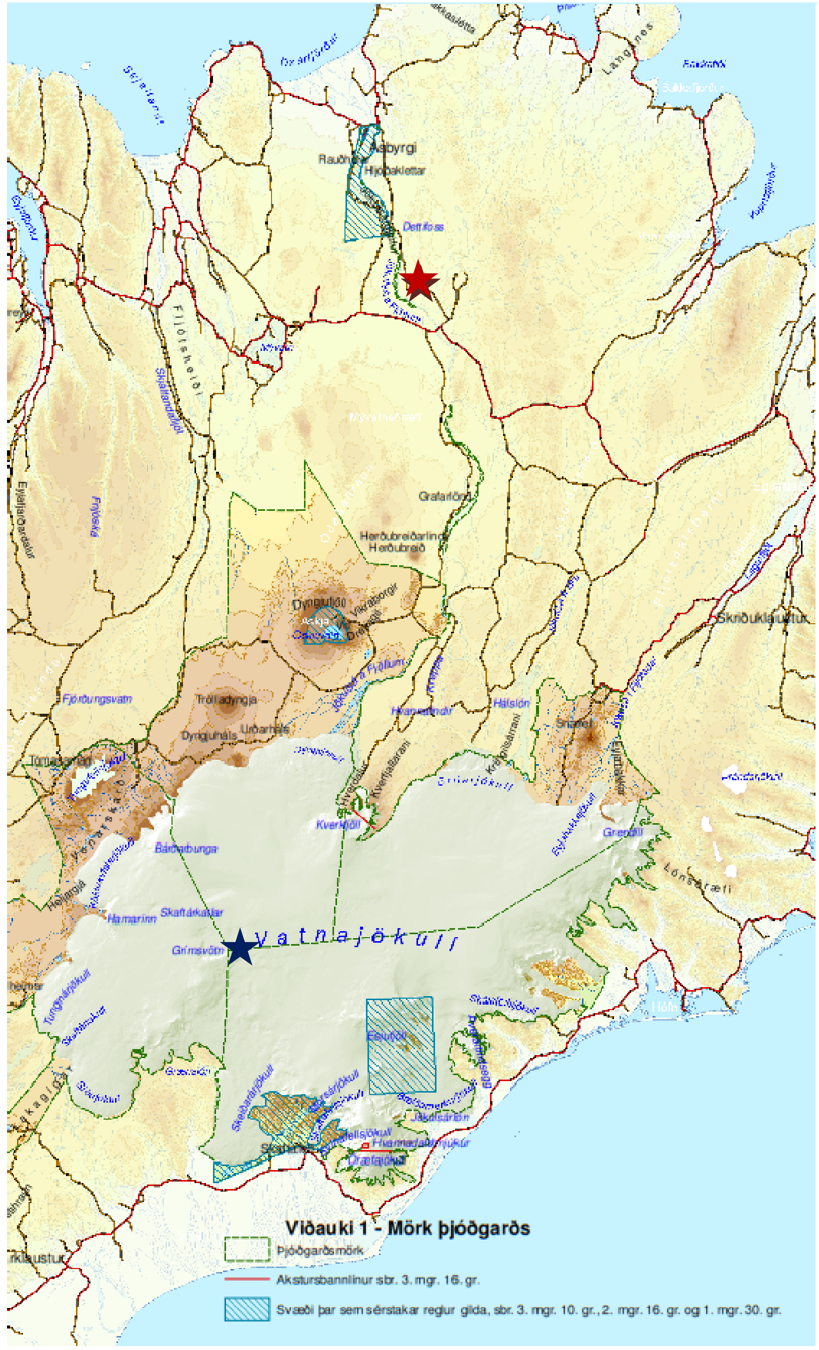

Figure 1: Overview of Vatnajökull, Iceland. Red star locates the Jökulsárgljúfur canyon; blue star locates Grímsvötn subglacial lake.

Pleistocene glacial-river canyons may have been formed in such catastrophic floods from subglacial lakes. Jökulhlaups often threaten human populations, farms, and hydroelectric power plants on glacier-fed rivers. They damage cultivated and vegetation areas, destroy roads on the outwash plains, and generate flood waves in coastal waters.

Prehistoric eruptions in the voluminous, ice-filled calderas of Bárdarbunga and Kverkfjöll in the northern areas of Vatnajökull (Figure 1) caused the largest and most catastrophic jökulhlaups in Iceland, with peak discharges of the order of >10 m/s. Floods sweeping down Jökulsá á Fjöllum carved a prominent scabland and the deep canyon, Jökulsárgljúfur (Figure 2); a significant factor in their creation was erosion by cavitation.

Figure 2: The 300 m deep Jökulsárgljúfur canyon, north of Vatnajökull, eroded and carved during prehistoric jökulhlaups (srosset.hopto.org)

In November 1996, an extraordinary jökulhlaup from Grímsvötn (the largest subglacial lake in Iceland) occurred. It was preceded and indirectly triggered by the Gjláp eruption, which took place inside the drainage basin of Grímsvötn. Meltwater accumulated for a month until it drained in the catastrophic jökulhlaup (Figure 3). The eruption broke through the ice cover at one location after erupting for 30 hours, but continued subglacially for 2 weeks on a 6 km long fissure. During the first 4 days meltwater was produced at a rate of 5000 m^3/s and the heat output at the eruption's peak was 10^{12} W (>100 times all the power stations producing electricity in Iceland at that time). The high rate of melting is due to fragmentation of the lava into glass (hyaloclastites) and rapid cooling of the fragments by quenching. The total ice volume melted during the first 6 weeks was 4.0 km^3; after one year the meltwater was 4.7 km^3. Owing to this jökulhlaup, the coastline moved seaward by over 900 m. During the lake drainage, a 6-km-long, 1-km-wide and 100-m-deep depression was created by collapse of the jökulhlaup flowpath across the ice dam. The volume of the depression was 0.3 km^3. Typical hydrogreaphs for the Grímsvötn jökulhlaups demonstrate an extremely rapid release of meltwater within the first few days of the jökulhlaup generation (Figure 4).

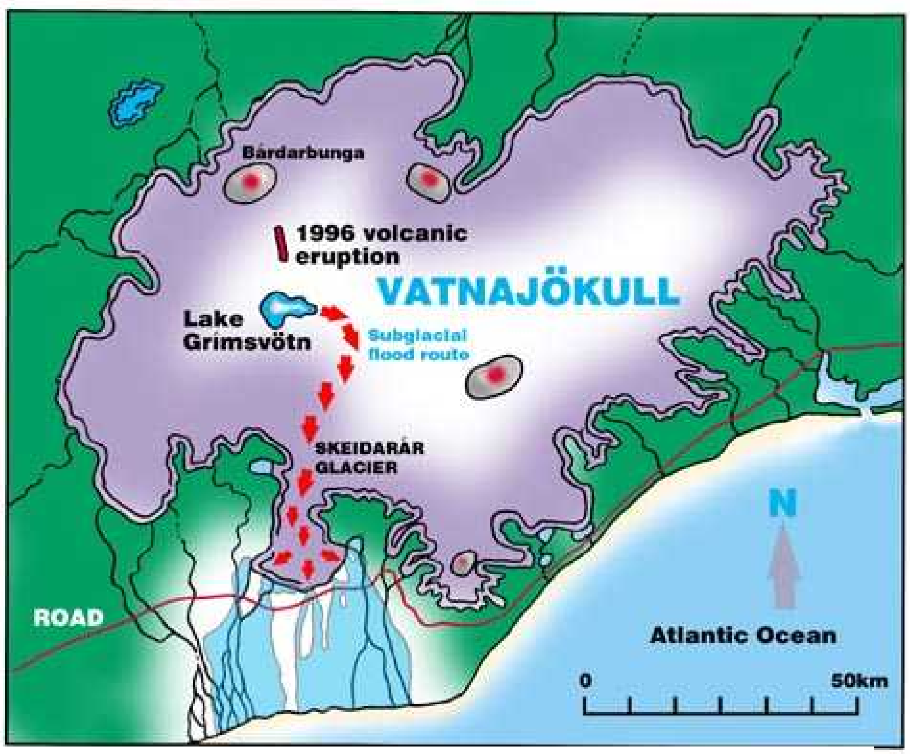

Figure 3: Schematic view of the 1996 jökulhlaup generated from Lake Grímsvötn (thewatchers.adorraeli.com)

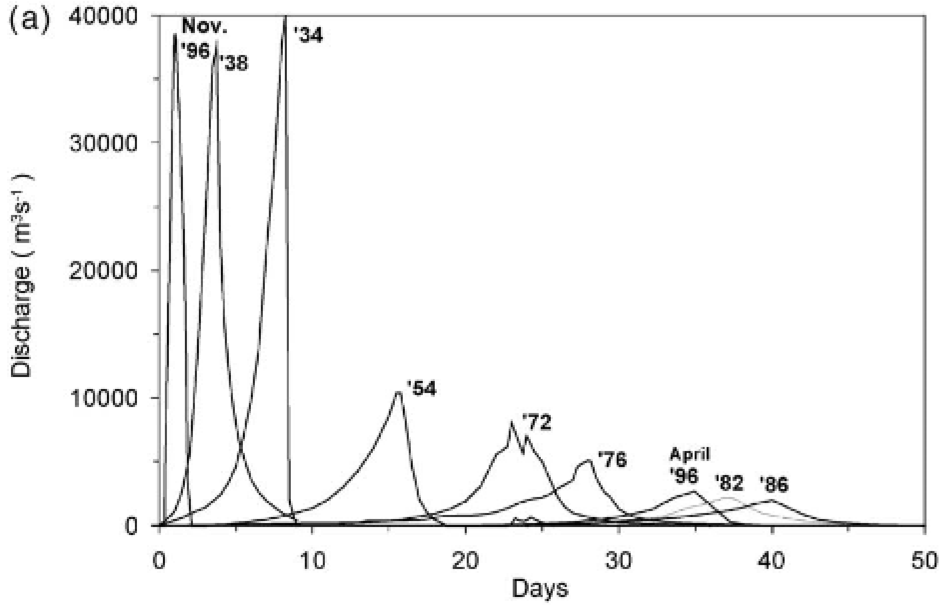

Figure 4: Typical hydrographs of jökulhlaups from Grímsvötn (1934, 1938, 1954, 1972, 1976, 1982, 1986 and 1996) (Björnsson, 2002).

More recently, the 2010 Eyjafjallajökull volcanic eruption caused two major jökulhlaups, with peak flows of approximately 2000-3000 m³/s, and a few smaller ones. Mainly, in the beginning of the eruption, the jökulhlaups were charged with volcanic debris as well as icebergs and advanced at a very high velocity (up to 20 km/h) and many were hot. Several of the jökulhlaups found their way along the bed of the glacier but others flowed over the surface of the glacier all the way to the ice margin (Figure 5).

Figure 5: Eyjafjallajökull: jökulhlaups in Markarfljót April 14, 2010 (en.vedur.is/hydrology/articles/nr/2097)

Debris flows and deposits from the major jökulhlaups left behind enormous sediments and large boulders (Figures 6 and 7).

Figure 6: A large boulder deposited by the 2010 jökulhlaup generated by the Eyjafjallajökull volcanic eruption (Russell, 2010).

Figure 7: Debris flow and sediments deposits from a 2010 jökulhlaup generated by the Eyjafjallajökull volcanic eruption (Russell, 2010).

