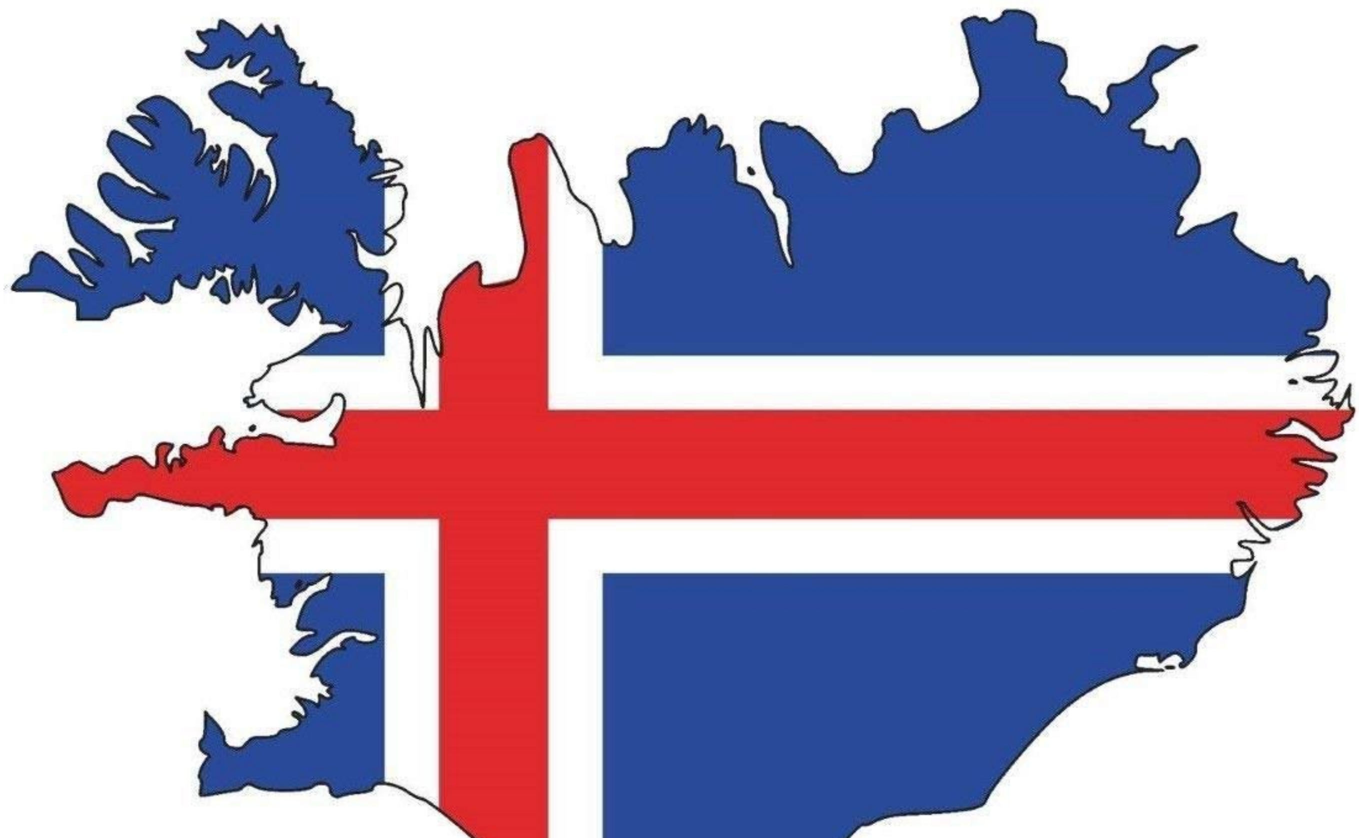
ICELAND SPRING BREAK TRIP 2023

UNIVERSITY OF PITTSBURGH AT JOHNSTOWN
DEPARTMENT OF ENERGY AND EARTH RESOURCES




ICELAND
0 km 20 40 60 km
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2000 m
1500 m
1000 m
500 m
200 m
100 m
0 m
NORÐURLAND VESTRA
VESTURLAND
SUÐURLAND
Hofsjökull
Langjökull
Myrdalsjökull
Faxaflói
Hellissandur
Stykkishólmur
Grundarfjörður
Búðardalur
Borgarnes
Akranes
REYKJANES
REYKJAVÍK
Hafnarfjörður
Kópavogur
Garðabær
Keflavík
Grindavík
Thorlákshöfn
Thingvallavatn
Thingvellir
Geysir
Lougarás
Selfoss
Eyrarbakki
Hella
Hvolsvöllur
Heimaey
Vestmannaeyjar
Surtsey
Skógar
Vík
Kirkjubæjarklaustur
Eyjafjallajökull
Hekla (Vavaland)
Eiriksjökull
Thórisvatn
Day 2
Day 3 & 4
Day 5
Day 6
Day 7
Day 8

The following was compiled by Ryan Kerrigan, Associate Professor pf Geology at University of Pittsburgh a Johnstown, Johnstown, PA in the winter of 2022-2023 as supporting material for the Pitt-Johnstown Geology Club Spring Break Trip to Iceland on March 4th to 12th, 2023.

Much of the details come from Wikipedia. If you use this field guide, please consider donating to Wikipedia.

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THINGS YOU SHOULD BRING

Please limit yourself to one checked bag and one carry-on (day-pack)

Most Important:
• Passport & credit card

Personal Items:
• Tissues
• Sunscreen
• Lip balm with sunscreen
• Sunglasses
• Toiletries
• Van/Plane Entertainment (books, cards, small board games, etc.)
• Travel Towel (the hostels will have towels for our use, the hot spring will have towels to rent, but you may want to bring your own)

Clothes:
• *Be prepared for horizontal rain/snow as well as "nice" weather.*
• Rain jacket (think polyester and gore-tex)
• Rain pants
• Waterproof hiking boots
• Wool socks
• Sneakers
• Swimming Suit
• Base layer (think thermal underwear or polypropylene)
• Hats (both for sun protection and warmth)
• Mittens/gloves

Equipment:
• Universal Adapters (they use different outlet plugs)
• Field Notebook
• Pencils/Pens
• Water Bottle
• Rock Hammer (must be packed in checked luggage)
• Hand lens

Money:
• You can get Icelandic Krona from your bank - go to the bank and ask. They usually require a few days to get it for you. You might be able to get a better exchange rate this way…
• You can also exchange money at the airport or at Icelandic banks
• Your credit/bank cards should work fine, but it is always a good idea to tell those companies you are going overseas so they don't shut you down to thinking it might be fraudulent.

Other:
• **WhatsApp** – I would like everyone to download WhatsApp. This is a phone/text service that is free and will allow us to stay in contact via Wifi. This way we will not need to add expensive international calling/data plans to our phone.

TRIP RULES

1. Don't do anything that would put yourself or others else in danger.
2. Buddy System – do not wander off by yourself, ALWAYS have another group member with you AT ALL TIMES!!!
3. Do not invite strangers back to our hotels
4. Please practice moderation – do not overdo it. Please.

You are representing the University of Pittsburgh at Johnstown. Do not embarrass the university. Do not do anything that would jeopardize future trips of the Geology Club!

After the trip:

After the trip, I would like you to download your pictures to Geology Club computer in Krebs 222. I use these pictures in lectures and advertising for future trips.

You will attend the Geology Banquet in late April (probably April 21^{st}), where the attendees of the Geology Club Spring Break trip will present pictures from the trip.

LOGISTICS AND BASICS

Flights

Departing Flight
Departure: Sat 4 Mar 2023, 19:40, Washington Dulles International (IAD)
Icelandair (FI 644), Duration: 05:50
Arrival: Sun 5 Mar 2023, 06:35, Reykjavik Keflavik International (KEF)

Return Flight
Departure: Sun 12 Mar 2023, 16:50, Reykjavik Keflavik International (KEF)
Icelandair (FI 645), Duration: 06:30
Arrival: Sun 12 Mar 2023, 19:10, Washington Dulles International (IAD)

Iceland Basics

Emergency Number: 112
USA embassy: 595-2200

- *Currency:* Icelandic króna (IKR)
- *Exchange Rate:* 1 USD = ~142 IKR ($10 = 1,420)
- *Time zone:* GMT (5 hour difference from EST)
- *Credit Cards:* Accepted at most locations, even in rural areas. VISA and MasterCard are ubiquitous, AmEx less so
- *ATMs:* Available in all towns
- *Electricity:* 220 V/50 Hz, 2-pronged (CEE-type) – these are rounded prongs, not NEMA like our prongs
- *Tipping:* None
- *Etiquette:* Smoking is illegal in enclosed public spaces, bars, and restaurants. Remove shoes when entering homes. Shower thoroughly before entering spas and hot springs
- *Temperature:* March weather and climate: daily highs average around 37°F (3°C) and lows around 28°F (-2°C)
- *Cloud Cover:* The median cloud cover is 89% (mostly cloudy) and does not vary substantially over the course of the month
- *Precipitation:* The average probability that some form of precipitation will be observed in a given day is 78%, with little variation over the course of the month.
- *Wind:* Over the course of March typical wind speeds vary from 4 mph to 25 mph (light breeze to strong breeze), rarely exceeding 39 mph (gale).
- *Daylight:* ~11 hours of daylight (08:00–19:00)

Icelandic Language

Descended from Old Norse, Icelandic is a Germanic language which retains several phonetic characters that have fallen out of use in modern English. Icelandic is the national language of Iceland, but citizens learn English in primary school and generally speak it well. As is always the case when travelling internationally, a little knowledge and effort in the local native language will go a long way, even if the conversation could easily be accomplished in English. Below is a list of common characters, and how they are pronounced1:

Below is a list of common characters, and how they are pronounced[1]:

Character	Pronunciation
Á á	ow (as in "how")
Ð ð	dh (as "th" in "that")
É é	ye (as in "yet")
Í í	ee (as in "see")
Ó ó	oh (as "note")
Ú ú	oo (as in "too")
Ý ý	ee (as in "see")
Þ þ	th (as in "think")
Æ æ	ai (as in "aisle")
Ö ö	eu (as "u" in "nurse")

Below is a list of common and useful expressions[1,2]:

Hello	Halló
How are you?	Hvað segir þú gott?
Excuse me	Afsakið
Yes	Já
No	Nei
Please	Takk
I'm fine	Allt fínt
Can you show me on the map?	Geturðu sýnt mér á kortinu?
What's your name?	Hvað heitir þu?
My name is…	Ég heiti…
Where are you from?	Hvaðan ertu?
I'm from…	Ég er frá
Good morning/afternoon	Góðan daginn
Goodbye	Bless
Cheers!	Skál!
How much is this?	Hvað kostar þetta?
Sorry	Fyrirgefðu
Thank you	Takk fyrir (or just takk)
How do you say … in Icelandic?	Hvernig segir maður … á íslensku?
Do you have vegetarian food?	Hafið þið grænmetisrétta?

[1]Lonely Planet: Iceland. Presser, B., Bain, C., and Parnell, F., 2013.
[2]Harvard EPS Graduate Student Field Trip to Iceland. Sterenborg, G., Crowley, J., Kiser, E., 2009.

BRIEF ITINERARY

Day 1: Saturday, March 4th, 2023 – Board flight

7:40 PM: Depart from Dulles, Washington, DC (IAD) Icelandair – Flight 644 (economy)
YOU WILL NEED TO GET YOURSELF TO DULLES AIRPORT
PLEASE ARRIVE AT LEAST 2 HOURS BEFORE THE FLIGHT

Day 2: Sunday, March 5th, 2023 – Reykjanes Peninsula

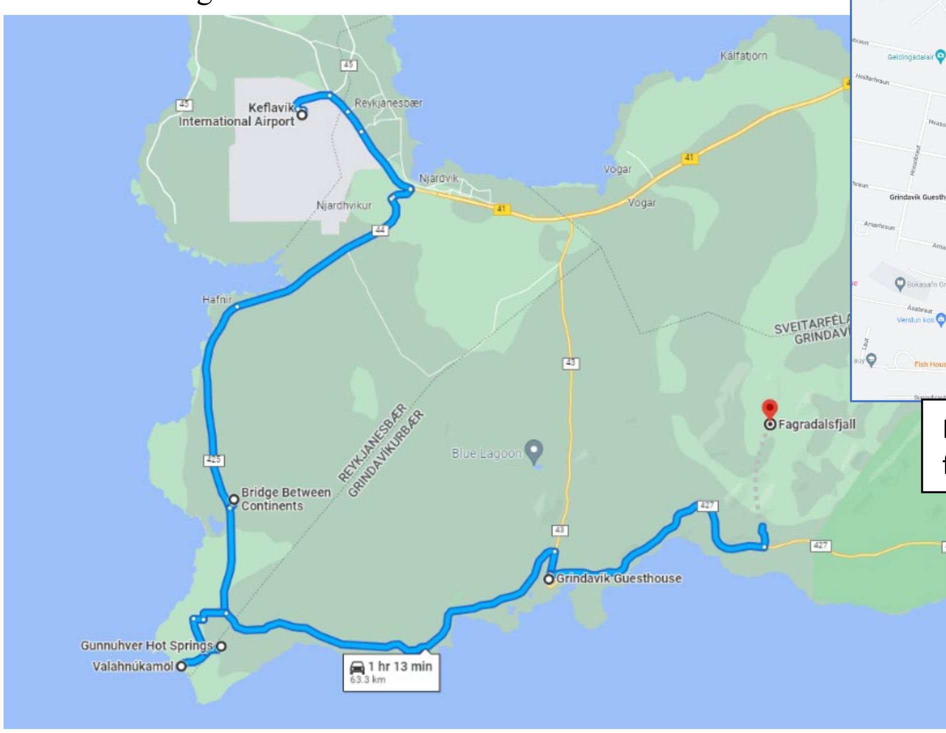
6:35: Arrive in Keflavik, Iceland on the Reykjanes Peninsula (30 miles south of Reykjavik)
7:30: After clearing customs, we'll meet by the café.
8:00: Grab breakfast at the airport
8:30: Load into the bus. Here is the info for the bus company:

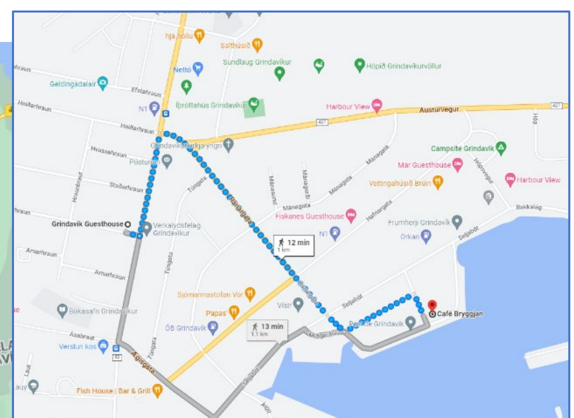
SBA - Norðurleið (https://www.sba.is/en)
Hjallahraun 2, 220 Hafnarfjörður, Iceland
Email: sba@sba.is, Phone number: +354 5 500 770
Emergency number: +354 858 0720

9:00: Stop at Bridge between Two Continents near Sandvik. We'll talk about Mid Atlantic Ridge, the boundary between the North American Plate and the Eurasian Plate.
10:00: Valahnúkamöl cliff. See the contact between tuff and pillow lava.
11:00: Gunnuhver hot spring and an introduction to geothermal activity.
12:30: Lunch in Grindavik – There is a café called Café Bryggjan (https://www.bryggjan.com/) that should be fine….
2:00 PM: Check into the guesthouse in Grindavik

Grindavik Guesthouse (https://www.grindavikguesthouse.is/)
Borgarhraun 2, 240 Grindavík, Iceland
Email: info@grindavikguesthouse.is, Phone: +3545114646

3:00 PM: Hike to Fagradalsfjall Volcano (Sunset is at 6:58 PM)
6:30 PM: Return to guesthouse, fend for yourself for dinner. You could go out or cook, the guesthouse has a kitchen.

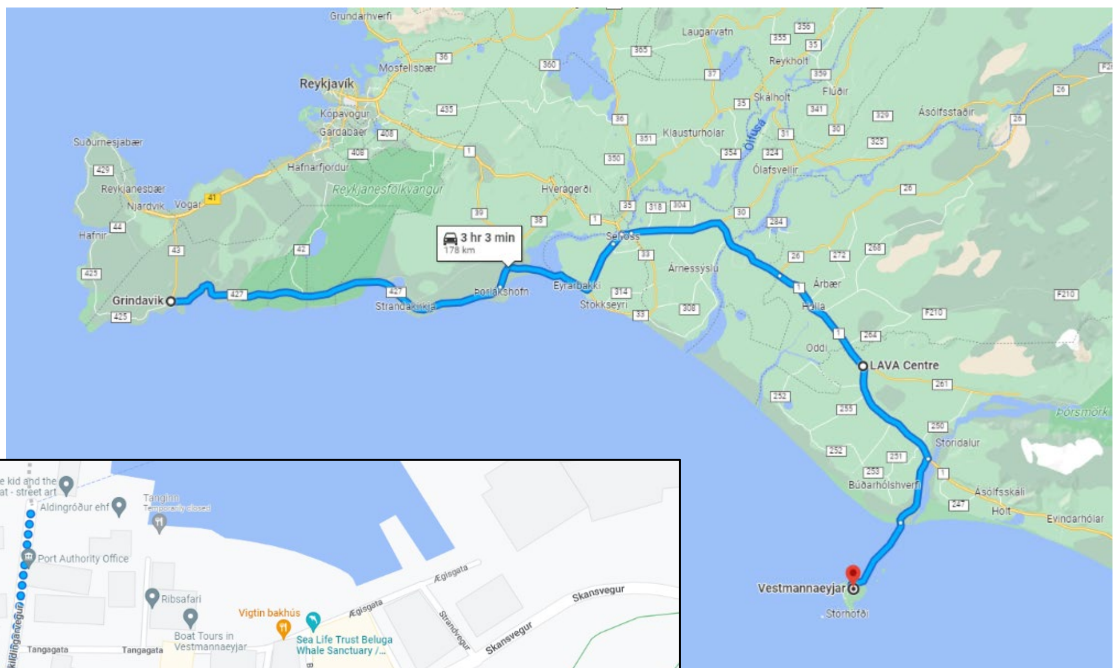


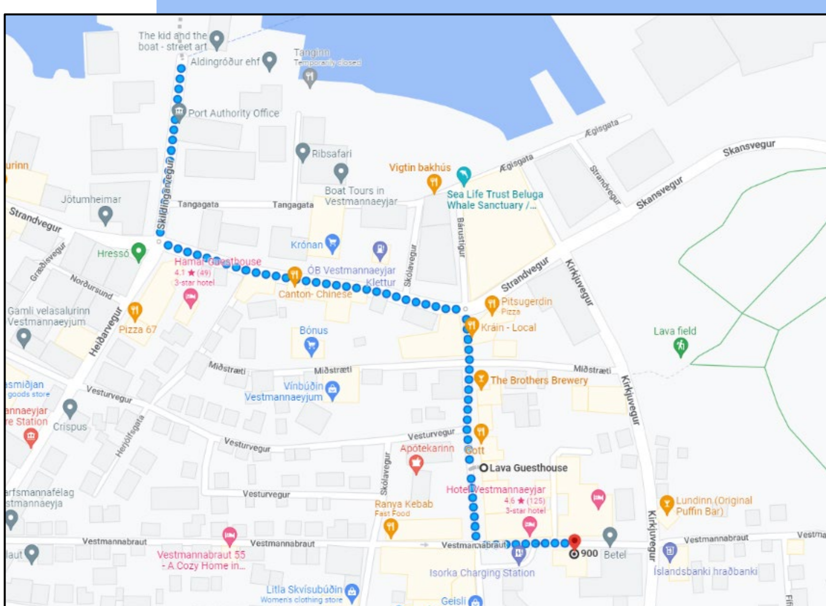


Downtown Grindavik with the route from the hostel to the lunch spot

Day 3: Monday, March 6th, 2023 – Grindavik to Vestmannaeyjar

7:00AM: Wake up, pack up, breakfast is provided at the guesthouse.
8:00AM: Load the bus and leave the guesthouse
10:00AM: Arrive at LAVA Centre (https://lavacentre.is/) and tour the museum, people can buy lunch here or on the ferry to Vestmannaeyjar
12:30PM: Depart from the LAVA Centre
1:00PM: Board the ferry and depart for Vestmannaeyjar
2:00PM: Arrive Vestmannaeyjar, check-in to the guesthouse
Lava Guesthouse (https://lavaguesthouse.com/)
Bárustígur 13, 900 Vestmannaeyjabær, Iceland
Email: info@lavaguesthouse.com Phone: +354 659 5400
3:00PM: Eldheimar Volcano Museum (https://www.eldheimar.is/)
6:00PM: Group dinner at 900 Grillhouse (http://www.900grillhus.is/)





Downtown Vestmannaeyjar with the route from the ferry terminal to the guesthouse and dinner location

Day 4: Tuesday, March 7th, 2023 – Vestmannaeyjar to the Rift Valley

7:00AM: Breakfast in the guesthouse, pack up, and load into the buses.

Breakfast is not included, so probably grab something at the store the night before…

8:00AM: Leave the hostel and drive around the island, first stop Elephant Rock

9:00AM: Pirate Cove & Storhofdi - south edge of the island, hike around, good view of Surtsey

11:00AM: Climb Eldfell Volcano

1:00PM: Go into town, grab lunch on your own, and wait for ferry

2:00PM: Board the ferry and depart for the mainland

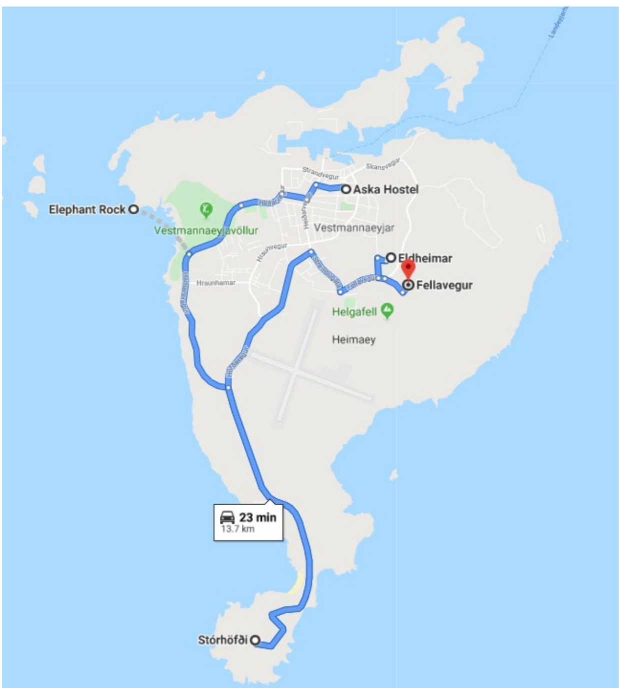
3:30PM: Reach Landeyjahofn and drive to the guesthouse

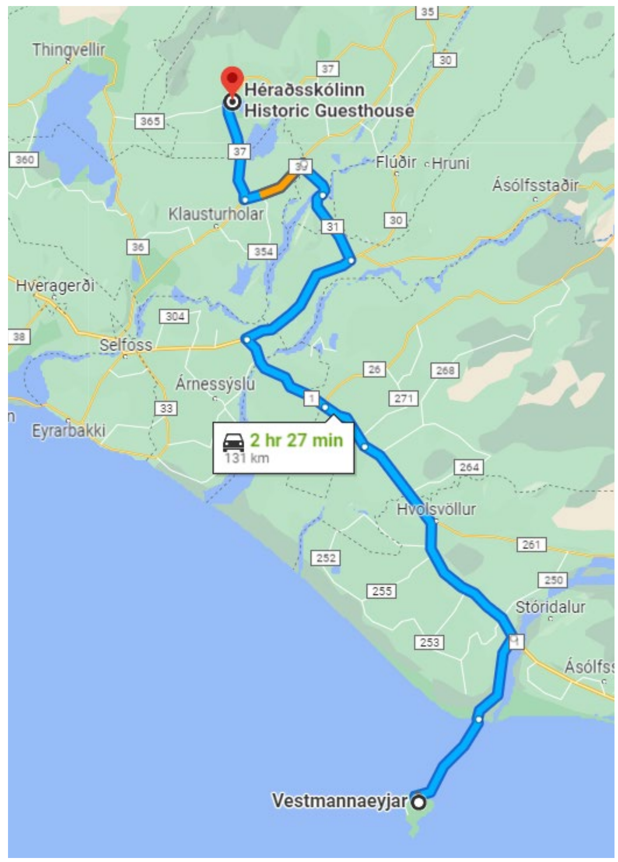
5:30PM: Check-in at the guesthouse

Héraðsskólinn Guesthouse (https://heradsskolinn.is/contact/)
840 Laugarvatn, Iceland
Email: booking@heradsskolinn.is, Phone: +354 537 8060

6:00PM: Group dinner at the guesthouse

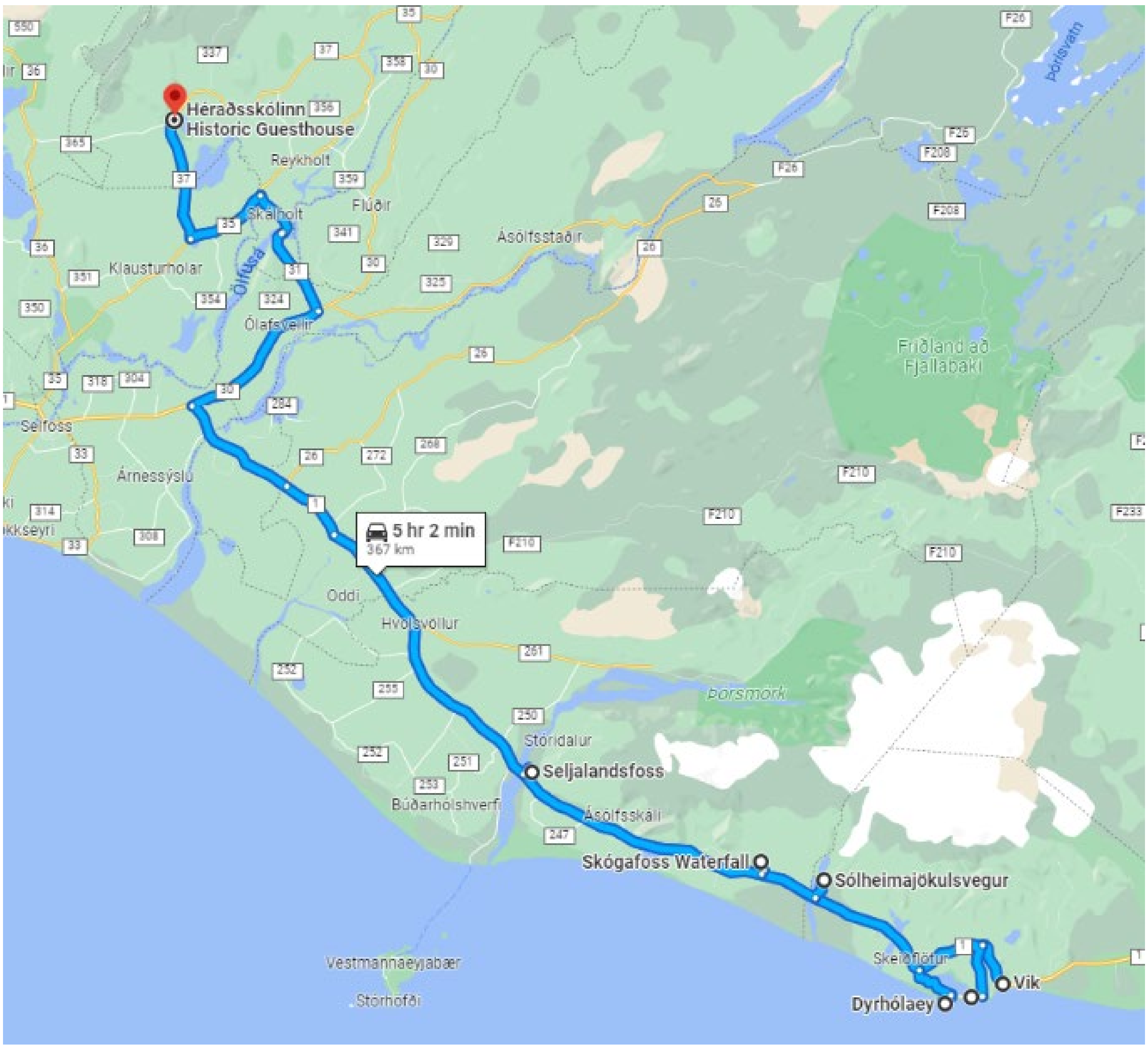
That evening: I am hoping this location will give us a good shot at seeing the Aurora Borealis





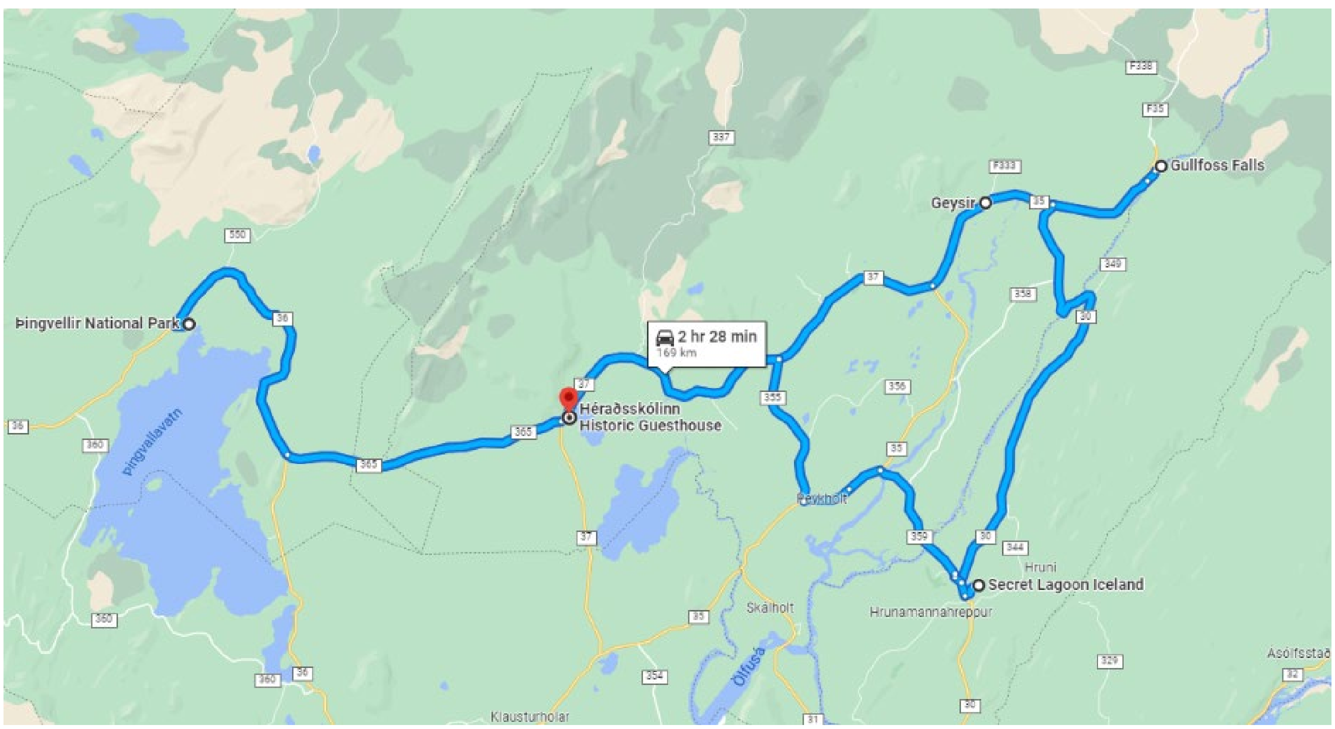
Day 5: Wednesday, March 8th, 2023 – Waterfalls, Glaciers and Vik Beaches

7:00AM: Wake-up, breakfast is provided by the guesthouse.
8:30AM: Depart from the hostel
11:00AM: Arrive at Vik – Walk along the beach
12:00PM: Lunch at the beach! (Our guesthouse will be providing box lunches to take with us)
1:00PM: Arrive at Renisfjara Beach
2:00PM: Arrive at Dyrholaey Viewpoint
3:00PM: Sólheimajökulsvegur Glacier
4:30PM: Arrive at Skogafoss waterfall.
5:15PM: Arrive at Seljalandsfoss waterfall.
6:30PM: Arrive back at the guesthouse
7:00PM: Group meal at the guesthouse



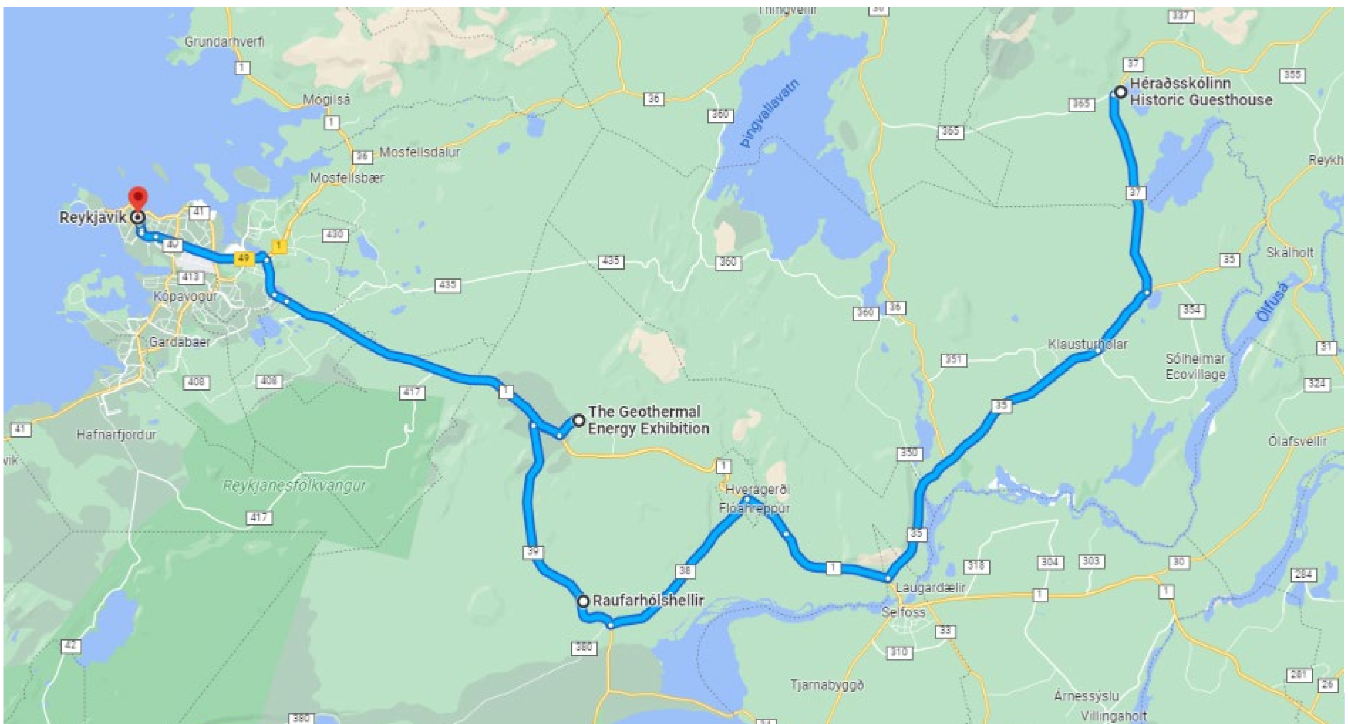
Day 6: Thursday, March 9th, 2023 – Þingvellir, Geysir, Gullfoss, and Hot Springs

7:00AM: Wake-up, breakfast at the guesthouse
8:30AM: Depart for Þingvellir National Park
9:00AM: Arrived at Þingvellir National Park
9:30AM: Walk to the Law Rock and through the rift valley
11:00AM: Depart for Geysir
12:00PM: Arrive at Geysir, have lunch at the café (Our guesthouse will be providing box lunches to take with us)
1:00PM: Walk the hydrothermal spring and geyser trail
1:45PM: Leave for Gullfoss (Golden Waterfalls)
2:00PM: Arrive at Gullfoss visit the fall and visitor's center
2:30PM: Depart for Secret Lagoon Hot Springs, Fludir (https://secretlagoon.is/)
3:00PM: Arrive at Secret Lagoon Hot Springs
5:00PM: Depart for the guesthouse or Dinner in Fludir? (https://minilik.is/)
6:00PM: Arrive at the guesthouse
6:30PM: Group dinner



Day 7: Friday, March 10th, 2023 – Raurfarholshellir Lava Tube, Hellisheiði Power Plant, and Reykjavik

7:00AM: Wake-up, have breakfast, pack our things, and load the vans.
8:00AM: Depart for Raurfarholshellir Lava Tube
9:00AM: Take a tour of the Raurfarholshellir Lava Tube (http://thelavatunnel.is/)
11:00AM: Take a tour of the Hellisheiði Power Plant geothermal museum and tour (https://www.on.is/en/geothermal-exhibition/)
12:30PM: Finished tour. Have lunch. (Our guesthouse will provide box lunches to take with us)
1:30PM: Arrive in Reykjavik. Check-in at the guesthouse
Guesthouse Aurora (https://www.aurorahouse.is/)
Freyjugata 24, 101 Reykjavík, Iceland
Email: book@aurorahouse.is, Phone: +354 899 1773
Rest of the Day: Enjoy Reykjavik, you are on your own.



Downtown Reykjavik

Day 8: Saturday, March 11th, 2023 – Free Day in Reykjavik

All day – This is a free day, there is a lot to do in the city, enjoy!
6:00 PM: Group Dinner, location to be determined.

Day 9: Sunday, March 12th, 2023 – Reykjavik, Blue Lagoon, and return home

Morning: Wake-up and have breakfast (provided by the guesthouse), hang out in Reykjavik
11:00: Check out of the guesthouse, load the bus, head to Blue Lagoon
12:00: Lunch and spa at Blue Lagoon (you have to pay for this on your own, it's about $55 each)
2:30PM: Into the bus and head to the airport
3:00PM: Arrive at the airport
4:50PM: Scheduled Departure Icelandair Flight 645
7:10PM: Scheduled Arrival in Dulles, Washington DC

YOU WILL NEED TO GET YOURSELF HOME FROM DULLES AIRPORT

INTRODUCTION

This entire section was taken from the 2010 Iceland Field Guide produced by the Columbia University Department of Earth and Environmental Sciences

General Information about Iceland

Contributed by Nevin Singh

Iceland is located in the Northern Atlantic Ocean, on the edge of the Arctic Circle, between latitudes 63^{0}24'N and 66^{0}33'N and between longitudes 13^{0}30'W and 24^{0}32'W. The closest countries are Greenland (286 km), Scotland (795 km), and Norway (950 km). The total area of Iceland is 103,000 km2 (39,756 mi2), which is about the size of Kentucky. The distance from the north to south coast is approximately 300 km (185 mi) and from east to west is approximately 500 km (305 mi). The coastline is 4,970 km long. The average elevation of Iceland is 500 m above sea level with the highest point being Hvannadalshnukur at 2,119 m (6,950 ft) on the Öræfajökull glacier. There are several islands that surround the coast, some of which are inhabited. These include the Westman Islands to the south, Hrisey in the north, and Grimsey in the Arctic Circle.

The climate of Iceland is a relatively mild (with respect to its northern latitude) coastal climate. The average summer temperature in Reykjavík is 10.6^{0}C (51^{0}F) in July, with average highs of 24.3^{0}C (76^{0}F). The average winter temperature in Reykjavík is about 0^{0}C (32^{0}F) in January. In general, the southern and western lowland coastal areas enjoy milder temperatures than the central highlands due to the warm waters of the Gulf Stream. The annual precipitation varies from 3,000 mm on the south coast to 400 mm in the highlands. Coastal areas tend to be windy especially in winter.

The Northern Lights can often be seen in autumn and early winter. Due to its latitude, Iceland receives highly variable amounts of sunlight throughout the seasons. For two to three months in summer there is nearly continuous daylight and from mid-November to the end of January, the country receives only about three to four hours of daylight.