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Landmannalaugar: the Torfajökull-Veidivötn Area

Jenna Fleck *(California State University, Northridg- Department of Geological Sciences)*

Landmannalaugar literally means “The people’s pools”. It consists of the Torfajökull central volcano and the Veidivötn fissure swarm. Torfajökull has the largest volume of silicic extrusives (~225km3), with a rhyolite to basalt ratio of 4:1, in contrast to the 1:5 seen at the other central volcanoes around the island. It is also home to Iceland’s most productive geothermal area.

Torfajökull has a 12x18km diameter caldera rising 600m, located in the northern edge of the Southern Flank Zone, southwest of the Veidivötn fissure swarm, which occupies an area of 85x10km2. The fissure swarm forms the southern part of the Eastern Rift Zone and has a recurrence interval of 600-800 years. Veidivötn fissure swarm intersects Torfajökull caldera.

Eruptions of basalt and rhyolite occurred in 871 and 1477A.D. Torfajökull erupted rhyolite and Veidivötn erupted tholeiitic basalts at the same time, leading to the conclusion that the magma plumbing system of the two are tectonically and hydraulically linked. A petrogenic model proposes that tholeiitic magmas (Veidivötn basalts) intrude beneath Torfajökull volcano where they were altered by hydrothermal fluid.

Torfajökull has persistent small-scale seismicity, both high frequency and low frequency events. High frequency events are located in the western part of the caldera, whereas low frequency events are in the southern portion and are surrounded by intense geothermal activity.

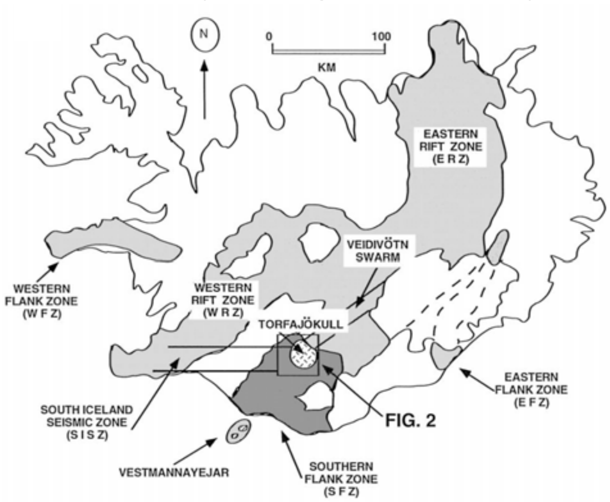


Fig. 1. The Torfajokull central volcano within the northern part of the SFZ, is located at the intersection of the southerly propagating Veidivotn volcanic fissure swarm of the ERZ and the South-Iceland Seismic Zone (SISZ), a transform fault. (Gunnarsson et al., 1998)

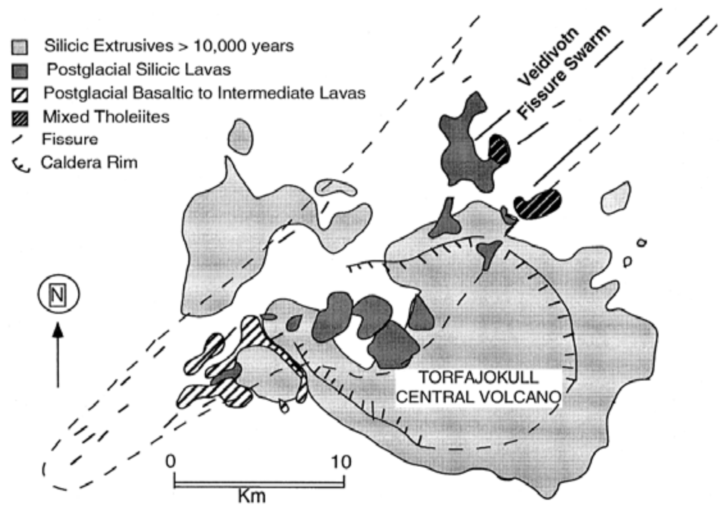


Fig. 2. Areal extent of silicic extrusives within the Torfajokull central volcano (450 km2) and the southern tip of the propagating Veidivotn fissure swarm (based on Saemundsson, 1988). (Gunnarsson et al., 1998)

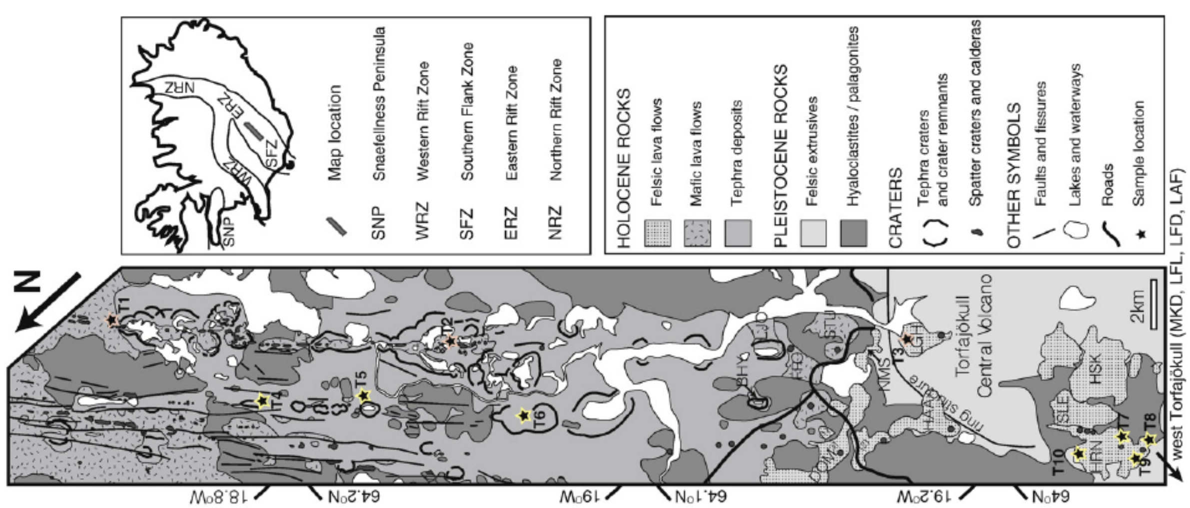
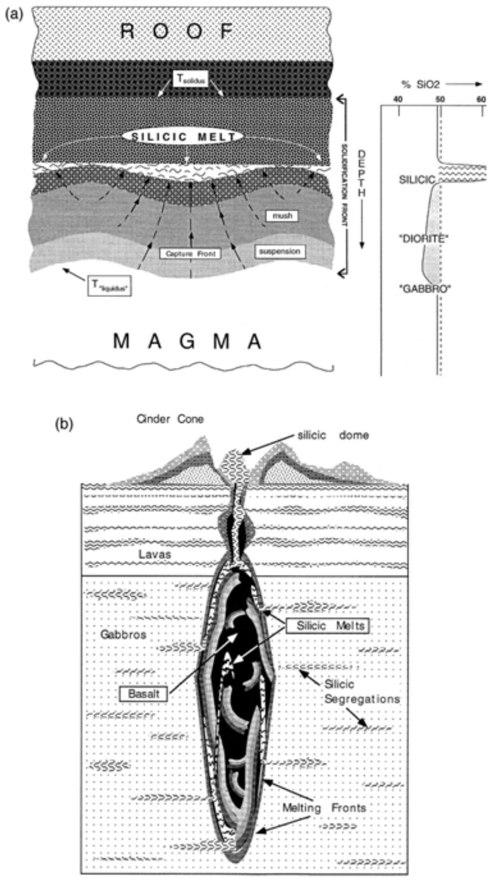


Fig. 3. Outline geological map of the Torfajökull Veidivötn area. Sampling locations are indicated by stars. (Gunnarsson et al., 1998)



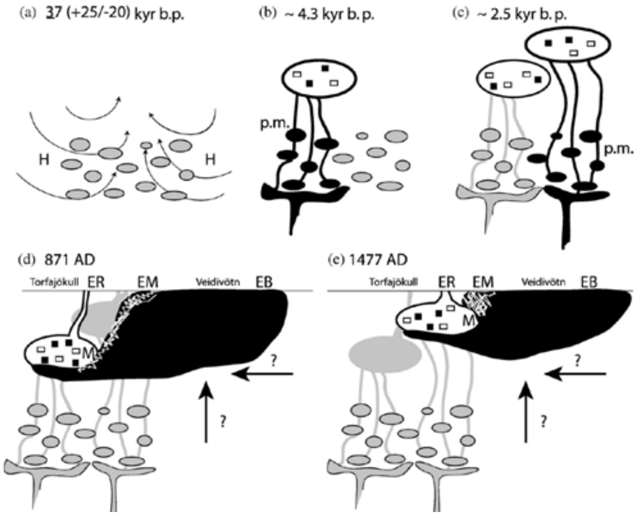


Fig. 4. Petrogenetic model for the most recent eruptions from the Torfajökull–Veidivötn volcanic system. (a) small tholeiitic protoliths were intruded into the mid crust where they suffer hydrothermal alteration ("H") and K-enrichment. (b) influx of hot basalt leads to partial melting ("p.m.") of altered tholeiitic protoliths and accummulation of rhyolitic melts in an upper crustal reservoir beneath Torfajökull, where they start to crystallize. (c) another thermal spike leads to further melting of altered protoliths and establishment of a second crystallizing upper crustal rhyolite reservoir. (d) tholeiitic magma influx into the upper crust results in magma mixing ("M"), and triggers eruption of rhyolite from the first rhyolitic reservoir ("ER"), basalt from the Veidivoetn fissures ("EB"), and some mixed magmas ("EM"). (e) A similar event occurs in 1477, triggering eruption from the second rhyolitic reservoir. Question marks indicate uncertainty in dike propagation direction. (Zellmer et al., 2008)

Fig. 5. Formation and melting of silicic segregations. a) Formation of horizontal segregation lenses due to solidification front instability (SFI) of the upper solidification front. The local, interstitial siliceous melt is drawn into the opening tears. b) Progressive partial melting of the hydrothermally altered crust by a propagating fissure. Basaltic magma is intermittently transferred horizontally through the fissure, which heats the crust. Destabilization of roof and wall rock during melting of previously formed segregation lenses in the crust allows collection at higher levels of silicic magma into larger bodies. (Gunnarsson et al., 1998)

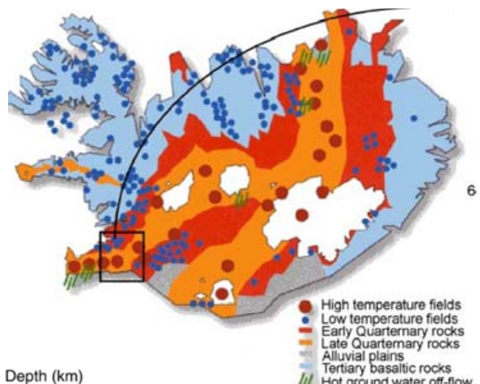


Fig. 6. The geological structure and geothermal systems in Iceland (left) and the MT site distribution (right). (Oskooi et al., 2005)

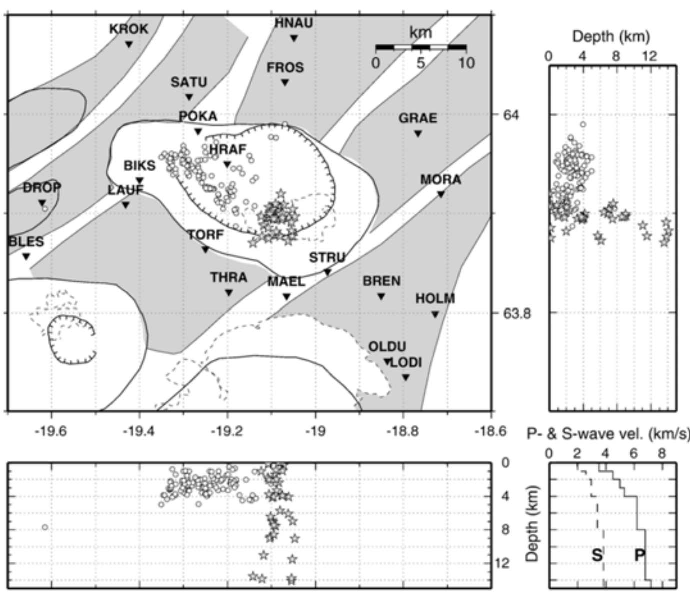


Fig. 7. Recorded seismicity in 2002. Black triangles are seismic networks. Earthquake locations shown in map view. Open circles are high-frequency events, whereas stars are low-frequency events. (Soosalu et al., 2006)

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ICELAND'S SILICIC VOLCANISM

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Iceland has active volcanic zones which are broken into rift zones and flank zones. Each zone contains multiple central volcanoes (defined as frequent eruptions from a centrally located volcano usually associated with high temperature geothermal systems). The rock types of Iceland are mainly basalt, with <10% abundance of silicic rocks and rare occurrences of intermediate rocks, formed by hybridization or mixing of the two. Silicic volcanic rocks are mainly produced by the central volcanoes in the form of lavas, domes, tephra layers, welded tuffs, and ignimbrites. The silicic rocks found within the flank zone are classified as trachytes and alkali rhyolites, whereas within the rift zones they are classified as dacites and low-alkali rhyolites. The rhyolites are the most common silicic volcanic rock, then dacite, and finally trachyte.

The petrogenetic origin of the silicic volcanic rocks is still not known. There are multiple fractional crystallization and/or partial melting hypothesis that are used to explain the origin. Near-solidus differentiation is another explaination instead of near-liquid differentiation. This is when silicic melts are extracted from an intrusive complex beneath the central volcano by melt segregation caused by deformation, which is supported by the distribution of the silicic rocks. Some possible deformations could be subsidence from the weight of the edifice, differential movement within a shear zone, or inflation/deflation in the central volcano. The tectonic movements would force the silicic melt out of the source rock forming dykes or veins.

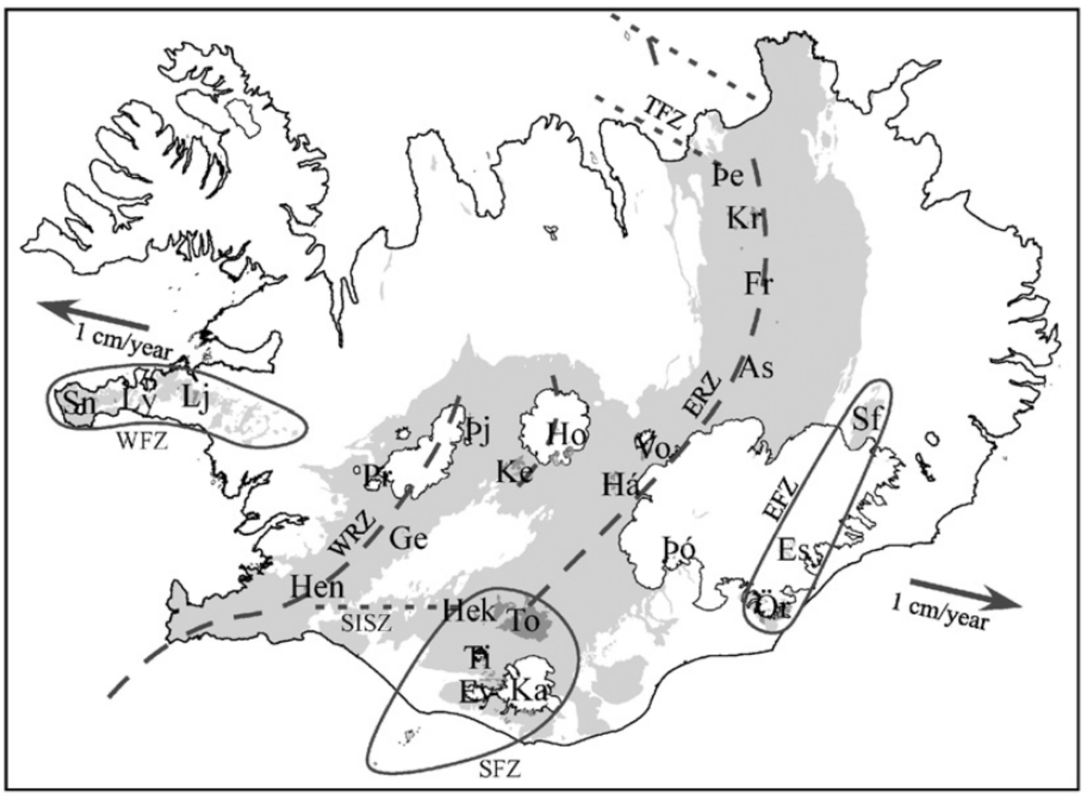

Fig. 1. Map of Iceland showing the location of central volcanoes known to have produced silicic rocks during the Brunhes magnetic epoch (<0.8 Ma). Shaded areas indicate Brunhes-age rocks. Dashed lines indicate the crest of the western and eastern rift-zones (WRZ and ERZ). The western, southern and eastern flank zones are delineated (WFZ, SFZ and EFZ) and the main transform zones are indicated (South Iceland Seismic Zone and Tjornes Fracture Zone). Plate motion is shown by arrows. The central volcanoes in the rift zones are: Hengill (Hen), Geysir (Ge), Prestahnukur (Pr), Þjofadalir (Þj), Kerlingarfjoll (Ke), Hofsjokull (Ho), Þorðarhyrna (Þ´o), Hagong (H´a), Vonarskarð (Vo), Askja (As), Fremri Namur (Fr), Krafla (Kr) and Þeistareykir (Þe). The central volcanoes in the western flank zone are: Snæfellsjokull (Sn), Lysuskarð (L´y) and Ljosufjoll (Lj). In the southern flank zone the central volcanoes are: Hekla (Hek), Torfajokull (To), Tindfjallajokull (Ti), Eyjafjallajokull (Ey) and Katla (Ka). The central volcanoes in the eastern flank zone are: Oræfajokull (O¨ r), Esjufjoll (Es) and Snæfell (Sf). (Jonasson, 2007)

Petrogenetic Hypothesis for the origin of Icelandic silicic magmas:

1) Fractional crystallization of basaltic magma
2) Fractional crystallization with crustal melting and magma mixing
3) Partial melting of hydrated basalt (amphibolites)
4) Partial melting of earlier fractional crystallized basalt
5) Partial melting of subsided, evolved magmas beneath the core of the central volcanoes
6) Remelting and collecting of silicic segregations formed within upper parts of intrusions

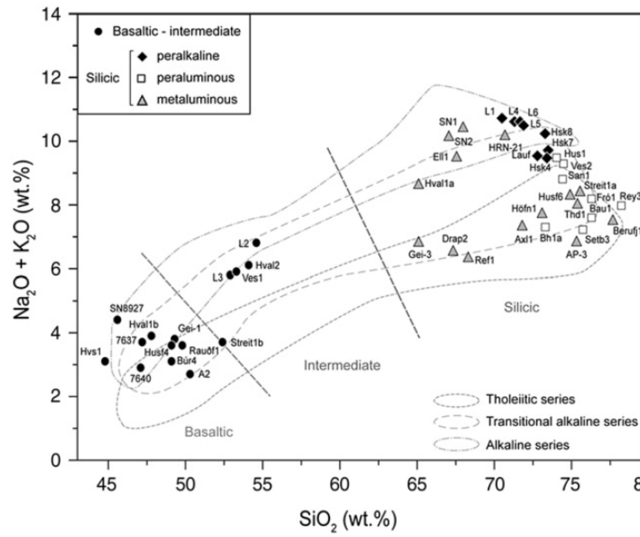

Fig. 2. Total alkali vs. SiO2 graph showing mafic samples ranging from basalt and basaltic andesite to intermediate transitional alkaline compostions and silicic samples ranging from trachytes and dacite to rhyolite with peralkaline, peraluminous, and metaluminous affinities. (Martin and Sigmarsson, 2010)

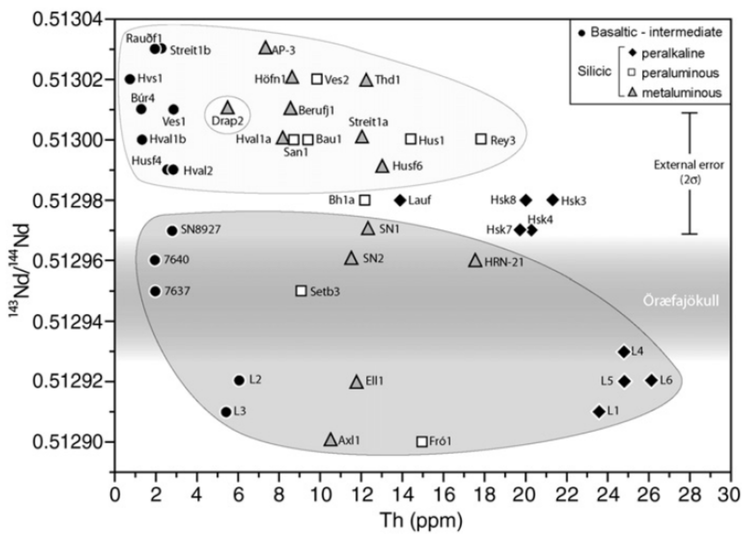

Fig. 3. The light grey area is the rift zone source and the dark grey area is the off-rift source comparing isotopic ratios in lavas. All samples from Snaefellsnes Peninsula plot in the off-rift zone and all others plot in the rift zone except SIVZ, which is in between. (Martin and Sigmarsson, 2010)

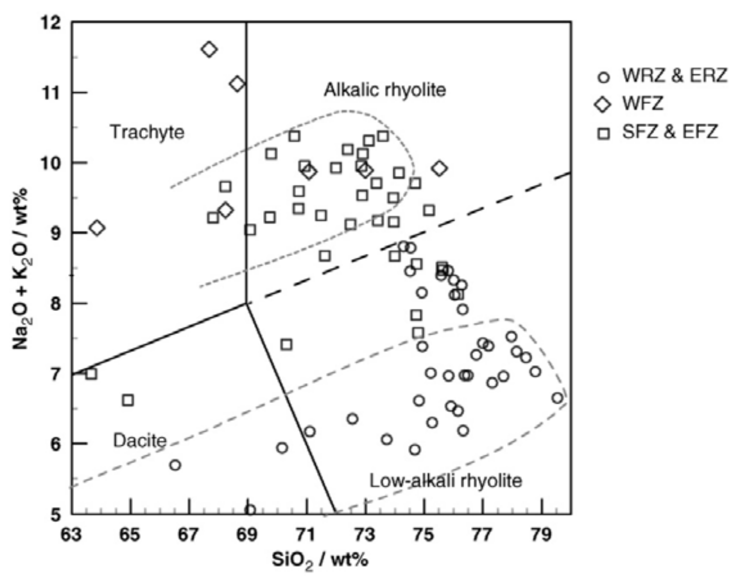

Fig. 4. Total alkalis vs. silica in silicic rocks from Iceland. Silicic rocks from the rift-zones are dacites and low-alkali rhyolites; most of them plot within the lower dashed area. Those that are richer in alkalis are from the Kerlingarfjoll, Þorðarhyrna and Geysir central volcanoes. Silicic rocks from the flank-zones are mostly trachytes and alkalic rhyolites. The upper dashed area encloses samples from Torfajokull. Silicic rocks from flank zones that plot in the dacite and low-alkali rhyolite fields include all samples from Hekla and Esjufjoll, in addition to some samples from Oræfajokull. The highest alkali contents are found in trachytes from Snæfellsjokull and Ljosufjoll. (Jonasson, 2007)