Iceland is the most sparsely populated country in Europe with an average of about 3 inhabitants per square kilometer. Almost 80 percent of the country is uninhabited, with most people living on the coasts, valleys, and southwest corner of the country. In 2022, the population was 372,000 with 2/3 of them living in the capital of Reykjavík . The life expectancies for men and women (78 and 82 years, respectively) are among the world's highest averages. The country's written and spoken language is Icelandic, a Nordic language very similar to that of the original settlers. Icelandic and Norwegian did not become markedly different until the 14th century. Icelanders have resisted change to their language and, still today, Icelandic is very similar to the language that existed in the 12th century. The literacy rate is 99.9%, the highest in the world.

Iceland's currency is the krona, which in December 2022 traded at 142 krona to the dollar. Iceland's economy had an estimated GDP of $25.5 billion in 2022, with a GDP per capita of $68,383 (US GDP per capita ~$69,287). The economy is based on a Scandinavian-type social market economy that combines a capitalist structure with an extensive welfare system. Iceland's economy is highly export-driven with marine products accounting for the majority of exports. The fishing industry provides 70% of export income and employs 6% of the workforce. Other exports include aluminum, machinery, electronic fishing equipment, software, and woolen goods. Through hydroelectric and geothermal resources, Iceland is able to generate 85% of its primary energy and 100% of their electricity from renewable energy sources. Their goal is to be completely energy independent, using 100% renewable energy by 2040.

Historical and Cultural Background

Contributed by Chris Hayes

Iceland may have been visited periodically by Irish-Scottish monks seeking solitude in the 8th century, but it is has been thought that they fled once the Norseman started arriving. The first permanent settler of Iceland was Ingólfur Arnarson, a Norseman who arrived in the year 874 C.E. As his ship approached the Icelandic coast, Ingólfur threw his “high seat”, or large carved wooden pillars, overboard. For good luck, he decided to make his settlement wherever the pillars washed ashore. Several years after he arrived in Iceland, he found the pillars on the shores of what is today Reykjavík, the country’s modern capital. Our group came to Iceland through Reykjavík just as Ingólfur had over 1,100 years ago but not by sea. Instead, we came by air and therefore we were not allowed to throw our high seats from the plane before arriving.

Iceland is unique among the European nations for having one of the earliest and longest lasting forms of democratic governance. The AlÞing, or General Assembly, was founded in 930 C.E. at Þingvellir (our second campsite). Once a year, representatives from all around the country would gather in Þingvellir to make new laws and recall existing ones, though nothing was written down. One poor fellow, the lawspeaker, would recite the existing law (or at least a portion of it) by memory at the Law Rock and other members would make sure he had remembered correctly. Crimes were also often dealt with at the AlÞing, but because there was no executive power to enforce decisions it was often up to the aggrieved party to exact retribution (often by quite brutal means). Luckily, our group did not make any infractions to punish (maybe only getting up late). The AlÞing continued in nearly this same form until 1800 when more conventional assemblies were founded in Reykjavík. Icelanders returned to Þingvellir for an assembly in 1944 when the independent Republic of Iceland was formed, finally free of the Norwegian and Danish monarchies, which had influences throughout prior centuries. Today, the sight is devoid of any man-made structures (and we are not sure if there were ever any). In addition, the water table has risen significantly (probably due to thermal subsidence of the region) turning a confined river ecosystem into a marshland.

On our first night in Reykjavík, we ate at a seafood restaurant where we became aware of Iceland’s close relationship to the fishing industry. It’s actually one of the reasons Iceland has been reluctant to join the European Union, for fear their fishing rights will be curtailed. The infamous Cod Wars of the 1950’s and 1970’s were fought between Iceland and the United Kingdom over who had rights to fish in which waters. Nets were cut, shots were actually fired, and ships were rammed. Nonetheless, following the 2008 financial crisis, Iceland has formally bid to join the EU (July 2010) and they may become members as soon as 2013. Back to dinner that night, as Iceland is one of the three countries (along with Norway and Japan) remaining to hunt whale commercially, our seafood buffet included strips of seasoned minke whale meat. Some ventured to try it, but it my opinion, moral quandaries aside, the brown and fatty cutlets did not look appetizing.

Icelanders are fiercely proud of their language. How else could one feel if their tongue had been nearly unchanged since the Vikings spoke it? Words are difficult for Anglophones to pronounce. There’s just no way around that. In fact, our glacier-walk guide (a native Icelander) said that even when listening to immigrants who have lived in Iceland for 10 years or more, he cannot understand a word they are saying. The guide told us his name was “Gummi” like a gummy-bear. It turned out his real name was something so unpronounceable for non-Icelandic speakers that he found it easier to go by the name of a familiar candy.

If one does venture out on the town in Reykjavík it is easy to find numerous establishments of social gathering within a fairly confined portion of downtown. The young people of the city pour out into the streets especially on weekend nights but not until the small hours of the morning – another manifestation of the seasonal sleep patterns of Icelanders. Similarly, Helgi Björnsson, an Icelandic glaciologist from the University of Iceland’s Science Institute whom we met with at Skaftafell, found it perfectly reasonable to stay out with us in the field until midnight; he only had a three hour drive back to Reykjavík afterwards. Apparently, it's usual to stay awake for some 18-20 hours a day in the summer, presumably to be compensated by extended slumbers in the winter.

All in all, Iceland has a very rich history colored by fabled characters, family feuds, and love triangles. Many of these stories are recorded in The Book of Settlements, written by the famous medieval writer Snorri Sturluson (who was twice elected Lawspeaker at the AlÞing) as well as in the many passionate and brutal Icelandic Sagas. Iceland is also unique to have such prodigious writings during what continental Europe might call the Dark Ages (1200-1500), of little intellectual progress. The modern culture still holds many superstitions and spiritual viewpoints conveyed by the Sagas, including the belief in elves and trolls. Considering the strange lunar-like landscapes of basalt and moss fields, steaming hydrothermal areas, and fissures, which pop up almost everywhere, I am not surprised. Even in my short time there, I could also swear I've seen human-sized figures lurking in the distance. In fact, it's not hard to see the same type of lurking figures in the alleyways of New York City. But in all seriousness, the Icelandic perspective of spirituality, common law, and observance of nature may have something to teach the rest of the world.

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GEOLOGIC OVERVIEWS

Introduction to the geology of Iceland

Iceland is located in the North Atlantic Ocean between Greenland and Norway between 63°23´N to 66°30´N and between 13°30´W to 24°30´W. It is a landmass that is part of a much larger entity situated at the junction of two large submarine physiographic structures, the Mid-Atlantic Ridge and the Greenland-Iceland-Faeroes Ridge.

Iceland is located where the asthenosperic flow under the northeast Atlantic plate boundary interacts and mixes with a deep-seated mantle plume. The buoyancy of the Iceland plume leads to dynamic uplift of the Iceland plateau, and high volcanic productivity over the plume produces a thick crust. The Iceland plume track of the northeastern Atlantic through history is presented by the Greenland-Faeroes Ridge (Fig. 1). During the last 60 Ma Greenland, Eurasia and the northeast Atlantic plate boundary have migrated north-westwards at a rate of 1-3 cm/a relative to the surface expression of the Iceland plume (Lawver & Müller 1994). Today the plume channel reaches the lithosphere under the Vatnajökull glacier, about 240 km southeast of the North American-Eurasian plate boundary (Lawver & Müller 1994). During the last 20 Ma the rift zones have migrated stepwise eastwards, because of the force of the Iceland plume, leading to a tricky and changing pattern (Fig. 2.) of the Icelandic rift zones.

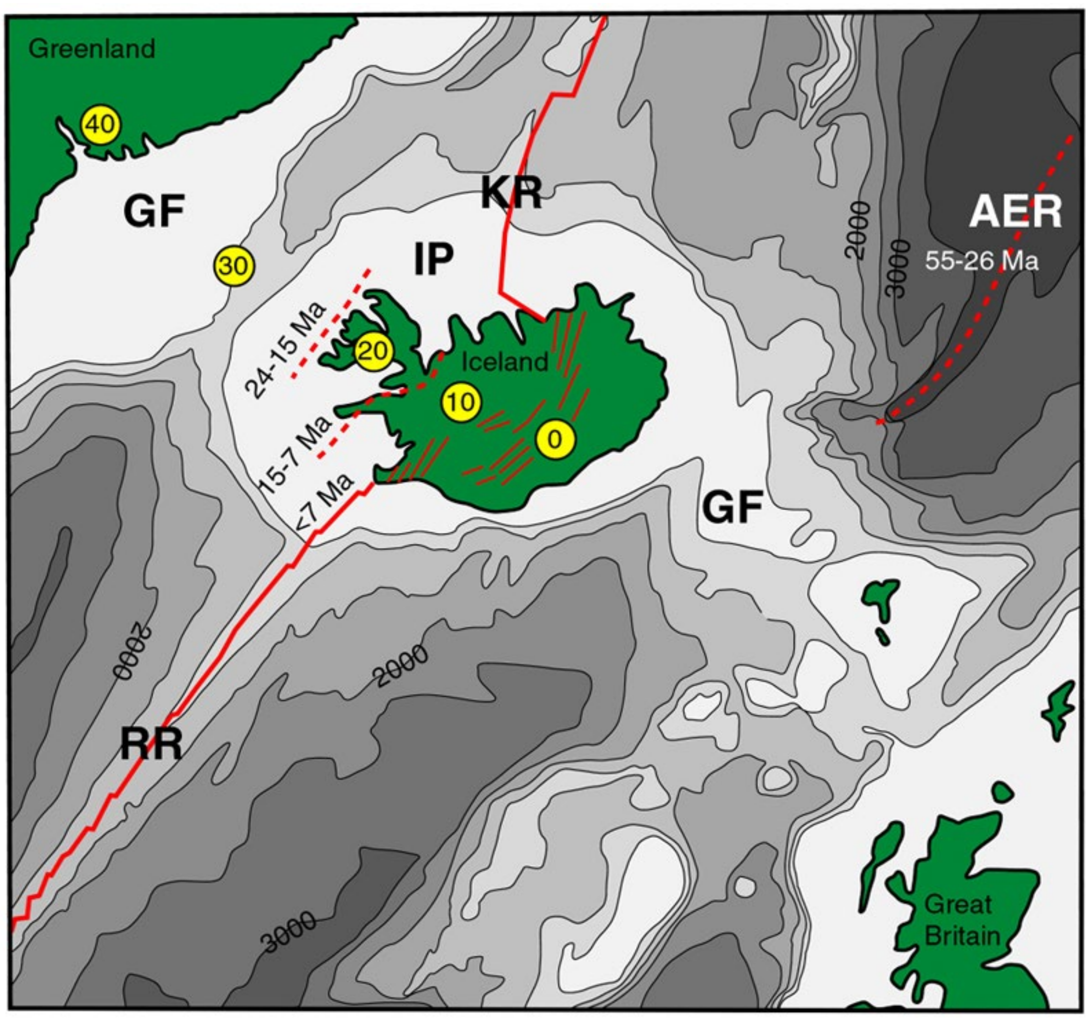

Fig. 1 Bathymetry of the area around Iceland (depth contours for each 500 m). The position of the Iceland plume relative to Greenland and Iceland at ages of 40, 30, 20, 10 and 0 Ma is indicated by the yellow circles. Continuous (red) and dashed (red) lines show the active and inactive spreading axes. The active rift zones in Iceland are shown as individual fissure swarms in red colour. RR: Reykjanes Ridge; KR: Kolbeinsey Ridge; AER: Aegir Ridge; IP: Iceland Plateau; GF: Greenland, Faeroer Ridge. Map modified after Maclennam (2001) and Kaban et al. (2002).

History of the North-East Atlantic

During the opening phase of the northeast Atlantic 60-55 Ma ago, the Iceland plume was centred under central Greenland. (Lawer & Müller 1994). The reconstruction of the Iceland plume track relative to Greenland, the Atlantic Ocean and northern Canada in combination with the locations of continental flood basalt may suggest that the plume activity goes back to about 130 Ma and causes mid-Cretaceous volcanism along the Arctic Mendelev and Alpha Ridges and on Ellsmere Island (Lawer & Müller 1994 1994; Johnston & Thorkelsen 2000). A large plume head 2000 km in diameter centered under Greenland accumulated prior to the early Tertiary continental break-up and rifting (Saunders et al. 1997).

The hot plume head material under the continental lithosphere eventually resulted in lithospheric doming and widespread basaltic volcanism (Saunders et al. 1997). 56-53.5 Ma ago the continental break-up and formation of ocean crust started (Vogt & Avery1974).

The early seafloor spreading occurred along the now extinct Aegir Ridge (Fig. 1), northeast of the Iceland plume track. The southern ends of the Aegir axis bends westwards to link with the Reykjanes Ridge on the southwestern side of the Greenland-Faeroer Ridge (Talwani & Eldholm 1977). The Greenland drift north-westwards reduced the distance between East Greenland continental margin and the plume stem, leading to another period of continent rifting along the outermost East Greenland margin at about 36 Ma (Vink 1984) The following seafloor spreading along the commencing Kolbeinsey Ridge occurred parallel with the Aegir axis spreading up to about 25 Ma, as the Aegir axis became extinct. At this stage the Icelandic rift segments became more firmly linked to the Iceland plume. At 20 Ma the Reykjanes-Kolbeinsey plate boundary passed over the plume and has since drifted to a position 240 km northwest of the Plume under Vatnajökull. The 300-400 km long Icelandic rift segments have jumped repeatedly southwestwards to maintain their position near the plume (Fig. 2).

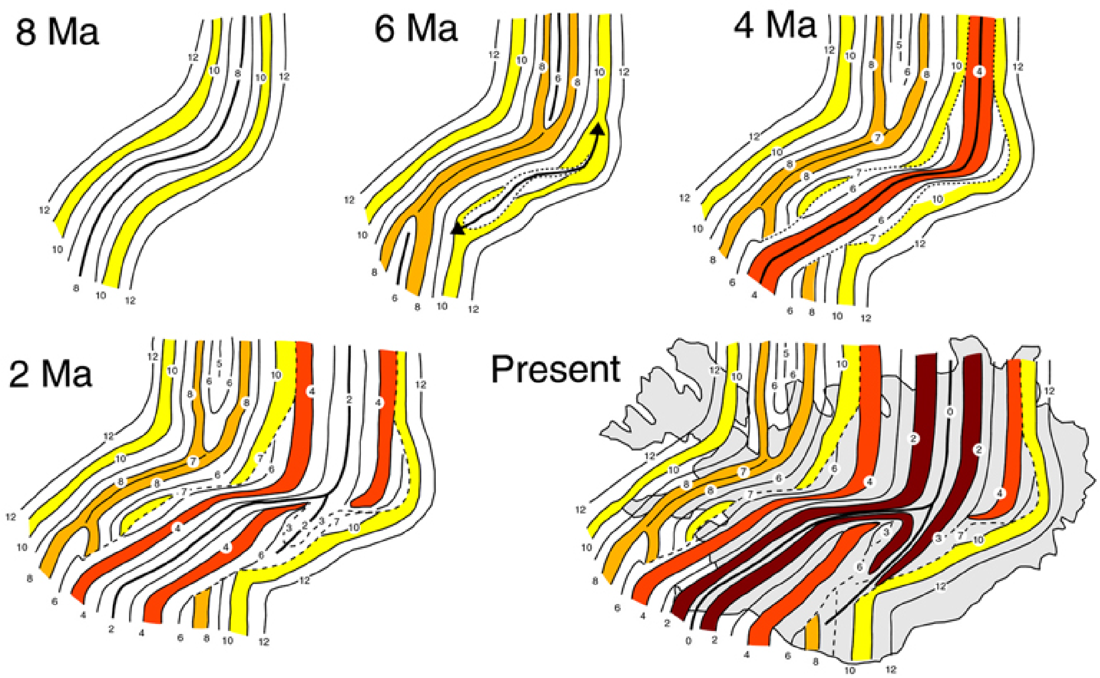

Fig. 2 Crustal accretion, relocation and propagation of the Icelandic rift zones in the last 12 Ma. The cartoons show map views for 8, 6, 4, 2 and 0 Ma. The 8 Ma cartoon shows the spreading along the Snaefellsnes and Skagi rift zones. The 6 and 4 Ma cartoons demonstrate the incipient propagation and mature development of the Western and Northern Rift Zones after the new rift initiation at about 7 Ma. The 2 and 0 Ma cartoons show the southwards propagation of the Eastern Rift Zone, initiated at about 3 Ma. Based on data from Saemundsson (1979) and J´hannesson (1980) and a synthesis by IVvarsson (1992).

The Icelandic volcanic system

The recent active volcanic systems in Iceland are shown in Fig. 3 (e.g. Saemundsson 1979; Einarsson 1991; Jóhannesson & Saemundsson 1998).

The 40-50 km wide rift zones (Northern, Eastern, Western and Reykjanes Rift Zones) contain en-echelon alignments of volcanic fissure swarms (5-15 km wide and up to 200 km in length), with 3-4 semi-parallel swarms across the rift zone width. With time, they develop volcanic centres with centralised volcanic production normally in the central part. The volcanic centres often develop into central volcanoes with high geothermal activity. Sometimes also caldera structures produced by large eruption of silicic magma (Einarsson 1991). In the non-rifting volcanic flank zones (e.g. Snaefellsnes, Eastern and Southern Flank Zone, see Fig. 3) the volcanic centres mostly have a lack of fissure swarms and additionally also the geothermal activity is generally lower in the off-rift volcanic systems (Jakobsson 1972; Einarsson 1991).

"A volcanic System (volcanic fissure swarm or together with central volcano) is a spatial grouping of eruption sites, including upper crustal feeder dikes, active within a relatively short period of time and with certain limited tectonic, petrographic and geochemical characteristics" (Jakobsson 1979).

The Reykjanes Peninsula is a zone of high seismicity and recent volcanism, with a large component of regional sinistral shear movement, and with four volcanic systems. The easternmost Hengill volcanic system lies at a triple junction between the Reykjanes Rift Zone (RRZ), Western Rift Zone (WRZ; Fig. 3) and the South Iceland Fracture Zone (SIFZ). The WRZ continues northeastward from the Hengill area and connects to the Northern Rift Zone (NRZ) via the Mid-Icelandic Belt (MIB), which may be formed a "leaky" transform zone (Einarssin 1991). The Western Volcanic Zone is presumably a dying rift zone, whereas the Eastern Volcanic Zone becomes the main spreading zone in South Iceland (Einarsson 1991).

The Northern Rift Zone (NRZ) continues the Icelandic rift zone system northward, from the Vatnajökull glacier (Fig. 3). The northern Vatnajökull area is currently the centre of the Iceland mantle plume (e.g. Wolfe et al. 1997). The active rifting along NRZ propagating southwards from the plume centre as the Eastern Rift Zone (ERZ). The Torfajökull volcanic system marked the transition between the ERZ and the South Eastern Zone (see Fig. 2).

Crustal structure

The Iceland Plateau and the Greenland-Faeroer Ridge are conspicuous bathymetric features in the North-East Atlantic (Fig. 1). As shown in figure 2.4 the shallow areas have anomalously thick oceanic crust, that results from the huge magma production in the plume (Kaban et al. 2002). The Moho beneath Iceland is seismically diffuse because of relatively low densities and seismic velocities in the uppermost mantle and relatively high densities and velocities in the lower crust. Recent models agree that the crustal thickness varies from about 45 km under the Vatnajökull glacier to less than 20 km under the northern part oft the Northern Rift Zone and the Reykjanes Peninsula (Fig. 4; Darbeshire et al. 2000; Kaban et al. 2002).

Dynamics of crustal accretion

The approximately 50 km wide rift zone is continuously covered by new (present day) lava flows and hyaloclastites. Nearly the entire rift zone area is covered with eruption products from Eem, Weichsel and Holocene (see Fig. 5, e.g. Jóhannesson & Saemundsson 1998), covering older units, which are subsided under the new surface load. Thermal subsidence force the burial of the older units, because the high volcanic productivity is anomalously high relative to the low spreading rate of about 1 cm/a in each direction (TRÖNNES 2002).

Observations from Tertiary areas in Eastern and Western Iceland confirm the subsidence of volcanic pile (e.g. Walker 1959). Glacial eroded areas expose 1500 m of the uppermost extrusive rocks (e.g. Walker 1959). The lava units dip gently towards the rift zones (current or extinct rift zones). The regional tilting is caused by the continuous loading and subsidence of the rift zone (Bödvarsson & Walker 1964; Saemundsson 1979). The dip is increasing gradually from near zero at the highest exposed levels of the pile to about 5-10° at sea level in east and west Iceland. The increasing dip is matched by individual lava groups thickening down the direction of dip (Saemundsson 1979). Based on these observations, Palmason (1981) developed a dynamic model for crustal accretion in Iceland (Fig. 6).

The cinematic processes of crustal accretion cause rocks deposited in the rift zone to subside towards higher temperatures where they suffer hydration and prograde metamorphism to zeolite, greenschist and amphibolite facies. This processes occur before becoming a part of the stable crustal plate (Òskarsson et al. 1982). As the hydrated rocks cross their solidus isotherm, silicic magma is formed by incongruent partial melting (Òskarsson et al. 1982).

Stratigraphy

The predominantly volcanic pile of Iceland, which ranges in age back about 16 Ma (Saemundsson 1979), is conventionally divided into four stratigraphic groups or series (see Fig. 5 and Fig. 7). This division is based on climatic evidence from inter-lava sediments or volcanic breccias and on palaeomagnetic reversal patterns supported by absolute age data (Saemundsson1979).

The four stratigraphic units are (after Saemundsson 1992):

Postglacial: last 9,000 to 13,000 a
Upper Pleistocene: back to 0.7 Ma
Plio-Pleistocene: 0.7 – 3.1 Ma
Tertiary: older than 3.1 Ma

Tertiary

The Tertiary area (Fig. 5) includes the classical plateau series typical of the fjord landscapes of Eastern Iceland and much of Northern and Western Iceland. Altogether Tertiary rocks cover about half of the total area of Iceland. The Tertiary lava pile shows little variation in lithologies; the stratigraphy is generally very regular with about 5 – 15 m thick lavas separated by minor clastic interbeds of volcanic origin. The monotony is interrupted where central volcanoes occur with their buried palaeotopography, acid rocks, hydrothermal alteration and irregular dip. About 15 of those have been defined and mapped in the Tertiary, but about 40 are suspected from occurrence of acidic rocks (Saemundsson 1979).

Plio-Pleistocene

Plio-Pleistocene rocks cover about a quarter of the total area of Iceland, occupying broad zones intermediate between the Tertiary areas and the neovolcanic zones (Fig. 5). The boundary between the Tertiary and Plio-Pleistocene series is somewhat arbitrarily fixed at the base of the Mammoth event 3.1 Ma ago. About this time the first tillites appear interstratified with the lavas in southwestern Iceland and in northeastern Iceland (Saemundsson 1979). Also at this time a marked climatic cooling occurred (Saemundsson 1979). Volcanism proceeded along the same pattern during the Plio-Pleistocene as during the Tertiary with elongated volcanic systems. Six central volcanoes have been mapped in southwestern Iceland and another four may exist in southeastern Iceland (Saemundsson 1979). The main part of the Plio-Pleistocene series is conformable with the Tertiary series, where is no stratigraphic or structural break between these two. Instead of primal subaerial flows of the Tertiary, from the Plio-Pleistocene subglacial volcanic material with pillow lavas and various types of breccia and hyaloclastites are commonly interstratified with the lavas (Saemundsson 1979). The Plio-Pleistocene is characterized by alternating warm and cold climate, when glaciers advanced to a degree that much of Iceland was covered by ice (Saemundsson1979).

Upper Pleistocene

The Upper Pleistocene series (Fig. 5) comprises rocks formed during the Brunshes magnetic epoch that began 0.7 Ma ago, excluding the Postglacial. It covers a quarter of the total area of Iceland, an area which is essentially identical with the neovolcanic zone. An unconformity usually marks the boundary to the underlying Plio-Pleistocene series (Saemundsson, 1979). The unconformity found at the base of the Upper Pleistocene series is caused by volcanic products of the axial rift zones extending far beyond the rift axis forming a transgressive apron of lava flows (Saemundsson 1979). The volcanic rocks from the Upper Pleistocene can be divided into two types. One type comprises extensive subaerial lava flows erupted during interglacial periods and the second type comprises subglacial pillow lavas and hyaloclastites rocks, that were preserved as ridges or table mountains (Saemundsson 1979).

Postglacial

The Postglacial series comprise lava flows and pyroclastics, unconsolidated marine clays, fluvioglacial and fluvial outwash and soil formed after deglaciation of the land area. Postglacial volcanism continued along the same pattern as during the last glacial and interglacial periods. 24 volcanic system (Fig. 5) have been active in postglacial time that covers 10 % of the total surface of Iceland (Saemundsson 1979).

Geothermal Power Generation

Contributed by Dan Huber

Iceland's unique geography allows the country to take advantage of its significant geothermal power potential. The area has high-grade heat at relatively shallow depths as well as numerous active volcanoes and geothermal sites due to its location over the Mid-Atlantic Ridge and a deep mantle plume. There are at least 20 sites where temperatures re over 250° C at a depth of 1000 meters. In addition, there are around 250 sites with low-grade heat at 150° C at a depth of 1000 meters that are of a lesser interest to geothermal generation projects[1]. As a result, geothermal power is one of two major sources of energy on the island (the other being hydroelectric power). Geothermal heating produces more than just electricity, it also supplies heat and hot water to almost 90% of all buildings in Iceland[1].

Iceland utilizes several different types of geothermal plants to make use of the available energy. The simplest and oldest design is a dry steam plant, which directly uses hot steam to power a turbine. However, at present the design is not commonly used in Iceland. The most common type of plant in Iceland is the flash steam cycle plant due to the high efficiency of the design. Flash steam power plants use hot water above 182° C from geothermal reservoirs. The reservoirs underground are at high pressures that keep the water in a liquid state despite the temperature being well above the boiling point at atmospheric temperature and pressure. At the surface the water is depressurized, causing the water to change phase into steam. This is the point at which the "flash" occurs. The resulting steam powers the turbines[2] that generate electricity. Flash steam plants emit small amounts of gasses that naturally occur in the underground reservoirs such as H_2S and CO_2. CarbFix, a project at the Hellisheiði Power Station seeks to re-inject the CO_2 underground where it mineralizes and is thus sequestered, potentially making the plant completely carbon neutral in the future [further discussion in the CO_2 Sequestration section][3]. Examples of the single and double flash steam cycle plants can be found at Krafla, Hellisheiði, and Nesjavellir[4].

Several plants are also of the Combined Heat and Power (CHP) variety. This type of plant uses excess heat from the electricity generation project to provide space heating and hot water to residential and industrial buildings. An interesting application of this concept is applied at the Svartsengi Power station where excess hot, mineral rich water is used to fill the Blue Lagoon, a large outdoor hot tub that is a major tourist attraction[5]. Other CHP plants include Hellisheiði and Nesjavellir, both of which provide heat and power to the greater Reykjavík area[4].

The other type of geothermal plant in use in Iceland is a binary combined cycle. This cycle uses a conventional flash steam cycle to generate electricity through the first turbine, but after that stage, the steam passes through heat exchangers. Heat exchangers use heat from the steam to vaporize a binary cycle fluid, such as isopentane. The cycle is able to use the lower pressure "waste" steam again due to the low boiling point of the binary cycle fluid. The fluid is vaporized by the steam and passes through a turbine to generate additional electricity. The vapor is then condensed and vaporized again by the effluent steam flow. The steam is re-injected into the geothermal field as a liquid after condensing in the binary fluid vaporizer and associated preheaters[2,6]. The binary cycle portion of the design is entirely self-contained and has no emissions of any kind. The only emissions would be as a result of an optional flash steam cycle prior to the binary cycle process. This type of process is newer and can be found in one of the plants at Svartsengi Power Station (OV4) and at the plant in Húsavík. The Húsavík plant runs a slightly different cycle known as the Kalina binary cycle. It uses a water-ammonia mixture as the binary fluid[4].

These technologies allow the power stations to extract energy more effectively from the geothermal fields. Cogeneration (CHP) and binary cycle plants increase the overall efficiency, although the thermal efficiency of a low temperature binary cycle is not high. Geothermal fields are not sources of limitless energy and the available heat must be used in a sustainable manner. Iceland is already a very low CO_2 emissions country, but the country is looking into ways to further reduce the impact by taking aim at vehicle emissions in the future. Geothermal power will continue to grow as demand increases and better technologies come online, increasing land use in areas with geothermal potential. Fortunately, most of the regions with wells are open to public access despite the industrial activity, which is a credit to the industry.

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Climate and Climate Change

Contributed by Amy Stypa

The climate of Iceland has a maritime climate with cool summers and mild winters. Due to Iceland's high latitude, the solar altitude is never large and there is a great difference in the length of day between summer and winter. Iceland is situated near the border between warm and cold ocean currents (Fig. 11) as well as warm and cold air masses. The polar front can almost always be found somewhere over the North Atlantic. The Icelandic Low is found a short distance from the country. A large part of precipitation in Iceland falls between the east and south while the forward part of cyclones arrive from the southwest. Cyclones bring large amounts of precipitation and strong winds. Additionally, Iceland's mountainous terrain is important to the weather, influencing temperature and precipitation based on elevation and the windward/leeward side. Iceland lies in a border region between two climatic types. In southern and western Iceland, a temperate rainy climate with cool and short summers dominates, but northern Iceland and the highlands have a snowy climate.

There have been at least five known major ice ages in the Earth's history, with the last glacial period of the Quaternary having ended approximately 10 ka. Within ice ages, there exist periods of more-temperate and more-severe glacial conditions referred to as glacial periods and interglacial periods, respectively. It is believed that temperatures during the period between 9 ka – 2.5 ka were several degrees warmer than today. Around 2.5 ka years ago, the climate in Iceland gradually became characteristic of the time of settlement.

The history of meteorological observations in Iceland is not long. The first nstrumental observations were made from 1749-1751 in Reykjavík. The first station with systematic and continuous weather observations was established in Stykkishólmur in 1845. In Iceland, glaciers began to retreat from the Little Ice Age maximum between 1850 and 1900. Retreats became quite rapid after 1930 and then experienced a slowdown after 1960. In 1985 the glaciers began to retreat again and today all non-surging glaciers in Iceland are receding. The monitoring of glacier mass balance (annual mass gain or loss at the surface) is the best way to infer climatic change with glaciers, but records are limited. Records of glacier lengths are long enough to provide information about climate variability.

For several decades, surface air temperatures in the Arctic have warmed at approximately twice the global rate. The average warming north of 60°N has been 1-2° C since a temperature minimum in the 1960s and 1970s. The three warmest years on record are 1939, 1941, and 2003. Iceland has an environment that is very sensitive to climatic changes. Deterioration in climate is usually accompanied by increased sea ice near the coasts, often obstructing navigation and hindering fisheries. A decrease in temperature has also caused the death of grasses and limits the growing season. On the other hand, the anticipated warming of 0.3° C per decade for Iceland could have dramatic effects including increased glacier surges, increased glacier outburst floods, and changes in runoff which influence hydroelectric power plants. Total glacial volume is expected to decrease by approximately 40% in the next century, with glaciers essentially disappearing in the next 200 years.

It is uncertain what impact climate change will have in Iceland. Natural fluctuations in temperature are greater in the North Atlantic than in most other oceanic areas, so the impact of increasing temperatures due to the greenhouse effect will differ depending on the direction of the short-term natural fluctuation. An increase in temperature could have some positive effects on marine resources and fish stocks. However, more insects could increase risks of disease in both plants and humans. A worst-case scenario for Iceland would be if climate change led to major disruptions in ocean circulation that may have a negative impact on fish stocks, thereby destroying the main export feeding their economy.

Changes in glacier runoff are one of the most important consequences of future climatic changes in Iceland. Rapid retreat of glaciers not only influences runoff, but also changes fluvial erosion patterns from currently glaciated areas and changes the course of glacial rivers, which all affect roads and communication lines. Glacial melt will also contribute to sea level rise. Future climate change is assumed to result in more warming in the winter than in the summer. Although glacier and ice caps in Iceland only constitute a small part of the total volume of ice globally, their responses to global warming are very important because they are some of the best monitored in the world.

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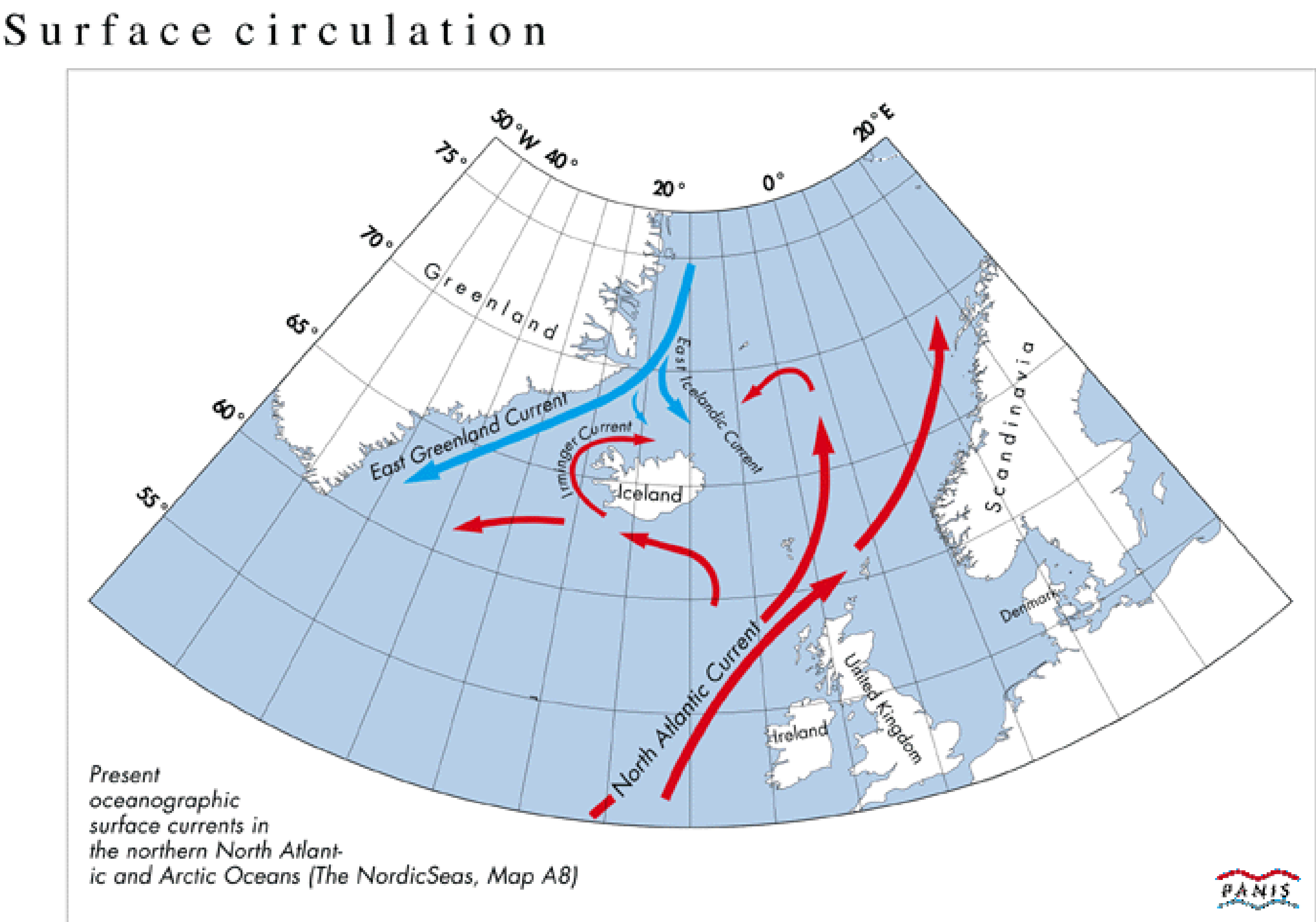


Figure 3. Present oceanographic surface currents around Iceland. Image source: http://www.hi.is/~jeir/panis_currents.html

An aurora, sometimes referred to as a polar light, is a natural light display in the sky, predominantly seen in the high latitude (Arctic and Antarctic) regions.[nb 1] Auroras are produced when the magnetosphere is sufficiently disturbed by the solar wind that the trajectories of charged particles in both solar wind and magnetospheric plasma, mainly in the form of electrons and protons, precipitate them into the upper atmosphere (thermosphere/exosphere), where their energy is lost. The resulting ionization and excitation of atmospheric constituents emits light of varying colour and complexity. The form of the aurora, occurring within bands around both polar regions, is also dependent on the amount of acceleration imparted to the precipitating particles. Precipitating protons generally produce optical emissions as incident hydrogen atoms after gaining electrons from the atmosphere. Proton auroras are usually observed at lower latitudes.[2] Different aspects of an aurora are elaborated in various sections below.

Occurrence of terrestrial auroras

Most auroras occur in a band known as the auroral zone,[3] which is typically 3° to 6° wide in latitude and between 10° and 20° from the geomagnetic poles at all local times (or longitudes), most clearly seen at night against a dark sky. A region that currently displays an aurora is called the auroral oval, a band displaced towards the nightside of the Earth. Day-to-day positions of the auroral ovals are posted on the internet.[4] A geomagnetic storm causes the auroral ovals (north and south) to expand, and bring the aurora to lower latitudes. Early evidence for a geomagnetic connection comes from the statistics of auroral observations. Elias Loomis (1860), and later Hermann Fritz (1881)[5] and S. Tromholt (1882)[6] in more detail, established that the aurora appeared mainly in the "auroral zone", a ring-shaped region with a radius of approximately 2500 km around the Earth's magnetic pole. It was hardly ever seen near the geographic pole, which is about 2000 km away from the magnetic pole. The instantaneous distribution of auroras ("auroral oval")[3] is slightly different, being centered about 3–5 degrees nightward of the magnetic pole, so that auroral arcs reach furthest toward the equator when the magnetic pole in question is in between the observer and the Sun. The aurora can be seen best at this time, which is called magnetic midnight.

In northern latitudes, the effect is known as the *aurora borealis* (or the northern lights), named after the Roman goddess of dawn, Aurora, and the Greek name for the north wind, Boreas, by Galileo in 1619.[7] Auroras seen within the auroral oval may be directly overhead, but from farther away they illuminate the poleward horizon as a greenish glow, or sometimes a faint red, as if the Sun were rising from an unusual direction.

Its southern counterpart, the *aurora australis* (or the southern lights), has features that are almost identical to the aurora borealis and changes simultaneously with changes in the northern auroral zone.[8] It is visible from high southern latitudes in Antarctica, South America, New Zealand, and Australia. Auroras also occur on other planets. Similar to the Earth's aurora, they are also visible close to the planets' magnetic poles. Auroras also occur poleward of the auroral zone as either diffuse patches or arcs,[9] which can be sub-visual.

Auroras are occasionally seen in latitudes below the auroral zone, when a geomagnetic storm temporarily enlarges the auroral oval. Large geomagnetic storms are most common during the peak of the eleven-year sunspot cycle or during the three years after the peak.[10][11] An aurora may appear overhead as a "corona" of rays, radiating from a distant and apparent central location, which results from perspective. An electron spirals (gyrates) about a field line at an angle that is determined by its velocity vectors, parallel and perpendicular, respectively, to the local geomagnetic field vector B. This angle is known as the "pitch angle" of the particle. The distance, or radius, of the electron from the field line at any time is known as its Larmor radius. The pitch angle increases as the electron travels to a region of greater field strength nearer to the atmosphere. Thus it is possible for some particles to return, or mirror, if the angle becomes 90 degrees before entering the atmosphere to collide with the denser molecules there. Other particles that do not mirror enter the atmosphere and contribute to the auroral display over a range of altitudes. Other types of auroras have been observed from space, e.g."poleward arcs" stretching sunward across the polar cap, the related "theta aurora",[12] and "dayside arcs" near noon. These are relatively infrequent and poorly understood. There are other interesting effects such as flickering aurora, "black aurora" and sub-visual red arcs. In addition to all these, a weak glow (often deep red) observed around the two polar cusps, the field lines separating the ones that close through the Earth from those that are swept into the tail and close remotely.