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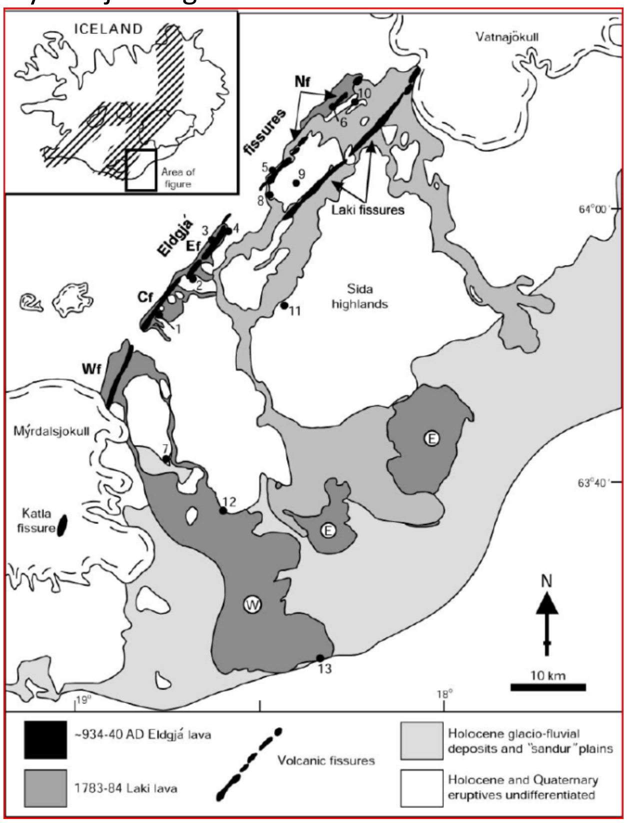
2. Jonasson, K., 2007, Silicic volcanism in Iceland: Composition and distribution within the active volcanic zones; Journal of Geodynamics, v. 43, p. 101-117.
3. Martin, E., Sigmarsson, O., 2010, Thirteen million years of silicic magma production in Iceland: Links between petrogenesis and tectonic settings; Lithos, v. 116, p. 129-144.

The 934 AD Eldgja eruption, Iceland which loaded 450Mt of sulfuric acid into the atmosphere.

By John Johnson

Location: Southern Iceland, east of Myrdalsjokull glacier.



The Eldgja Eruption:

-Date of Occurrence: 934 AD

-One of the two most voluminous and vigorous basaltic eruptions on earth in the last millennium.

-The other is the Laki eruption of 1783 AD. The Eldgja vent system belongs to the Katla volcanic system of the Eastern Volcanic Zone.

-Fishers trendingN45^{o}E

-Discontinuous fishers from edge of Myrdalsjokull glacier in the west to Vatnajokull ice cap in the east.

-The fissure system is greater than 57 km long.

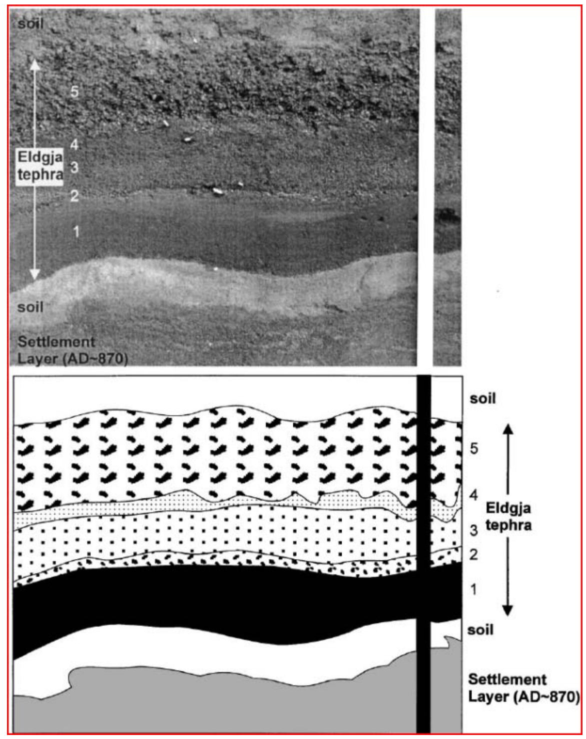
-Produced an estimated 19.6 Km^3 volume of lava including 1.3 Km^3 of explosive tephra.

Description of Events:

-At least 8 events, five of which are shown in the figure below.

-Forced early settlers off their farm lands

-Erupted through the Myrdalsjokull glacier with angular, blocky clasts that are poorly to moderately vesicular.

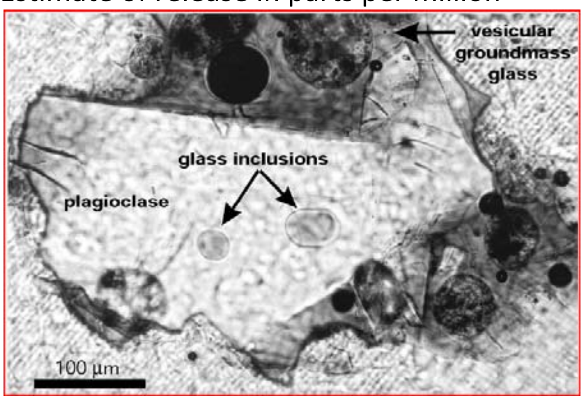


Photograph and line drawing of 5 separate fall units as follows:

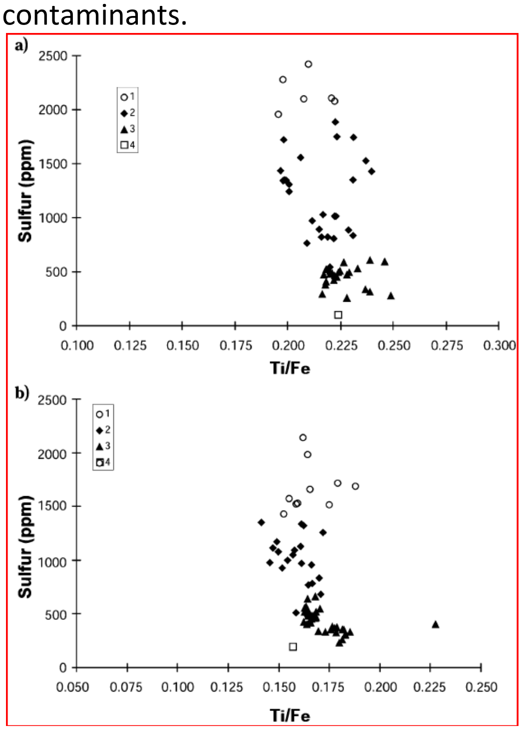
1. Phreatomagmatic fall unit black very fine to fine ash.
2. Strombolian fall unit fine lapilli scoria
3. Strombolian fall unit brown medium to coarse gray ash.
4. Strombolian fall unit a shiny black medium ash
5. Strombolian fall unit black fine to medium lapilli scoria.

An environmental disaster?
->20Km high eruption columns
-Controlled by the western jet stream
-The high eruption columns circumnavigate the Northern Hemisphere to reach the Greenland ice cap in 4-6 weeks.
-approximately 450 Mtons of H_2SO_4 is higher than previous estimates.

Estimate of release in parts per million



Glass inclusions in plagioclase contained small vesicular clast used to estimate actual contaminants.



The gas release in a) is for Eldgja and for b) is for the Laki. The figure shows the variation in Sulfur as a function of the ration of Ti/Fe.
-Laki eruption lasted 8 months
-Eldgja lasted for at least 2 years and possibly up to 8 years.

Flows-
-Both Laki and Eldgja flows were inflated pahoehoe based upon flat-topped sheet lobes and lava rise plateaus, along with flow structures such as tumuli, lava-rise pits, inflation clefts, and lava-rise sutures.

Unusual weather
-Short lived 3-5 years of hemispheric cooling of about 0.5 to 1.0 ^{0}C.
-fragmental records of the middle ages reports:
1. Volcanic haze or dry fog
2. Acid precipitation

Reference:
Thordarson, T., Miller, D.J., Larsen, G., Self, S., Sigurdsson, H., 2001. New estimates of sulfur degassing and atmospheric mass-loading by the 934 AD Eldgja eruption, Iceland, Jouranl of Volcanology and Geothermal Research, v. 108, p. 33-54.

Why the Mantle and Hotspot move together.
(summarized by John Johnson)

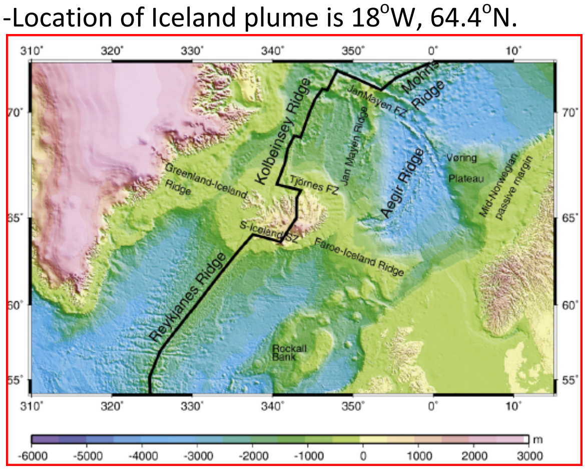
TWO MAJOR OUTSTANDING PROBLEMS IN MANTLE CONVECTION:

1. ORIGIN OF PLUMES
2. PLUME RELATION TO MID-OCEANIC RIDGES

The classical plume hypotheses:
That the origin of plumes is related to a thermal boundary layer at the core mantle boundary.

-Seismic studies present evidence for deep plume, but tomography signal is lost between 1000 and 2000 km.
-The plume hypothesis was to explain island chains in the Pacific by a strong hot upwelling mantle flow relative to lithosphere movement.
-Plumes also seem to interact with mid-ocean spreading ridges.
-Lithospheric thickness increases away from ridges due to lithospheric cooling forming a negative drainage pattern for buoyant material under the lithosphere. Thus the plume head is controlled.

Current location of plume head
-based upon the Bouguer anomaly minimum and the thickest crust from receiver function analysis.
-Location of Iceland plume is 18°W, 64.4°N.



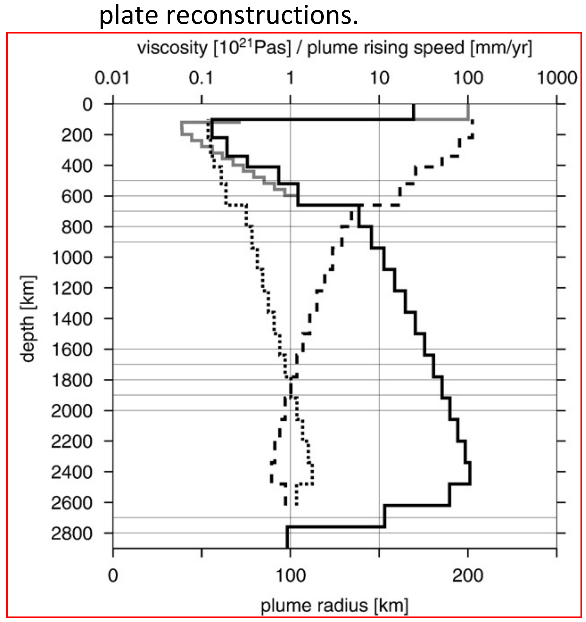
Of importance to plume movement is the Greenland-Iceland ridge and the Faroe-Iceland Ridge. These ridges show evidence of the plume movement.

-Along Faroe-Iceland ridge mantle is 25-30 km thick and mantle potential temperature is elevated by 200-250°C.
-The Northern Volcanic Zone of Iceland it is 19km thick.
-Northeastern Iceland it is 35km thick.
-Central Iceland it is 22km thick.
-Between Iceland and Jan Mayen has a thickness of 20 km.
-Jan Mayen ridge is 50km thick and is considered a continental fragment.

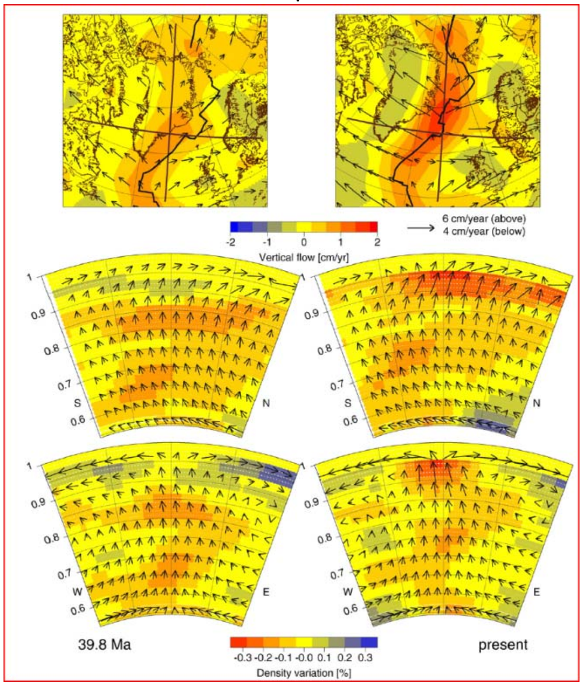
Mantle Flow in the North Atlantic
-Rheological assumptions and density anomalies from seismic tomography, surface plate velocities can be calculated, a north or southward flow is expected in the asthenosphere.

Interaction of Iceland Plume and mid-Atlantic ridge is more actualistic due to the following aspects:

1. The model includes global mantle flow.
2. The model uses time-dependent relative plate motion.
3. Location of the plume relative to ridge is time-dependent based on global plate reconstructions.

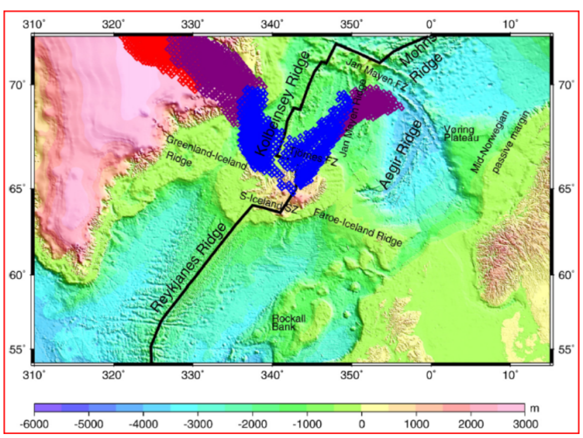


Solid line is ambient mantle viscosity, black for models 2 a-g, grey for models 2h and 3, plume radius dotted line, buoyant plume rising speed dashed line vs mantle depth.

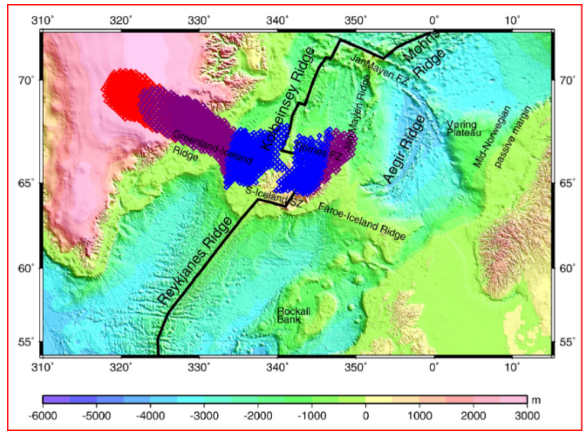


Top panels are flow at depth of 215 km, second and third row are cross sections through density anomalies and flow along the N-S and E-W profiles.

-Northward flow in upper mantle, southward flow in lower mantle. Due to backward advection the Iceland plume at 39.8 Ma is only present in lower mantle.



Moving source plume head track.



Fixed Source, Red diamonds 50-40 Ma, purple diamonds 40-20Ma, blue diamonds 20-0 Ma. Model predicts southern tract unless hotspot confined to 660km deep. Then it explains the ridges.

-A westward moving plume source would be better to explain the Faroe-Iceland Ridge.

Reference:

Mihalffy, P., Steinberger, B., Schmeling, H., 2008. The effect of the large-scale mantle flow field on the Iceland hotspot track, Tectonophysics, v. 447, p. 5-18.

Skeiðarársandur

Kris Tacsik, California State University, Northridge, Department of Geography

Sandur is an Icelandic term that has recently gained widespread use to describe a glacial outwash plain (plural is Sandar) The original meaning was simply sandy ground. The term Sandur comes from the physiographic feature Skeiðarársandur, which is located on Iceland's southeastern coast between the Vatnajökull icecap (3rd largest in the world) and the Atlantic Ocean.

Introduction

Skeiðarársandur (see Figure 1) is the largest active sandur in the world, covering an area of 1,300 km^2 (320,000 acres). This large desolate expanse of deposited sediments from the Skeiðarársandurjökull glacier forms a broad plain characterized by extensive braided streams, sand bars, kettle holes, and aeolian dunes.

The glacially eroded sediments that have created the Skeiðarársandu plain are the result of regular melt-water runoff from Skeiðarársandurjökull and high magnitude jökulhlaups (glacial outbursts). The primary transport vehicles of the sediment are three rivers draining Skeiðarársandjokull, a melting outlet glacier. The rivers draining Skeiðarársandur are Núpsvötn in the west, Gigjukvísl in the central western section and Skeiðará in the east.

Jökulhlaups, or glacial outbursts, are the result of either a sub-glacial volcanic eruption or the repeated slow filling and sudden drainage of a large sub-glacial lake. Skeiðarársandur experiences episodic jökul-hlaups on an average of five to ten years for smaller events and 100 years for larger events. In 1996, one of the largest recorded jökulhlaups occurred when the Grímsvötn lake caldera failed. The outflow began

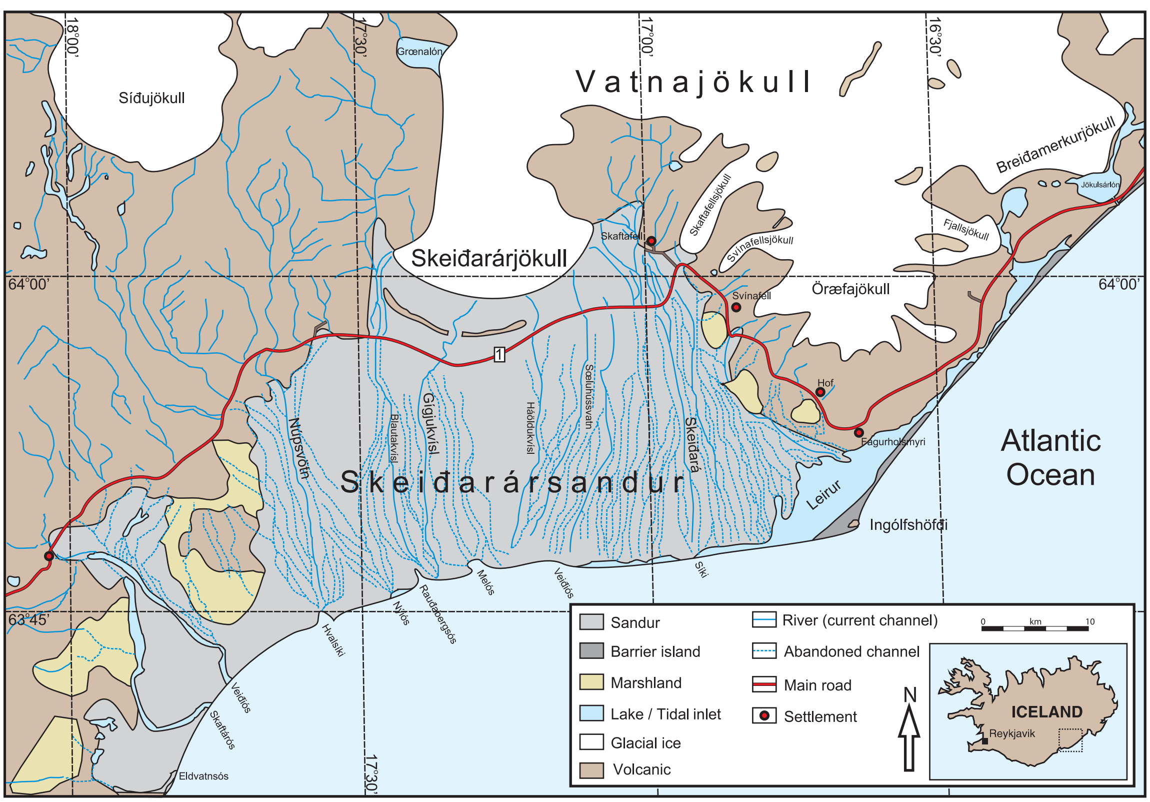


Figure 1. Skeiðarársandur, Iceland

along the Skeiðará River and then spread westward along the entire ice margin, coalescing to inundate 75% of the outwash plain. The rate of flow reached 50,000 cubic meters per second and destroyed parts of the Ring Road and the Gigjukvisl Bridge. It is estimated that this outburst was responsible for the transportation and deposition of at least 180 million tons of sediment.