Visual forms and colors

The aurora frequently appears either as a diffuse glow or as "curtains" that extend approximately in the east-west direction. At some times, they form "quiet arcs"; at others ("active aurora"), they evolve and change constantly.

The most distinctive and brightest are the curtain-like auroral arcs. Each curtain consists of many parallel rays, each lined up with the local direction of the magnetic field, consistent with auroras being shaped by Earth's magnetic field. In-situ particle measurements confirm that auroral electrons are guided by the geomagnetic field, and spiral around them while moving toward Earth. The similarity of an auroral display to curtains is often enhanced by folds within the arcs. Arcs can fragment or 'break-up' into separate, at times rapidly changing, often rayed features that may fill the whole sky. These are the 'discrete' auroras, which are at times bright enough to read a newspaper by at night.[19] and can display rapid sub-second variations in intensity. The 'diffuse' aurora, on the other hand, is a relatively featureless glow sometimes close to the limit of visibility.[20] It can be distinguished from moonlit clouds by the fact that stars can be seen undiminished through the glow. Diffuse auroras are often composed of patches whose brightness exhibits regular or near-regular pulsations. The pulsation period can be typically many seconds, so is not always obvious. Often there black aurora i.e. narrow regions in diffuse aurora with reduced luminosity. A typical auroral display consists of these forms appearing in the above order throughout the night.[21]

- **Red:** At the highest altitudes, excited atomic oxygen emits at 630.0 nm (red); low concentration of atoms and lower sensitivity of eyes at this wavelength make this color visible only under more intense solar activity. The low amount of oxygen atoms and their gradually diminishing concentration is responsible for the faint appearance of the top parts of the "curtains". Scarlet, crimson, and carmine are the most often-seen hues of red for the auroras.
- **Green:** At lower altitudes the more frequent collisions suppress the 630.0 nm (red) mode: rather the 557.7 nm emission (green) dominates. Fairly high concentration of atomic oxygen and higher eye sensitivity in green make green auroras the most common. The excited molecular nitrogen (atomic nitrogen being rare due to high stability of the N_2 molecule) plays A role here, as it can transfer energy by collision to an oxygen atom, which then radiates it away at the green wavelength. (Red and green can also mix together to produce pink or yellow hues.) The rapid decrease of concentration of atomic oxygen below about 100 km is responsible for the abrupt-looking end of the lower edges of the curtains. Both the 557.7 and 630.0 nm wavelengths correspond to forbidden transitions of atomic oxygen, slow mechanism that is responsible for the graduality (0.7 s and 107 s respectively) of flaring and fading.
- **Blue:** At yet lower altitudes, atomic oxygen is uncommon, and molecular nitrogen and ionized molecular nitrogen takes over in producing visible light emission; radiating at a large number of wavelengths in both red and blue parts of the spectrum, with 428 nm (blue) being dominant. Blue and purple emissions, typically at the lower edges of the "curtains", show up at the highest levels of solar activity.[22] The molecular nitrogen transitions are much faster than the atomic oxygen ones.
- **Ultraviolet:** Ultraviolet light from auroras (within the optical window but not visible to virtually all humans) has been observed with the requisite equipment. Ultraviolet auroras have also been seen on Mars,[23] Jupiter and Saturn.

- **Infrared:** Infrared light, in wavelengths that are within the optical window, is also part of many auroras.[23][24]
- **Yellow** and **pink** are a mix of red and green or blue. Other shades of red as well as orange may be seen on rare occasions; yellow-green is moderately common. As red, green, and blue are the primary colors of additive synthesis of colors, in theory practically any color might be possible but the ones mentioned in this article comprise a virtually exhaustive list.

Causes of auroras

A full understanding of the physical processes which lead to different types of auroras is still incomplete, but the basic cause involves the interaction of the solar wind with the Earth's magnetosphere. The varying intensity of the solar wind produces effects of different magnitudes, but includes one or more of the following physical scenarios.

1. A quiescent solar wind flowing past the Earth's magnetosphere steadily interacts with it and can both inject solar wind particles directly onto the geomagnetic field lines that are 'open', as opposed to being 'closed' in the opposite hemisphere, and provide diffusion through the bow shock. It can also cause particles already trapped in the radiation belts to precipitate into the atmosphere. Once particles are lost to the atmosphere from the radiation belts, under quiet conditions new ones replace them only slowly, and the loss-cone becomes depleted. In the magnetotail, however, particle trajectories seem constantly to reshuffle, probably when the particles cross the very weak magnetic field near the equator. As a result, the flow of electrons in that region is nearly the same in all directions ("isotropic"), and assures a steady supply of leaking electrons. The leakage of electrons does not leave the tail positively charged, because each leaked electron lost to the atmosphere is replaced by a low energy electron drawn upward from the ionosphere. Such replacement of "hot" electrons by "cold" ones is in complete accord with the 2nd law of thermodynamics. The complete process, which also generates an electric ring current around the Earth, is uncertain.
2. Geomagnetic disturbance from an enhanced solar wind causes distortions of the magnetotail ("magnetic substorms"). These 'substorms' tend to occur after prolonged spells (hours) during which the interplanetary magnetic field has had an appreciable southward component. This leads to a higher rate of interconnection between its field lines and those of Earth. As a result, the solar wind moves magnetic flux (tubes of magnetic field lines, 'locked' together with their resident plasma) from the day side of Earth to the magnetotail, widening the obstacle it presents to the solar wind flow and constricting the tail on the night-side. Ultimately some tail plasma can separate ("magnetic reconnection"); some blobs ("plasmoids") are squeezed downstream and are carried away with the solar wind; others are squeezed toward Earth where their motion feeds strong outbursts of auroras, mainly around midnight ("unloading process"). A geomagnetic storm resulting from greater interaction adds many more particles to the plasma trapped around Earth, also producing enhancement of the "ring current". Occasionally the resulting modification of the Earth's magnetic field can be so strong that it produces auroras visible at middle latitudes, on field lines much closer to the equator than those of the auroral zone.
3. Acceleration of auroral charged particles invariably accompanies a magnetospheric disturbance that causes an aurora. This mechanism, which is believed to predominantly arise from wave-particle interactions, raises the velocity of a particle in the direction of the guiding magnetic field. The pitch angle is thereby decreased, and increases the chance of it being precipitated into the atmosphere. Both electromagnetic and electrostatic waves, produced at the time of greater geomagnetic disturbances, make a significant contribution to the energising processes

that sustain an aurora. Particle acceleration provides a complex intermediate process for transferring energy from the solar wind indirectly into the atmosphere.

The details of these phenomena are not fully understood. However it is clear that the prime source of auroral particles is the solar wind feeding the magnetosphere, the reservoir containing the radiation zones, and temporarily magnetically trapped, particles confined by the geomagnetic field, coupled with particle acceleration processes

Auroral particles

The immediate cause of the ionization and excitation of atmospheric constituents leading to auroral emissions was discovered in 1960, when a pioneering rocket flight from Fort Churchill in Canada revealed a flux of electrons entering the atmosphere from above.[28] Since then an extensive collection of measurements has been acquired painstakingly and with steadily improving resolution since the 1960s by many research teams using rockets and satellites to traverse the auroral zone. The main findings have been that auroral arcs and other bright forms are due to electrons that have been accelerated during the final few 10,000 km or so of their plunge into the atmosphere.[29] These electrons often, but not always, exhibit a peak in their energy distribution, and are preferentially aligned along the local direction of the magnetic field. Electrons mainly responsible for diffuse and pulsating auroras have, in contrast, a smoothly falling energy distribution, and an angular (pitch-angle) distribution favouring directions perpendicular to the local magnetic field. Pulsations were discovered to originate at or close to the equatorial crossing point of auroral zone magnetic field lines.[30] Protons are also associated with auroras, both discrete and diffuse.

Auroras and the atmosphere

Auroras result from emissions of photons in the Earth's upper atmosphere, above 80 km (50 mi), from ionized nitrogen atoms regaining an electron, and oxygen atoms and nitrogen based molecules returning from an excited state to ground state.[31] They are ionized or excited by the collision of particles precipitated into the atmosphere. Both incoming electrons and protons may be involved. Excitation energy is lost within the atmosphere by the emission of a photon, or by collision with another atom or molecule:

oxygen emissions

green or orange-red, depending on the amount of energy absorbed.

nitrogen emissions

blue or red; blue if the atom regains an electron after it has been ionized, red if returning to ground state from an excited state.

Oxygen is unusual in terms of its return to ground state: it can take three quarters of a second to emit green light and up to two minutes to emit red. Collisions with other atoms or molecules absorb the excitation energy and prevent emission. Because the highest atmosphere has a higher percentage of oxygen and is sparsely distributed such collisions are rare enough to allow time for oxygen to emit red. Collisions become more frequent progressing down into the atmosphere, so that red emissions do not have time to happen, and eventually even green light emissions are prevented. This is why there is a color differential with altitude; at high altitudes oxygen red dominates, then oxygen green and nitrogen blue/red, then finally nitrogen blue/red when collisions prevent oxygen from emitting anything. Green is the most common color. Then comes pink, a mixture of light green and red, followed by pure red, then yellow (a mixture of red and green), and finally, pure blue.

Auroras and the ionosphere

Bright auroras are generally associated with Birkeland currents (Schield et al., 1969;[32] Zmuda and Armstrong, 1973[33]), which flow down into the ionosphere on one side of the pole and out on the other. In between, some of the current connects directly through the ionospheric E layer (125 km); the rest ("region 2") detours, leaving again through field lines closer to the equator and closing through the "partial ring current" carried by magnetically trapped plasma. The ionosphere is an ohmic conductor, so some consider that such currents require a driving voltage, which an, as yet unspecified, dynamo mechanism can supply. Electric field probes in orbit above the polar cap suggest voltages of the order of 40,000 volts, rising up to more than 200,000 volts during intense magnetic storms. In another interpretation the currents are the direct result of electron acceleration into the atmosphere by wave/particle interactions.

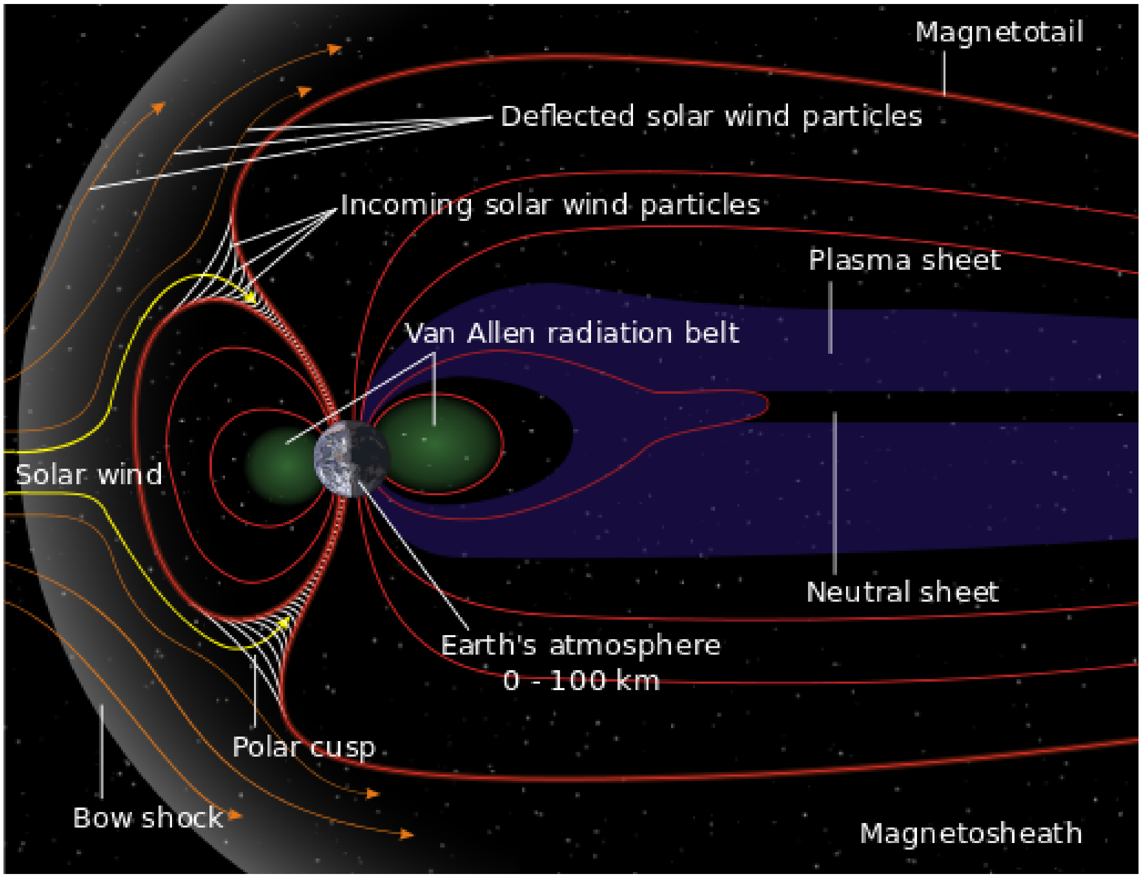
Ionospheric resistance has a complex nature, and leads to a secondary Hall current flow. By a strange twist of physics, the magnetic disturbance on the ground due to the main current almost cancels out, so most of the observed effect of auroras is due to a secondary current, the auroral electrojet. An auroral electrojet index (measured in nanotesla) is regularly derived from ground data and serves as a general measure of auroral activity. Kristian Birkeland[34] deduced that the currents flowed in the east-west directions along the auroral arc, and such currents, flowing from the dayside toward (approximately) midnight were later named "auroral electrojets" (see also Birkeland currents).

Interaction of the solar wind with Earth

The Earth is constantly immersed in the solar wind, a rarefied flow of hot plasma (a gas of free electrons and positive ions) emitted by the Sun in all directions, a result of the two-million-degree temperature of the Sun's outermost layer, the corona. The solar wind reaches Earth with a velocity typically around 400 km/s, a density of around 5 ions/cm^3 and a magnetic field intensity of around 2–5 nT (for comparison, Earth's surface field is typically 30,000–50,000 nT). During magnetic storms, in particular, flows can be several times faster; the interplanetary magnetic field (IMF) may also be much stronger. Joan Feynman deduced in the 1970s that the long-term averages of solar wind speed correlated with geomagnetic activity.[35] Her work resulted from data collected by the Explorer 33 spacecraft. The solar wind and magnetosphere consist of plasma (ionized gas), which conducts electricity. It is well known (since Michael Faraday's work around 1830) that when an electrical conductor is placed within a magnetic field while relative motion occurs in a direction that the conductor cuts across (or is cut by), rather than along, the lines of the magnetic field, an electric current is induced within the conductor. The strength of the current depends on a) the rate of relative motion, b) the strength of the magnetic field, c) the number of conductors ganged together and d) the distance between the conductor and the magnetic field, while the direction of flow is dependent upon the direction of relative motion. Dynamos make use of this basic process ("the dynamo effect"), any and all conductors, solid or otherwise are so affected, including plasmas and other fluids. The IMF originates on the Sun, linked to the sunspots, and its field lines (lines of force) are dragged out by the solar wind. That alone would tend to line them up in the Sun-Earth direction, but the rotation of the Sun angles them at Earth by about 45 degrees forming a spiral in the ecliptic plane), known as the Parker spiral. The field lines passing Earth are therefore usually linked to those near the western edge ("limb") of the visible Sun at any time.[36] The solar wind and the magnetosphere, being two electrically conducting fluids in relative motion, should be able in principle to generate electric currents by dynamo action and impart energy from the flow of the solar wind. However, this process is hampered by the fact that plasmas conduct readily along magnetic field lines, but less readily perpendicular to them. Energy is more effectively transferred by temporary magnetic connection between the field lines of the solar wind and those of the magnetosphere. Unsurprisingly this process is known as magnetic reconnection. As already mentioned, it happens most readily when the interplanetary field is directed southward, in a similar direction to the geomagnetic field in the inner regions of both the north magnetic pole and south magnetic pole.

Auroras are more frequent and brighter during the intense phase of the solar cycle when coronal mass ejections increase the intensity of the solar wind.

Schematic of Earth's magnetosphere



Magnetosphere

Earth's magnetosphere is shaped by the impact of the solar wind on the Earth's magnetic field. This forms an obstacle to the flow, diverting it, at an average distance of about 70,000 km (11 Earth radii or Re),[38] producing a bow shock 12,000 km to 15,000 km (1.9 to 2.4 Re) further upstream. The width of the magnetosphere abreast of Earth, is typically 190,000 km (30 Re), and on the night side a long "magnetotail" of stretched field lines extends to great distances (> 200 Re). The high latitude magnetosphere is filled with plasma as the solar wind passes the Earth. The flow of plasma into the magnetosphere increases with additional turbulence, density and speed in the solar wind. This flow is favored by a southward component of the IMF, which can then directly connect to the high latitude geomagnetic field lines.[39] The flow pattern of magnetospheric plasma is mainly from the magnetotail toward the Earth, around the Earth and back into the solar wind through the magnetopause on the day-side. In addition to moving perpendicular to the Earth's magnetic field, some magnetospheric plasma travels down along the Earth's magnetic field lines, gains additional energy and loses it to the atmosphere in the auroral zones. The cusps of the magnetosphere, separating geomagnetic field lines that close through the Earth from those that close remotely allow a small amount of solar wind to directly reach the top of the atmosphere, producing an auroral glow. On 26 February 2008, THEMIS probes were able to determine, for the first time, the triggering event for the onset of magnetospheric substorms.[40] Two of the five probes, positioned approximately one third the distance to the moon, measured events suggesting a magnetic reconnection event 96 seconds prior to auroral intensification.[41]

Geomagnetic storms that ignite auroras may occur more often during the months around the equinoxes. It is not well understood, but geomagnetic storms may vary with Earth's seasons. Two factors to consider are the tilt of both the solar and Earth's axis to the ecliptic plane. As the Earth orbits throughout a year, it experiences an interplanetary magnetic field (IMF) from different latitudes of the Sun, which is tilted at 8 degrees. Similarly, the 23 degree tilt of the Earth's axis about which the geomagnetic pole rotates with a diurnal variation, changes the daily average angle that the geomagnetic field presents to the incident IMF throughout a year. These factors combined can lead to minor cyclical changes in the detailed way that the IMF links to the magnetosphere. In turn, this affects the average probability of opening a door through which energy from the solar wind can reach the Earth's inner magnetosphere and thereby enhance auroras.

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DETAILED ITINERARY

Day 1: Saturday, March 4th, 2023 – Board flight

7:40PM: Depart from Dulles, Washington, DC (IAD) Icelandair – Flight 644

Day 2: Sunday, March 5th, 2023 – Reykjanes Peninsula

6:35: Arrive in Keflavik, Iceland on the Reykjanes Peninsula (30 miles south of Reykjavik)

7:30: After clearing customs, we'll meet by the café.

8:00: Grab breakfast at the airport

8:30: Load into the bus. Here is the info for the bus company:

SBA - Norðurleið (https://www.sba.is/en)
Hjallahraun 2, 220 Hafnarfjörður, Iceland
Email: sba@sba.is, Phone number: +354 5 500 770
Emergency number: +354 858 0720

9:00: Stop at Bridge between Two Continents near Sandvik. We'll talk about Mid Atlantic Ridge, the boundary between the North American Plate and the Eurasian Plate.

10:00: Valahnúkamöl cliff. See the contact between tuff and pillow lava.

11:00: Gunnuhver hot spring and an introduction to geothermal activity.

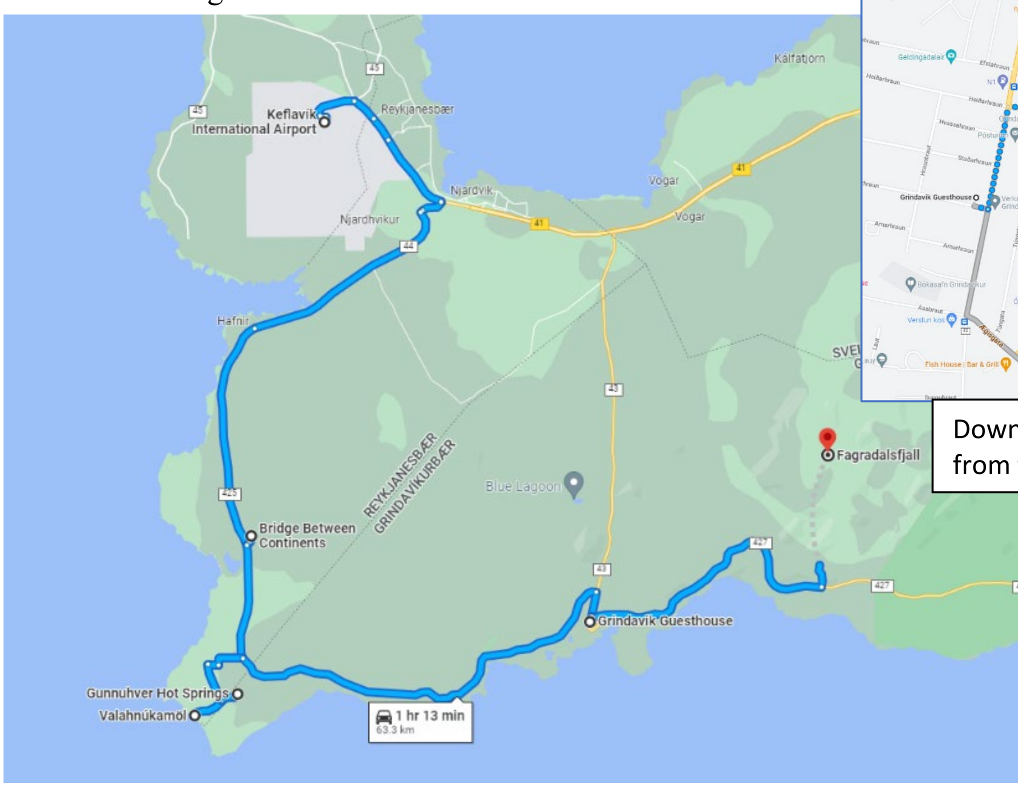
12:30: Lunch in Grindavik – There is a café called Café Bryggjan (https://www.bryggjan.com/) that should be fine….

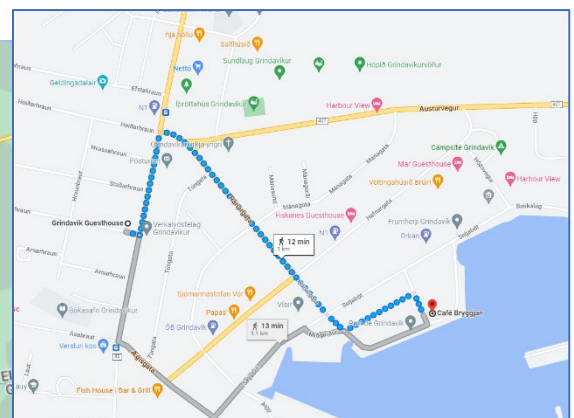
2:00 PM: Check into the guesthouse in Grindavik

Grindavik Guesthouse (https://www.grindavikguesthouse.is/)
Borgarhraun 2, 240 Grindavík, Iceland
Email: info@grindavikguesthouse.is, Phone: +3545114646

3:00 PM: Hike to Fagradalsfjall Volcano (Sunset is at 6:58 PM)

6:30 PM: Return to guesthouse, fend for yourself for dinner. You could go out or cook, the guesthouse has a kitchen.





Downtown Grindavik with the route from the hostel to the lunch spot

General Background

Reykjanes Peninsula at the southwestern end of Iceland is the on-shore part of Mid-Atlantic Ridge that separates the Eurasian Plate and the North American Plate. The peninsula is constructed of young basaltic formations, and is transected by a NE–SW trending fault zone[1]. The Reykjanes volcanic system lacks central volcanoes and is characterized by oblique extensional tectonics and episodic fissure eruption volcanism[2]. Volcanic activity on the Reykjanes peninsula has been intense during postglacial times. The most recent volcanic eruptions occurred in the late 12th and early 13th centuries. The active volcanic system and complex local tectonics produce the significant geothermal activity on the peninsula.

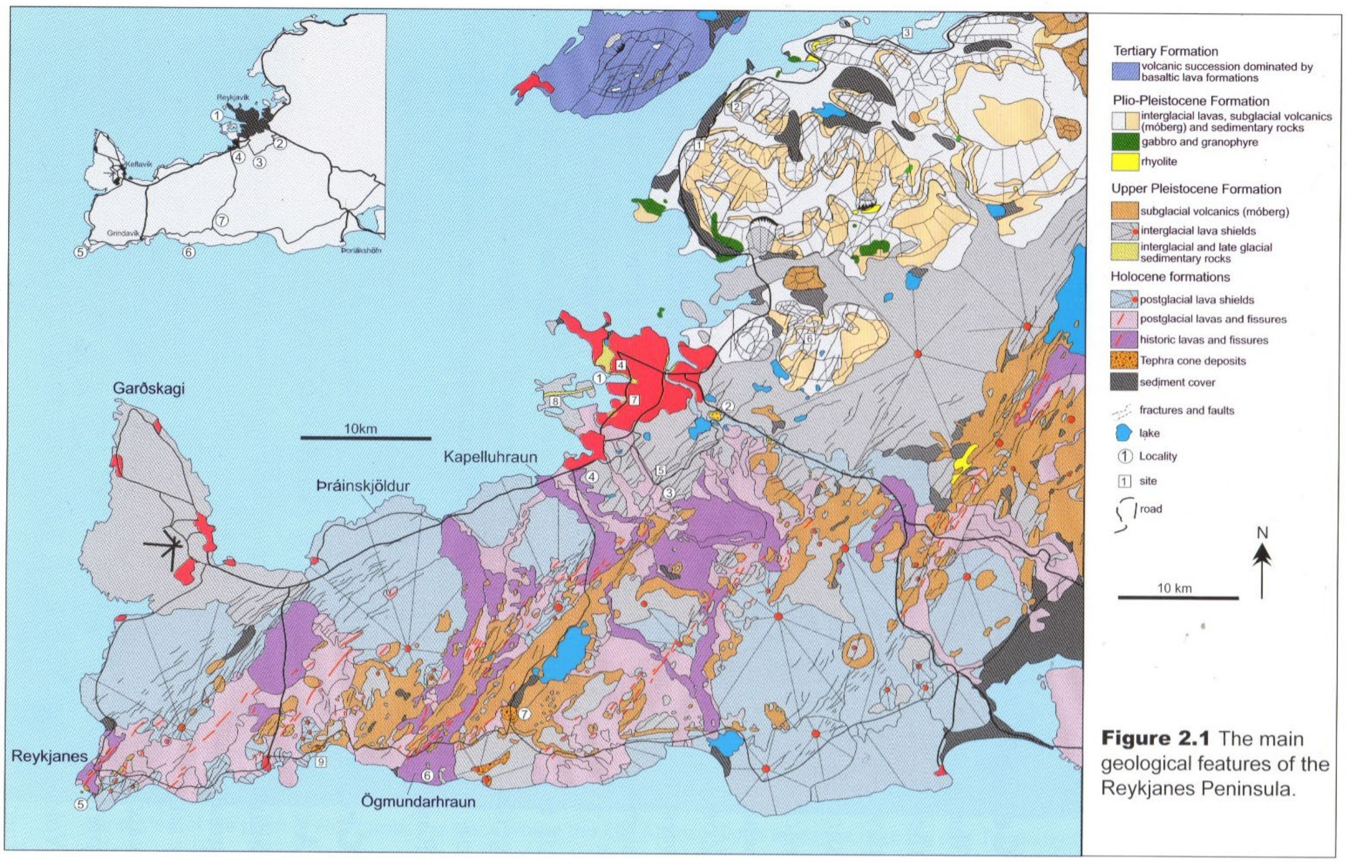


Figure 2.1 The main geological features of the Reykjanes Peninsula.

(Thordarson & Holskuldsson, 2019)

STOP 2.1 - *The Bridge between Two Continents (Leif the Lucky Bridge)*

The Bridge Between Two Continents, or Leif the Lucky Bridge, is located on the black sand beach of Sandvík, near the town of Hafnir, on the Reykjanes peninsula. This small footbridge spans the Álfagjá rift valley (60 feet wide and 20 feet deep) and marks the boundary of the Eurasian and North American plates. It was built in 2002 and named in honor of Icelandic explorer Leif Eriksson who traveled from Europe to America 500 years before Columbus[3]. There are great examples of volcanic features like columnar joints and pressure bows at this location.

The following is from: Gudmundsson, A., 2017, The Glorious Geology of Iceland's Golden Circle. Springer International Publishing, Cham, Switzerland, pgs. 257-260.

Bridge Between Two Continents

We now walk back to the car park, drive to Road 425, and follow that road to the north. On the way we cross the Yngri-Stampar Volcanic fissure and see many crate cones, some primarily spatter cones, two of which are known as the **Stampar** (from which the fissure derives its name). We follow the road through several young lava flows until we come to the final main stop in this excursion, namely the tenth stop (10), a parking place to the east of the road from which you can walk to the so-called **Bridge Between Two Continents**. The bridge is across a tectonic fracture, more specifically a pure tension fracture (Figure 2.1.1). The fracture is formed by the same plate-tectonic tensile forces or stresses as the tension fractures at Thingvellir (See Day X Stops).

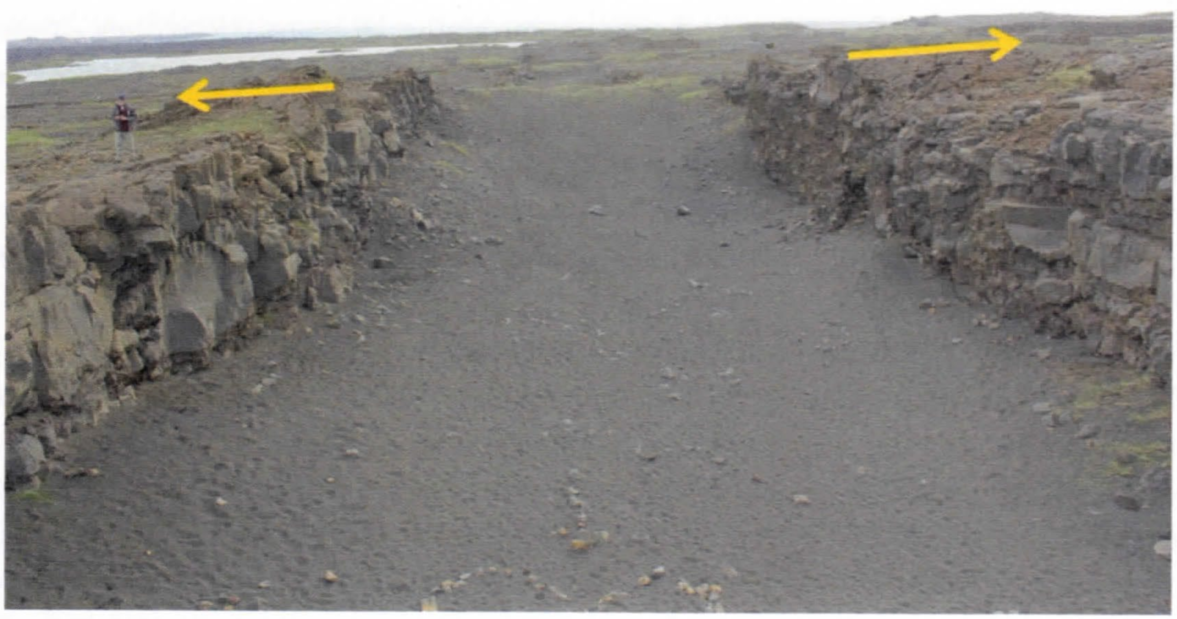


Figure 2.1.1. Tension fracture seen from the 'Bridge Between Two Continents'. View southwest the maximum opening of aperture of the tension fracture is about 30 m, but about 15 m where the bridge itself crosses the fracture. This is a pure tension fracture, as indicated by the orange arrows and as can be seen in that the fracture walls on either side of the opening are at the same elevation. The person on the left (east) fracture wall provides a scale.

However, the present fracture is not filled with ground water as are the fractures at Thingvellir, but rather sand. The direction or trend of this tension fracture is northeast and the maximum opening or aperture as great as 30 m (the opening is around 15 m where the bridge itself is). The opening of 30 m is among the largest on any tension fracture in Iceland. Such large fractures are in some ways like **narrow grabens**, as we discussed in connection with Almannagja, the western boundary fault of the Thingvellir Graben. Like most other large tension fracture in Iceland, this one is located in a pahoehoe lave flow which, in this case, derives from the lava shield **Langholl**, The structure of the lava flows, as well as the flow units and **tumuli** in cross-section, are seen in the walls of the tension fracture (Figure 2.1.2). You may recall seeing lava tumuli at the surface of some of the pahoehoe flows on your way from Keflavik to Reykjavik.

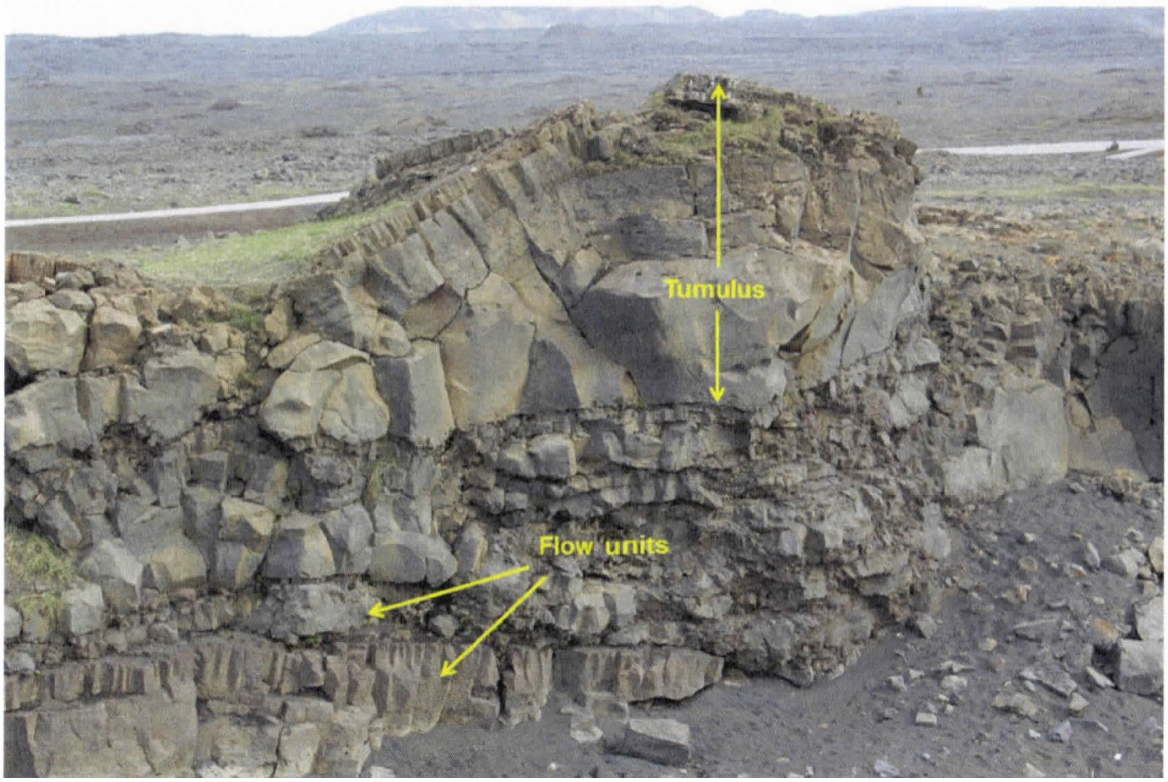


Figure 2.1.2. View south of a tumulus and pahoehoe flow units seen in a vertical cross-section in the southeastern wall of the tension fracture in Figure X. Compare the flow units in the walls of Almannagja and the tumulus, seen at the surface in a cross-section in Figure X.

Does the bridged tension fracture really mark the separation between two continents? Hardly, because Iceland is not a continent or part of a continent. The tension fracture is, however, without a doubt a part of the on-land continuation of the Reykjanes Ridge which is a **boundary** between **two tectonic plates**: namely, the Eurasian Plate and the North American Plate. If you want to mark that plate boundary by one fracture, then this one is a good as any other. In reality, however, the bridged tension fracture is part of a much larger set of tension fractures and normal faults which together constitute the northwestern edge of the main **5-6 km wide graben** that marks the on-land continuation of the mid-cean Reykjanes Ridge. You saw the southeastern boundary fault of that graben from Valahnukur (Stop X.X), and the fracture set here may be regarded as the northwestern boundary of that graben. Part of the main fault, the normal fault that actually marks the boundary of the graben, is seen in a close-up in Figure 2.1.3, which also shows a large **tumulus** and flow units of the lava flow from the Langholl lava shield.

How deep into the crust does the fracture in Figure 2.1.1 extend? Using the theory explained in Chapt. 5, the maximum depth of this tension fracture is **several hundred meters**. If the fracture tried to extend to greater depths it would change into a normal fault such as the one in Figure 2.1.3. The stresses forming the tension fracture in Figure 2.1.1. are not large, for the simple reason that rocks are very weak in tension. The tensile strength of pahoehoe lava flows such as the one in Figure 2.1.2 and 2.1.3 is a few mega-pascal, and that is the tensile stress responsible for their formation. You may recall that one mega-pascal corresponds to the pressure or stress your body would feel at the depth of about 100 m in a lake or the sea.

Figure 2.1.3. Main northwestern boundary fault of the 5-6 km wide graben on Reykjanes, an on-land continuation of the mid-ocean Reykjanes Ridge. Also seen is a vertical cross-section through flow units and a large tumulus (compare with Figure 2.1.2). The person provides a scale.

STOP 2.2 - *Valahnúkamöl Cliff*

Valahnukur cliff is on the southern tip of the Reykjanes Peninsula. The eastern side of the cliff exhibits a well-exposed section of massive basalts with columnar jointing, pillow basalts, and laminated tephra. These exposures suggest a transition from subaerial to submarine volcanic flows.

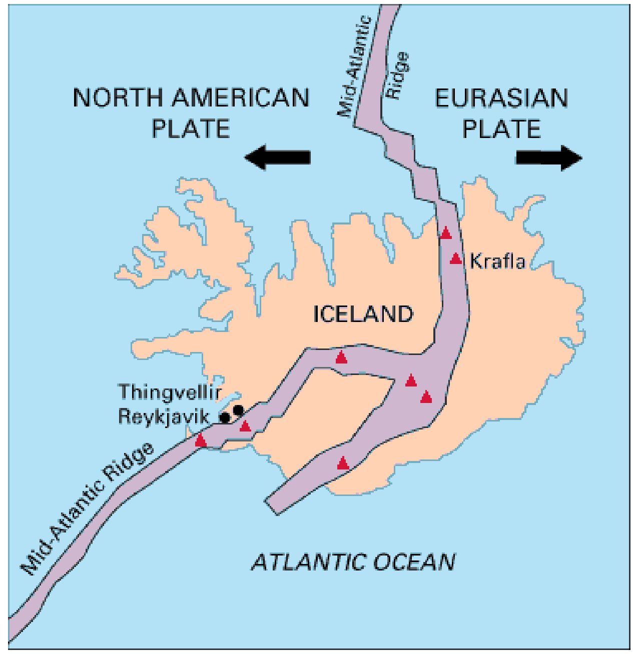


Figure 2.2.1. Valahnukur cliff: view south, showing the contact between laminated tephra and pillow basalts.

The following is from: Thordarson, T. and Hoskuldsson, A., 2019, Iceland: Classic Geology in Europe 3 (Second Edition). Dunedin Academic Press Ltd., Edinburgh, Scotland, pgs. 67-73.

Mid-ocean ridge Rising out of the Sea

If you travel west on Highway 41 towards the international airport at Keflavik, as you pass the town of Njardvik follow the signs to the town of Hafnir [63.9339, -22.6838] (Road 44). Head directly south on Road 425, through Hafnir, towards the geothermal plant at Reykjanes. From there follow the signs to Reykjanesviti [63.8155, -22.7043] (the lighthouse at Reykjanes and, passing the lighthouse, you have reached the destination.

Reykjanes [63.8128, -22.7147] is the southwestern outpost of Iceland and the point where the Mid-Atlantic Ridge rises out of the sea. On land the ridge crest (i.e., the rift valley) is defined as a distinct fault zone delineating a shallow 10 km-wide composite graben structure trending northeast from Reykjanes to Vatnsleysustrond. Along the center of the rift is a series of 40-100 m-high steep moberg hills composed of pillow lava and hydroclastic tephra and breccia, including Baejarfell [63.8155, -22.7043], where the present lighthouse stands, and Valahnukur [63.8108, -22.7114], where the foundations of the old lighthouse can still be seen. On both sides, lava shields border the moberg hills, which in turn are partly covered by younger Holocene and historical lava flows (see Figure 2.2.2), But not all of Reykjanes is volcanic. The cove south of Valahnukur features a spectacular boulder beach formed by the rampant storms of the North Atlantic, and farther to the north the black sand dunes at Stora-Sandvik are a blunt reminder that the wind blows fearlessly through Reykjanes. It also hosts a small (~1 km^2) high-temperature geothermal area with small steaming vents and bubbling solfataras. However, these hot springs are only a shadow of what they used to be, partly because the area is now utilized for power generation.

The moberg mountains of Syrfell [63.8369, -22.6598], Baejarfell and Valahnukur were formed by submarine fissure eruptions when sea level was standing about 70 m higher than today, during the waning stages of the Weichselian glaciation. These moberg mountains consist of pillow lava, breccias, and tuffs, which in the case of Syrfell are capped by small scoria cones and thin lava flows, indicating that the volcano rose out of the sea to form a small island. However, Valahnukur volcano seems to have remained fully submerged during its period of activity, as it features a basal sequence of pillows capped by a breccia unit and another pillow-lava sequence. The hill itself is split in the middle by a 20 m-wide graben structure, and the walls on either side provide an excellent outcrop of the pillows and breccia units (Figure 2.2.2a). The youngest tephra layers in the **regolith** that laps onto the eastern slopes of Valahnukur are from a volcanotectonic episode that raged at Reykjanes in the thirteenth century, suggesting that this graben structure is very young and was formed in historical times.

The youngest volcanic formation at the Reykjanes is the 4.5 km-long Yngri Stampar [63.8197, -22.7220] cone row, along with the lavas and the tuff it produced, which now cover the northern part of the point. These were formed in the so-called Reykjanes Fires, a major volcanotectonic episode within the Reykjanes system between 1210 and 1240.

Vatnsfell [63.8150, -22.7234] us a rather inconspicuous rise on the coast north of Valahnukur, but is worth a visit for those interested in having a closer look at the internal make-up of tuff cones (Figure 2.2.1). It is made up of lapilli tuff deposits, which are the remnants of two tuff cones formed by submarine explosive eruptions in the early stages of the Reykjanes Fires in about 1210. The internal structures of these cones are best exposed in outcrops opposite Karl, the sea stack rising about 300 m offshore. The older cone, which makes up the bulk of Vatnsfell proper, was 30 m high and 650 m wide, with the crater located 100 m offshore. The lower part of the older tuff cone consists of wavy to cross-bedded ash deposits formed by repeated base surges, whereas the upper part consists of coarser-grained lapilli tuff composed of alternating base surge and tephra fall units. On either side of Vatnsfell, the older cone is capped and flanked by the deposits from the younger cone, which consists of fine-grained lapilli tuff with repeated pairs of base-surge and tephra-fall layers (Figure 2.2.2b). Many impact craters formed by ballistic blocks ejected from the craters during the eruptions commonly disrupt bedding in both cones. The younger tuff cone was a much larger structure than its earlier counterpart, at least 55 m high and with a basal diameter of about 1600 m. The main crater was located about 400 m offshore near the current position of sea stack Karl. This cone is probably the mountain, described in the thirteenth-centruy chronicles, that rose out of the sea of Reykjanes in 1211. The lavas of Yngri Stampar were formed wither in the same eruption of the second eruption of the Reykjanes Fires in 1223, Some of the feeder dykes dissect the Vatnsfell tuff connecting to the overlying flows of the Yngri Stampar cone row.

The thirteenth-century chronicles also mention an explosive eruption of the shore of Reykjanes in 1226, which caused widespread tephra to fall on land. This tephra layer is known as the Middle Ages Tephra (Midaldarlagid) and is found in soils all over the Reykjanes Peninsula, including Reykjavik and the Esja region. It forms an important time maker and has been used extensively for dating historical lava flows in the area. Eldrey, a steep-sided islet 14 km offshore, is yet another remnant of an emergent submarine volcano formed by the Reykjanes Fires, and it may be the source vent for the Middle Ages Tephra. Now it hosts the largest gannet-breeding ground in the Northern Hemisphere and its top is completely covered by a knee-deep layer of guano.

The chronicles also mention eruptions at Reykjanes in 1231, 1238, and 1240. The last eruption made the Sun appear ‘red as blood’, which implies volcanic plumes rich in sulphuric aerosols, and atmospheric perturbations on a regional scale. Such plumes can be generated by effusive basalt eruptions, provided that

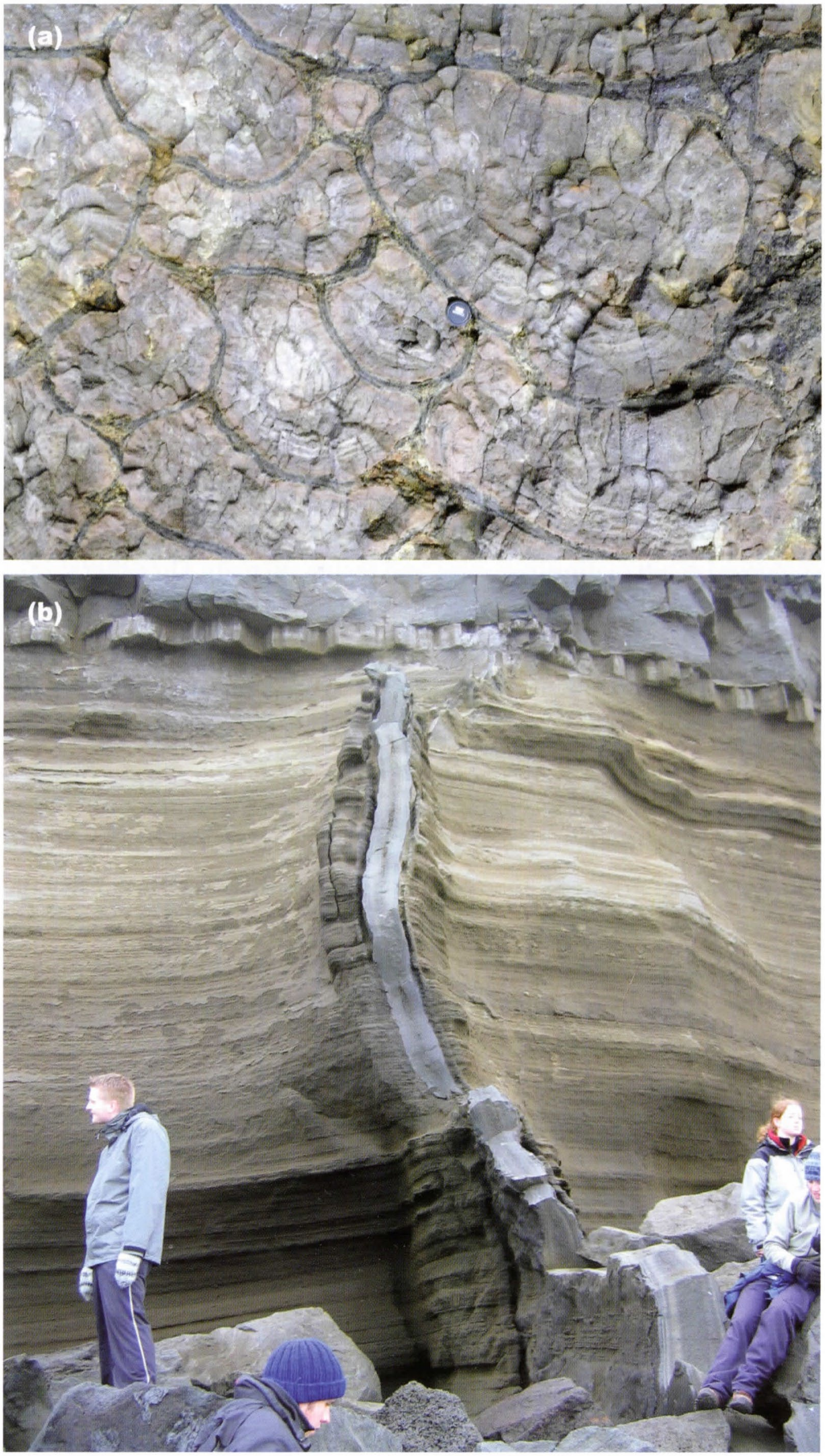
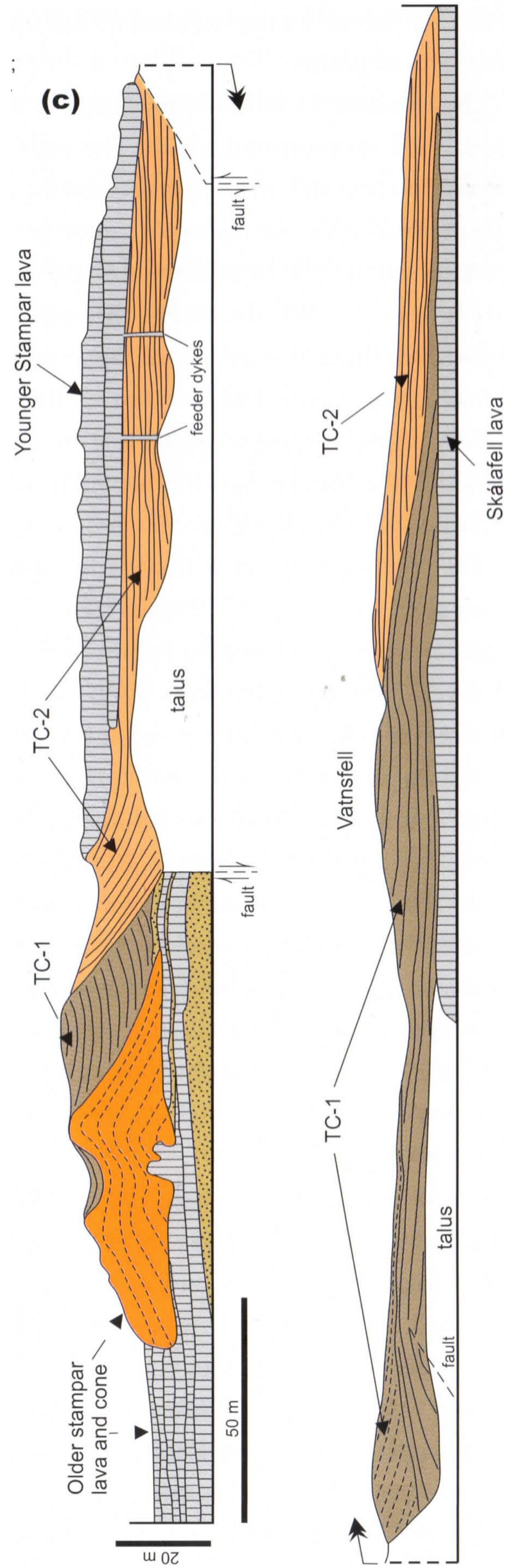

(a)
(b)

Figure 2.2.2. (a) (*previous page*) Pillow lava at Valahnukur; **(b)** (*previous page*) lapilli tuff beds in the younger Vatnsfell tuff cone; **(c)** cross section showing the arrangement of the Vatnsfell tuff cones and Stampar feeder dykes at the coast of Reykjanes.



the volume of erupted magma is reasonably large. The only historical eruptions that fit the requirements of correct setting, age, and size are those that produced the Arnarsetur and Illahraun lavas north of Svartshengi, some 18 km to the northeast of Reykjanes. Tephrochronlogy shows that these two lava flows were formed several years after the Middle Ages Tephra fell in 1226 and thus may represent the final episode in the Reykjanes Fires.

The second-youngest formations at Reykjanes are the Eldri Stampar [63.8250, -22.7172] and Tjaldastadargja [63.8528, -22.6553] cone rows and lavas formed by another volcanotectonic episode 1500-2000 years ago. Other fissure volcanoes in the area are of unknown age but pre-date the volcanoes mentioned above, illustrating that fires have raged at Reykjanes periodically throughout the Holocene. The oldest Holocene formations at Reykjanes lava shields Sandfellshaed, Skalafell [63.8125, -22.6822] and Haleyjarbunga [63.8166, -22.6510] which together are the largest lava formations in the area and solely composed of pahoehoe flows. Haleyjarbunga may hold a special interest for petrology enthusiasts, because it is composed of picrite basalt and is exceptionally rick in olivine phenocrysts. Some of the lava outcropping in the walls of the summit crater and cliffs along the southern coast is green with olivine.

On the way

Continue on Road 425 along the southern coast towards the town Grindavik [63.8453, -22.4351]. The route will take you through several older Holocene lava flows and, as you approach the putting greens of the Grindvik golf course, the mountain Þorbjarnarfell [63.8641, -22.4405] will appear on the skyline to your left. It is the highest (243 m) subglacial moberg volcano within the Reykjanes volcanic system and is noteworthy for the spectacular graben structure that cuts across its top. On the other side of Þorbjarnarfell is Svartshengi [63.8801, -22.4319], the geothermal field that supplies the communities on the Reykjanes Peninsula with hot water for domestic use and house heating, but probably better known for its spa, the Blue Lagoon. It is an ideal spot for a relaxing dip in the warm mineral-rich water to recharge the batteries for the second half of the excursion.

Return to Road 427 travelling east towards Krysuvik [63.8869, -22.0651], which initially traverse the lavas of Sundahnukur and Vatnsheidi. The former lava flowed into the sea to form the point Þorkotlunes and the inlet that hosts the harbour at Grindavik. It is one of the larger Holocene fissure-fed flows on Reykjanes (volume 0.6 km^3) and it poured out of an 8.5 km-long fissure about 2400 years ago. The olivine-rich Vatnsheidi lavas are pahoehoe flows derived from three small picrite lava shields northeast of Grindavik that were constructed by eruptions during the early Holocene. The Vatnsheidi lavas host abundant gabbro xenoliths and large (2-3 cm) feldspar xenocrysts, which are readily discernible in the coastal outcrop at Hrolfsvik [63.8494, -22.3661].

A little farther to the east, where the road climbs a steep incline, is Festarfjall [63.8573, -22.3373], at 100 m high the tallest seacliff on the Reykjanes Peninsula, which consists of weakly consolidated hydroclastic tephra and is capped by a lava flow. The feeder conduit that fed the summit lava can be seen as a dyke dissecting the tuff sequence in the cliff facing the sea. The mountain's name is derived from the dyke, which was thought by locals to be the chain anchoring the mountain to the bedrock; hence, the name Festarfjall ('anchored mountain'). In geological terms, Festarfjall is a remnant of a submarine table mountain, a Surtseyan volcano that was formed in an eruption towards the very end of the Weichselian glaciation. A word of warning; rockfall is a common occurrence at Festarfjall and therefore we do not recommend hiking along the sandy beach in front of the cliff face. Northeast of Festerfjall is the 350 m-high table mountain, Fagradalsfjall [63.8961, -22.2934], with a cap of subaerial lava indicating that the Weichselian glacier was at least 300 m thick in the area when the volcano formed.

The following is from: Gudmundsson, A., 2017, The Glorious Geology of Iceland's Golden Circle. Springer International Publishing, Cham, Switzerland, pgs. 243-257.

I should add this, but I am getting lazy….

STOP 2.3 - *Gunnuhver Hot Spring*

This is one of the most famous high temperature geothermal areas on the Reykjanes Peninsula. The name Gunnuhver comes from the witch called Guðrún, who caused a great disturbance until Eiríkur Magnússon, a priest at Vogsósar set a trap that made her fall into the spring. Gunnuhver is an exception to other geothermal areas because the groundwater here is 100% seawater. Mud pools and steam vents are formed where steam generated in a geothermal reservoir emanates, condenses, and mixes with surface water. The accompanied gases, such as carbon dioxide and hydrogen sulfide, make the water acidic and alter the fresh lavas to clay. Steam released at the surface has increased markedly since 2006 as a consequence of groundwater exploitation by a nearby geothermal power plant. Evaporites and sulfuric minerals can be seen throughout this hydrothermal area. At depth, metal ores are concentrated, especially copper sulfates.

The following is from: Fraedrich, W. and Heidari, N., 2019, Iceland from the West to the South. Springer International Publishing, Cham, Switzerland, pgs. 154-155.

High-Temperature Area Gunnuhver

On road no. 427 you go to Grindavik, until reaching 63º 50' 36.40"N / 22º 26' 09.70" W on road no. 43, in which one is turning right north. After approximately 600 m, leave at 63º 51' 03.00"N / 22º 25' 57.50" W to the left and turn onto road no. 425. Drive around Grindavik in the northwest and take road no. 425 more or less parallel to the coast towards the west until it leaves at the branch at 63º 49' 29.20"N / 22º 39' 43.70" W to the southwest. You have to drive a little more than 1 km to find a parking lot at 63º 49' 08.70"N / 22º 40' 55.40" W or another small parking lot at 63º 49' 30.06"N / 22º 41' 13.55" W. From there you can only on marked paths through the area with the mud springs and fumaroles of the high-temperature Gunnuhver (Figure 2.3.1)

Figure 2.3.1. Volcanic gases emitted in the high-temperature area of Gunnuhver.

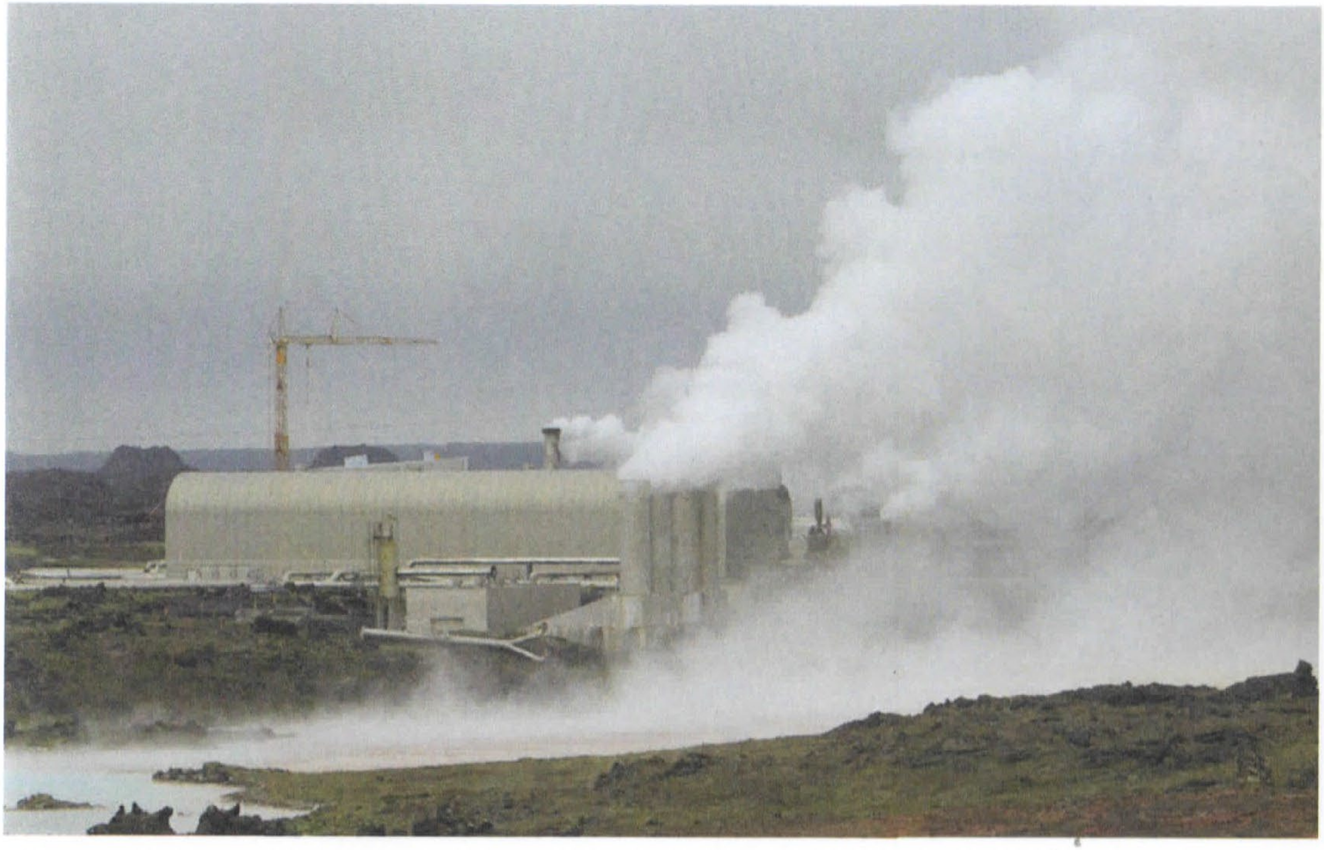


Figure 2.3.2. View on Sudurnes Geothermal Power Plant

Gunnuhver is highly active volcano, which continues to the southwest in the Atlantic over the so-called Reykjanes Ridge. Southeast of the island of Eldey, which is situated on this ridge, there was an eruption in 1926. Since 2006, the activity has been limited to small explosions, where clay scrapes are thrown up to 5 m high by rising lava lacquers. Therefore, parts of the area had to be blocked in 2008. Only since 2010 the area is conditionally accessible again. It is, therefore, important to always keep the required distance and under no circumstance block barriers. The high-temperature area Gunnuhver is the hottest in the southwest of Iceland with more than 300ºC. This fact forms the basis for the nearby Sudurnes Geothermal Power Plant. Worth mentioning is the name of the high-temperature area because Gunnuhver is connected to the legend by Gunna (by Gudrin Onun dardottir). According to the legend, was a murderous poltergeist. The parishioner Eirikur Magnesson finally succeeded in placing the ghost in the hot spring, which has been carrying the name Gunna since then.

STOP 2.4 - *Grindavik*

Landnáma or The Book of Settlements mentions that around 934 two Viking settlers, Molda-Gnúpur Hrólfsson and Þórir Haustmyrkur Vígbjóðsson, arrived in the Reykjanes area. Þórir settled in Selvogur, and Krísuvík and Molda-Gnúpur in Grindavík.

The sons of Moldar-Gnúpur established three settlements; Þórkötlustaðahverfi, Járngerðarstaðarhverfi and Staðarhverfi. The modern version of Grindavik is situated mainly in what was Járngerðarstaðarhverfi.

The origins of the municipality can be traced to Einar Einarsson's decision to move there to build and run a shop in 1897. During that time the population was only around 360. Fishing had for centuries been a crucial element in the survival of Grindavik's population, but fishing trips were often dangerous. Men were frequently lost at sea and the catch not always stable. However, when a safer access point to land was created at Hópið in 1939, fishing conditions changed dramatically. From 1950 serious development in the fishing industry had begun to take place. Grindavik was declared a municipality in 1974.

STOP 2.5 - *Fagradalsfjall Volcano*

The following is take from Wikipedia…

Fagradalsfjall (Icelandic: [ˈfaɣraˌtalsˌfjatl̥] is a tuya volcano formed in the Last Glacial Period on the Reykjanes Peninsula, around 40 kilometres (25 mi) from Reykjavík, Iceland. Fagradalsfjall is also the name for the wider volcanic system covering an area 5 kilometres (3 mi) wide and 16 kilometres (10 mi) long between the Svartsengi and Krýsuvík systems. The highest summit in this area is Langhóll (385 m (1,263 ft)). No volcanic eruption had occurred for 815 years on the Reykjanes Peninsula until 19 March 2021 when a fissure vent appeared in Geldingadalir to the south of Fagradalsfjall mountain. The 2021 eruption was effusive and continued emitting fresh lava sporadically until 18 September 2021.

The eruption was unique among the volcanoes monitored in Iceland so far and it has been suggested that it may develop into a shield volcano. Due to its relative ease of access from Reykjavík, the volcano has become an attraction for local people and foreign tourists. Another eruption, very similar to the 2021 eruption, began on 3 August 2022. It is still considered ongoing, although there has been no visible activity since 21 August 2022.

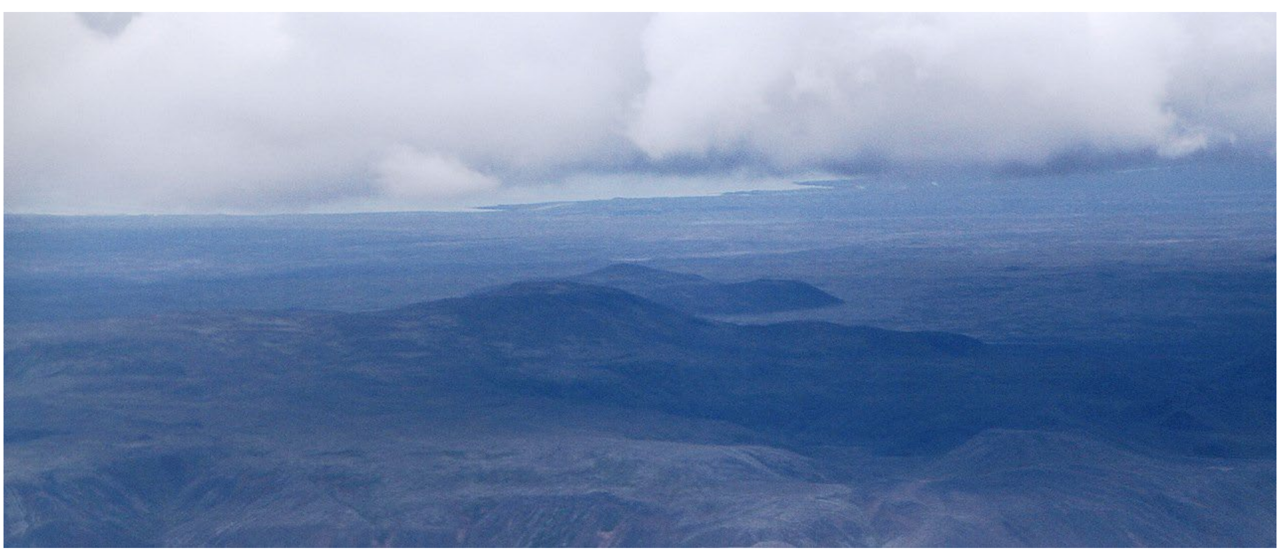


Figure 2.5.1. Fagradalsfjall with its main peak Langhóll and Geldingadalir to the right (2012 photo).

Etymology

The name is a compound of the Icelandic words 'fagur' ("fair", "beautiful"), 'dalur' ("dale", "valley") and 'fjall' ("fell", "mountain"). The mountain massif is named after Fagridalur ("fair dale" or "beautiful valley") which is at its northwest. The 2021 lava field is named Fagradalshraun.

Tectonic setting

The mountain Fagradalsfjall is a volcano in areas of eruptive fissures, cones and lava fields also named Fagradalsfjall. The Fagradalsfjall fissure swarm is considered in some publications to be a branch or a secondary part of the Krýsuvík-Trölladyngja volcanic system on the Reykjanes Peninsula in southwest Iceland. Other scientists propose that Fagradalsfjall could represent a separate volcanic system from Krýsuvík and it is regarded as such in some publications. It is in a zone of active rifting at the divergent boundary between the Eurasian and North American plates. Plate spreading at the Reykjanes peninsula is highly oblique and is characterized by a superposition of left-lateral shear and extension. The Krýsuvík volcanic system has been moderately active in the Holocene, with the most recent eruptive episode before the 21st century having occurred in the 12th-century CE. The Fagradalsfjall mountain was formed from an eruption under the ice sheet in the Pleistocene period, and it had lain dormant for 6,342 years until an eruption fissure appeared in the area in March 2021.

The unrest and eruption in Fagradalsfjall are part of a larger unrest period on Reykjanes Peninsula including unrest within several volcanic systems and among others also the unrest at Þorbjörn volcano next to Svartsengi and the Blue Lagoon during the spring of 2020. However, eruptions at this location were unexpected as other nearby systems on the Reykjanes Peninsula had been more active.

The 2021 eruption is the first to be observed on this branch of the plate boundary in Reykjanes. It appears to be different from most eruptions observed where the main volcanoes are fed by a magma chamber underneath, whose size and pressure on it determine the size and length of eruption. This eruption may be fed by a relatively narrow and long channel (~ 17 km) that is linked to the Earth's mantle, and the lava flow may be determined by the properties of the eruption channel.

2021 eruption series

Precursors

Beginning December 2019 and into March 2021, a swarm of earthquakes, two of which reached magnitude Mw5.6, rocked the Reykjanes peninsula, sparking concerns that an eruption was imminent, because the earthquakes were thought to have been triggered by dyke intrusions and magma movements under the peninsula. Minor damage to homes from a 4 February 2021 magnitude 5.7 earthquake was reported. In the three weeks before the eruption, more than 40,000 tremors were recorded by seismographs.

Eruption fissures in Geldingadalir

On 19 March 2021, an effusive eruption started at approximately 8:45 PM local time in Geldingadalir to the south of Fagradalsfjall, the first known eruption on the peninsula in about 800 years. Fagradalsfjall had been dormant for 6,000 years. The eruptive activity was first announced by the Icelandic Meteorological Office at 9:40 PM. Reports stated a 600–700-metre-long (2,000–2,300 ft) fissure vent began ejecting lava, which covered an area of less than 1 square kilometre (0.39 sq mi). As of the March eruptions, the lava flows posed no threat to residents, as the area is mostly uninhabited.

Figure 2.5.2. Geldingadalir eruption near Fagradalsfjall, 24 March 2021.

Figure 2.5.3. People on the slopes of Fagradalsfjall, watching the Geldingadalir eruption.

Figure 2.5.4. Satellite image from 29 April 2021.

Figure 2.5.5. The new eruption fissures to the left, the older ones to the right, seen from a helicopter, view to the east.

The eruption has been called Geldingadalsgos ("Geldingadalur eruption"). On the 26 March, the main eruptive vent was at 63.8889 N, 22.2704 W, on the site of a previous eruptive mound. The eruption may be a shield volcano eruption, which may last for several years. It could be seen from the suburbs of the capital city of Reykjavík and had attracted a large number of visitors. However, high levels of volcanic gases such as carbon dioxide and carbon monoxide made parts of the area inaccessible.

On 13 April 2021, 4 new craters formed in Geldingadalir within the lava flows. The lava output which had been somewhat reduced over the last days, increased again.

Eruption fissures on Fagradalsfjall

Around noon on 5 April a new fissure, variously estimated to be between about 100 and 500 metres (300 and 2,000 ft) long, opened a distance of about 1 kilometre (0.5 mi) to the north/north-east of the still-active vents at the center of the March eruption. As a precaution the area was evacuated by the coast guard.

Some time later, another eruption fissure opened parallel to the first on the slopes of Fagradalsfjall.

The lava production of all open eruption fissures in the whole was estimated on 5 April 2021, being around 10 m^3/s (350 cu ft/s) and is flowing into the Meradalir valleys ("mare dales") via a steep gully.

About 36 hours later, around midnight on 6–7 April, another eruption fissure opened up. It is about 150 m (490 ft) long and about 400–450 m (1,300–1,500 ft) to the north-east of the first fissure, between the Geldingadalur fissures and the ones on the slope of the mountain. Search and rescue crews observed a new depression, about 1 m (3 ft) deep there the previous day. The lava from this fissure flowed into Geldingadalur valley.

Another fissure opened during the night of 10–11 April 2021 between the two open fissures on the slopes of Fagradalsfjall. In total, 6 fissures had opened until the 13 April and at each fissure, activity concentrated and formed individual vents. Towards the end of April, activity at most vents, apart from V ent 5, started to decrease.

By 2 May 2021, only one fissure, Vent 5 that appeared near the initial eruption site on Geldingadalir, remained active. It developed into a volcano with the occasional explosive eruptions within its crater that sometimes reached heights of hundreds of meters. The rim of the volcano itself had risen to a height of 334 m (1,096 ft) above sea level by September 2021. The lava flowed into the Meradalir valleys, and later the Nátthagi valley.

A number of smaller openings appeared temporarily, one small vent was reported to have erupted near the main crater on 1 July. On 14 August, lava spurted from what appeared to be a hole on the crater wall, and this turned out to be an independent eruption. Cracks appeared on Gónhóll that was once popular with spectators in August but no lava flowed at the site. After eight and a half days of inactivity at the main volcano, lava broke through the surface in the lava field to the north of the crater in a number of places.

Lava and gas output: Development of the eruption

The eruption showed distinct phases in its eruption pattern. The first phase lasted for about two weeks with continuous lava flow of around 6 m^3/s (210 cu ft/s) from its first crater, the second phase also lasted around two weeks with new eruptions to the north of the first crater with variable lava flow of 5–8 m^3/s (180–280 cu ft/s). This is followed by a period of two and a half months of eruption at a single crater with largely continuous and sometimes pulsating eruption and lava flow of around 12 m^3/s (420 cu ft/s) lasting until the end of June. From then on until early September was a phase of fluctuating eruption with periodic strong lava flow interrupted by periods of inactivity.

On 12 April, scientists from the University of Iceland measured the lava field's area to be 0.75 km^2 (0.29 sq mi) and its volume to be 10.3 million m^3 (360 million cu ft). The flow rate of the lava was 4.7 m^3/s (170 cu ft/s), and sulfur dioxide, carbon dioxide and hydrogen fluoride were being emitted at 6,000, 3,000 and 8 tons per day (5,900, 3,000 and 7.9 long tons per day) respectively.

The lava produced by the eruption shows a composition differing from historical Reykjanes lavas. This could be caused by a new batch of magma arriving from a large magma reservoir at a depth of about 17–20 km (11–12 mi) at the Moho under Reykjanes.

Figure 2.5.6. Examples of basaltic lava collected in late March 2021

Results from measurements published by University of Iceland on 26 April 2021 showed that the composition of eruption products had changed, to more closely resemble the typical Holocene basalts of Reykjanes peninsula. The eruption itself also changed in character at the same time, and was producing lava fountains up to 50 m (160 ft) in height on Sunday, 25 April 2021. On 28 April 2021, the lava fountains from the main crater reached a height of 250 m (820 ft).

The eruption pattern changed on 2 May from a continuous eruption and lava flow to a pulsating one, where periods of eruptions alternated with periods of inactivity, with each cycle lasting 10 minutes to half an hour. The magma jets became stronger, producing lava fountains of 300 m (980 ft) in height, visible from Reykjavík, with the highest one measured at 460 m (1,510 ft). The lava jets have been explained as explosive release of ancient trapped water or magma coming in contact with groundwater. The lava flow rate in the following weeks was also double that of the average for the first six weeks, with an average lava flow rate of 12.4 m^3/s (440 cu ft/s) from 18 May to 2 June.

Figure 2.5.7. Lava fountains of the Fagradalsfjall eruption, seen from Reykjavík on 9 May 2021

The increase in lava flow is unusual, as eruption outputs typically decrease with time. Scientists from the University of Iceland hypothesize that there is a large magma reservoir deep under the volcano, not the typical smaller magma chamber associated with these kinds of eruptions that empty over a short time. From the composition of the magma sampled, they also believe that there is a discrete vent feeding the main lava flow from a depth of 17–20 kilometers (11–12 mi) from the Earth's mantle, and may be of a more primitive kind than those previously observed. The channel widened in the first six weeks leading to increased lava flow. The eruption may create a new shield volcano if it continues for long enough. The formation of such volcano has not been studied before in real time, and this eruption can offer insights into the working of the magmatic systems.

Two defensive barriers were created starting 14 May as an experiment to stop lava flowing into the Nátthagi valley where telecommunication cables are buried, and further on to the southern coastal road Suðurlandsvegur. However, the lava soon flowed over the top of eastern barrier 22 May, and cascaded down to the Nátthagi. Lava flowed over the western barrier on 5 June. Lava flow blocked the main trail that provide access to the main viewing area on Gónhóll, first on 4 June, then again early in the morning of 13 June at another location. A further wall five meters high and 200 meters long was then created on 15 June in an attempt to divert lava flow away from Nátthagakriki with important infrastructure to its west and north. A barrier of 3 to 5 m high started to be constructed on 25 June at the mouth of Nátthagi to delay the flow of the lava over the southern coastal road and properties on Ísólfsskáli, although it was expected that the lava would eventually flow over the area into the sea. A proposal to build a bridge over the road to allow the lava flow underneath was rejected.

Around three months after the volcano first erupted, the lava flow was a steady 12 m^3/s (420 cu ft/s), and the lava now covered an area of more than 3 km^2 (1.2 sq mi) increasing by around 60,000 m^2/d (650,000 sq ft/d). Lava had accumulated 100 m (330 ft) deep around the volcano. The lava flow became continuous, which can be either above or below ground, although the eruptions also became calmer with the occasional increase in activity. There appeared to be no direct connection between the activity at the crater and lava flow. The lava flow can be tracked by helicopter or satellite, for example via radar imaging that can penetrate through the clouds and volcanic smog that had become more frequent in the area by July.

The eruptions stayed unusually constant until 23 June, and the activity then reduced significantly on 28 June, becoming inactive for many hours, and resuming on 29 June. It shifted to a pattern of many hours of inactivity, for example on 1 July and 4 July, with the eruptions resuming later. Lava flow from the crater ceased for 4 days from 5 July until 9 July, when eruptions resumed, initially with a periodicity of around 10 to 15 minutes, then lengthening to 3 to 4 an hour by 13 July. Lava has also been observed emerging from the bottom of the volcano on 10 July with considerable amount of lava flowing into the Meradalir valleys, and a section of the volcano on the northeastern side also broke off on the 14 July. Lava flow was estimated to be around 10 m^3/s (350 cu ft/s) but averaged to 5 to 6 m^3/s (180 to 210 cu ft/s) due to the periods of inactivity from late June to mid-July, half of the flow rate in May and June. The periodic lull in activity continued, with 7 to 13 hours of inactivity and similar period of eruption by late July, which lengthened to a pattern of mostly around 15 hours of inactivity alternating with around 20 hours of continuous eruption in August. It has been speculated that there are blockages at the top hundred metres of the eruption channel. By July, this eruption had become larger than most eruptions that have ever occurred on the Reykjanes peninsula. Measurement taken on 27 July indicated that the lava flow had increased again, returned to and possibly exceeding the peak level last seen in June. The measurement indicated an average flow of 17–18 m^3/s (600–640 cu ft/s) over 8–10 days, the highest observed thus far, but with a large margin of error. After a couple of months where the lava flowed mainly into the Meradalir valleys, the lava started to flow down the Nátthagi valley again on 21 August. The eruption by now had become the second longest in Iceland of the 21st century.

The volcano stopped erupting on 2 September, but lava flow resumed on 11 September, with the magma breaking through the lava field surface in several places. However, the main crater channel appeared to have been blocked, and the crater was filled with lava from a source underneath the northwestern wall through a crack on the wall, and lava also flowed outside the volcano through the wall. The average lava flow over the past 32 days had returned to 8.5 m^3/s (300 cu ft/s), and the lava field of 143 million m^3 (5.0 billion cu ft) now covered an area of 4.6 km^2 (1.8 sq mi). After a period of continuous eruption, a pulsing pattern of activity last seen in April/May started on 13 September, a pattern believed to be similar to what is observed in geysers where the frequency of eruption may be determined by the size of the reservoir below and how quickly it is filled up. The volcano was pulsing at a rate of around eight eruptions per hour on 14 September. No lava flowed out directly from the crater, instead lava began to emerge in significant amount from outside the volcano on 15 September. On 16 September 2021, after 181 days of eruption, it became the longest eruption of the 21st century in Iceland. Average lava flow was 16 m^3/s (570 cu ft/s) from 11 to 17 September when flow resumed, with the lava field increasing to 151 million m^3 (5.3 billion cu ft) covering an area of 4.8 km^2 (1.9 sq mi). The eruption stopped again on 18 September, but the activity decreased unusually slowly. On October 18, the alert level was lowered from "Orange" to "Yellow" due to no lava having erupted since September 18. The Icelandic meteorological office also stated that "it is assessed that Krýsuvík volcano is currently in a non-eruptive state. The activity might escalate again, so the situation is monitored closely".