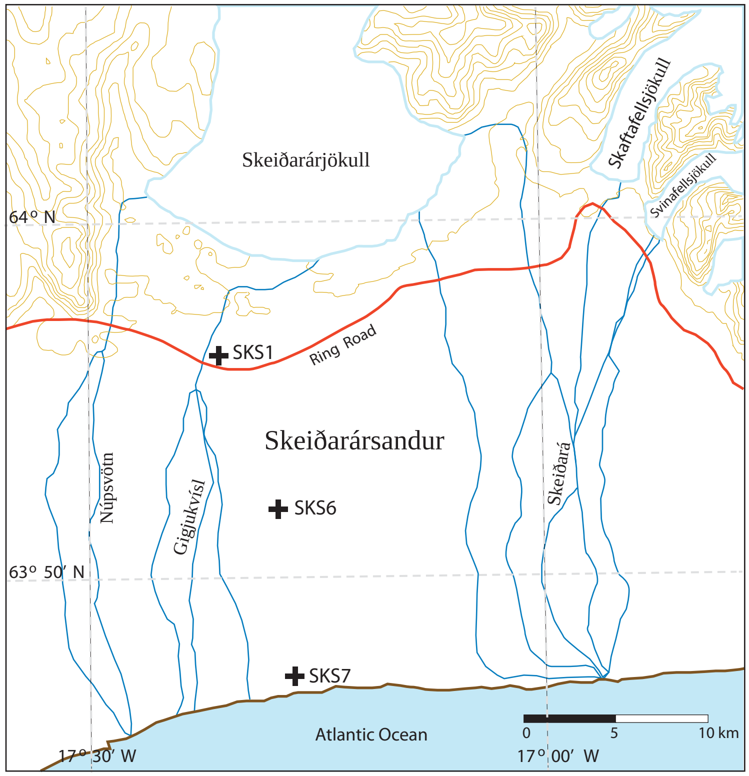


Figure 2. Location of seismic profiles.

Sedimentation

The Skeiðarársandur plain can be divided into three zones; proximal, intermediate and distal. The proximal zone, which is closest to the glacier and steepest, is characterized by a few main rivers with well defined channels. These high energy channels transport and deposit ice blocks, large boulders and course gravel in this zone. Kettle holes develop where blocks of ice have melted leaving a depression that fills with water, creating a rough pitted landscape.

Due to the decrease in the plain slope, river channels within the intermediate zone become wide and shallow causing the rivers to become extensively braided. The network of braided streams tends to shift position rapidly from east to west, creating a maze of active and abandoned channels. It is in the intermediate zone that gravel and sand are laid down by the streams.

In the distal zone, the area farthest away from the glacier, the rivers become so shallow they may merge into a single sheet of water during high flow. The finest sediment material such as sand and silt are deposited by these sheet flows.

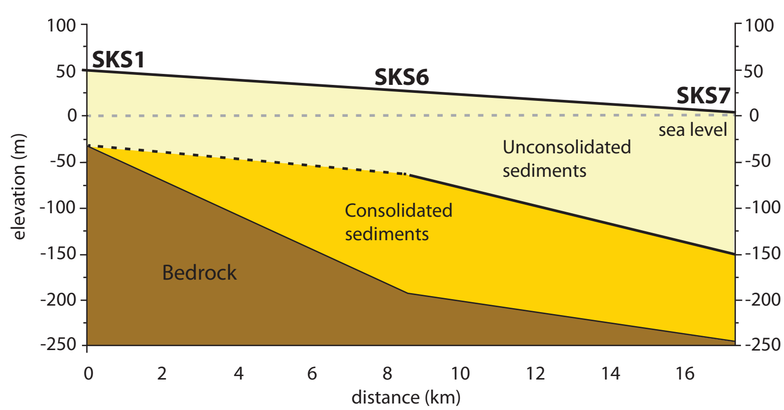


Figure 3. Cross section showing the stratification of the sediments across Skeiðarársandur from north to south from SKS1 to SKS7.

In a 1997 - 1999 study, a University of Iceland team generated seismic waves through 10 sites on the Skeiðarársandur plain in order to create a sediment profile. The results of the reflective waves differentiated between bedrock, consolidated and unconsolidated sediments. Sites nearest to the terminus of Skeiðarársandurjökull glacier revealed a sediment thickness of 80 – 100 m thick (see Figures 2 and 3) Near the coast, the results showed sediment thickness to be about 250 m. From the study, it was estimated that the total volume of sediments making up Skeiðarársandur is 100 – 200 km^3. The majority of the material has not been subjected to compaction under glaciers, it was therefore concluded the sediments date from the Holocene era. Further calculations determined that the average growth of the sandur body over the last 10,000 years has been about 1 km^3/century.

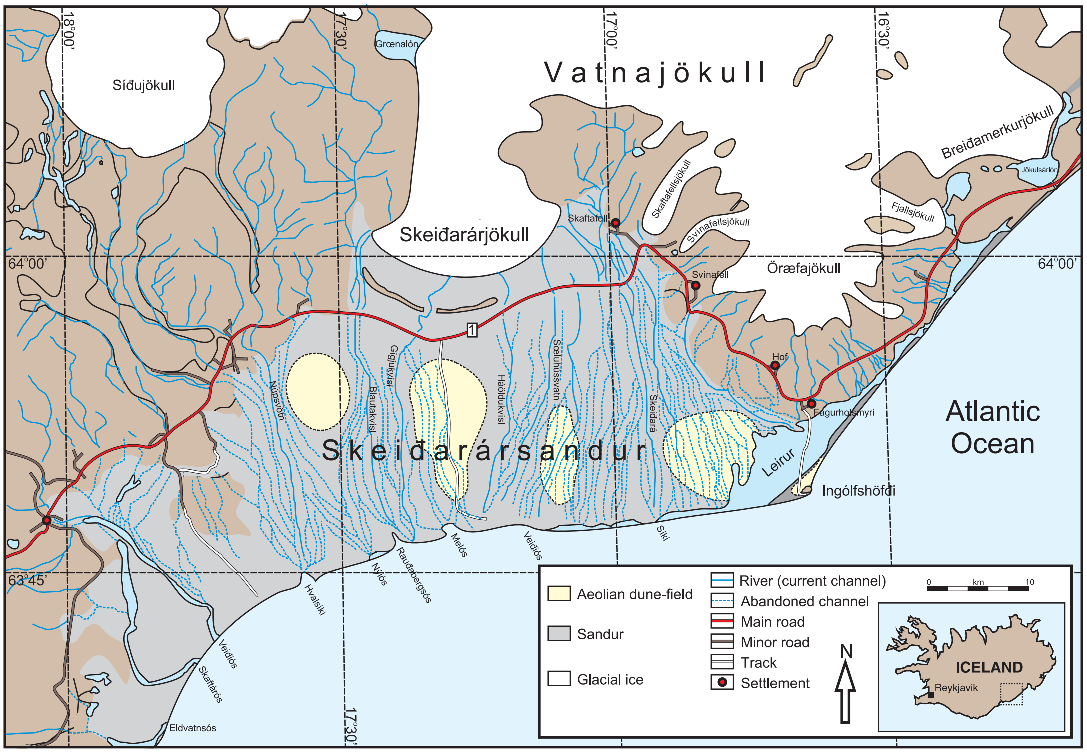


Figure 4. Location of Aeolian dune fields on Skeiðarársandu.

Dunes

Due to the high winds around this area of Iceland, aeolian dune fields are found in all the zones of the Skeiðarársandur plain, but mainly in the proximal and intermediate zones. The largest dune field is located between the Gigjukvísl and Háöldukvisl rivers. Jökulhlaups which inundate the plain periodically are the principal source of supply of sand grade sediment needed for dune construction. It is believed that the 1861 Storhlaup jökulhlaup, which inundated the entire sandur surface, is the starting point for the onset of present day dune fields. Subsequent jökulhlaups have generally remained confined to the three main river channels in the proximal area allowing complex dunes within this zone to develop. It is in the distal parts of the sandur where flood waters become unconfined and deposit extensive sheets of sand and gravel dune where development is limited.

In summer months the water table is high which limits sediment availability. Active construction and migration of the dune sediment occurs during winter months when the water table falls slightly and allows parts of the sandur surface to dry out temporarily. Coupled with interdune pond freezing, sand sediment becomes more mobile and is transported by strong winds across the plain.

Prevailing wind direction is inland from the coast and secondary wind direction is from the northern glacier margin toward the sea.

Aeolian dune systems on Skeiðarársandur comprise several types: spatially isolated dunes, damp and wet interdune flats, small dune fields and larger dune fields.

Figure 5. Complex dunes within a major aeolian dune field. The width of the view in the center of the photograph is approximately 150 m.

Figure 6. Isolated dunes separated by wet interdunes. The width of view in the center of the photograph is approximately 2 km.

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Subglacial Lakes

Martha Peggye Ahlstrom, *Department of Geological Sciences, California State University, Northridge*

A subglacial lake is a lake under a glacier, typically an ice cap or ice sheet. In Icelandic ice caps, several lakes are known to exist beneath surface depressions created above hydrothermal systems. These Icelandic sub-glacial lakes rise as domes above the bed, often capping mountains (Figure 1). Scientific theory combined with topographic maps proposes that the slopes of glacier-bed depressions beneath ice caps in Iceland are not sufficient to accumulate water without accompanying depressions in the glacier surface. Subglacial lakes are often situated where there is no gradient in the fluid potential that constrains water along the glacier bed. The shape of the lake results from a balance of vertical forces as the overlying glacier floats in static equilibrium. The subglacial lake roof slopes almost 10 times more steeply than the glacier surface, and in the opposite direction Figure 2a). The water below the ice remains liquid because geothermal heating balances the heat loss at the ice surface. The pressure causes the melting point of water to be below 0°C. Thus, the ceiling of the subglacial lake is at the level where the pressure melting point of water intersects the temperature gradient.

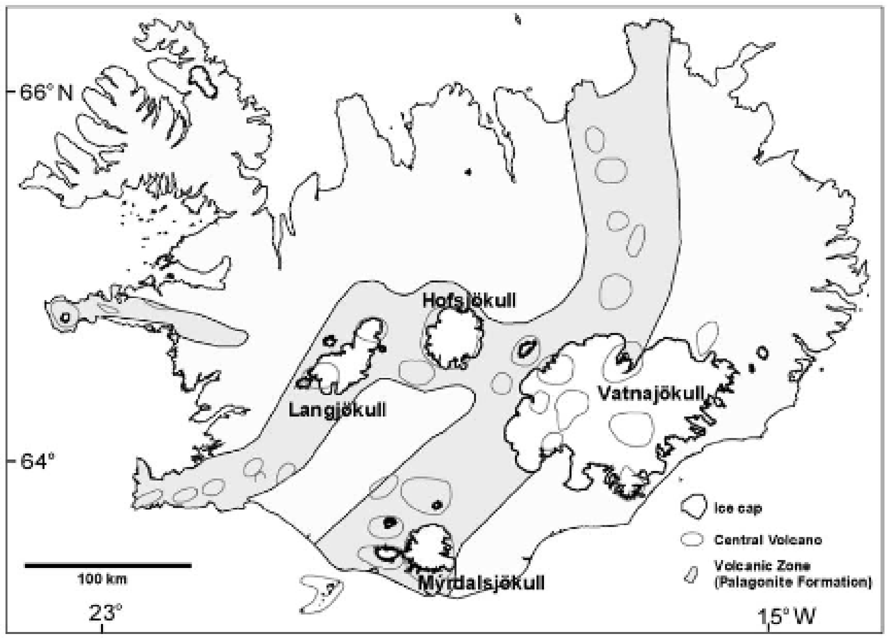


Figure 1: Location map of Iceland showing ice caps, the volcanic zone (The Palagonite Formation) and the central volcanoes (Björnsson, 2002).