2022 eruption

On 3 August 2022, after weeks of unrest on the Reykjanes Peninsula including over 10,000 recorded earthquakes from 30 July to 3 August with two quakes measuring over 5.0 Mw, another eruption began at Fagradalsfjall. A live stream from a camera at the site showed magma spewing from a narrow fissure vent. On 4 August the Icelandic Meteorological Office estimated it 360 meters in length. Over 1,830 people visited the volcano on the first day. It erupted over a lava flow from the 2021 eruption. The Icelandic Meteorological Office initially advised people not to go near Fagradalsfjall due to the new eruption.

Figure 2.5.8. Eruption on the 4 August 2022 of the Meradalir effusive eruption

Iceland's Department of Civil Protection and Emergency Management stated that no lives or infrastructure were currently at risk from the eruption. Iceland's main airport, Keflavík Airport, was briefly on alert, which is a standard procedure during eruptions, though the facility did not cancel any flights. Airplanes were prohibited from flying over the site, although some helicopters were sent in to survey the eruption. The eruption was not producing large plumes, though it was likely to affect air quality and pollution in immediately surrounding areas. Professor of geophysics Magnús Tumi Guðmundsson said, judging from the initial lava flow, that the eruption was likely five to ten times bigger than the 2021 eruption, but that it was not "the big one". From the nearby geomorphology, the lava was likely to flow into the Meradalir valleys.

The lava flow decreased around 17 August and stopped on 21 August 2022. Since then, there has been no visible activity at the new site.

Risk mitigation and tourism

Due to the volcanic site's proximity to the town of Grindavik, Vogar and to a lesser extent Keflavik, Keflavik International Airport and the Greater Reykjavík Area, Iceland's Department of Civil Protection and Emergency Management has created protocols for evacuation plans of nearby settlements and in case of gas pollution and/or lava flows. The large number of tourists visiting the eruption sites is also a concern to authorities, especially under-equipped tourists and those who do not heed official closures during inclement weather or new lava flows.As of the second eruption in 2022, there is little risk of lava flows blocking roads or reaching settlements, but this could change if the Meradalir valleys fill with lava or another fissure opens up in a different area.

Air traffic

The eruption site is only around 20 km from Iceland's main international airport, Keflavik International Airport. Due to the eruption's effusive nature with little to no ash production, it is not considered a risk to air traffic. The ICAO Aviation Colour code has mostly stayed orange (ongoing eruption with low to no ash production). This has meant that no interruptions to flight traffic to and from Keflavik International Airport. Icelandic Coast Guard helicopters have conducted many research and monitoring flights around the volcano as well as large numbers of helicopter tour companies operating and landing in the vicinity, as well as small private aviation and sightseeing fixed wing aircraft circling the eruption site. Many unmanned drones are also active around the volcano site.

Roads and utilities

The main concerns are if lava flows were to reach the main highway to Keflavik and the airport, Road 41, as well as the south coast road, Road 427, an important evacuation route for the town of Grindavik. In addition, if the lava flows travel northwards, an important high-voltage transmission line to Keflavik is in danger of being cut off. Communications fiber routes both to the north and south side of the volcano are also in danger of being cut off, which could impact communications and the data center industry in Keflavik. However, the fissure's location as of August 2022 is unlikey to affect the roads and utilities.

Within a week of the starts of the 2021 eruption, power and fiber-optic lines were laid from Grindavik to support operations of the authorities near the eruption site as well as 4G cell and TETRA masts were set up to ensure access to communications and emergency services (112) for tourists and authorities.

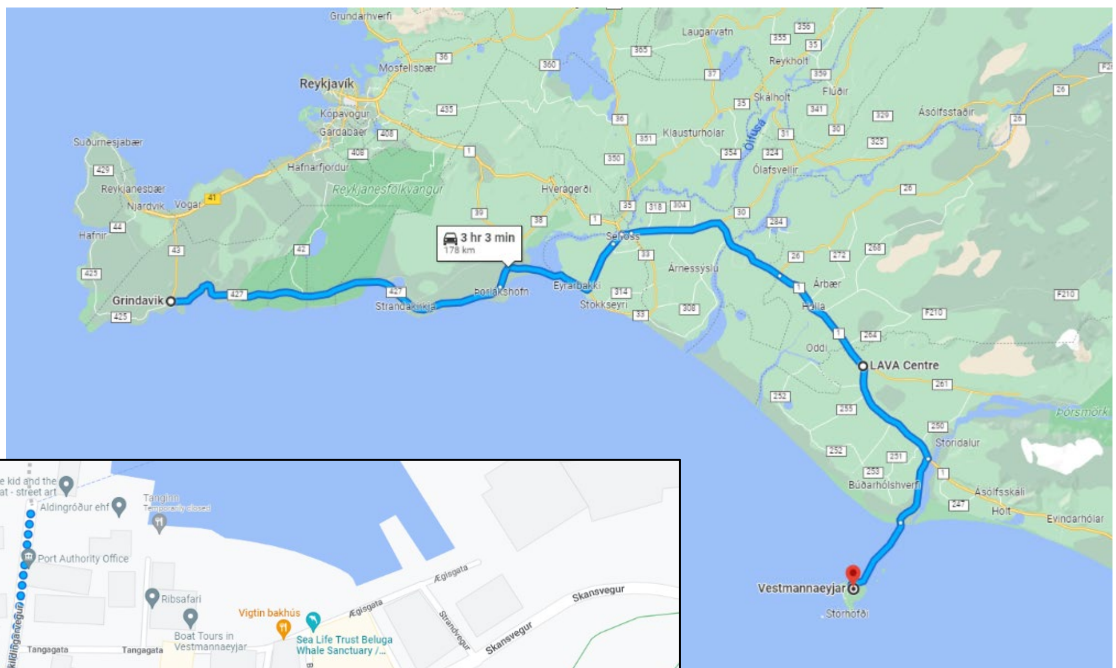
Lava flow experiments

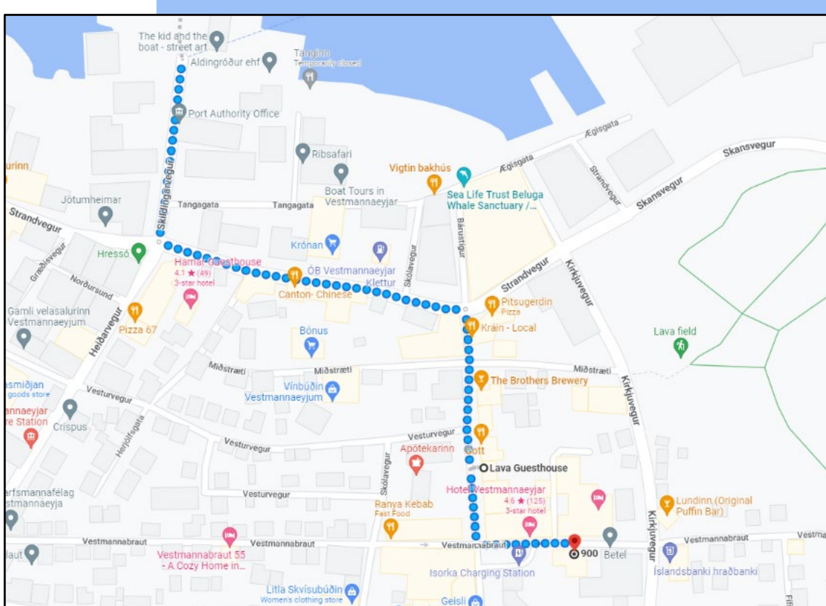
In July 2021, in collaboration with Iceland's Department of Civil Protection and Emergency Management, utility companies conducted an experiment by burying various types of utilities (underground electrical cables, fibers, water lines and sewage line) with varying levels of insulation to see how overland lava flows affect buried utilities. Another separate experiment was conducted by constructing large levees to control direction of lava flows; they were moderately effective in controlling slow moving lava flows.

Figure 2.5.9. Lava levee constructed as an experiment in summer 2021 to control lava flows at the Fagradalsfjall volcano.

Day 3: Monday, March 6th, 2023 – Grindavik to Vestmannaeyjar

7:00AM: Wake up, pack up, breakfast is provided at the guesthouse.
8:00AM: Load the bus and leave the guesthouse
10:00AM: Arrive at LAVA Centre (https://lavacentre.is/) and tour the museum, people can buy lunch here or on the ferry to Vestmannaeyjar
12:30PM: Depart from the LAVA Centre
1:00PM: Board the ferry and depart for Vestmannaeyjar
2:00PM: Arrive Vestmannaeyjar, check-in to the guesthouse
Lava Guesthouse (https://lavaguesthouse.com/)
Bárustígur 13, 900 Vestmannaeyjabær, Iceland
Email: info@lavaguesthouse.com Phone: +354 659 5400
3:00PM: Eldheimar Volcano Museum (https://www.eldheimar.is/)
6:00PM: Group dinner at 900 Grillhouse (http://www.900grillhus.is/)





Downtown Vestmannaeyjar with the route from the ferry terminal to the guesthouse and dinner location

STOP 3.1 – *LAVA Centre*

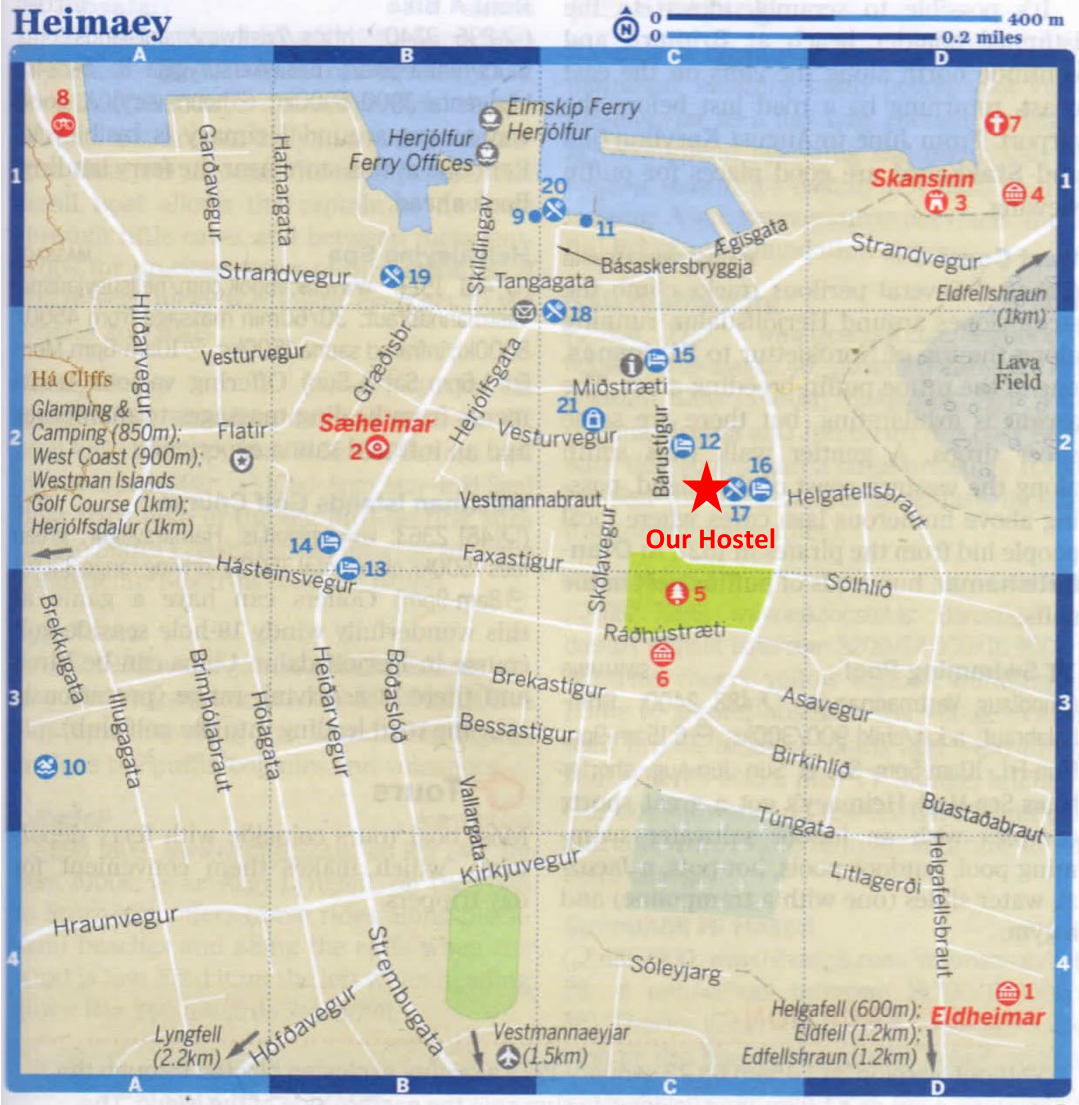
This day is mostly a travel-day, but we will have two museum stops, the first being the LAVA Centre

The LAVA centre features an interactive exhibition exploring the art and science of geology and the volcanic systems in Iceland. Information from the past century's eruptions demonstrate just how strong a presence volcanoes have in contemporary Iceland. Feel the forces of nature as you experience an earthquake and see the Fiery Heart of Iceland, a 12m high structure simulating the Mantle plume and the magma flow underneath Iceland. In an educational learning centre you can explore the wonders of volcanoes and earthquakes through interactive computers and there's also a cinema auditorium where visitors can see the magnificence of volcanic eruptions in HD 4K.

STOP 3.2 – *Vestmannaeyjar - Heimaey*

Vestmannaeyjar (sometimes anglicized as Westman Islands) is a town and archipelago off the south coast of Iceland. The largest island, Heimaey, has a population of 4,135. The other islands are uninhabited, although six have single hunting cabins. Vestmannaeyjar came to international attention in 1973 with the eruption of Eldfell volcano, which destroyed many buildings and forced a months-long evacuation of the entire population to mainland Iceland. Approximately one fifth of the town was destroyed before the lava flow was halted by application of 6.8 billion liters of cold sea water.

This evening we will have a group meal.



Heimaey

Top Sights

1 Eldheimar....D4
2 Sæheimar....B2
3 Skansinn....D1

Sights

4 Landlyst....D1
5 Public Park....C3
6 Sagnheimar Byggðasafn....C3
7 Stafkirkjan....D1
8 Stóraklif & Heimaklettur....A1

Activities, Courses & Tours

Eyja Tours....(see 9)
Rent A Bike....(see 9)
9 Ribsafari....B1
10 Swimming Pool....A3
11 Viking Tours....C1

Sleeping

12 Aska Hostel....C2
13 B&B Hrafnabjörg....B2
14 Gistiheimilið Hreiðrið....B2
15 Hótel Eyjar....C2
16 Hótel Vestmannaeyjar....C2
Sunnuhöll HI Hostel....(see 16)

Eating

17 Einsi Kaldi....C2
Gott....(see 12)
18 Krónan....C2
19 Slippurinn....B1
20 Tanginn....C1

Shopping

21 Vínbúðin....C2

(Lonely Plant, 2022)

STOP 3.3 – *Eldheimar Volcano Museum*

The following is from: Fraedrich, W. and Heidari, N., 2019, Iceland from the West to the South. Springer International Publishing, Cham, Switzerland, pgs. 177-179.

Eldheimar

From Helgafellsbraut the streets to Gerdisbraut and Austurgerdi lead towards the lava field. There, the excavation of the houses had begun in 2010. The Tephra deposits that were partly more than 6 m thick, had covered numerous houses completely. In the meantime, the Eldheimar Volcanic Museum, a building that was built on top of the old houses. has been existing as a museum since 2014 (Figure 3.3.1), The story of the volcanic eruption and the fate of the inhabitants of Vestmannaeyjar are illustrated based on the example of Mrs. Gerdur Sigurdardottir and Mr. Gudni Olafsson and their three children. This includes the reconstruction of the town, the Vestman Islands (including Surtsey) and the whole island of Iceland. A visit to the museum (http"//eldheimar.is), which is also known as the Pompeii of the north, is worthwhile in any case.

Figure 3.3.1. View on the museum Eldheimar, 'Pompeii of the north'

STOP 3.4 – *Vestmannaeyjar Swimming Pool*

That evening is free, people can hang around the downtown, or head to the community pool. Here is the information from their website:

The inside swimming pool is 25 m in length and 11 m in width. The water in the pool is slightly saline or with 0.09% salt water and heated to about 29.5°C. There are many toys in the shallow end of the pool as well as a basketball ring. The deeper end has a 1 m springboard.

The outside area is family friendly with tubs, sauna and water slides. There are three tiled hot tubs with temperature ranging from 37°C to 42°C and a wading pool with temperature around 34°C.

The tubs have numerous nozzles for back and calf massage, high pressure massage for the brave one and a massage waterfall. The wading pool is ideal for relaxation and sunbathing in the shallow water.

Associated with the wading pool is a deeper pool with water nozzle, traditional rounded waterfalls, basketball ring and a climbing wall with the outlines of Heimaklettur (the highest mountain in Westmann Islands).

There are three water slides in the outside area, one is connected to the pool with the climbing wall and two are connected to a deep pool facing the the big hot tub.

• The ELDFELL water slide (the Volcano) aimed for children.

• The STÓRHÖFÐI water slide (the Big Cape) which consists of three open tubes which delivers you fast and straight into the pool.

• The DUFÞEKJA water slide (the cliff Dufþekja) which is a steep tube that ends on a big trampoline, more than 20 meters long.

There is also a sauna (46-47°C), outdoor shower and a sunbathing area.

http://vestmannaeyjar.is/is/page/aeskulyds-og-ithrottamal

Swimming pool, Brimholalaut, 900 Vestmannaeyjar

It closes at 9:00PM

Day 4: Tuesday, March 7th, 2023 – Heimaey to the Rift Valley

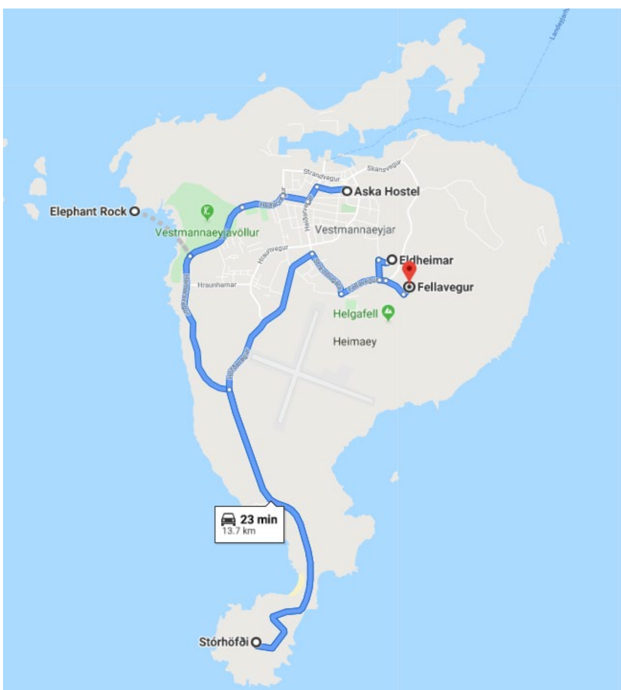
7:00AM: Breakfast in the guesthouse, pack up, and load into the buses.

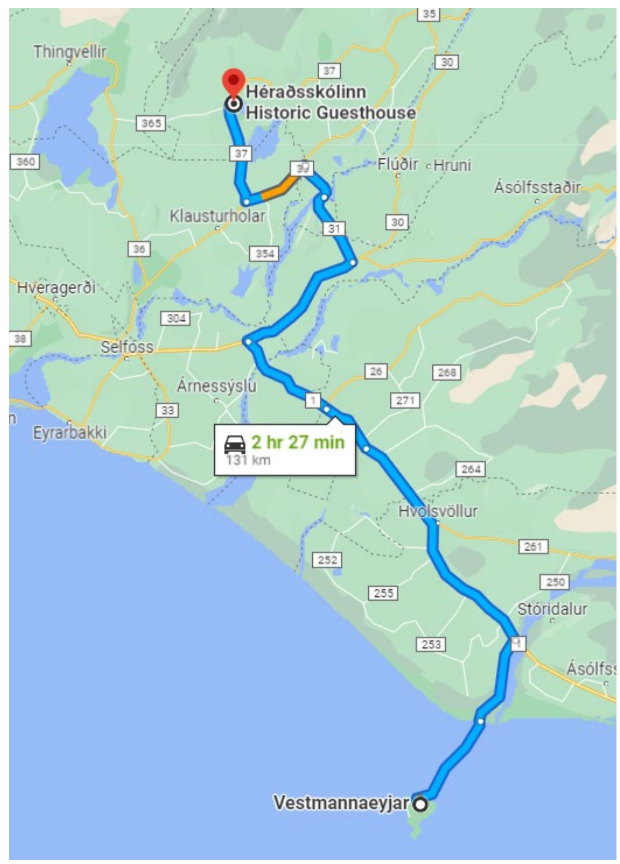
Breakfast is not included, so probably grab something at the store the night before…

8:00AM: Leave the hostel and drive around the island, first stop Elephant Rock
9:00AM: Pirate Cove & Storhofdi - south edge of the island, hike around, good view of Surtsey
11:00AM: Climb Eldfell Volcano
1:00PM: Go into town, grab lunch on your own, and wait for ferry
2:00PM: Board the ferry and depart for the mainland
3:30PM: Reach Landeyjahofn and drive to the guesthouse
5:30PM: Check-in at the guesthouse

Héraðsskólinn Guesthouse (https://heradsskolinn.is/contact/)
840 Laugarvatn, Iceland
Email: booking@heradsskolinn.is, Phone: +354 537 8060

6:00PM: Group dinner at the guesthouse
That evening: I am hoping this location will give us a good shot at seeing the Aurora Borealis





Overview of the Vestmannaeyjar Islands:

From Wikipedia

Heimaey, literally Home Island, is an Icelandic island. At 13.4 square kilometres (5.2 sq mi), it is the largest island in the Vestmannaeyjar archipelago, and the largest and most populated island off the Icelandic coast. Heimaey is 4 nautical miles (7.4 km; 4.6 mi) off the south coast of Iceland. It is the only populated island of the Vestmannaeyjar islands, with a population of 4,500. The airport and the Vestman Island Golf Course cover a large part of the island. In January 1973, lava flow from nearby Eldfell destroyed half the town and threatened to close its harbour, its main income source. An operation to cool the advancing lava with sea water saved the harbour.

The following figures is from: Fraedrich, W. and Heidari, N., 2019, Iceland from the West to the South. Springer International Publishing, Cham, Switzerland, pgs. 263.

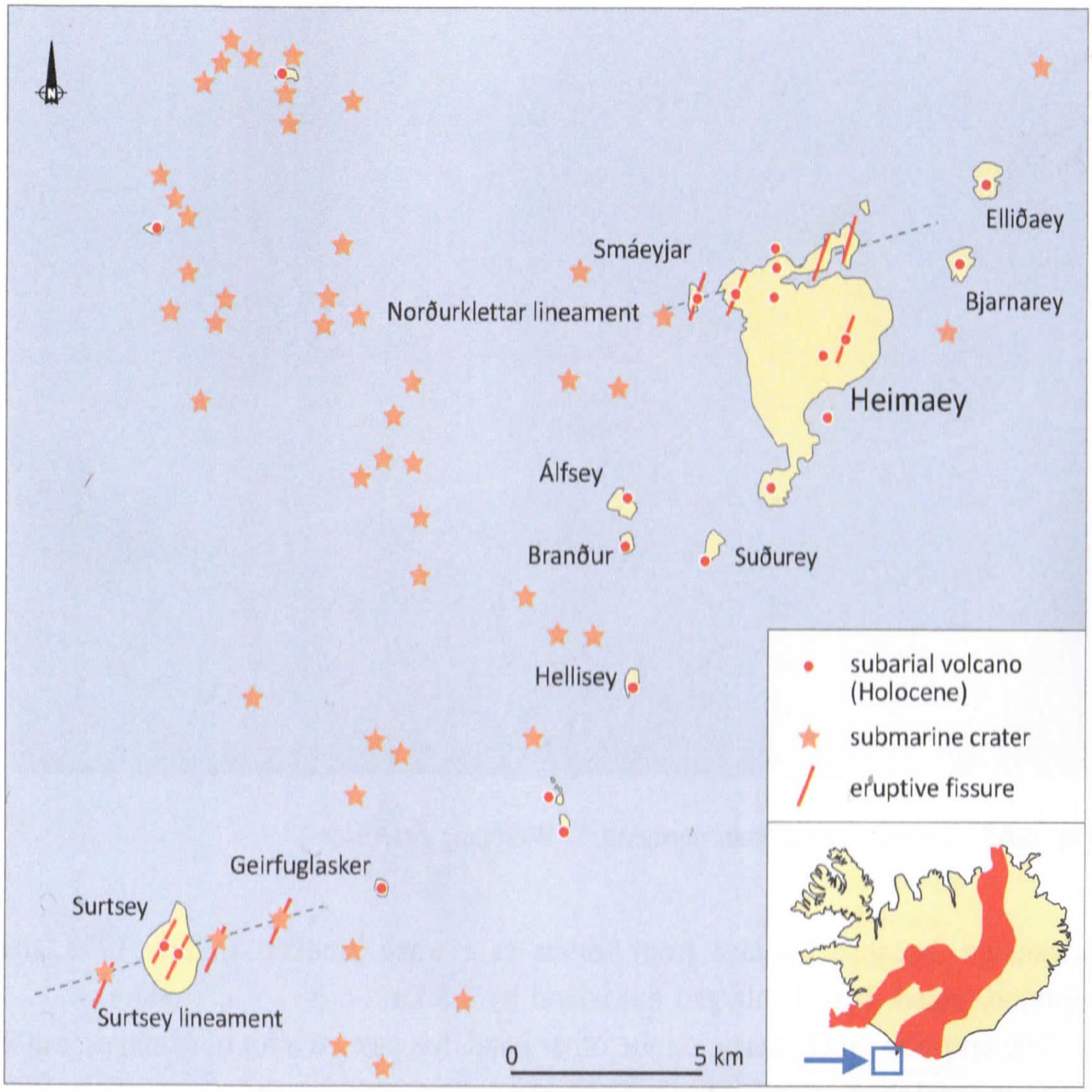


Figure 4.0.1. The Westman Islands near Iceland's south coast

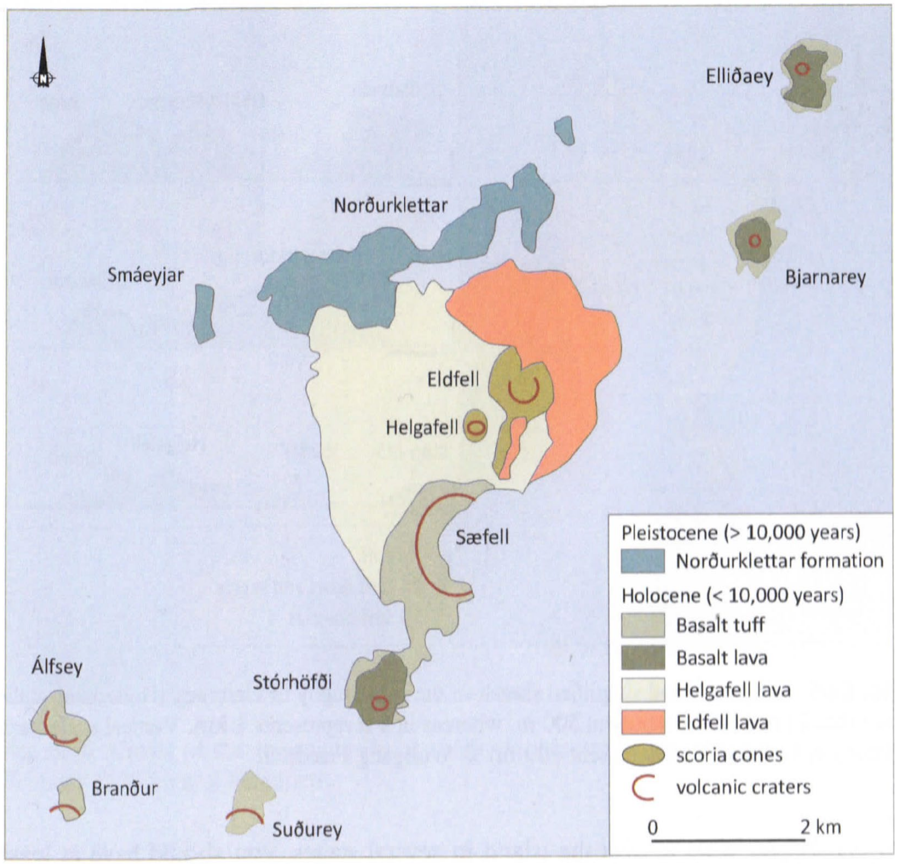


Figure 4.0.2. Simplified geological map of des Vestman Islands

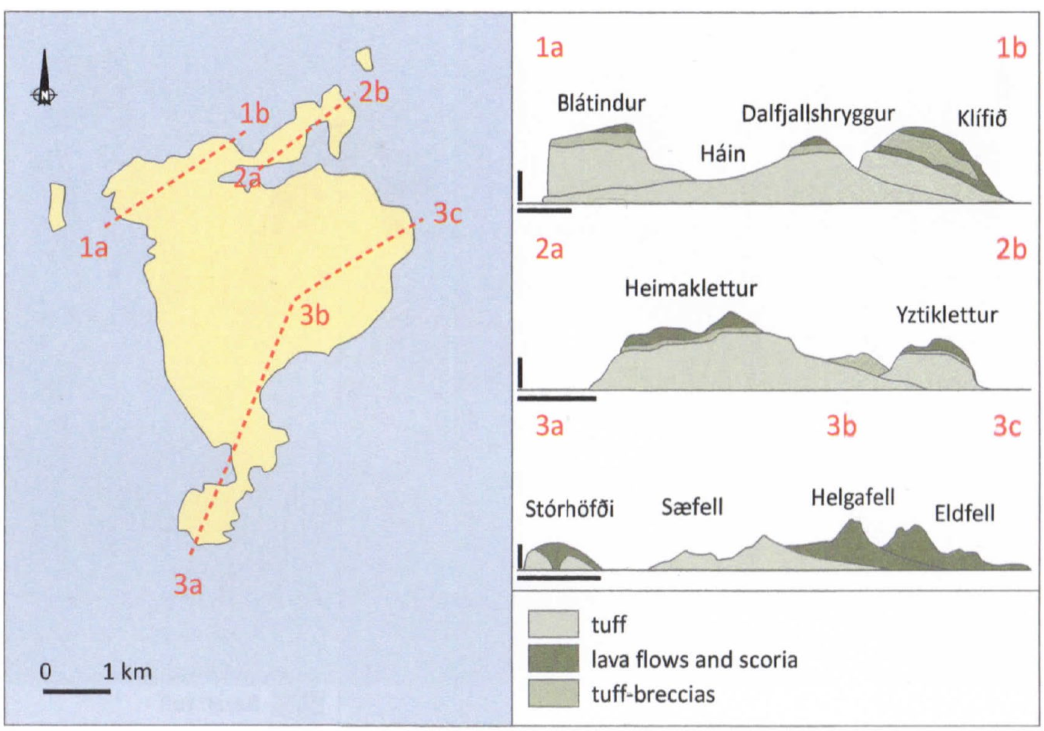
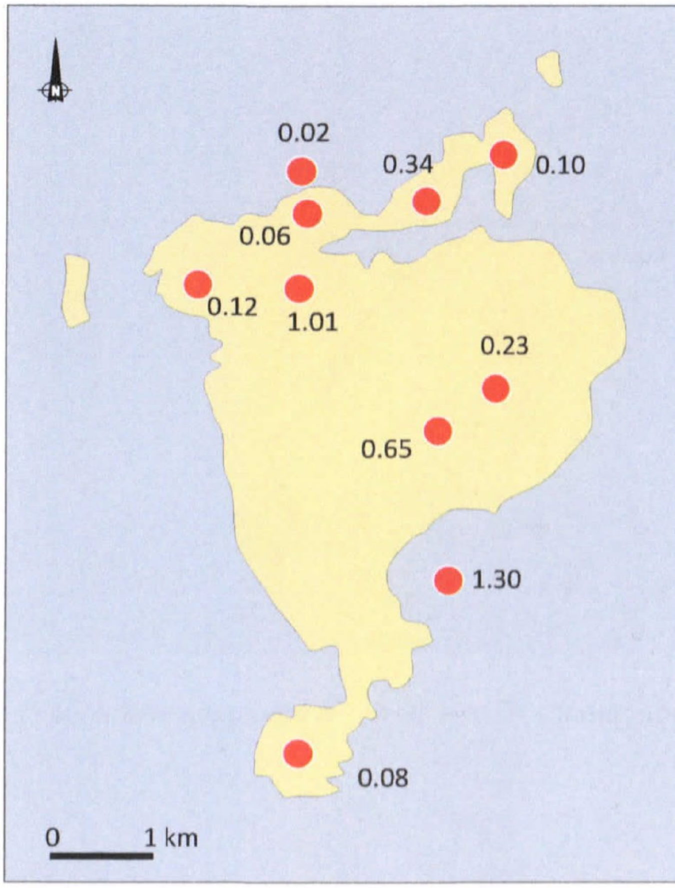


Figure 4.0.3. Schematic and simplified sketch of the stratigraphy of Heimay (Horizontal scale bars [black] in 1 and 2 represent 500 m, whereas in 3 it represents 1 km. Vertical scale bars [black] in 1, 2, and 3 all represent 100 m)



unit	tuff (km^3)	lava and scoria (km^3)
Háin	0.74	0.27
Blátindur	0.05	0.07
Klífið	0.05	0.01
Dalfjallshryggur	0.00	0.02
Heimaklettur	0.24	0.10
Yztiklettur	0.07	0.03
Stórhöfði	0.05	0.03
Sæfell	1.30	0.00
Helgafell	0.00	0.65
Eldfell	0.00	0.23
total	2.49	1.41

eruptive vent and volume (km^3)

Figure 4.0.4. Crowd of the volcanic material which was erupted by the different volcanoes on Heimay

STOP 4.1 – *Elephant Rock*

The following is from: Fraedrich, W. and Heidari, N., 2019, Iceland from the West to the South. Springer International Publishing, Cham, Switzerland, pgs. 180-183.

The 'Elephant'

Follow the coastline and go up to the towering cliffs of Nordurklettar. These basalts, formed at the end of the last Ice Age, make up the northwestern edge of Heimay. On the steep flanks of the eroded volcanic complex, the typical column basalt structures can be encountered. Column basalts arise when the lava solidifies. Slow cooling processes lead to contraction and form hexagonal column structures, which are perpendicular to the cooling surface. Nordurklettar is by now heavily over-shaped by weathering and by erosion. The surf of the sea has, for example, created caves. The view of the 'elephant' is absolutely impressive and a fantasy image at the same time. It clearly represents unique structures exclusively created by nature (63º 26' 22.20" N / 20º 18' 23.90" W, Figure 4.1.1)

Figure 4.1.1. The elephant at Nordurklettar

STOP 4.2 – *Pirate Cove & Storhofdi*

The following is from: Fraedrich, W. and Heidari, N., 2019, Iceland from the West to the South. Springer International Publishing, Cham, Switzerland, pgs. 185-189.

Saefellcrater - Pirate Cove - Storhofdi

It is also worthwhile to visit the southern tip of the island off Heimaey. Here you will find the remnants of previous eruptions. The Saefell tuff ring was created 6620 ± 180 years ago by a submarine eruption in low sea depth, which is similar to the emergence of Surtsey in 1963. The tuff ring has a basic diameter of about 3 km, a maximum margin of 188 m above sea level and a crater diameter of about 1000 m. One reaches its crater edge from a road junction at 63º 24’ 59.20” N / 20º 16’ 52.30” W. You can climb to the ridge from here.

Saefell has been completely removed from the sea at its complete east side. The panorama from the edge over the western crater half is impressive. An insight into the internal structure of such a tuff ring is much better and less dangerous further south (Figure 4.2.1). To return to the main road, drive back about 120 m and turn left. Follow this narrow road, which then changes leading from Vestmannaeyjar to Storhofdi (63º 24’ 45.90” N / 20º 16’ 47.90” W). From here, continue along the road for about 800 m, then head south for a small car park at Pirate Cove (63º 24’ 52.20” N / 20º 16’ 52.30” W).

Figure 4.2.1. View from the south over the Pirate Cove to the Saefell tuff ring

At the car park you can find the narrowest point of the entire island of about 200 m. Towards the sea to the east, there is an information board which provides information on significant historical events (Figure 4.2.2). Three ships with pirates from Algeria, under Turkish rule, reached Heimaey on July 17, 1627. The fortifications built on Heimaey under Danish rule at the end of the 15th century did not help. The priates forced their way through the coast and docked more south in the bay between Saefell and Storhofdi.

Three shipyards conquered the entire island, murdered 36 people and held 242 of the then 500 inhabitants on Heimaey. Only the merchant, Lauritz Bagge, could escape with his family as they rowed to Iceland. The initial ambition of a high ransom was not met. Most of the prisoners had already died on their way to Africa. Only a few prisoners were sold - at small proceeds - on the slave market. An old man named Olafur Einarsson could not be sold as a slave. He survived and was sent back to demand ransom. At first, his attempts failed until he wrote a book on the abduction. Its success freed 37 prisoners after a few years. Only 27 of the 242 prisoners were able to return to Heimaey ten years after their abduction.

Figure 4.2.2. Information board retelling the story of the pirate invasion of 1627.

A short beach walk is recommended along the west side of the Island towards the north. Here, you have a good view of the Saefell tuffs, on which you can walk along. There are numerous volcanic bombs that have once been thrown out of the crater with fine materials (Figure 4.2.3). Due to their weight on the ground, they squeezed the loose materials together. As shown in Figure 4.2.4, the ejected material is from different depths since the explosions occurred at increasing depth during the eruption.

The volcano Storhofdi was built about 6600 years before today, which makes it the oldest volcano in the south. It is the remnant of a volcano, formed by numerous streams of lava flowing in different directions, large parts of which are submarine. The lava streams of the Storhofdi must have had a very low viscosity (Figures 4.2.5 and 4.2.6).

Figure 4.2.3. Volcanic bomb embedded in Saefell tuff

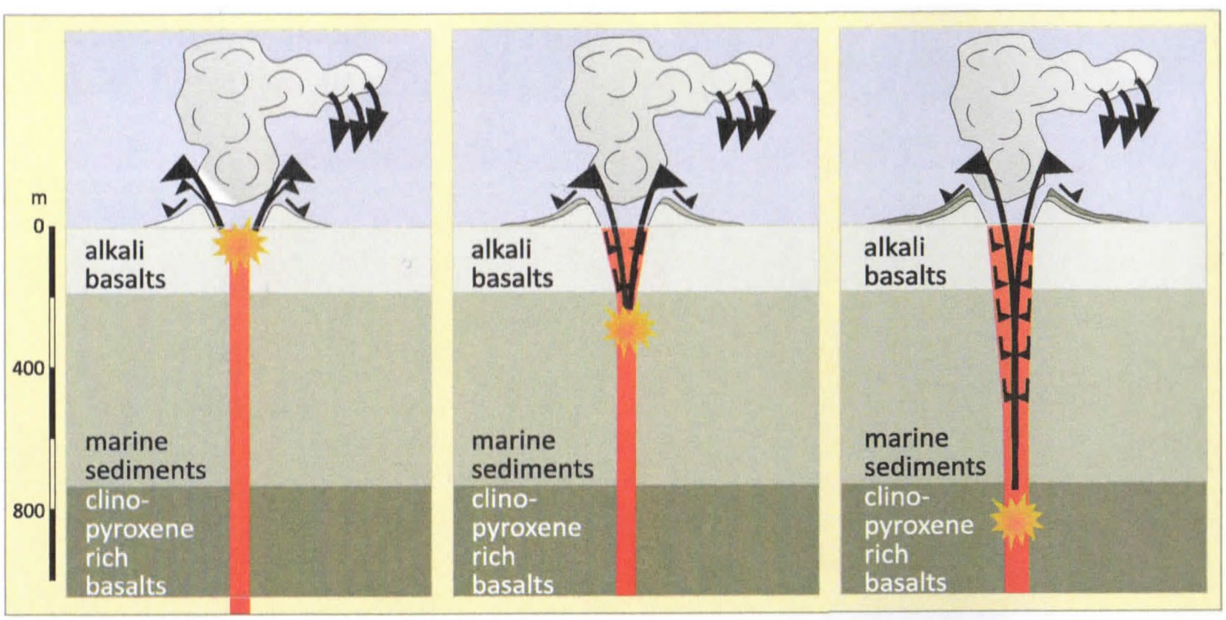


Figure 4.2.4. Schematic sketch showing the growth of the diameter beneath Saefell. (Left: The eruption begins and explosions are shallow-seated carrying alkali basaltic xenoliths (Type I) to the surface. Middle: Explosion focus moves downward into the sedimentary basement rocks and sedimentary xenoliths (Type II) are deposited at the surface. Right: Explosion focus has migrated downward to a depth exceeding 820 m and starts to carry cpx-bearing FeTi-basalts to the surface (Type III xenoliths). Star represents location of explosion focus).

Figure 4.2.5. View to the south Heimaey with Storhofdi

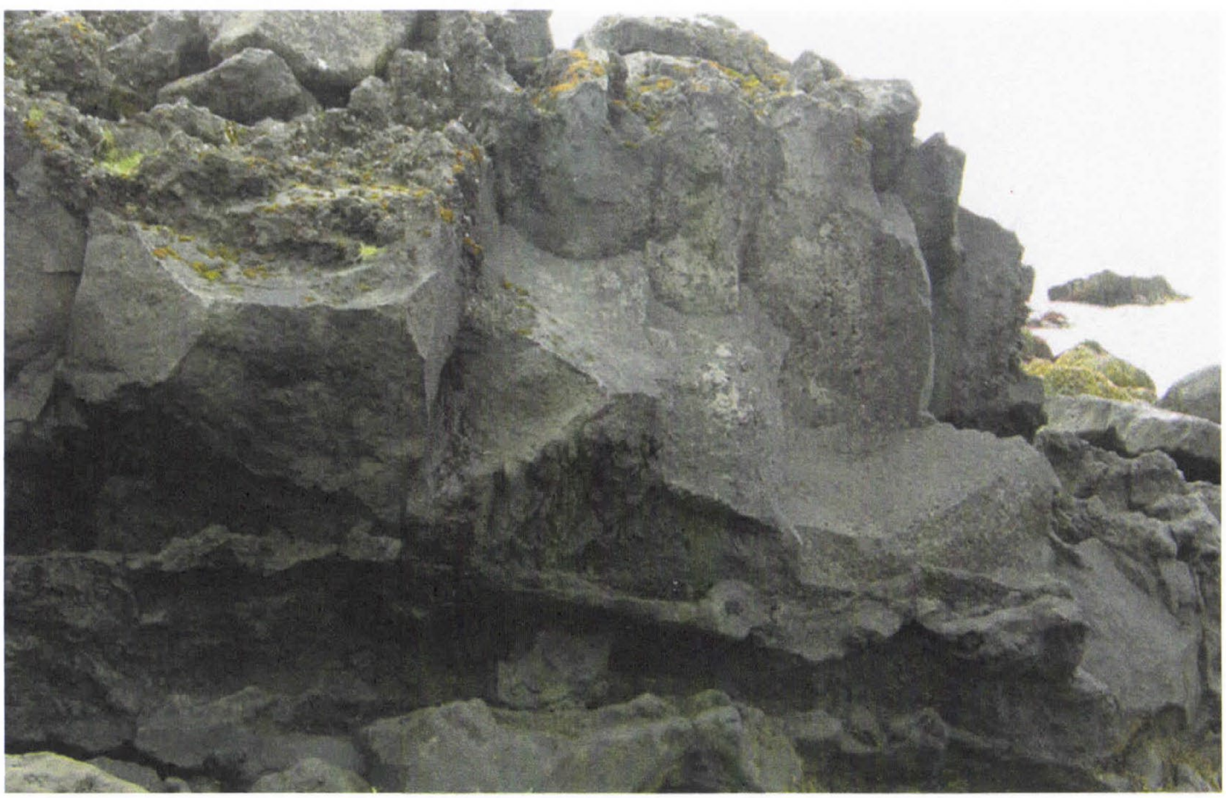


Figure 4.2.6. Lava flow at the north edge of Storhofdi

STOP 4.3 – *The Story of Surtsey*

The following is from: Thordarson, T. and Hoskuldsson, A., 2019, Iceland: Classic Geology in Europe 3 (Second Edition). Dunedin Academic Press Ltd., Edinburgh, Scotland, pgs. 107-108.

The 1963-7 Surtsey Eruption
An island emerging from the sea

Surtsey [63.3015, -20.6038] is a small volcanic island situated about 33 km off the central-south coast of Iceland and is the westernmost island of the Vestmannaeyjar archipelago. The island is the subaerial part of the larger Surtsey volcano, a 6 km-long east-northeast-trending submarine ridge that rises from a depth of 125 m and covers about 14 km^2 (Figure 4.3.1). The prominent features on Surtsey are two abutting 140 m-high tuff cones and a small pahoehoe lava flowfield that caps the southern half of the island.

Surtsey is also the youngest of the Vestmannaeyjar, formed by a prolonged eruption that was first noticed on November 14th 1963 by fishermen attending their nests about 20 km southwest of Heimaey. The eruption intensified and gradually built an island that in its prime rose to 170 m above sea level. It was named Surtsey after Surtur, the fire-raising giant of Norse mythology who was to set fire to the Earth on Judgement Day. Surtsey rumbled and lava flowed for 3 ½ years until June 1967, when Surtur called it quits - the longest eruption in Iceland since settlement was over and, for the first time, Icelanders had witnessed the formation of a submarine table mountain.

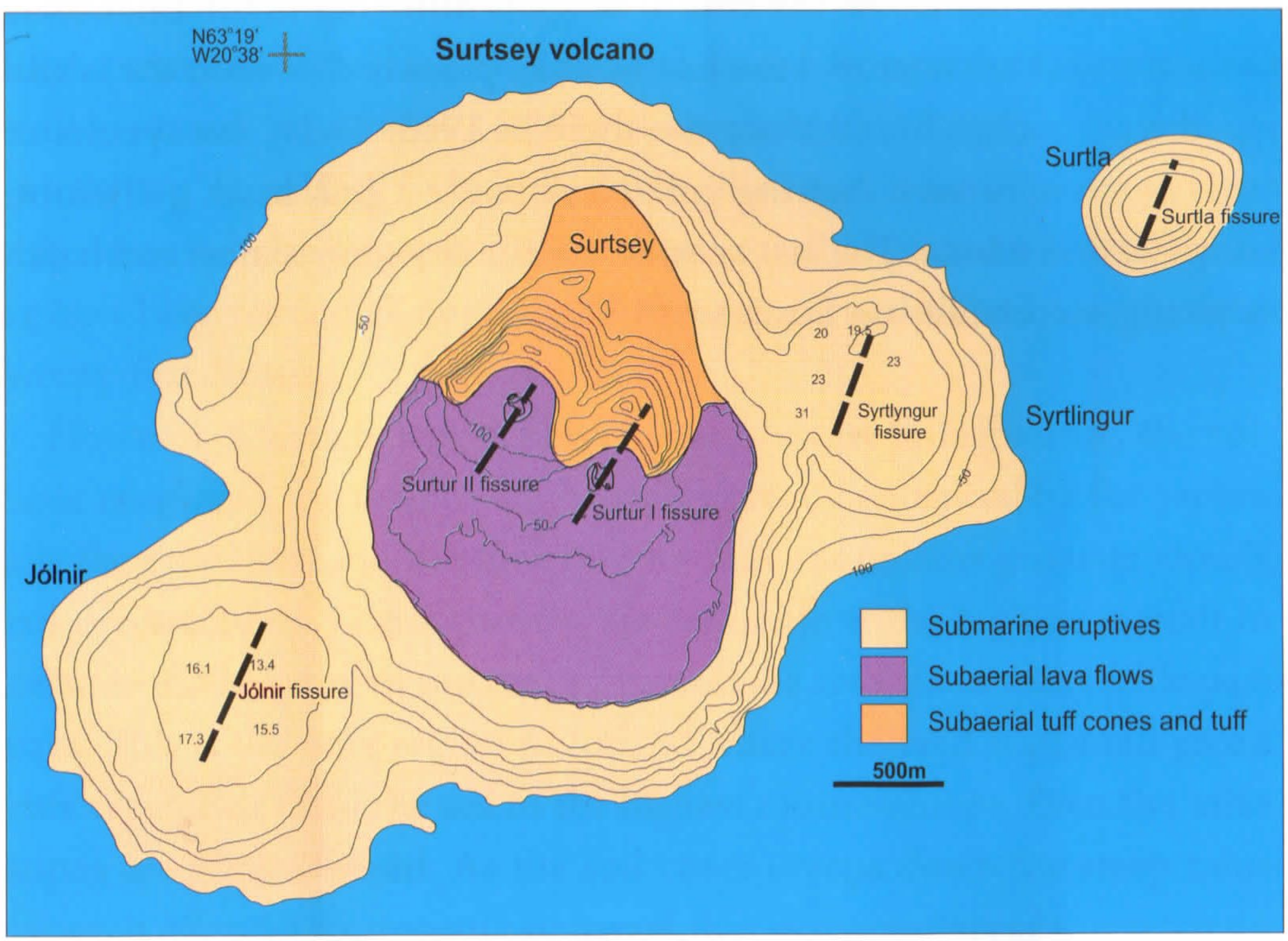


Figure 4.3.1. Geological map of the Surtsey volcano

The tuff cones, Surtur I and II (Figure 4.3.1), were built by Surtseyan explosive eruptions over a period of five months between November 1963 and April 1964. During this stage the eruption columns rose as high as 13 km. When the island had grown large enough to seal the volcanoic conduit from the invading seawater, the activity changed from being wholly explosive to purely effusive. The eruption featured two prolonged subaerial effusive eruption phases, the first erupting through the Surtur II crater and lasting for 13 ½ months (April 1964 to May 1965). It prolonged a 100 m-high lava shield that covered 1.53 km^2 above sea level. In the second phase the Surtur I crater came to life again to produce a 70 m-high and 1 km-wide lava shield between August 1966 and June 1967. The total volume of tephra and lava produced by the Surtsey eruption amounts to about 1.2 km^3, of which about 0.4 km^3 is lava. Today, erosion is the main force at work on Surtsey and, since the end of the eruption in 1967, wave erosion has reduced the surface area of the island by 1 km^2.

Long before the eruption stopped, the island was proclaimed a nature reserve and all visits to it were restricted, so biologists could make the most of this unique opportunity to study how life would migrate to and develop on this new and desolate land. In 1964 the first living organism was found in the ash deposits closest to the shore, and in May that same year a single fly was found on the island. Seagulls hung out in the tidewaters farstest from the crater and the first vascular plant to flower on the island was the sea rocket, found along the shore in 1965. Today five species of birds nest on Surtsey: herring gull, black-backed gull, black guillemot, kittiwake, and fulmar. The last species was the first one to nest and hatch its young successfully on Surtsey in 1970.

The following is from: https://www.icelandreview.com/news/dirty-secret-uncovered-doing-business-surtsey/

Dirty Secret Uncovered: Doing Business on Surtsey

Iceland Review: February 12, 2015

Ágúst Bjarnason, who used to monitor the progress of plants on volcanic island Surtsey, has uncovered an incident he has kept secret for 45 years. In the summer of ’69, he found a tomato plant on the island, which had grown out of human faeces.

“Once when I was in Reykjavík I received the message from Surtsey that a mysterious plant had been discovered in the lava. Those who discovered the plant, three or four foreign nature scientists and one Icelandic botanist, weren’t able to identify it,” Ágúst wrote in Vestmannaeyjar newspaper Eyjafréttir yesterday.

He traveled to Surtsey as soon as he could and found the plant quickly. “At first I was stunned because of the strange plant which looked like a potato plant. I bent down and rolled two lava rocks aside which lay against the plant on either side. Underneath was a peculiar pile which was very soft when I poked it.”

“Suddenly it dawned on me what it was. Someone had done their business [there] … and this beautiful tomato plant (Solanum lycopersicum), 15-cm [5-in] tall, had grown out of the faeces. … I put everything in a plastic bag and closed it securely. I made sure not to leave anything behind so that the natural settlement [of plants] wouldn’t be compromised,” Ágúst revealed.

The discovery would have shocked the scientific community, because ever since the island was created in an underwater eruption from 1963 to 1967, Surtsey has been preserved as a living laboratory. Only scientists and a handful of other people have been allowed to visit the island to keep the human impact minimal. Surtsey is now a UNESCO World Heritage Site.

STOP 4.4 – *Eldfell Volcano*

Eldfell (*from Wikipedia*)

At 01:00 on 23 January, 1973, a volcanic eruption of the mountain Eldfell began on Heimaey. The ground on Heimaey started to quake and fissures formed. The fissures grew to 1,600 metres (5,200 ft) in length, and lava began to erupt. Lava sprayed into the air from the fissures. Volcanic ash was blown to sea. Later, the situation deteriorated. When the fissures closed, the eruption converted to a concentrated lava flow that headed toward the harbour. The winds changed, and half a million cubic metres of ash blew on the town. During the night, the 5,000 inhabitants of the island were evacuated, mostly by fishing boats, as almost the entire fishing fleet was in dock.

The encroaching lava flow threatened to destroy the harbour. The eruption lasted until 3 July. Townspeople constantly sprayed the lava with cold seawater, causing some to solidify and much to be diverted, thus saving the harbour. The people were elated that their livelihoods remained intact, even though much of their town was destroyed. During the eruption, half of the town was crushed and the island expanded in length. The eruption increased the area of Heimaey from 11.2 km^2 (4.3 sq mi) to 13.44 km^2 (5.19 sq mi). Only one man died in the eruption. The eruption is described by John McPhee in his book The Control of Nature.

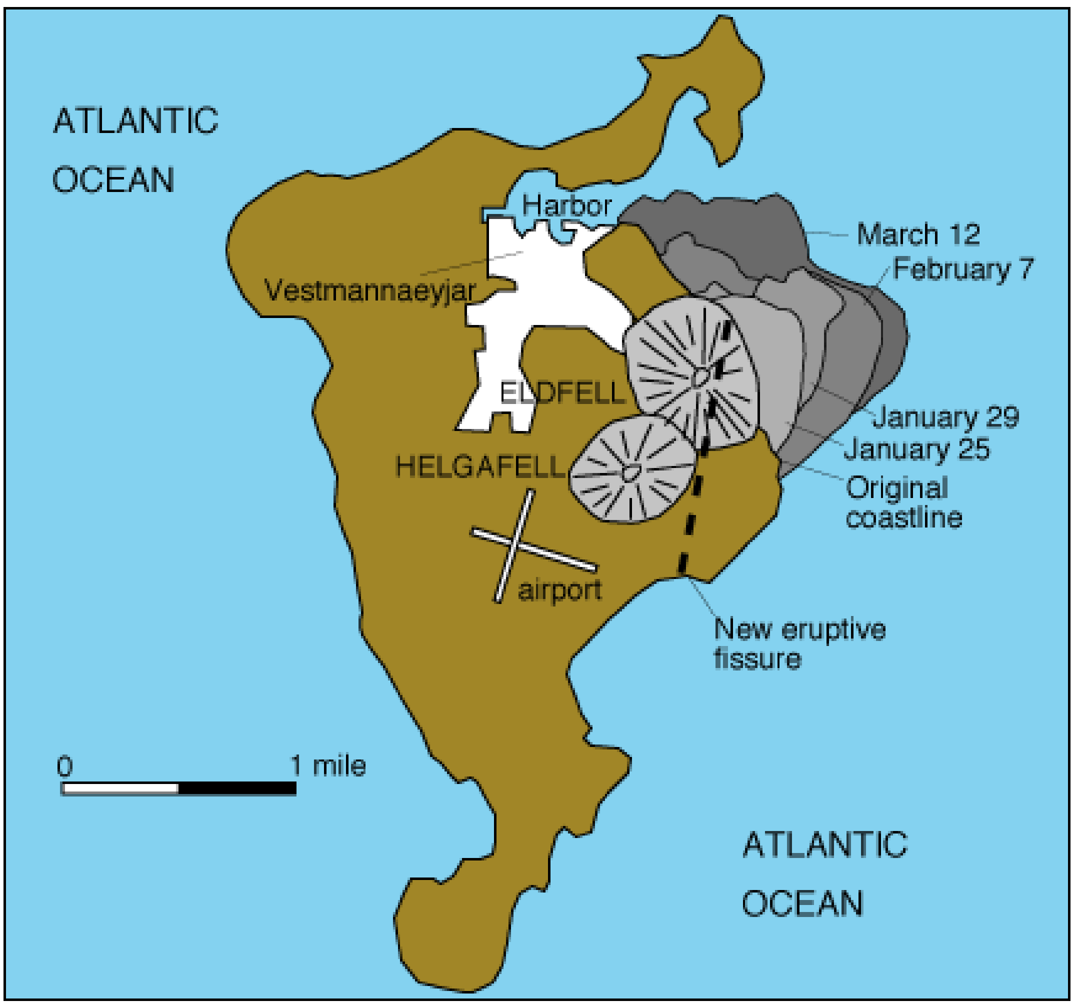


Figure 4.4.1. Sketch showing the changes to Heimaey caused by the eruption of Eldfell.

The following is from: Fraedrich, W. and Heidari, N., 2019, Iceland from the West to the South. Springer International Publishing, Cham, Switzerland, pgs. 178.

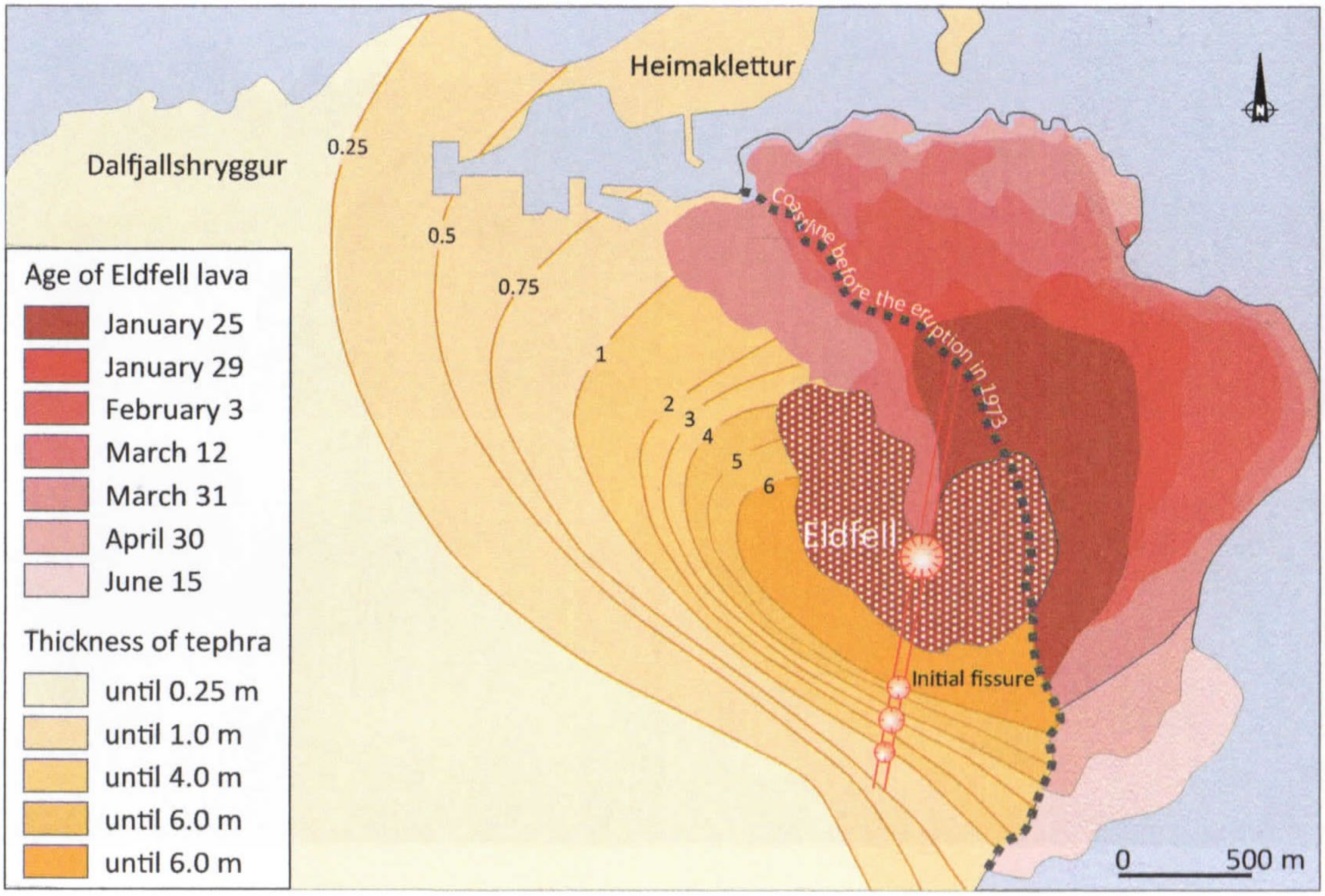


Figure 4.4.2. Eldfell - age of lava and thickness of ashes

The following is from: Thordarson, T. and Hoskuldsson, A., 2019, Iceland: Classic Geology in Europe 3 (Second Edition). Dunedin Academic Press Ltd., Edinburgh, Scotland, pgs. 104-106.

Eldfell

The most recent addition to Heimaey is the scoria cone Eldfell ('mountain of fire') and its lava flow, both formed in 1973. The onset of the eruption came with little warning. A few mild earthquakes were felt after 10pm on January 22nd and the sharpest one occurred in the early morning of the 23rd at 1:40 am. At this time only two seismometers were in operation in Iceland, one in Reykjavik and the other in Vik in Myrdalur, and using these two meters it could not be resolved whether the seismic epicentre was in the Torfajokull volcano or Heimaey. Of these two, Torfajokull was deemed the more likely source, which explains why the eruption appears to have caught everyone off guard. On Monday night, January 22nd, people in Heimaey went to bed as usual after a normal workday. The whole fishing fleet was in dock because of a severe storm. Just before 2 am there was a telephone call to the local police station informing the officers on duty that the eruption had started at 200-300 m east of the farm, Kirkjubaer. At first the officer did not take the reporter seriously, but soon it became clear that something unusual was underway, thus police officers drove to the area for further investigation. Upon arrival, they saw an erupting fissure east of Kirkjunaer, extending from the harbour mouth in the north and to the sea in Stakkabot, the vent of the Saefell tuff cone (Figure 4.4.2).

The eruption began on Tuesday January 23rd at 1:55 am an initially formed a semi-continuous curtain of fires (lava fountains) along the whole length of the fissure. Within three days the activity was reduced to one vent, and it is this vent that built up the cone we now as Eldfell. Initially, the lava advanced down slope from the fissure, or to the east and the northeast towards the sea. The emergency alarm was sounded in town. The police and the fire bridgade drove around town with their sirens on to alert the inhabitants. In about two hours most of the inhabitants were afoot, and as a measure of caution the council decide to evacuate the whole town immediately, apart from a few volunteers who remained to undertake necessary duties. It was quickly realized that there could be imminent danger of the fissure lengthening, either to the north, potentially blocking off the harbour, or to the south, threatening to damage the airport. Furthermore, the mainland civil-defense, domestic airlines and the NATO Defense Force in Keflavik were contacted to provide air transport for hospitalized and elderly people. That night, 300 people, mostly the sick and aged, were airlifted to Reykjavik. The rest of the town's population rushed down to the harbour, having just had time to pout on warm clothing and cram a few necessary belongings into a duffle bag. Thanks to the storm from the day before, around 60-70 fishing boats were in dock. They were quickly prepared for departure and the first one left for Þorlakshofn at 2:30 am, followed by a steady stream of fishing vessels packed with people. The whole operation went remarkably smoothly and without mishaps, thanks to the decisive response from local authorities, favorable weather conditions and a little luck. In the first 12 hours the eruption spewed forth more than 30 million tonnes of tephra and lava, which were initially dispersed to the north and east.

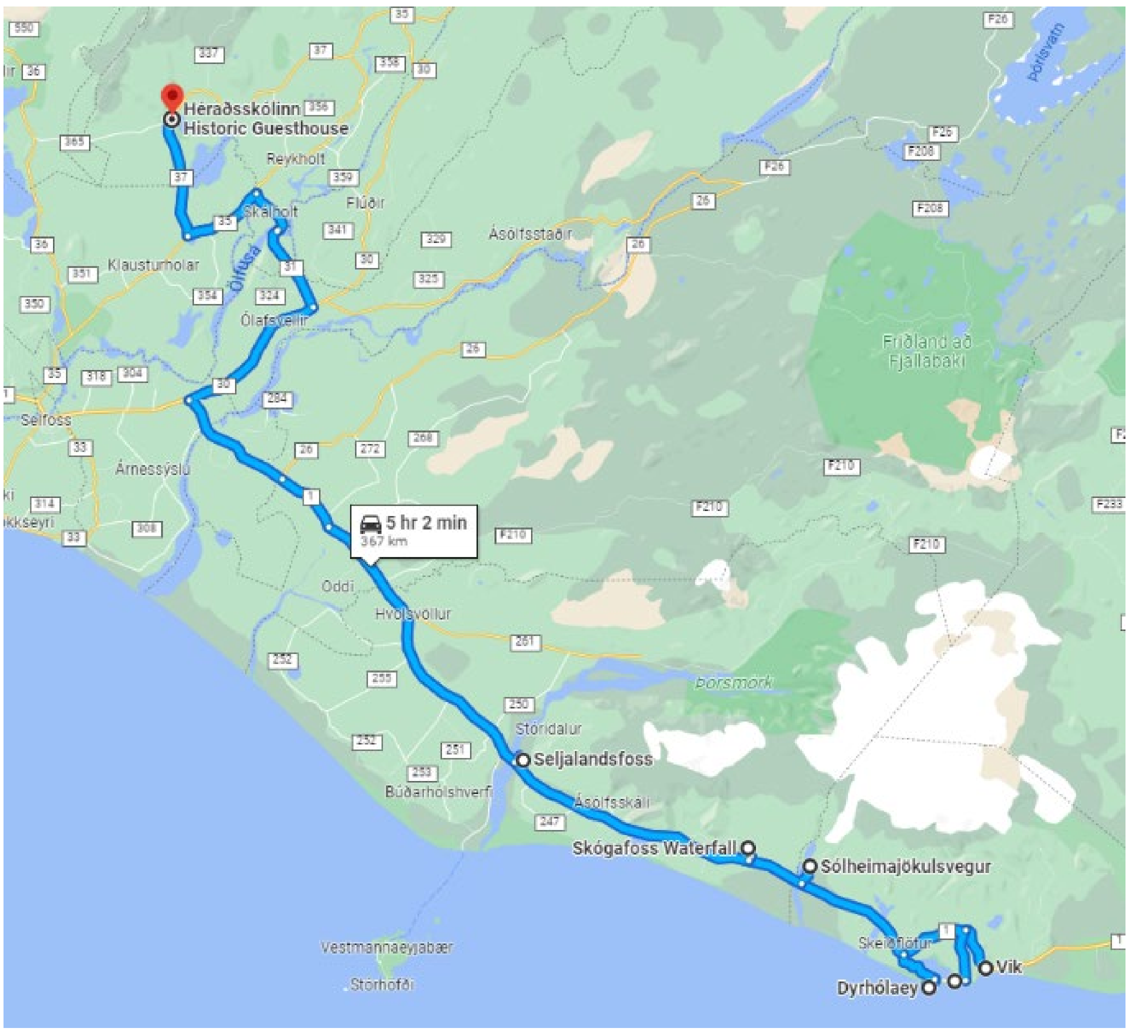
The eruption lasted just over five months until July 3rd 1973. It covered most of the town with several meters of tephra, and about a quarter of the town was buried by the lava. An extensive network of pipes and pumps was installed to spray the lava with seawater. In total 6.2 million tons of seawater were sprayed on the lava, and this action was successful in slowing down the advance and redirecting the flow. However, despite ample efforts, parts of the town could not be saved and 417 houses got buried under lava and volcanic ash. Remains of some houses can still be seen in the lava field. The remains of the old swimming pool are visible at [63.4424, -20.2598]. a house is protouding from the lava at [63.4410, -20.2646], and the old electric cable poles are still standing at [63.4433, -20.2607]. A project nicknamed 'Pompeii of the North' began excavating some of the houses buried in tephra.

The summit of the Eldfell cone provides a good overview of the lava field. From there one can easily hike to the so-called Paskshraum branch of the lava [63.4300, -20.2401], which advanced into the sea during Easter 1973, as well as Vagabond, which is a scoria mound representing a section of the Eldfell cone that broke off on February 19th and was then carried by lava flow towards the sea. Kirkjubaejarhraum [63.4393, -20.2430], the bulldozed sector of the lava flow field, is the site where it is thickest, of 70-120 m. In this area the lava was harnessed for its heat. This was achieved by spraying the lava with seawater and collecting the steam generated for space-heating in the town over a period of 25 years or until 1998. A rather peculiar lighthouse can be found at [63.4365, -20.2278] as it is mounted on wheels, so it can be relocated due to the rapid erosion of the coastline.

The size of Heimaey increased by 2.2 km^2 in the 1973 eruption and the Eldfell eruption expelled about 0.25 km^3 of magma onto the surface, compared to the 1.2 km^3 erupted by the 1963-7 Surtsey eruption, and produced a lava flow field covering 3.3 km^2. It added 2.2 km^2 to the island of Heimaey, increasing its size by approximately 20%.

Day 5: Wednesday, March 8th, 2023 – Waterfalls, Glaciers, and Vik Beaches

7:00AM: Wake-up, breakfast is provided by the guesthouse.
8:30AM: Depart from the hostel
11:00AM: Arrive at Vik – Walk along the beach
12:00PM: Lunch at the beach (Our guesthouse will provide box lunches to take with us)
1:00PM: Arrive at Renisfjara Beach
2:00PM: Arrive at Dyrholaey Viewpoint
3:00PM: Sólheimajökulsvegur Glacier
4:30PM: Arrive at Skogafoss waterfall.
5:15PM: Arrive at Seljalandsfoss waterfall.
6:30PM: Arrive back at the guesthouse
7:00PM: Group meal at the guesthouse



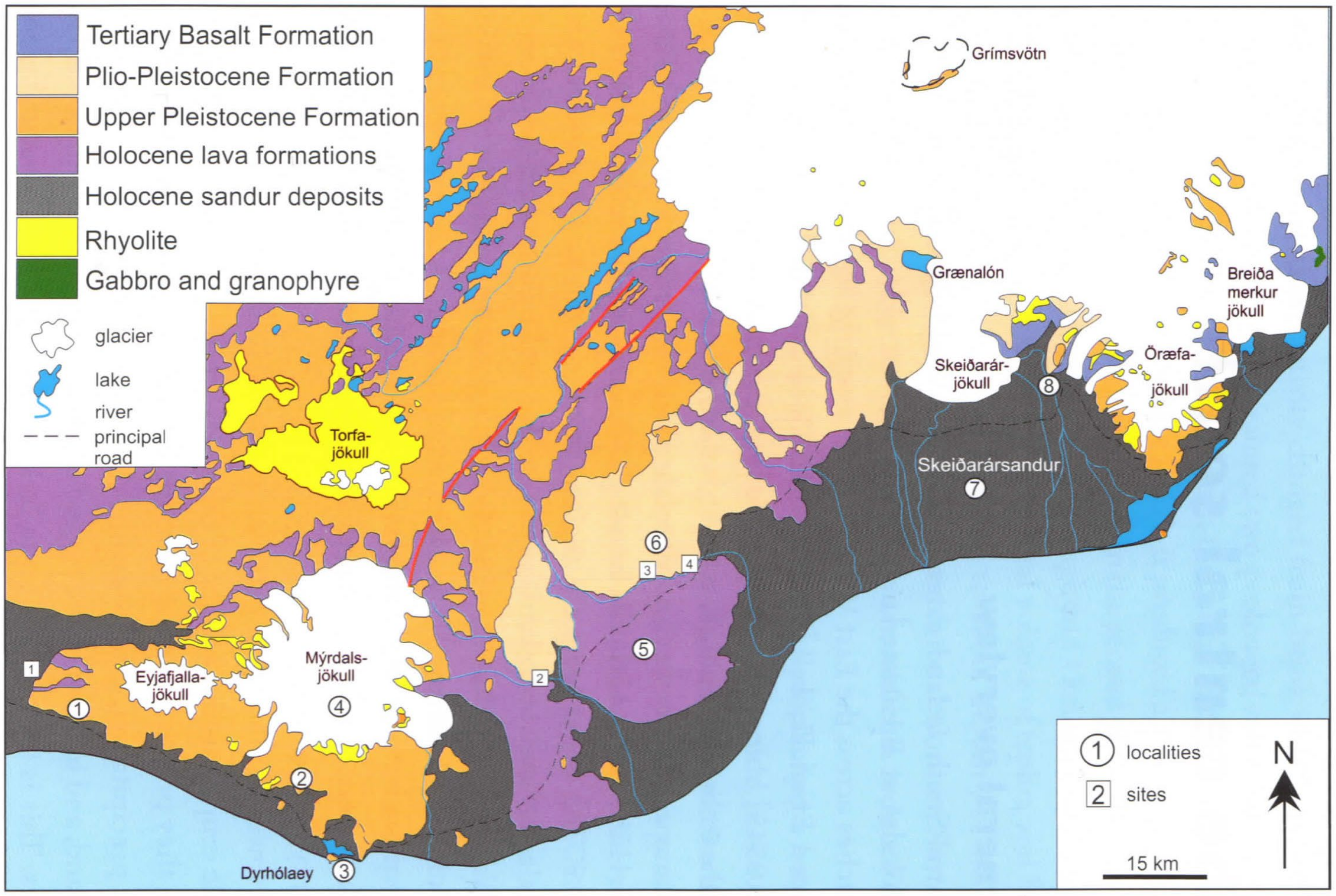


Figure 5.0.1. The main geologic features of Central-South Iceland Thordarson, T. and Hoskuldsson, A., 2019, pg. 110

Eyjafjallajökull Volcano – Internal Structure and the 2010 Eruption

The following is from: Gudmundsson, A., 2017, The Glorious Geology of Iceland's Golden Circle. Springer International Publishing, Cham, Switzerland, pgs. 276-285.

From here we drive along Road 1 to the east along the high cliffs of Eyjafjallajökull (Figure 5.5.1). The name means literally 'the ice cap of the island mountains', the islands being Vestmannaeyjar. If the visibility is good, the part of the mountain that is seen can be extraordinarily impressive and beautiful, in addition to being geologically of great interest. To explore and understand the interior of the volcano, and how it related to its 2010 eruption, there are many places that you could stop at. The one I have chosen, the fifth stop (5), is selected just because there the sea cliffs are very clean and clear and the structure can be easily observed and understood. I show photographs from this stop, and one additional one a short distance further east, but the photographs are all basically from the same large cliff exposure in the vicinity of the fifth stop.

What we see are major cliffs which range in height from about 200 m (Figure 5.0.2) to a maximum of about 350 m (Figures 5.0.3 and 5.0.4). These cliffs, as indicated above, are primarily sea cliffs, even if the sea never reached to heights of more than about 100-150 m above the present sea level. As the action of the sea erodes the lower parts of the cliffs, the upper parts collapse, thereby keeping the entire cliff section close to vertical. These cliffs form the lowermost exposed part of the volcano which rises to a maximum elevation of 1666 m above sea level. The top parts is the site of an ice cap, Eyjafjallajökull, and also of a small caldera with a diameter of about 3 km (Figures 5.5.1c and 5.0.5).

Figure 5.0.2. Vertical cliff, partly an old sea cliff formed where the sea level was much higher some 13 thousand years ago, in southwestern side of Eyjafjallajökull. The vertical cliff is about 200 m high and primarily composed of hyaloclastite.

Figures 5.0.2, 5.0.3, and 5.0.4 show us that the volcano is made of a variety of rock layers. These include hyaloclastite layers, lava flows, cube-jointed lavas (Icelandic: kubbaberg), pillow lavas, sedimentary layers (glacial sediments, tillites), sills, and dikes. Eyjafjallajökull is a volcano composed of strata (layers) of widely different properties, and is thus a stratovolcano/composite volcano. The volcano has been active for about 800 thousand years, and is therefore comparatively old. Most central volcanoes (stratovolcanoes and calderas) in Iceland are active for about five hundred thousand to million years - only a few are active for longer than a million years.

Eyjafjallajökull erupts infrequently when compared with, for example, Hekla and Katla. In historical time in Iceland, that is, the past 1100 years, Hekla has erupted 23 times, Katla 21 times, but Eyjafjallajökull only 4 times. The most frequent eruptions, during historical time, however, have neither been in Hekla or Katla but rather in the caldera Grimsvotn. Grimsvotn is located in the Vatnajokull ice sheet, and thus outside this excursion, but is the most active volcano in Iceland in terms of frequency of eruptions. During the past 1100 years Grimsvotn has erupted about 70 times of once every 16 years. The four historical eruptions in Eyjafjallajökull include the eruptions in 2010, which we shall now describe briefly.

A typical basaltic effusive fissure eruption began March 20th 2010 in the pass between the glaciers Eyjafjallajökull and Myrdaljokull. This fissure eruption, producing low-viscosity primitive basalt, came to an end April 12th. The associated volcanic fissure has a north-northeast direction and is about 500 m long with an estimated maximum opening (aperture, feeder-dike thickness) of about 1 m. The length/opening ratio of this fissure/feeder dike is in good agreement with measured ratios elsewhere in Iceland and shows that the overpressure or driving pressure of the magma when the feeder-dike reached the surface was low (several mega-pascals). Consequently, the eruption was a vey small (total volume 0.02 km^2) 'gentle' outpouring of aa lava - the kind of eruption that some refer nowadays to as a 'touristic eruption'.