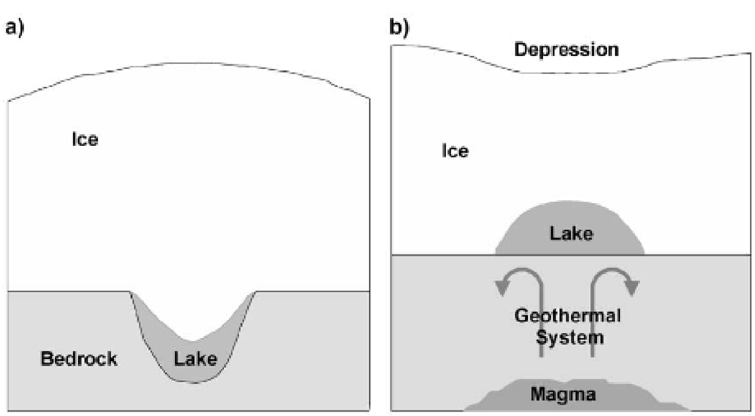


Figure 2: Schematic drawing of two main types of subglacial lakes; (a) a stable lake, (b) an unstable lake that drains in jökulhlaups, showing the roof slopes (Björnsson, 2002).

Periodically, subglacial lakes under ice-surface depressions drain in outburst floods, jökulhlaups. When the subglacial lake progressively expands, the water flows toward the depression, the basal water pressure increases, and the overlying glacier is lifted (Figure 2b). Before the surface depression is entirely flattened, the hydraulic seal is broken and water begins to drain out of the lake at the bottom under the ice dam. Then, water escapes through narrow passages at the ice-bed interface and the pressure head maintained by a voluminous lake drops slowly. However, the pressure of the ice squeezes the tunnel draining water from the lake and the water flow is mainly controlled by tunnel enlargement. In many cases, tunnel enlargement occurs as the ice walls melt by the frictional heat generated from the flowing water and thermal energy stored in the lake. The lake then becomes sealed again, often before it is empty and accumulation of water begins until a new jökulhlaup occurs.

The water in the lake can have a floating level much above the level of the ground threshold. In theory, a subglacial lake could exist on the top of a hill, provided the ice over it is much thinner so that it creates the required hydrostatic seal. The floating level is considered similar to the water level in a hole drilled through the ice into the lake. So, it is equal to the level at which a piece of the ice over it would float if it were a normal ice shelf. The ceiling can be visualized as an ice shelf that is grounded along its entire perimeter, which explains why it is called a captured ice shelf. As it moves over the lake, it enters the lake at the floating line, and it leaves the lake at the grounding line.

A hydrostatic seal must exist along the entire perimeter, if the floating level is higher than the threshold, and is created when the ice is much higher around the lake that the equipotential surface dips down into impermeable ground. Water from underneath this ice rim is pressed back into the lake by the hydrostatic seal. The ice surface is ten times more important than the bed surface in creating the hydrostatic seal. If the hydrostatic seal is penetrated when the floating level is high, the water will start flowing out in a jökulhlaup. With the melting of the channel the discharge increases exponentially, unless other processes allow the discharge to increase faster. Jökulhlaups reach very high rates of discharge due to the high head that is reached in subglacial lakes

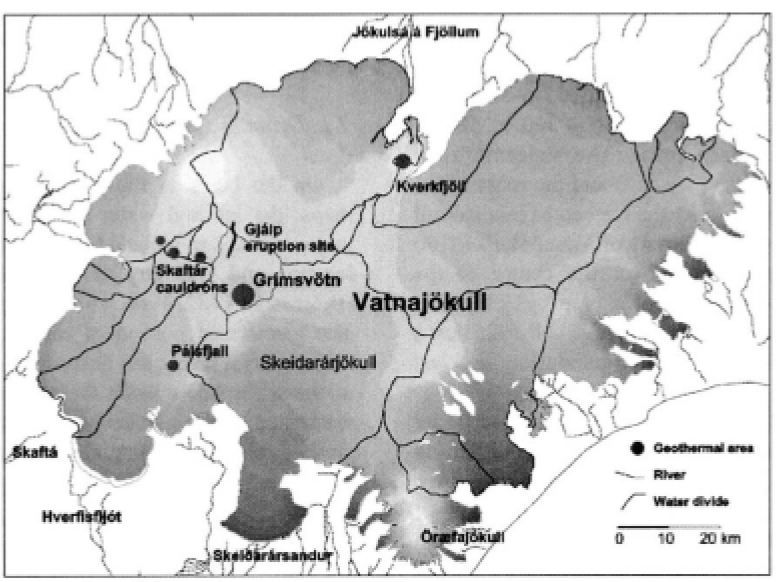
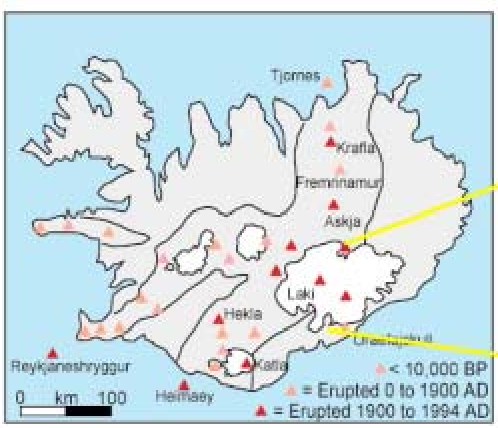
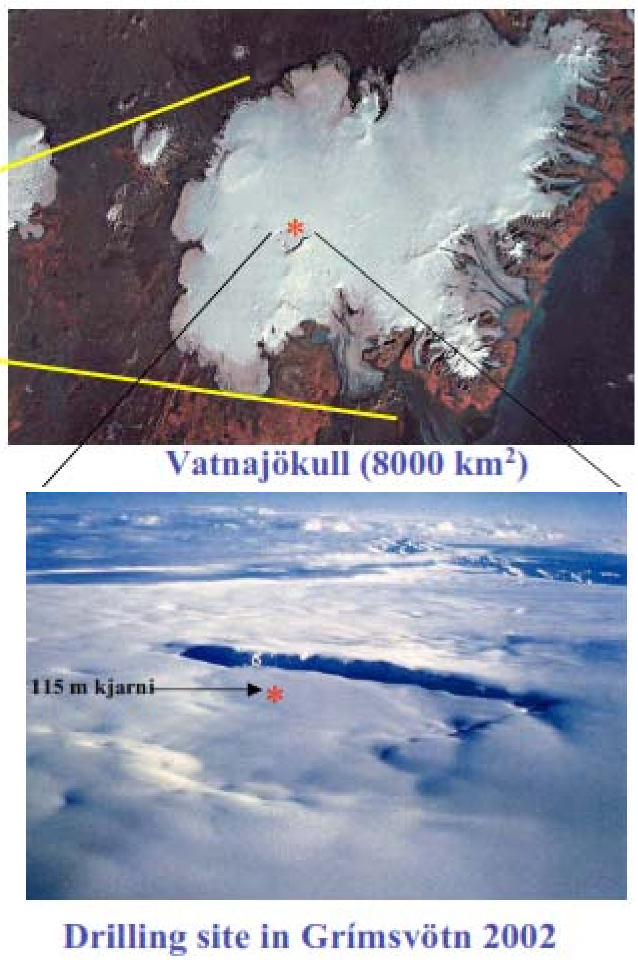


Figure 3: Location map of Grímsvötn and Skaftár cauldrons ((Björnsson, 2002).

Several subglacial lakes formed by the continuous melting of ice above geothermal areas exist beneath the Vatnajökull ice cap in Iceland. The best known are the Grímsvötn, a 25 km ^{2} lake beneath a 100-300 m thick ice shelf within a subglacial volcanic caldera, and the two Skaftá cauldrons (Skaftárkatlar), located 10-15 km NW of Grímsvötn (Figure 3). Jökulhlaups, which sporadically occur from Grímsvötn, have been investigated by several researchers. Jökulhlaups from Grímsvötn vary widely in size and periodicity, due to changes in geothermal activity and sudden volcanic events, whereas jökulhlaups from the Skaftár cauldrons occur more regularly every 1-2 years. The water level in Grímsvötn and the mass balance of the drainage area is closely monitored. Ice flow velocities in the Grímsvötn basin and changes in ice-shelf thickness are also studied as well.

In 2002, scientists drilled into the subglacial lake Grímsvötn to determine its unique characteristics. The statistics of this lake are: altitude = 1400 m, volume of ~1-5 km^3, depth of 150 m, ice cover of 250m, glacial drainage basin of 300 km^2, 4250 MW over 100 km^2, and episodic drainage (1 km^3@ 10^4 m^3/s) (Figures 4, 5, and 6). The main results of 2002 study on the Grímsvötn subglacial lake revealed: microorganisms are in the lake water and bottom sediment; the DNA analysis indicates that the lake community is distinct from communities in the snow and ice; and the gene sequences are highly similar to known psychrophilic organisms, which are extremophilic organisms that are capable of growth and reproduction in cold temperatures, ranging from −15°C to +10°C. Temperatures as low as −15°C are found in pockets of very salty water (brine) surrounded by sea ice. Studies similar to these continue to reveal scientific discoveries unique to subglacial lakes (Figure 7).





Figures 4, 5, and 6: The Grímsvötn volcanic caldera beneath the Vatnajökull ice cap and locations with dates of eruptions and the 2002 drilling site (Thorsteinsson, 2005).

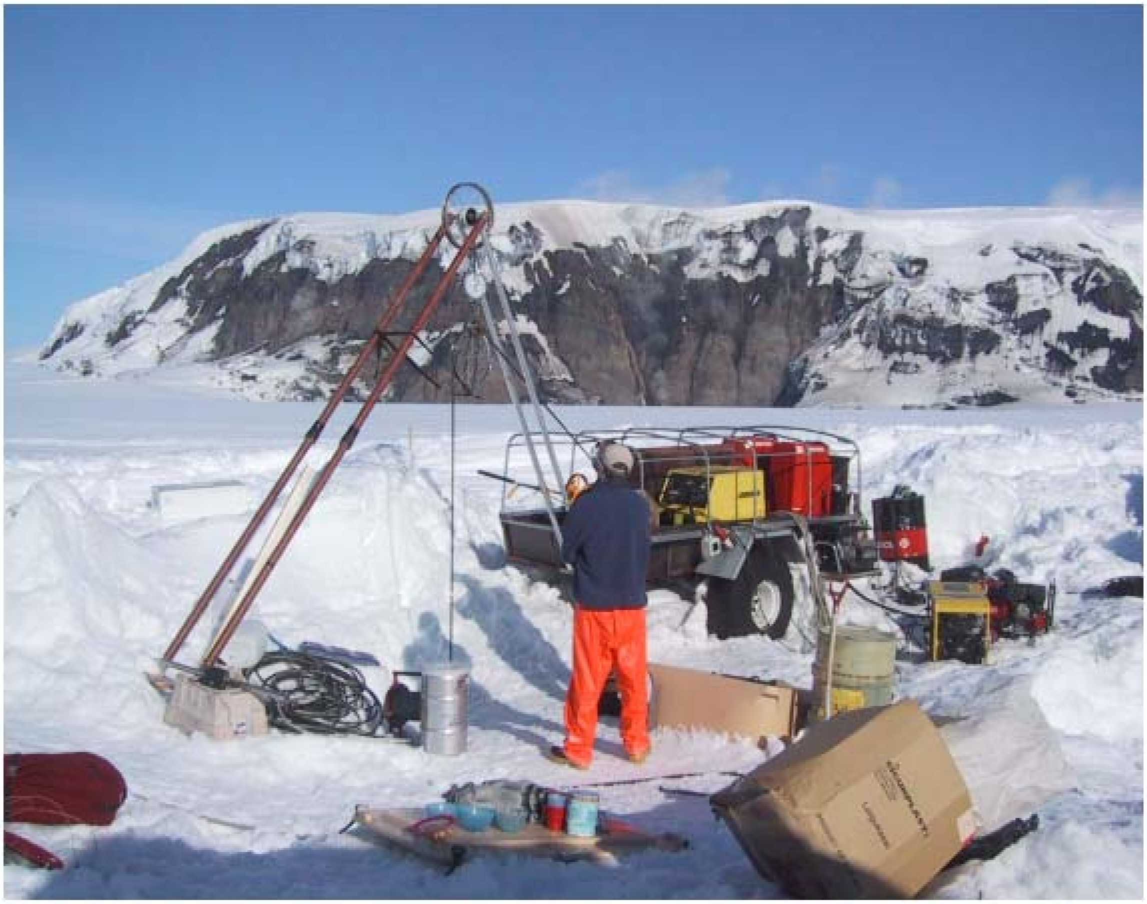


Figure 7: Drilling study into Grímsvötn volcanic caldera, 2002 ((Thorsteinsson, 2005).

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Thverartindur Central Volcanic Complex

Jenna Fleck *(California State University, Northridge-Department of Geological Sciences)*

The Thverartindur Central Volcanic Complex is located in the southeast and consists of four main intrusive rock types: ultramafic rocks, gabbros, granite/granophyres, and hybrids (which are indistinguishable in hand sample, intermediate in chemical composition). Granites make up 75% of the total volume of intrusives. These rocks form the intrusive component of the Thverartindur complex and may represent the uppermost plutonic section of the oceanic crust. There is generally seven emplacement phases for the intrusives.

The interior core of the Thverartindur cone is made mostly of a swarm of inclined sheets tectonically rotated into a rift-parallel monocline. The magma source is located approximately 3km below the pre-erosional surface where the swarm projects upward to a fan/bowl shaped swarm. The magma chamber is spheroidal with dimensions of 7.2km wide and 4km thick totaling a volume of 140+/-50km^3.

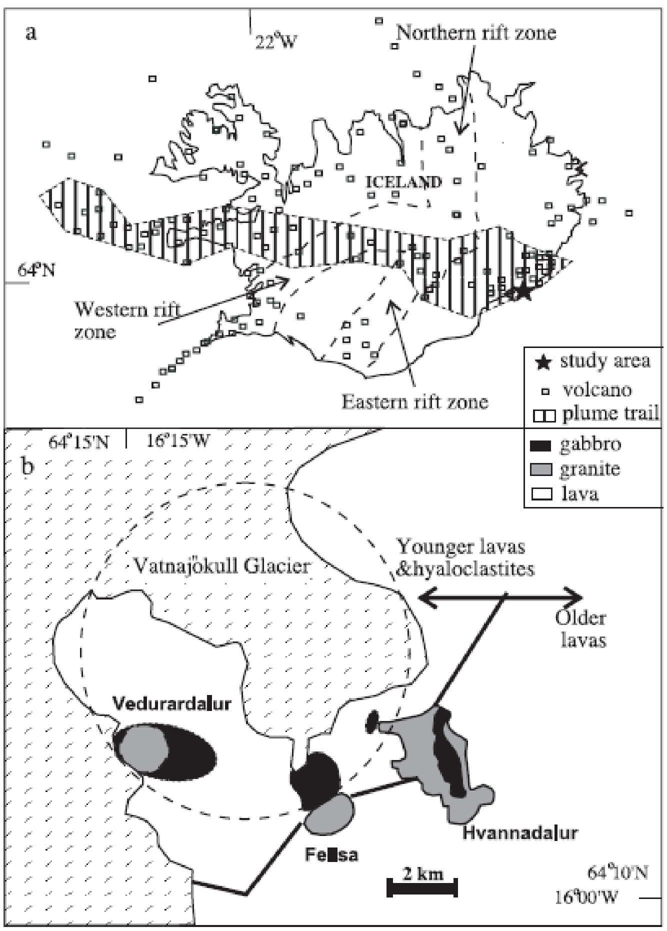


Figure 1. a) Map showing central volcanic complexes, plume migration trail, and the rift zones. b) The three plutonic complexes of Thverartindur (Soesoo, 1998).

Three Plutonic Complexes

Hvannadalur (4km^2)

Four main intrusive phases:

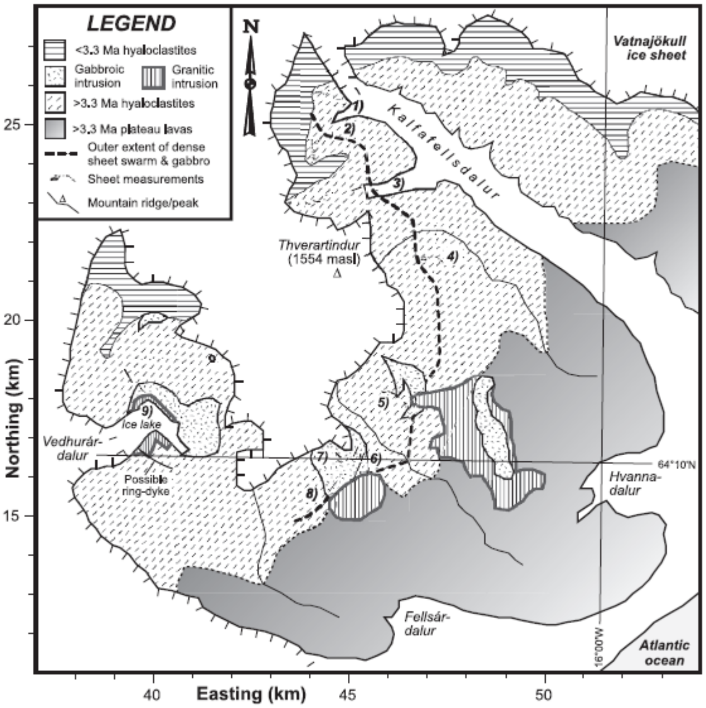
1. Quartz-bearing gabbros in sheet-like bodies
2. Granite/granophyres (2.5-3 km^2) in parallel injections 10-60cm thick
3. Ultramafic rocks in thick sills and dikes
4. Minor dikes and sheets

Fellsa (<3km^2)

1. Gabbro rocks in subparallel 15-60m thick sills
2. Intrusive varieties:
   a. Medium grained leucogabbros
   b. Spotted gabbros
   c. Gabbros with elongate euhedral plagioclase
3. Miarolitic Granite
   a. Contain fine-grained basaltic xenoliths

Vedhurardalur (3km^2)

1. Gabbros: leuco- to melanocratic
   a. Fine to coarse grained
2. Granophyres form large central body 2km in diameter



Multiple emplacement history within intrusives:

1) Possibly 3 main pulses of gabbroic sill injections
2) Minor gabbro sheets (0.5-1m thick)
3) Gabbroic sheets (tens of m thick)
4) Fine-grained boundaries between basaltic lava and gabbroic intrusions
5) Granites/granophyres
6) Ultramafic sills & dikes
7) Vertical gabbroic dikes cut through entire intrusive complex

Figure 2. A simplified Geologic Map of the Thverartindur volcanic complex (Klausen, 2004).

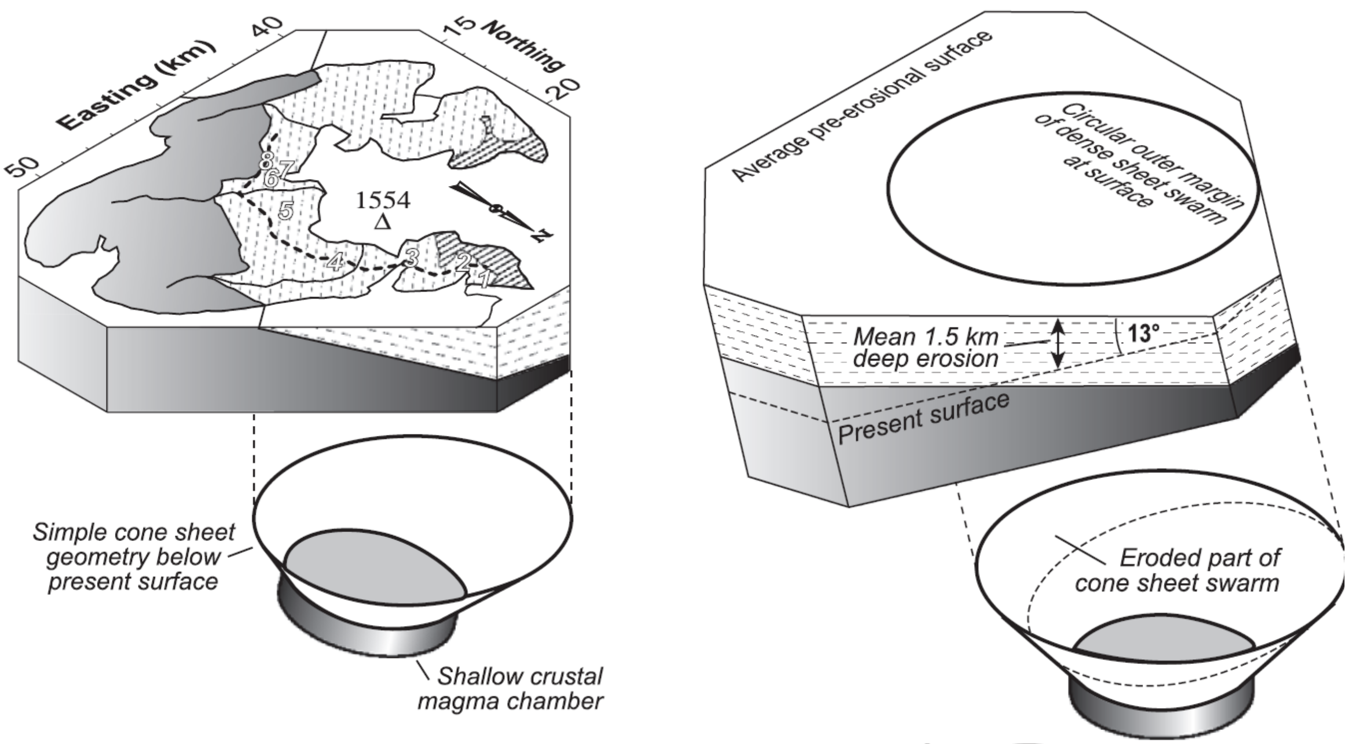


Figure 3. The left block diagram of the upper ~3km of a NW-dipping crust beneath the presently exposed surface around Thverartindur peak, where an equally tilted cone-shaped sheet swarm from a penny-shaped magma chamber schematically illustrates its igneous interior. The right block diagram and model interior from (a), after an average 138 back-rotation and 1.5 km crustal addition (Klausen, 2004).

References:

1. Klausen, M.B., 2004, Geometry and mode of emplacement of the Thverartindur cone sheet swarm, SE Iceland; Journal of Volc. And Geothermal Res., v. 138, p. 185-204.
2. Martin, E. and Sigmarsson, O., 2010, Thirteen million years of silicic magma production in Iceland: Links between petrogenesis and tectonic settings; Lithos, v. 116, I. 1-2, p. 129-144.
3. Soesoo, A., 1998, Episodic magmatism and diverse plutonic products within the Thverartindur central volcanic complex at the former Icelandic plate margin; Journal of the Geol. Soc., London, v. 155, p. 801-811.