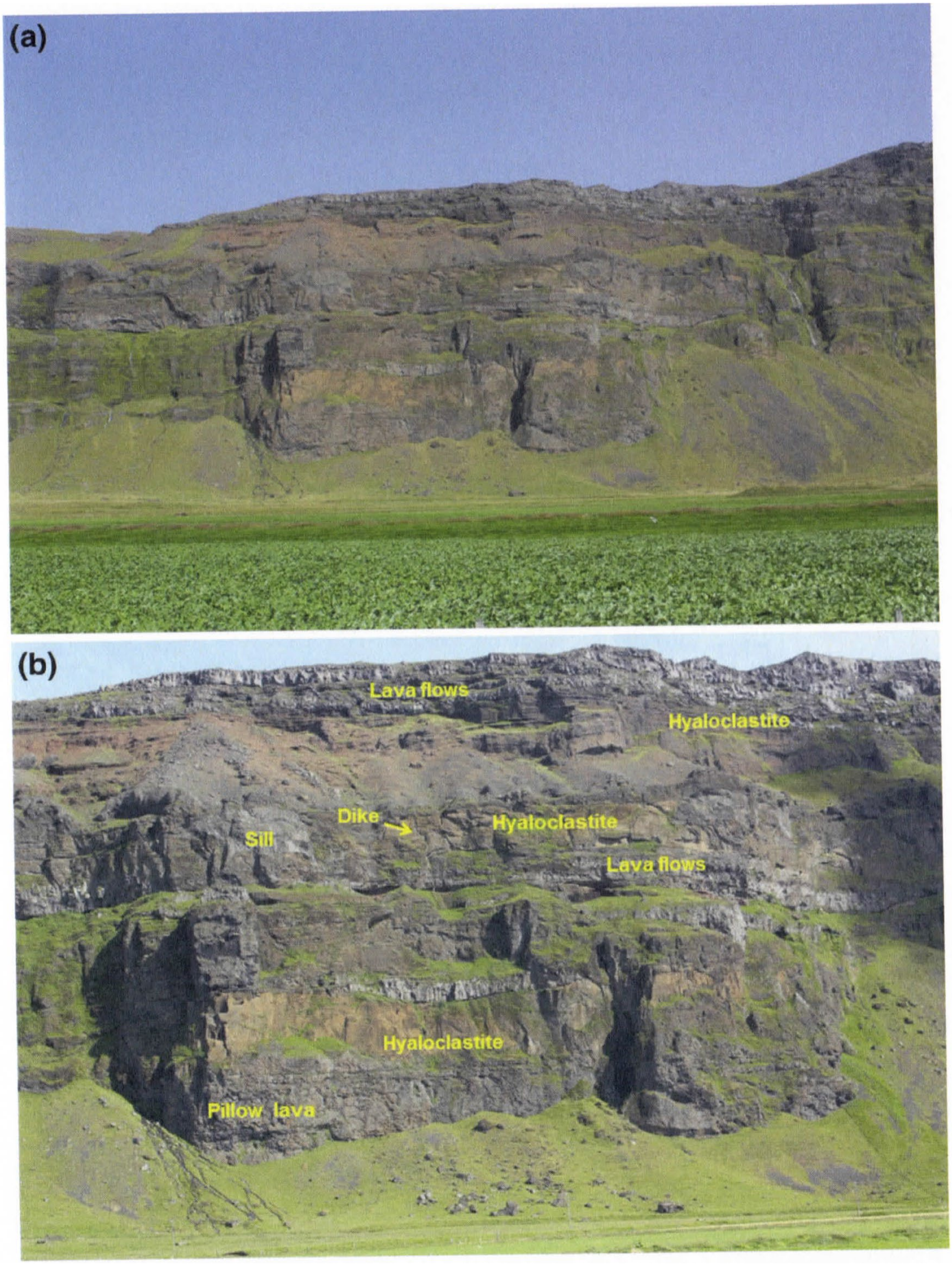


Figure 5.0.3. Vertical cliff showing the internal structure of part of Eyjafjallajökull as seen from Road 1. **a.** The cliff section seen here reaches a height of about 350 m and is composed of a variety of rack layers and units. **b.** Close-up of a part of the cliff-section in **a.** Eyjafjallajökull is primarily composed of hyaloclastite and lava flows, including pillow lava in the lowermost section. There are also many intrusions, primarily sills and dikes

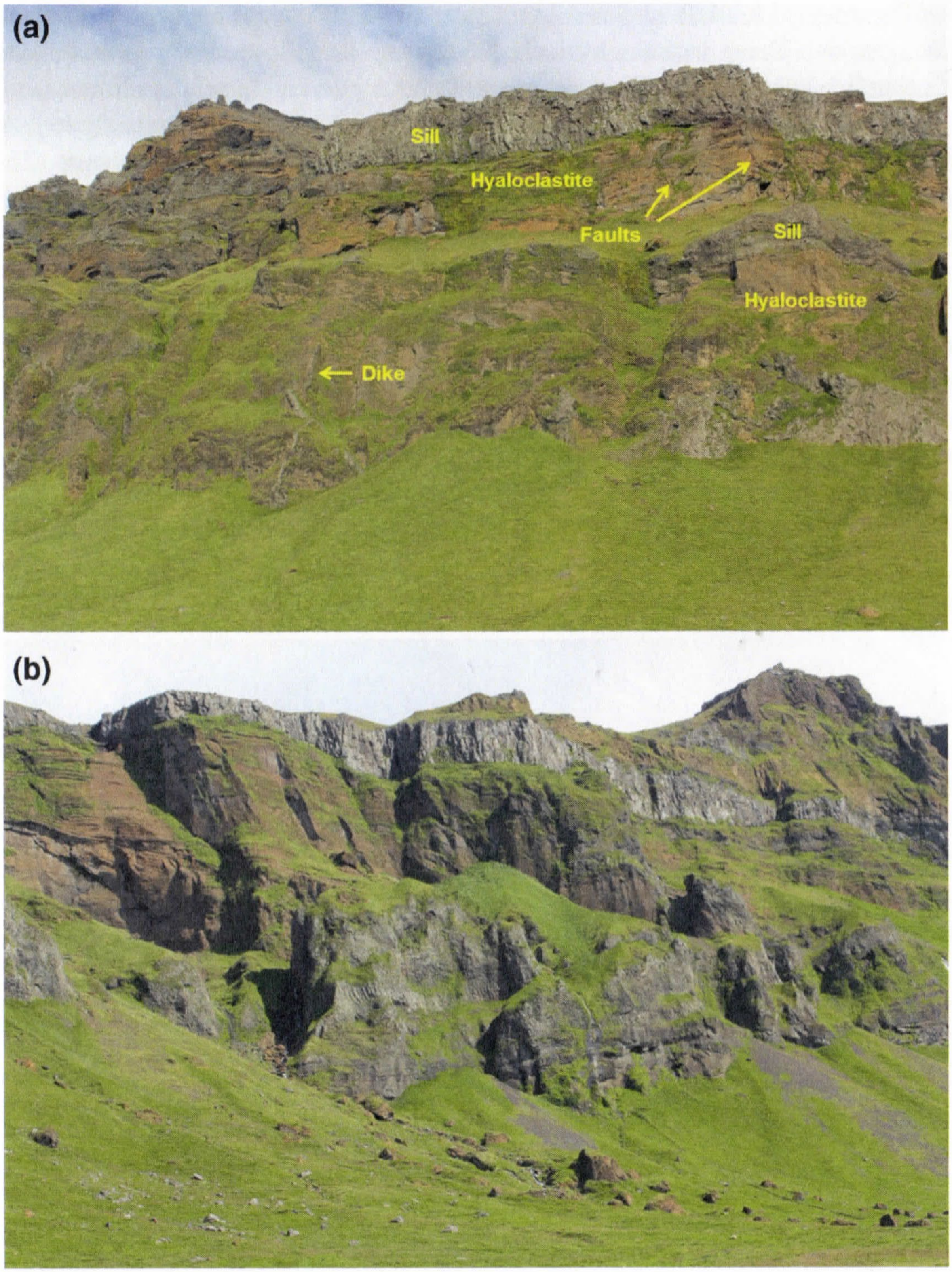


Figure 5.0.4. More details on the internal structure of Eyjafjallajökull as seen from Road 1. **a.** The internal structure of Eyjafjallajökull, as seen here, is characterized by thick layers of hyaloclastite, together with lava flows (seen in 5.0.3). In addition, the volcano is intruded by many, mostly thin, dikes and, normally much thicker, sills. **b.** Direct continuation (panorama), to the east, of the cliff section seen in **a.**, showing the same rock layers and intrusions.

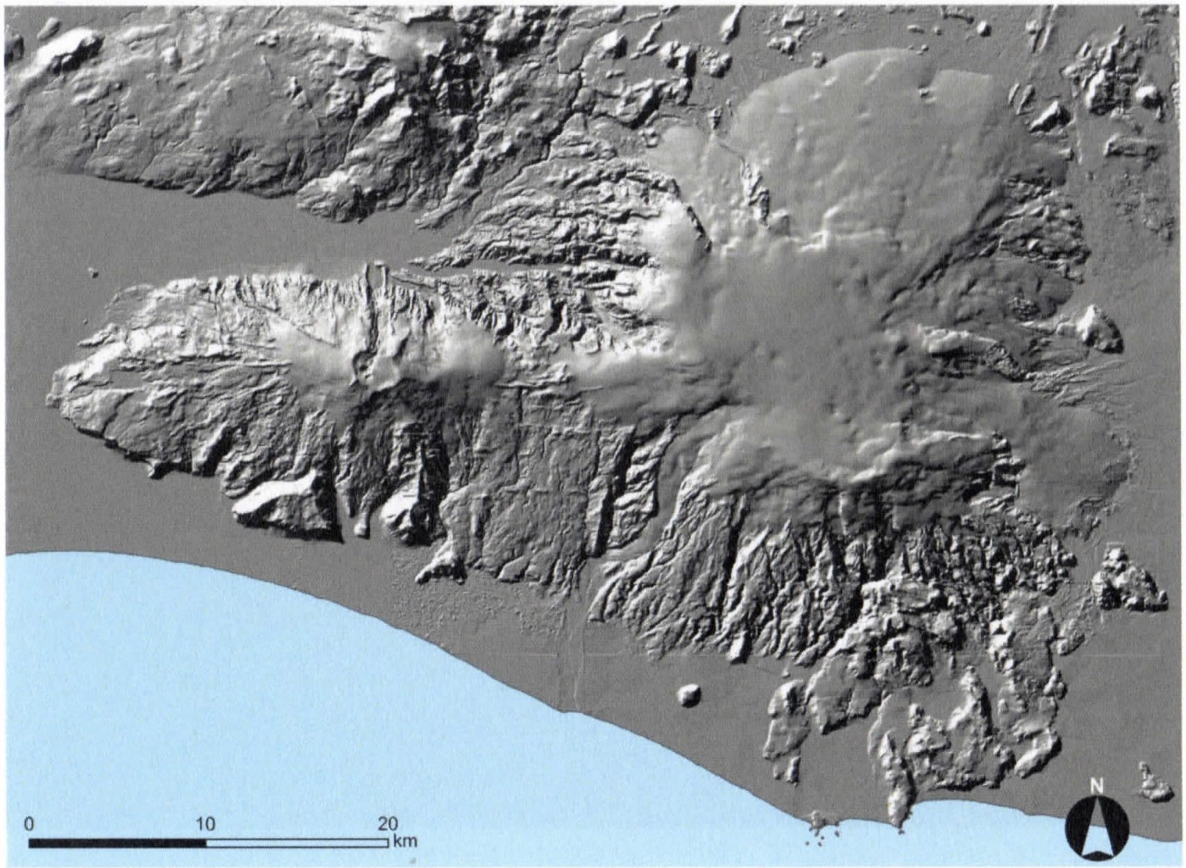


Figure 5.0.5. Digital elevation map of Eyjafjallajökull and Myrdalsjokull showing the shapes of the volcanoes and their calderas.

The first eruption faded away and finally came to an end on April 12th. Then a second eruption began April 14th 2010, but this time beneath the ice cap in the summit caldera (Figure 5.0.5). This eruption melted its way through the 250 m thick ice cap, was highly explosive, and produced ash of an intermediate (andesitic) composition, which means that the magma erupted was more gas-rich and viscous than the one in the earlier (March) eruption. The magma supplied during the second eruption came from a shallow magma chamber, at about 4-5 km depth which is associated with the summit collapse caldera. The eruption column reached a maximum altitude of about 11 km, and the resulting ash clouds had major disrupting effects on air traffic in Europe for many days. The second eruption came to an end on May 22nd 2010.

It is convenient to regard the first and second eruptions as two phases of a single eruption. The second, explosive, phase produced about 0.18 km^3 of ash and lava. The total volume of ash (calculated as solid rock) and lava in both phases of the was thus about 0.2 km^3. This is thus a typical small eruption form a central volcano in Iceland in terms of volume of eruptive materials calculated as solid rock (or as magma volume). The volume of ash or tephra produced, however, was large in comparison with the size of the eruption. The volume of fresh ash (not calculated as solid rock or magma) was about 0.3 km^3. To give you an indication of what that means we can consider the following hypothetical case (which could never happen in the real world). Imagine all this ash falling on Reykjavik with a total area of 275 km^2. Then that total area would have been covered with ash of an average thickness just over 1 m. In reality, much of the ash fell on Eyjafjallajökull itself and its close surroundings, whereas part went to Europe. The ash clouds carried to Europe had major disrupting effects on air traffic, particularly in West and North Europe, for many days. More specifically, many airports had to be closed for days on because of the ash clouds. Part of the ash was particularly fine-grained (composed of very small particles), which was one reason for its potentially damaging effects on the jet engines of airplanes, hence the closure of the airspaces.

There were three fissures associated with the 2010 eruption, all of them several hundred meters long (maximum length 600-700 m). Two of the fissures are directed north-northeast; one is inside the caldera, the other is outside the caldera. The third fissure, which produced most of the eruptive material, is directed east west. These three fissures thus reflect the main tectonic trends in Eyjafjallajökull, namely the east-west trend, which is also the direction of the long axis of the volcano itself (Figure 5.0.5), and the northeast trend which is the general trend of the East Volcanic Zone.

The 2010 eruption was the culmination of an unrest process lasting decades. More specifically, there were several earthquake and deformation episodes in Eyjafjallajökull prior to the 2010 eruption. There were at least four earthquake swarms in the 1990s, two of which were clearly related to doming or uplift (inflation) of the volcano, namely in 1993-1994 and in 1999. There were few earthquakes and little deformation began again. The rate of deformation and earthquake increased much from early March 2010 until the eruption began on March 20th.

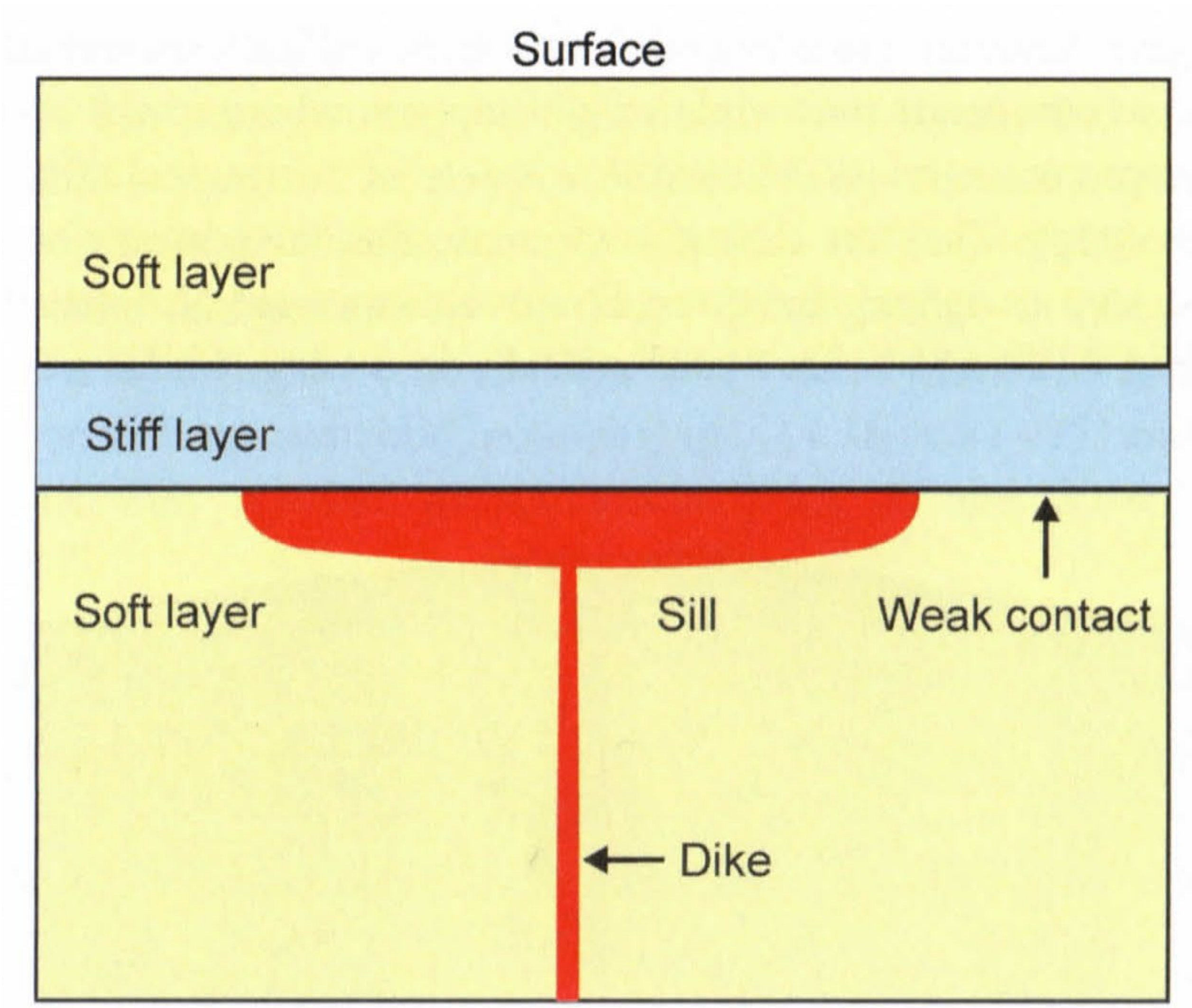


Figure 5.0.6. Dikes are commonly deflected into sills at contacts between mechanically dissimilar rock layers. Here the dike was transformed into a sill at the contact between a still layer (for example, a basaltic lava flow or an earlier sill) above and a softer (more compliant) layer below (for example, hyaloclastite or tuff). Many of the sills in Eyjafjallajökull are formed at such contacts. Alternatively, if the driving magmatic pressure (overpressure) in the dike is low when the dike meets the contact, the magma is not able to open the contact to form a sill and the dike simply ends vertically.

All these earthquake and deformation episodes in Eyjafjallajökull have been interpreted as being related to dike injections from great depths (some 20 km) that become deflected into sills (Figures 5.0.3, 5.0.4, and 5.0.6) at depths between about 3 and 6 km below the top of the volcano. Thus, all the injected dikes during these 17 years became arrested in the sense that they changed into sills, or alternatively just stopped their vertical propagation at contacts, and thus did not erupt until the dike that fed the March eruption of 2010. It has been suggested tat some of the sills may reach lateral dimensions (diameters) of as much as 17 km. One remarkable thing is that it appears that the dike that fed the March 2010 was deflected into the sill at a shallow depth, but then deflected again into a dike to reach the surface. Such changes in dike paths are, in fact, common, but this one apparently had an unusually long (lateral) sill part before it changed again into a dike and erupted.

Is there anything about these dike-sill intrusive events in the past 17 years? Certainly not. The cliffs sections show exactly the same structures, even at shallow depths, namely dikes and sills. In particular, Figures 5.0.3 and 5.0.4 show many sills and dikes. As is common, the dikes tend to be much thinner than the sills (Figure 5.0.6). Most sills are supplied with magma through dikes, and very few sills reach the surface. This means that most of the sills you see in the cliffs of Eyjafjallajökull were fed by dikes that never reached the surface to erupt. It follows that the processes that occurred at depths of 3-6 km beneath the top of Eyjafjallajökull in the period from 1993 to 2010 are exactly the same as seem at depth of 1-1.6 km below the top of the volcano in the cliff sections in Figures 5.0.3 and 5.0.4; namely injected dikes failing to reach the surface - becoming arrested - and man changing into sills (Figure 5.0.6).

Why is dike arrest and dike deflection into sills so common in Eyjafjallajökull (and stratovolcanoes in general). Answer: because Eyjafjallajökull and other similar volcanoes are composed of layers with widely different mechanical properties. Some of the layers are stiff and brittle, others are soft (compliant) and more ductile. For example, the hyaloclastite layers tend to be rather soft, particularly when young, whereas the lava flows (and existing sills) tend to be stiff. Such materials in general are referred to as composite materials, of which plywood is perhaps the best-known example. Composite materials are used in a variety of things, including airplanes, to make them strong. They are strong in the sense that the contacts between layers tend to arrest, stop or deflect, fractures. Stratovolcanoes are also called composite volcanoes and behave mechanically in a very similar way to artificial composite materials. Thus, when a dike is propagating it induces stresses ahead of its tip or top. The stresses may be high in the stiff layers, and encouraging dike propagation, but suppressed or very low in the soft layers, encouraging dike arrest. Commonly, when the dike meets a contact between stiff and soft layers it thus either becomes arrested altogether - its top stops propagating - or the dike become deflected into a sill along the contact (Figures 5.0.6 and 5.0.7). This latter is what we see as common in the present cliff sections (Figures 5.0.3 and 5.0.4) and was inferred from geodetic and seismic measurements prior to the 2010 eruptions in Eyjafjallajökull.

Because composite volcanoes, composed of widely different layers such as Eyjafjallajökull, more easily stop or deflect fractures - not just dikes but all rock fractures - than volcanoes whose layers have all basically the same mechanical properties, such as lava shields and basaltic edifices (for example, the shield volcanoes of Hawaii), composite volcanoes/stratovolcanoes are mechanically stronger than basaltic edifices (Figure 5.0.7). It is therefore easier to fracture, say, a lava shield than a stratovolcano. This is one reason why normal faults and tension fractures are much more common in lava shields of Iceland than in areas composed of widely different rocks types, such as hyaloclastite mountains and stratovolcanoes.

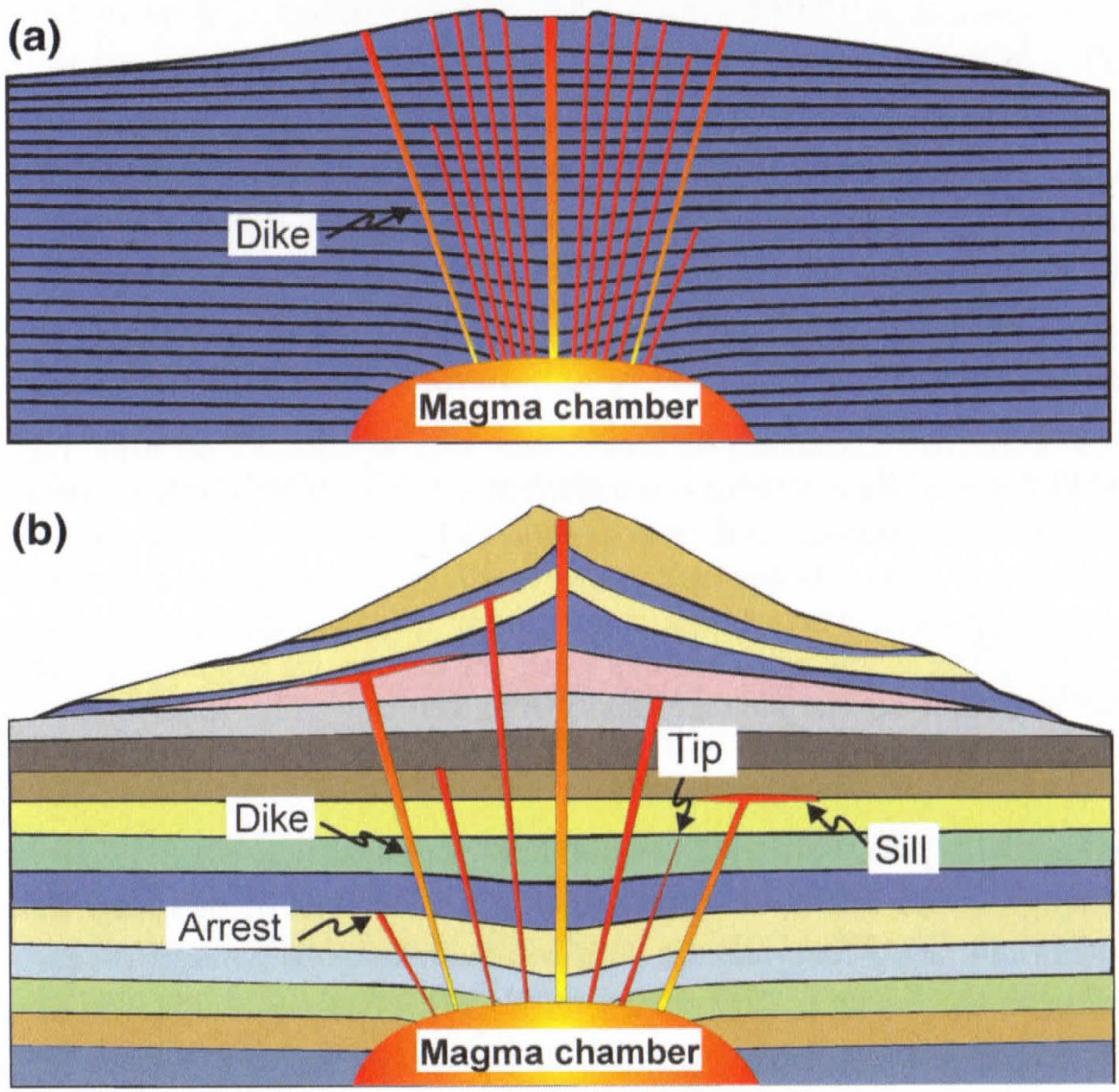


Figure 5.0.7. Basaltic edifices are composed of rock layers all of which have very similar mechanical properties (basaltic lava flows) whereas stratovolcanoes (central volcanoes, composite volcanoes) are composed of rock layers with widely different mechanical properties (including lava flows of various compositions, layers of pyroclastics [e.g., hyaloclastites] and sediments, and intrusives). It is thus easier for any type of fracture to propagate through a basaltic edifice **a** than a stratovolcano/composite volcano **b** for the simple reason that many more fractures, such as dikes, become arrested or deflected into sills, and therefore do not reach the surface, in stratovolcanoes than in a basaltic edifice. The shape or profile of the basaltic edifice in **a** is based on the shield volcano of Mauna Loa, Hawaii, whereas that of the stratovolcano in **b** is based on that of Mt Fiji in Japan.

STOP 5.1 – *Vik*

From Wikipedia

The village of Vík is the southernmost village in Iceland, located on the main ring road around the island, around 180 km (110 mi) by road southeast of Reykjavík. Despite its small size (291 inhabitants as of January 2011) it is the largest settlement for some 70 km (43 mi) around and is an important staging post, thus it is indicated on road signs from a long distance away. It is an important service center for the inhabitants and visitors to the coastal strip between Skógar and the west edge of the Mýrdalssandur glacial outwash plain.

In 1991, the US journal Islands Magazine counted this beach as one of the ten most beautiful beaches on Earth. Its stretch of black basalt sand is one of the wettest places in Iceland. The cliffs west of the beach are home to many seabirds, most notably puffins which burrow into the shallow soils during the nesting season. Offshore lie fingers of basalt rock (stacks) remnants of a once more extensive cliffline Reynisfjall, now battered by the sea. There is no landmass between here and Antarctica and the Atlantic rollers can attack with full force. Folklore tells us that they are former trolls who tried to drag their boats out to sea only to be caught by the rising dawn. The sea around them is rather wild and stormy, so travelers will not be surprised to discover a monument to the memory of drowned seamen on the beach.

Contemporary legends note the story of a husband who found his wife taken by the two trolls, frozen at night. The husband made the two trolls swear to never kill anyone ever again. His wife was the love of his life, whose free spirit he was unable to provide a home for; she found her fate out among the trolls, rocks, and sea at Reynisfjara.

Danger from Katla

Vík lies directly beneath the Mýrdalsjökull glacier, which itself is on top of the Katla volcano. Katla has not erupted since 1918, and this longer than typical repose period has led to speculation that an eruption may occur soon. An eruption of Katla could melt enough ice to trigger an enormous flash flood, potentially large enough to obliterate the entire town. The town's church, located high on a hill, is believed to be the only building that would survive such a flood.[6] Thus, the people of Vík practice periodic drills and are trained to rush to the church at the first sign of an eruption.

Climate

Like most of coastal Iceland, Vík í Mýrdal has a subpolar oceanic climate (Koppen: Cfc) with cold but not severe winters and cool, short summers. Because it lies on the windward side of the Gulf Stream, Vík í Mýrdal is the wettest coastal town in Iceland, with an annual rainfall of 2,275 millimetres (90 in), which is three times more than Reykjavík, five times more than Akureyri on the north coast of the island and many times more than its far northernly location would normally indicate. Precipitation on the Mýrdalsjökull and Vatnajökull glaciers near the town is believed to be as high as 160 inches (4,100 mm) of rainfall equivalent, which would mean at least 160 feet (49 m) of snow at those higher altitudes.

STOP 5.2 – *Renisfjara Beach*

The following is from: Gudmundsson, A., 2017, The Glorious Geology of Iceland's Golden Circle. Springer International Publishing, Cham, Switzerland, pgs. 297-305.

The Beach of Reynisfjara

We now drive back west alone Road 1 through the village of Vik I Myrdal and continue until we come to Road 215. Then we drive that road south to the beach of Reynisfjara, which is our tenth stop (10). As we walk from the parking place down to the beach we see the famous landmark Dyrholaey in the east (Figure 5.2.1). Some of you might like to visit that locality as well. This is easy along Road 218. Dyrholaey is currently the southernmost point of Iceland (for a long time following the 1918 Katla eruption, Kotlutangi, the point of land south of Hjorleifshofdi was the southernmost part of Iceland). Dyrholaey is the remnant of a hyaloclastite mountain formed in an eruption in the sea, very similar to Petursey, Hjorleifshofdi, and other mountains located close to the coast and of similar age. The maximum height of Dyrholaey is 120 m above sea level. It was formerly an island (hence the ending 'ey', meaning island, in its name) but is now a point. It is primarily of hyaloclastite, which is partly covered with a cap of pahoehoe basaltic lava flows that extend into the sea as pillars or sea stacks. The famous semi-circular hole through the southernmost part of Dyrholaey is formed by sea erosion.

As for the coast of Reynisfjara itself, the first thing to mention is that there can be sudden large and very dangerous waves. So please be aware of the waves all the time and take care. With this warning, we first take a look at the mountain itself, Reynisfjall (Figure 5.2.2). We saw its eastern slopes from a distance at the eighth stop, and here we take a much closer look at its western slopes. Reynisfjall is a typical

Figure 5.2.1. View west, Dyrholaey with its famous semi-circular hole. Dyrholaey is the remnant of a hyaloclastite mountain and reaches a maximum height of 120 m above sea level.

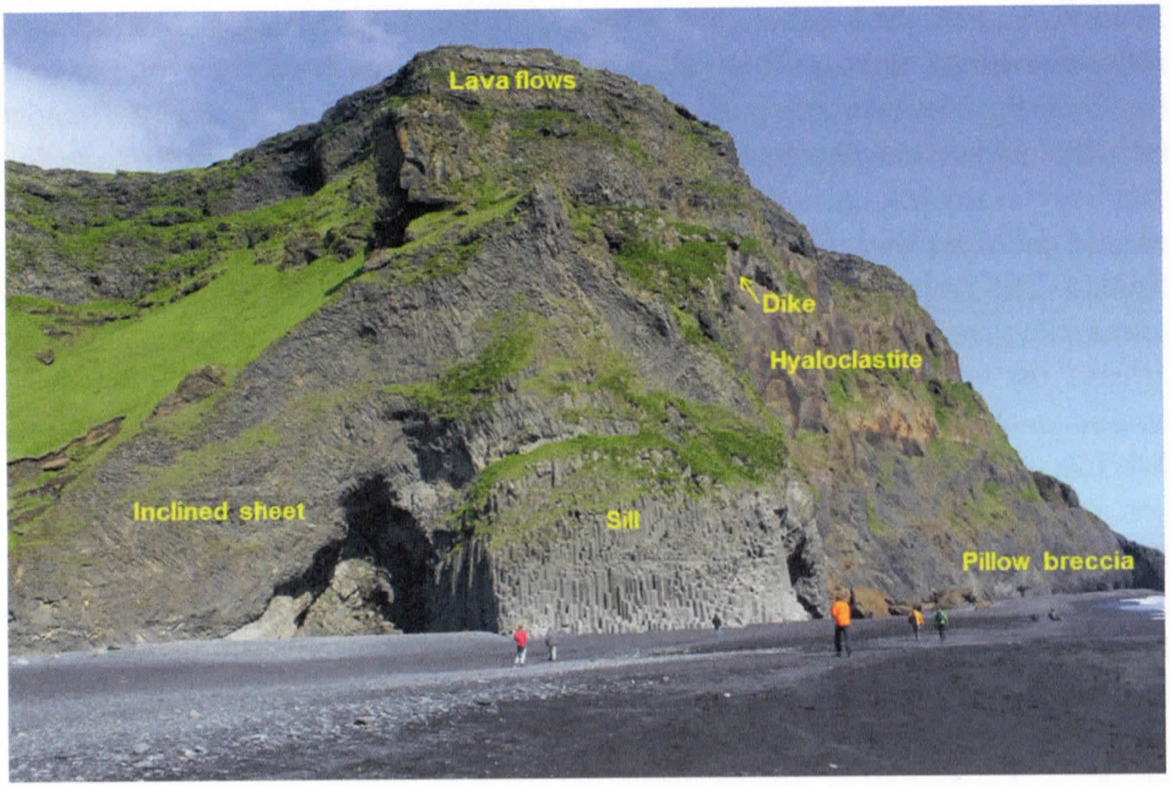


Figure 5.2.2. View east, the southernmost part of the hyaloclastite mountain Reynisfjall and Reynisfjara beach. The mountain is 5 km long and reaches a maximum height of 340 m above sea level. However, at the coast here the height is about 150 m. On the top is a cap of lava flows supplied with magma by a feeder-dike (both indicated). In the lower part of the mountain are an inclined sheet and a sill. Close-ups of the sill are in Figures 5.2.3 and 5.2.4 and of the feeder-dike in Figure 5.2.6. The people also provide scale.

hyaloclastite mountain, just like Petursey, Hjorleifshofdi, and Dyrholaey. The length of the mountain is about 5 km. It is elongated, with a maximum width of about 0.7 km (700 m). Its top is remarkably flat; the maximum height is about 340 m above sea level and occurs in its northern part. Close to the coast (Figure 5.2.2) the height is about 150 m above sea level. Reynisfjall is of similar age to the mountain mentioned above, and most likely formed in several eruptions, partly in the sea and perhaps partly ice caps, during the past 200 thousand years.

Reynisfjall is compose of a variety of rock units and layers. These include units of hyaloclastites (basaltic breccias and tuff), basaltic lava flows (in the top part), pillow breccias, and intrusions (dikes and sills/sheets). Perhaps the most striking features that catch the eye, however, are the rocks that form the beautiful columns at the base of the cliffs (Figure 5.2.2), Columns of this type form as the magma/rock body (here a basaltic intrusion) contracts or shrinks during the cooling of the magma - from the original temperature of 1200-1300ºC. The shrinkage is because solids (including rocks) normally occupy less volume than fluids of the same material (the well-known exception being frozen water, ice, which occupies a larger volume than liquid water).

The fractures are called columnar or cooling joints, and we have seen them many times before in sills, lava flows, and dikes, but not as beautiful as here. The joints that form the beautiful rock columns begin to form when the magma has cooled down to about 800ºC and continue to develop as the rock cools further. Heat transport of 'flow' is always primarily along the steepest temperature gradient, in a similar way as a fluid flows downhill along the steepest slope of the hill. (This is, however, only an analogy; in heat transport there is strictly nothing that 'flows'. Heat is disorderly transfer of energy through

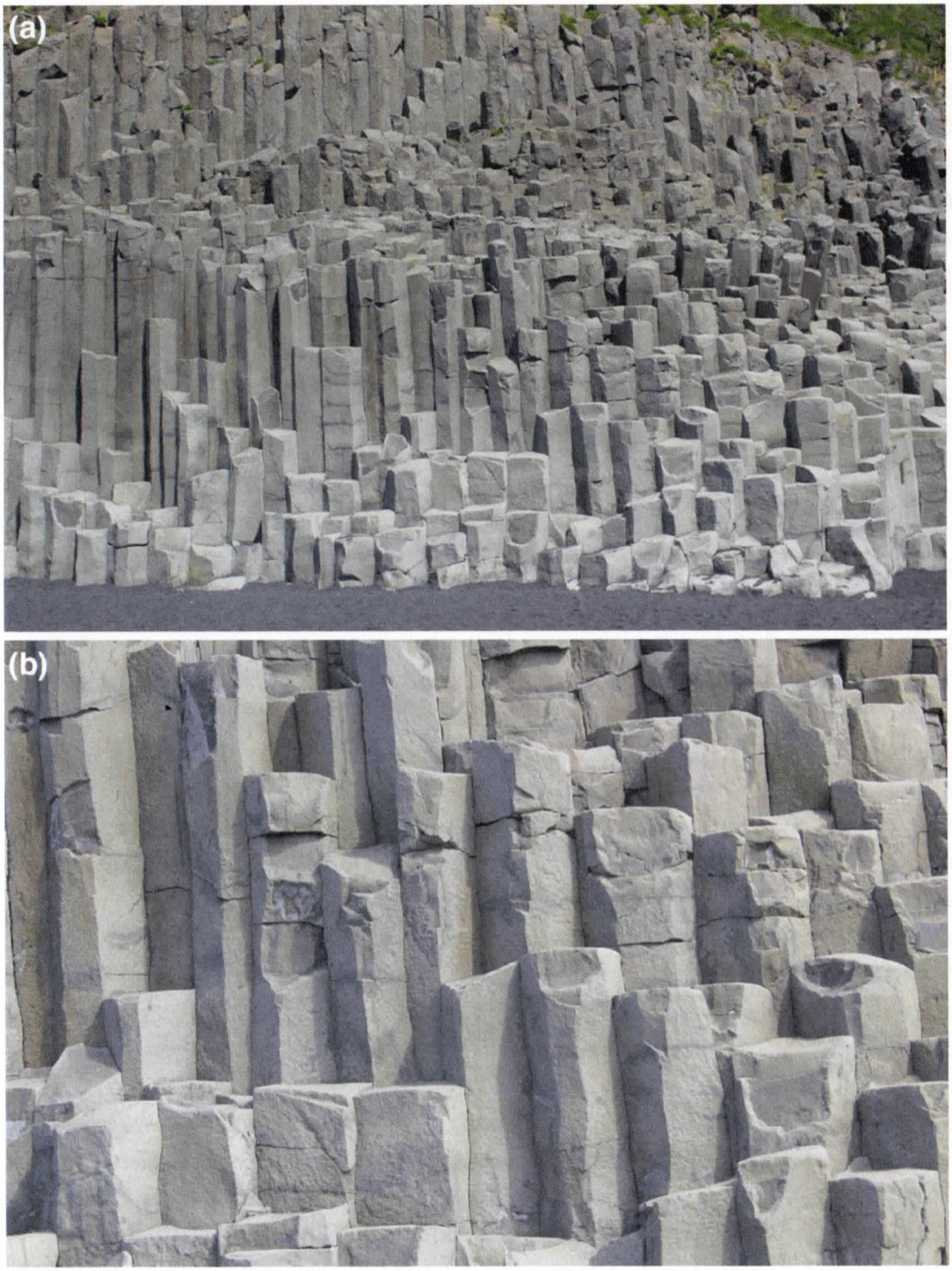


Figure 5.2.3. Close-ups of the sill in Figure 5.2.2. **a** Vertical rock columns indicate that the cooling surfaces were horizontal, as is typical for a sill intrusion. **b** Close-up of some of the columns seen in **a**. All the rock columns are generated through the development of cooling joints, columnar joints, as the magma cools down following emplacement as a sill.

uncoordinated motion of particles [atoms and molecules], that is, heat is energy in transit.) The steepest temperature gradient is in the direction of the greatest temperature difference between the hot magma and the surrounding cold rock. The columnar joints thus initiate at the contact between the magma and the surrounding rock, the host rock, and the columns that form are oriented perpendicular, at right angles, to the contacts. This is the reason why the columnar joints, and thus the rock columns, are horizontal in vertical dikes and vertical in horizontal sills and lava flows.

In Figure 5.2.2 we see that in the upper part the columns are steeply inclined, meaning that the cooling surface, the contact with the host rock, at the time of their formation was also inclined - in fact the contact was sloping similar to the present grass field in the photograph and belongs to an inclined sheet. In the lower part, down at the beach, the columns are close to vertical. So this part had a horizontal contact with the host rock when the columns formed - and is a sill.

Figure 5.2.4. View southeast, some of the rock columns in the sill seen in Figures 5.2.2 and 5.2.3 are very tall. The height of these columns is about 10 m.

If we now take a closer look at this lower at this lower part (Figure 5.2.3) we see that the columns are exceptionally well formed. So well-developed columns are very rare in lava flows and are normally found only in intrusions. The main reason is that in order to develop so regular and well-shaped columns, the rate of solidification('freezing') of the magma and subsequent cooling of the rock to the same temperature as that of the host rock, must be slow - the cooling must take a long time. If the magma is emplaced at the surface, the cooling is normally rapid (the magma being in contact with air or water or both), whereas if the magma is emplaced at depth inside older rocks, then poor conduction of heat through rocks ensures that the cooling of the magma, that is, of the intrusion, will be slow. Given that the rock columns in this part are very well shaped, the cooling must have been slow, so that this is an intrusion itself was horizontal, and thus was a sill. Some of the columns at Reynisfjara are as tall as 10 m (Figure 5.2.4). Similar columns are found in many sills in Iceland, although rarely as well-developed ans finely shaped as here.

To get a better three-dimensional view of the columns, we can enter the cave Halsanefshellir which is just around the corner (Figure 5.2.5). In the ceiling of the cave we see that in plan view the columns have a variety of shapes. Most are 5-sided (pentagons) or 6-sided (hexagons). When the intrusions are uniform in composition, thickness, and other properties, and the cooling surfaces are straight and of uniform properties, then hexagons are most common. But there are normally, as here, some variations in intrusion

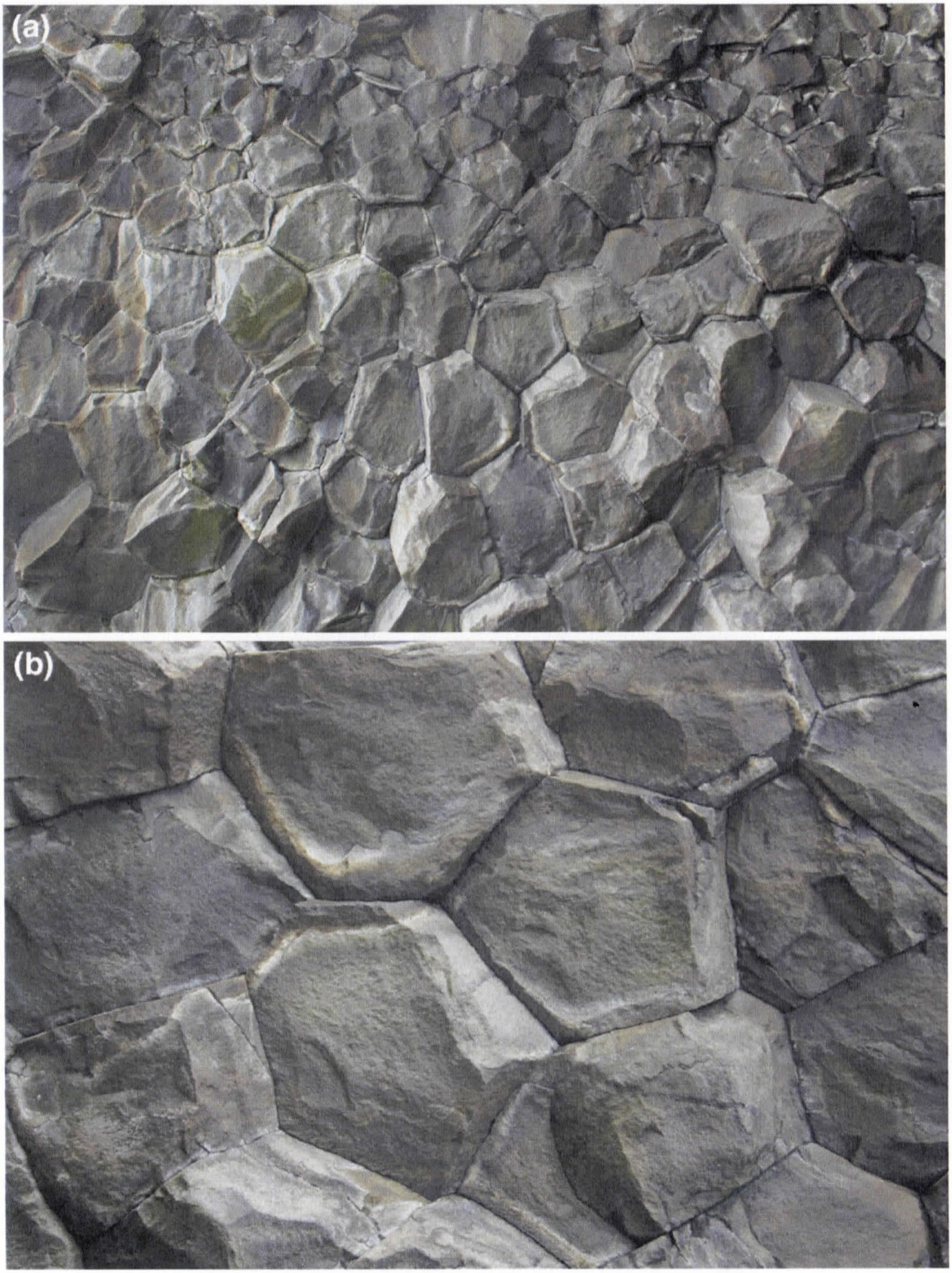


Figure 5.2.5. Cross-sectional shapes of the rock columns as seen in the ceiling of the cave of Halsanefshellir. While the columns have a variety of shapes most are 5-sided (pentagons) of 6-sided (hexagons). **a** General view of the ceiling. **b** Close-ups of some of the columns.

properties and thickness, as well as in those of host rocks, in which case pentagons and other geometries may also be common.

A short walk to the east of Halsanefshellir allows us to observe a basaltic feeder-dike to the lava flows at the top Reynisfjall (Figure 5.2.6). The lower part of the dike is steeply inclined, mostly 1-2 m thick, but its uppermost part is close to vertical and thinner. This change in geometry of dikes as they approach the surface is very common and follows from the fact that the forces and stresses in the crust demand that a dike meets the Earth's surface at (roughly) a right angle. The surrounding rock, the host rock, is mostly hyaloclastite, breccia, and tuff.

We end the excursion by viewing the rock pillars or sea-rock pillars Reynisdrangar. These basaltic pillars or sea stacks, reaching a maximum height of 66 m, were already described at depth at the eighth stop. But because we are much closer to them here, and view them from a different angle, they are really worth a closer look. In Figure 5.2.7 we view them from a greater distance, and all three are seen, although the third one (whose two peaks are seen) is somewhat hidden behind the one closest to us. Reynisdrangar are a famous landmark in Iceland, and an appropriate one for the last formal geological stop in this excursion.

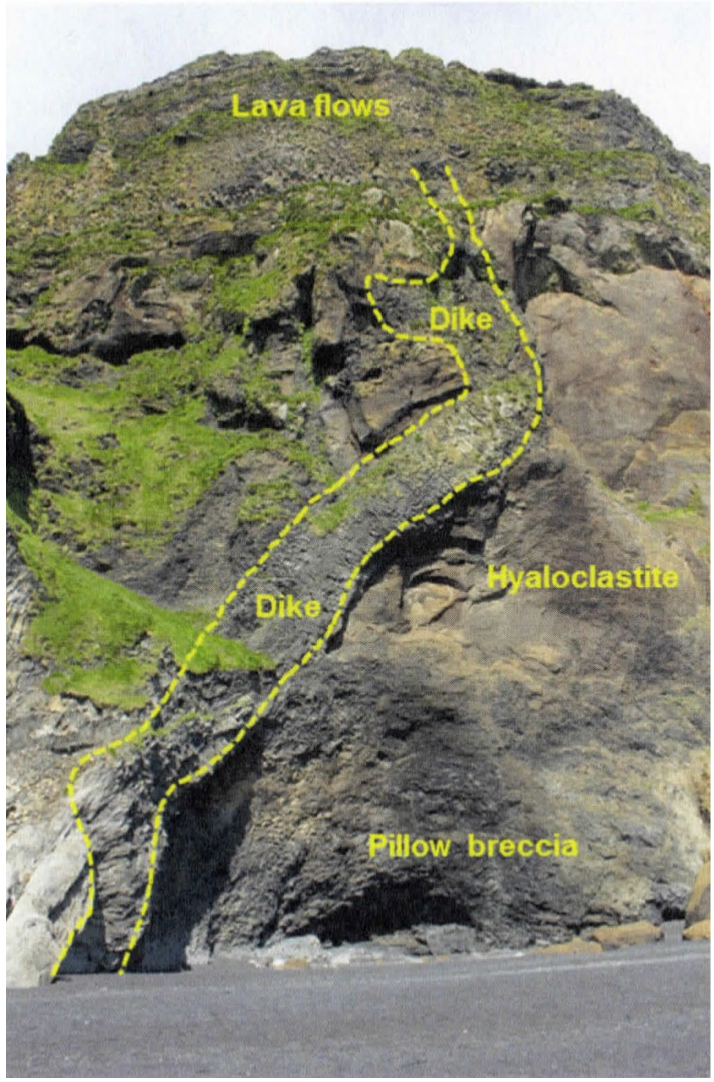


Figure 5.2.6. View north of the basaltic feeder-dike to the lava flows on the top of Reynisfjall. The lower part of the dike is steeply inclined, mostly 1-1 m thick, but its uppermost part is much thinner and close to vertical.

Figure 5.2.7. View southeast, the three sea-rock pillars that constitute Reynisdrangar. All the three pillars can be seen here, although the third one (whose two peaks are seen) is somewhat hidden behind the one closest to us. The pillars reach a maximum height of 66 m.

STOP 5.3 – *Dyrholaey Viewpoint*

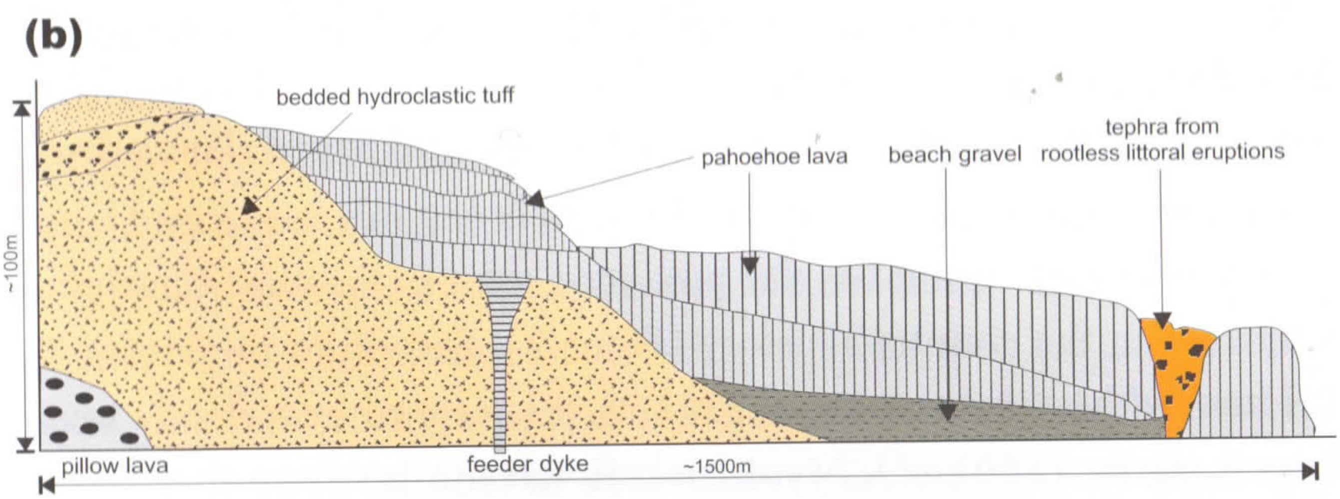
The following is from: Thordarson, T. and Hoskuldsson, A., 2019, Iceland: Classic Geology in Europe 3 (Second Edition). Dunedin Academic Press Ltd., Edinburgh, Scotland, pgs. 120-122.

Dyrholaey and the islands in the sand: volcanoes telling the tale of a different past

Some of the unusual features of the region around Myrdalur are the mountains Petursey [63.4673, -19.2711], Dyrholaey [63.4075, -19.1137], and Hjorleifshofdi [63.4166, -18.7551], which stand as isolated crags in a sea of sand and generally a good distance inland form the current coastline. Now sand and generally a good distance inland form the current coastline. Now on dry land, these structures are remnants of emergent submarine volcanoes formed when these low-lying coastal plains were fully submerged. Since then, the rivers have transported enough debris to raise the area out of the sea and link the former islands with the main landmass of Iceland.

Dyrholaey (Portland) is the southernmost point of Iceland (63º 23'N) and is a heavily eroded submarine volcano of the Surtseyan type (Figure 5.3.1). The main part of Dyrholaey, the tuff sequence is capped by compound pahoehoe lava, which in places exhibits cube jointing, indicating water-enhanced cooling of the lava. The lava flows represent the subaerial phase of the eruption when the tuff cone had grown large enough to prevent seawater from accessing the vent. Flowing away from the vent(s), the lava re-entered the sea and cooled rapidly to form the cube-jointed lobes. The Dyrholaey sequence is typical or Surtseyan eruptions and, if visibility allows, the type-volcano Surtsey can be seen from this location as the southernmost island of the Westman Islands.

Figure 5.3.1. (a) Aerial view of Dyrholaey; **(b)** Simplified cross section showing the structure of the Dyrholaey tuff cone (~100 m deep, ~1500 m wide)



Other, perhaps a little more obscure, evidence of submarine volcanic activity is found above Myrdalur in the moberg mountain above the Skammidalur [63.4512, -19.1005] farm. The mountain is a remnant of a submarine tuff cone made up of bedded lapilli tuff containing isolated blocks of fossiliferous marine sandstones and conglomerates. The fossil-bearing blocks, up to 1 m in diameter, were plucked from the underlying substrate by the Surtseyan explosions in the volcano conduit and incorporated as accidental clasts (i.e., xenoliths) in the tuffs.

Most of the fossils are molluscs, with 15 species of bivalves (lamellbranchia) and 9 species of snails (gastropoda), but they also include species of brachiopods, echinoderms (sea urchin), crabs (crustacea) and worms. Although the Skammidalur fossil assemblage bears a strong resemblance to modern marine fauna around Iceland, almost half are warm-ocean species that now reside farther south in the Atlantic or are extinct. Thus, when these fossil animals were living off the coast of Iceland, the ocean was considerably warmer than it is today. The age of the Skammidalur shell-bearing blocks is 2-3 million years (early Quaternary), as suggested by the similarity of the fauna to that found in the Serrpes layers at Tjornes in North Iceland.

Similar shell-bearing blocks are found sporadically in the moberg tuffs extending from Petursey in the west to Hofdabrekka [63.4267, -18.8982] in the east, indicating that the volcanic formations of Myrdalur rest on an extensive sequence of marine sediments that also covers the submerged bedrock shelf to the south, well beyond the Westman Islands. A progressive southward younging of the sediments is suggested by the fossil-bearing sandstone xenoliths ejected by the explosive eruptions at Surtsey in 1963-64, which contain fossils of only modern day species. Thus, some 2-3 million years ago the sea inundated the Myrdalur area, and it is likely that the now-majestic volcanoes of Myrdalsjokull and Eyjafjallajokull began their like some 600,0000-700,000 years ago in a similar fashion to the Westman Islands, as a cluster of small volcanic islands in the middle of the sea.

STOP 5.4 – *Sólheimajökulsvegur Glacier*

The following is from: Jordan, B.T., Carley, T.L., and Banik, T.J., 2019, Iceland: The Formation and Evolution of a Young, Dynamic, Volcanic Island – A Field Trip Guide. Geological Society of America Field Guide 54, pgs. 47-49.

Sólheimajökull [63.5264ºN, 19.3673ºW]

The purpose of this stop is to examine Solheimajokull, an outlet glacier of the Myrdalsjokull ice cap which covers the summit area of the volcano Katla.

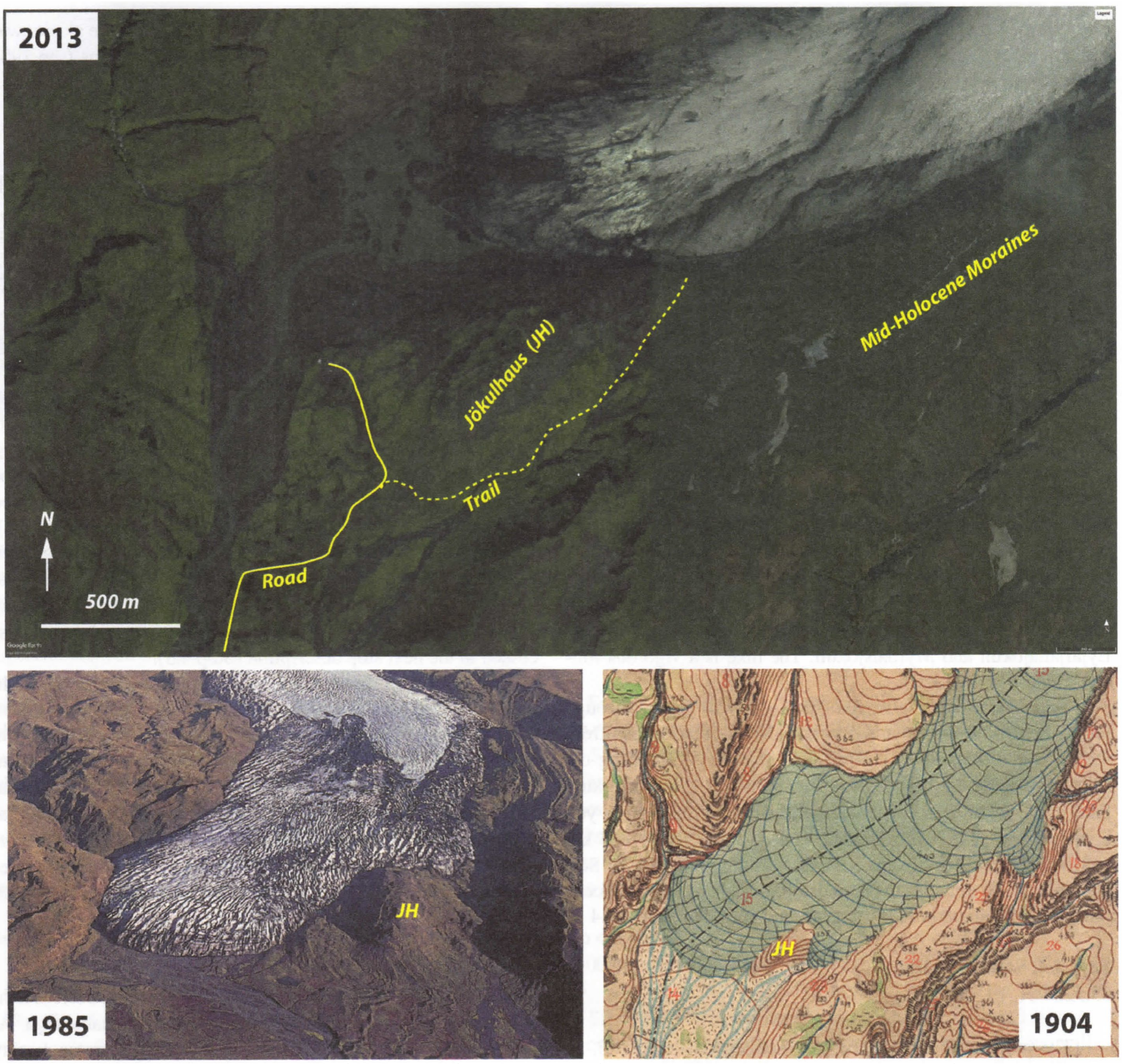


Figure 5.4.1. Maps and photos of the area of the termius of Solheimajokull, and outlet glacier of Myrdalsjokull: 2013 satellite image (Google, Digital Globe); 1985 photo from Sigurdsson and Williams (2008); and 1904 from map No. 69 NV, Danish General Staff, 1905 (scale 1:50,000, surveyed in 1904). Note the difference in both the position of the terminus and the amount of ice on the northeast side of the hill Jokulhaus (JH).

From the parking area, walk a short distance along the road looking for a trail that takes off to the east; once found, follow the trail (Figure 5.4.1). For a period of years this trail provided the principal access for glacier walks on Solheimajokull. The trail heads northeast up a small valley and is ~1.5 km in length leading to an overlook of Solheimajokull a bit above its terminus. The mountain ridge that separates this valley from the main glacial valley of Solheimajokull is called Jokulhaus. The trail begins by ascending over low moraines. Several recessional end moraines are passed along the route. Of note is a small but well-defined moraine at 63.5299ºN, 19.3490ºW. This point marks the position of a lobe of Solheimajokull that flowed on the east side of Jokulhaus during its maximum recent advance at ca. 1904 when the glacier was thick enough to cover the northern end of Jokulhaus (see 1904 map, Figure 5.4.1). The glacier extended farther down valley and covered much of Jokulhaus at ca. 1860 (Friis, 2011).

The fluvial sediment and channel pattern along the floor of the valley clearly reflect stream flow, but upon arriving at the end of the hike, one finds that there is no current source. The trail ends at a steep drop off overlooking the surface of Solheimajokull. As recently as 2007 the valley we ascended carried outwash because the glacier was significantly thicker at this point (aerial photographs in Friis, 2011). Immediately south of the glacier overlook point is a small (~3.5 m) round hill interpreted as a kame (Figure 5.4.2).

Solheimajokull is widely known for its rapid retreat, which was features via time-lapse photography, by James Balog o Extreme Ice Survey, in the 2013 documentary film "Chasing Ice." The glacier has retreated ~625 m from 2007 to 2015 (Burkhart et al., 2017)

Focusing on the glacier, a conspicuous tephra layer can be traced along the near southeast margin of the glacier; its folded trace can be followed back across the glacier (Figure 5.4.1 and 5.4.3). This is the Katla 1918 tephra, ~20 cm thick within the glacier. The 1918 eruption of Katla is, at the time of this writing, the last confirmed Katla eruption (several subsequent jokulhlaups may have reflected small subglacial eruptions). Katla volcano is discussed in the next stop description (Stop 4.5).

Figure 5.4.2. A small kame hill at the end of the trail.

Figure 5.4.3. The view looking over Solheimajokull from the end of the trail, Note the black tephra layer deformed within the glacier; this is the 1918 tephra.

Return along the trail back to the parking area. The main parking area 0.5 km farther up the road is an Optional Stop in this itinerary (63.5303ºN, 19.3708ºW). From this parking area, a short hike leads to the terminus of the glacier. About 400 m from the parking area is a sign showing the annual glacier retreat observations made by Hvolsollur School. Due to the rapid retreat of Solheimajokull at this time, the length of the hike and character of the terminus change from year to year.

STOP 5.5 – *Skógafoss waterfall*

Skógafoss is a waterfall situated on the Skógá River in the south of Iceland at the cliffs of the former coastline. After the coastline had receded seaward (it is now at a distance of about 5 kilometers (3.1 miles) from Skógar), the former sea cliffs remained, parallel to the coast over hundreds of kilometers, creating together with some mountains a clear border between the coastal lowlands and the Highlands of Iceland.

The Skógafoss is one of the biggest waterfalls in the country with a width of 25 meters (82 feet) and a drop of 60 m (200 ft). Due to the amount of spray the waterfall consistently produces, a single or double rainbow is normally visible on sunny days. According to legend, the first Viking settler in the area, Þrasi Þórólfsson, buried a treasure in a cave behind the waterfall. The legend continues that locals found the chest years later, but were only able to grasp the ring on the side of the chest before it disappeared again. The ring was allegedly given to the local church. The old church door ring is now in a museum, though whether it gives any credence to the folklore is debatable. The waterfall was a location for the filming of the Marvel Studios film Thor: The Dark World, as well as The Secret Life of Walter Mitty.

The following is from: Gudmundsson, A., 2017, The Glorious Geology of Iceland's Golden Circle. Springer International Publishing, Cham, Switzerland, pgs. 285-286.

Skogarfoss Waterfall

We now drive on along Road 1 to the east along the cliffs of Eyjafjallajökull until we come to the sixth stop (6), namely the river Skoga, which is roughly at the boundary between Eyjafjallajökull and the next volcano to the east, namely Katla. The river Skoga (Figure 5.5.1a), however, not only marks the boundary between these two large and active volcanoes, but also hosts the famous and beautiful waterfall Skogarfoss, seen in Figure 5.5.1b, It is worthwhile to drive the road to Skogarfoss to have a closer look at this exceptionally well-formed waterfall. Like Seljalandsfoss (Stop 5.6), Skogarfoss falls off a 60-m high cliff, an old sea cliff, formed when the sea level was much higher some 13,000 years ago. The width of the waterfall is about 25 m. There is commonly a rainbow produced by the interaction of sunrays with the drizzle from the waterfall (Figure 5.5.1b). The rock that constitutes the cliff is mainly of hyaloclastite, similar to that found along the cliff of Eyjafjallajokull and at Seljalandsfoss. There is a path to the top of the waterfall.

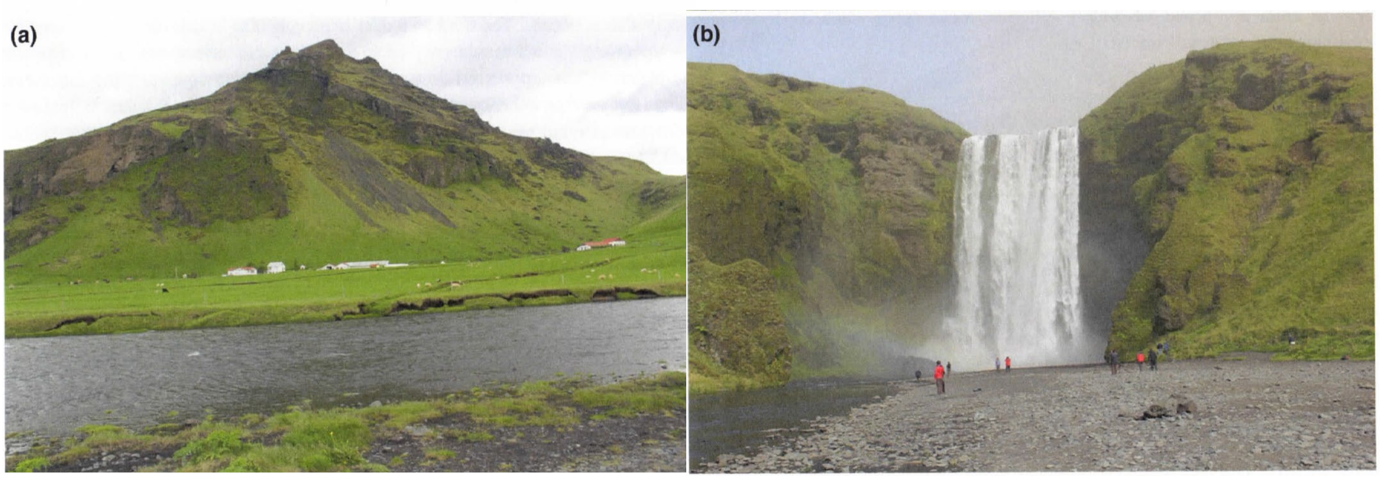


Figure 5.5.1. River Skoga and its waterfall Skogarfoss. **a.** View west, Skoga is roughly at the boundary between the volcanoes Eyjafjallajokull in the west and Myrdalsjokull/Katla in the east. **b.** The waterfall Skogarfoss, 60m high, is one of the best-known landmarks in Iceland.

The following is from: Thordarson, T. and Hoskuldsson, A., 2019, Iceland: Classic Geology in Europe 3 (Second Edition). Dunedin Academic Press Ltd., Edinburgh, Scotland, pgs. 118-120.

Hofsa River - myth and truth about the formation of Skogasandur and Solheimasandur

The Book of Settlement tells the story of a dispute between Þrasi at Skogar [63.5279, -19.4995] and Lodmundur at Solheimar [63.4946, -19.3281] two farms on either side of Jokulsa at Solheimasandur [63.4735, -19.3761]. According to the folklore, one morning Þrasi saw a great flood approaching from the mountains and used sorcery to force it into more easterly path towards Solheimar. Lodmundur, who was blind, was told by one of his slaves that an ocean of water was cascading down the mountain slopes and heading their way. Lodmaundur knew Þrasi's game, so he used his own powers to redirect the floodwaters westwards in the direction of Skogar. Þrasi responded and Lodmundur repeated his act. This apparently went on for a while until they agreed on a floodpath midway between the farms, whee River Jokulsa [63.4984, -19.3989] on Solheimasandur now runs directly to the sea. Also, according to one version of the tale, these floods formed the sandur plain of Solheimasandur.

For a long time, it was thought that the floods mentioned in the tale of Þrasi and Lodmundur had formed the whole outwash plain of Skogasandur [63.5039, -19.4831] and Solheimasandur, because geological evidence appeared to suggest an age within historical times for the main tephra-laden flood deposits on both sandur plains. However, recent findings show that the main flood deposits at Skogasandur are prehistoric (Figure 5.5.2) and were formed by a jokulhlaup that accompanied a seventh century Katla eruption. In this eruption the vents were in the western part of the caldera and within the drainage area of Solheimajokull outlet glacier. However, Younger flood deposits of lesser volume that formed during Settlement age cover part of Solheimasandur. We also know from tephrachronological studies that the early settler soon became acutely aware of the awesome nature of Katla, because within 70 years of the arrival of the first settlers it had erupted three times. After being exposed to two relatively small Katla eruptions in the late ninth and early tenth centuries, the newcomers witnessed the largest flood-lava eruption on Earth in the past 2000 years, the AD 934-40 Eldgja-Katla Fires. One of these eruptions is likely to have been responsible for the historical jokulhlaups into Solheimasandur, which supposedly kindled the dispute between Þrasi and Lodmundur.

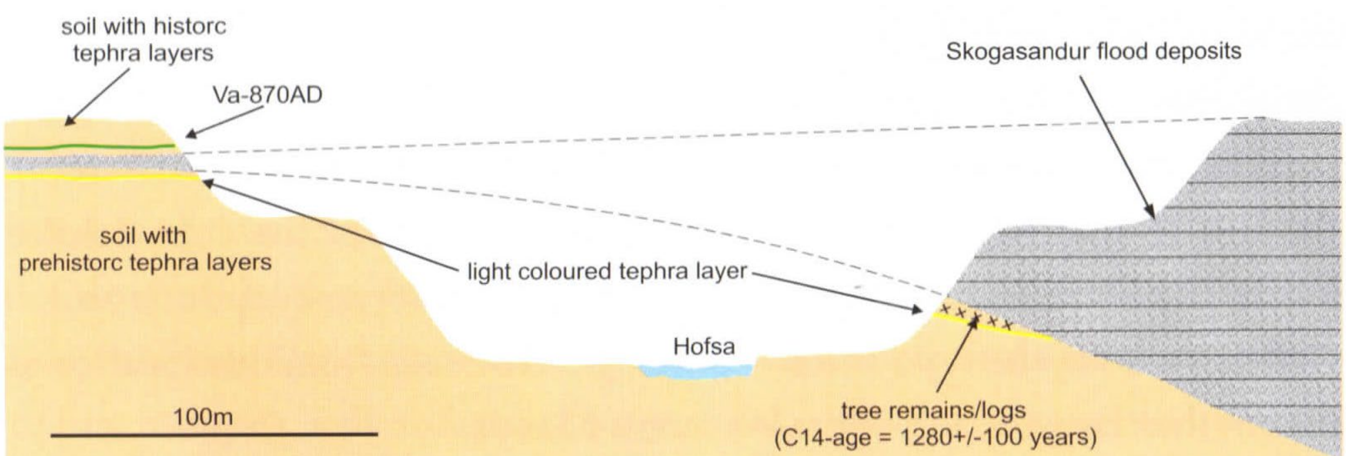


Figure 5.5.2. Schematic cross section of the Hofsa River [63.5237, -19.4552] channel where it dissects the main Skogasandur flood deposits. On the east bank of the river the tephra-rich flood deposits are several meters thick and overlays a soil containing many prehistoric tephra layers and a distinct horizon with tree-remains near the top. The ^{14}C age obtained from these tree remains is 1280±100 years (i.e., about AD 600). In the west bank the flood deposits are much thinner (0.5 m) and overlain by soil containing historical tephra layers including the Settlement layer formed around 870. Therefore, the Skogasandur floods occurred well before the first settlers arrived in Iceland.

STOP 5.6 – *Seljalandsfoss waterfall*

An impressive waterfall site is within easy reach from Route 1, the main road that encircles Iceland. Just at the intersection with the rugged road to Þórsmörk is the Seljalandsfoss, named for the nearby farm Seljaland. The falls are among the tallest in Iceland (60 m), cascading vertically over a former sea cliff. While the falls are not voluminous, their attraction is a walkway that puts visitors behind the falls, creating a magical show of water droplets, changing sunlight, and a sharp green of the moss-covered rocks and dewy pastures in the distance. The trail is wet and slippery, but only requires 10-20 minutes to complete.

The following is from: Gudmundsson, A., 2017, The Glorious Geology of Iceland's Golden Circle. Springer International Publishing, Cham, Switzerland, pgs. 273-276.

Seljalandsfoss Waterfall

Seljalandfoss is one of the better known waterfalls in Iceland (Figures 5.6.1 and 5.6.2). To reach this waterfall, we first cross the bridge across the glacial river Markarfljot. The glacial water is mainly derived from the ice caps of Eyjafjallajokull and Myrdalsjokull, both of which we discuss further. Markarfljot is normally small, such as many glacier rivers are, but can become large during floods. In particular, eruptions beneath these two glaciers can result in discharges of many thousand cubic meters per second.

A second feature to mention just as you approach the river Markarfljot is the archipelago of Vestmannaeyjar (Figure 5.6.1b). The main island, Heimaey, can usually be seen when you are that close ot the coast. You also see part of the town of Vestmannaeyjar. If the visibility is very good you may, here or earlier on Road 1, see some of the other islands - including the southernmost one, namely the island of Surtsey (Figure 5.6.1b), a table mountain formed in the sea in an eruption that lasted from 1963 to 1967.

Driving now to the fourth stop, the cliff that makes the Seljalandsfoss waterfall is an old sea cliff - here with a height of about 60 m. As indicated earlier, at the end of the last ice period, some 13,000 years ago, the sea level in Iceland rose to some 100-150 m above the present sea level. The vertical 60-m high cliffs, from which the water falls, are thus formed primarily by wave erosion when the sea level was, for a while, much higher that it is today. The same applies to most of the vertical cliffs that constitute the lower part of Eyjafjallajokull, and which we will see in a moment.

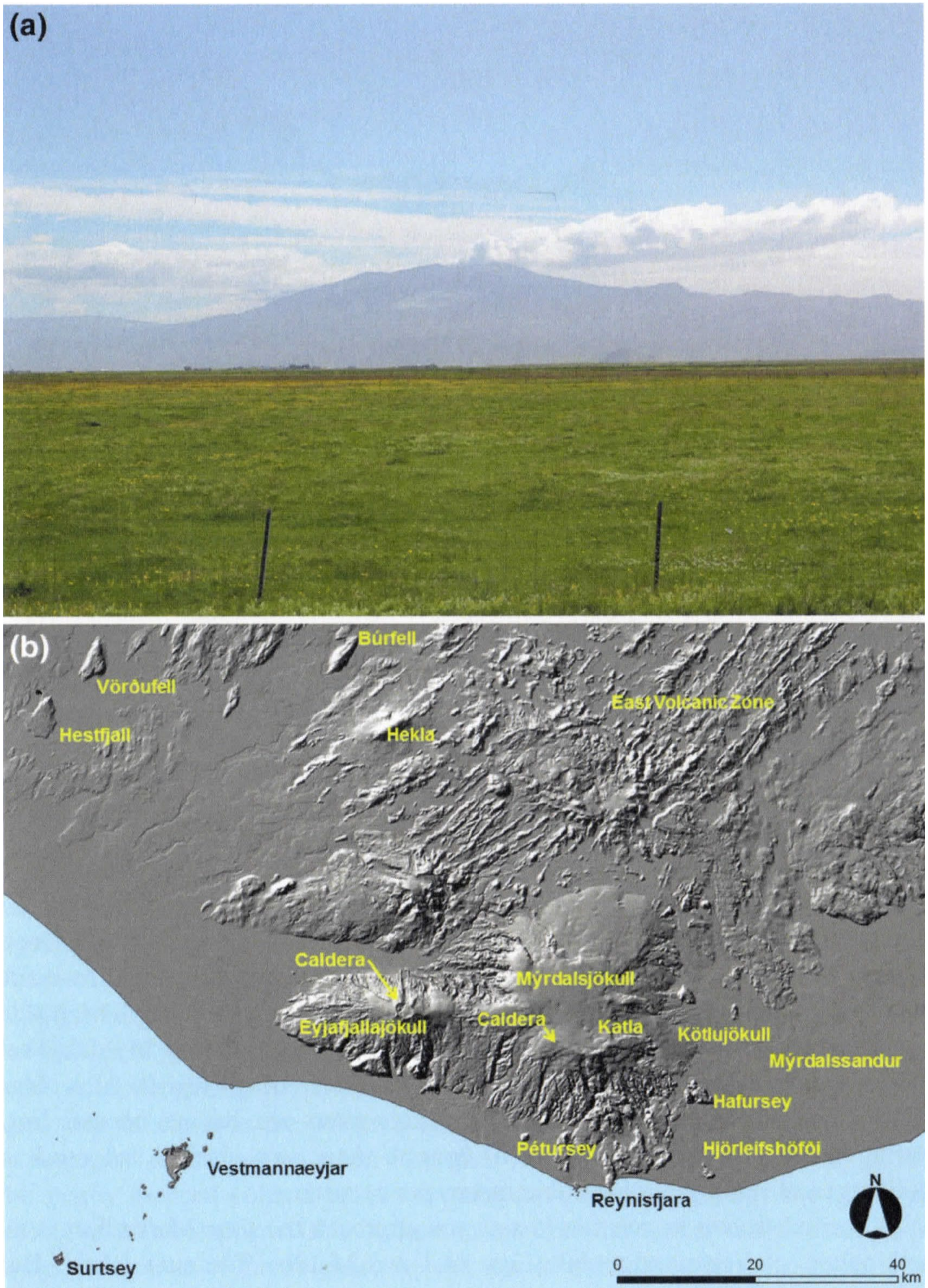
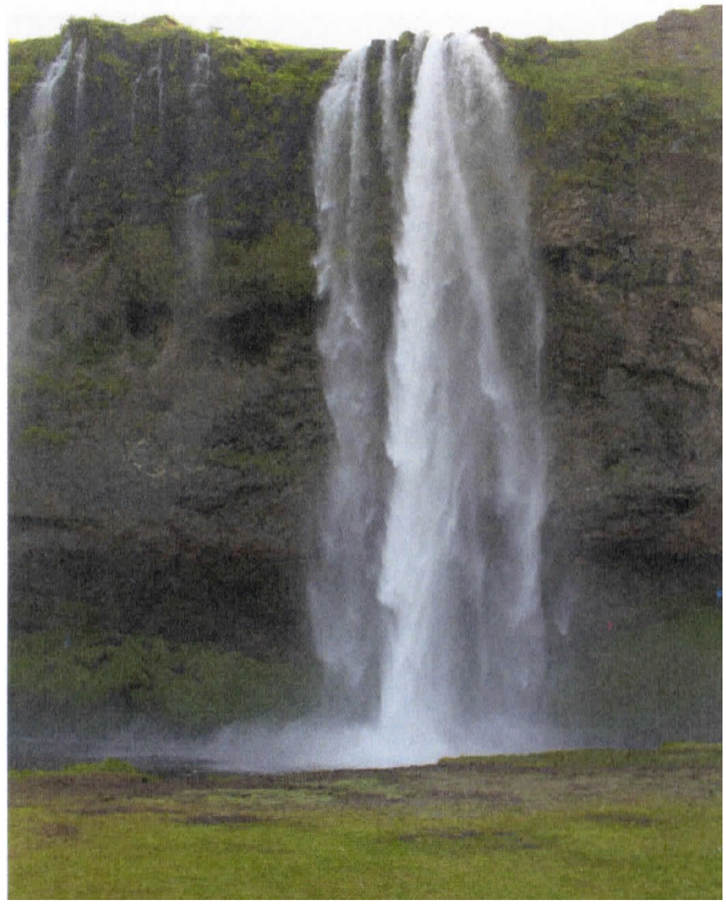


Figure 5.6.1. a. View east, the Eyjafjallajokull Volcano seen from a distance. This photograph is taken soon after the 2010 eruption. The inclined while column is due to heating from the eruptive materials in the caldera. The mist or haze is due to the ash in the air, carried by the wind when the photograph was taken. **b.** Location of Eyjafjallajokull, showing its caldera, as well as the names and locations of other mountains and landscape features discussed in this chapter.

Figure 5.6.2. View north, the waterfall Seljalandsfoss. The 60 m high cliff from which the water falls is an old sea cliff, formed by wave erosion when the sea level was much higher some 13 thousand years ago

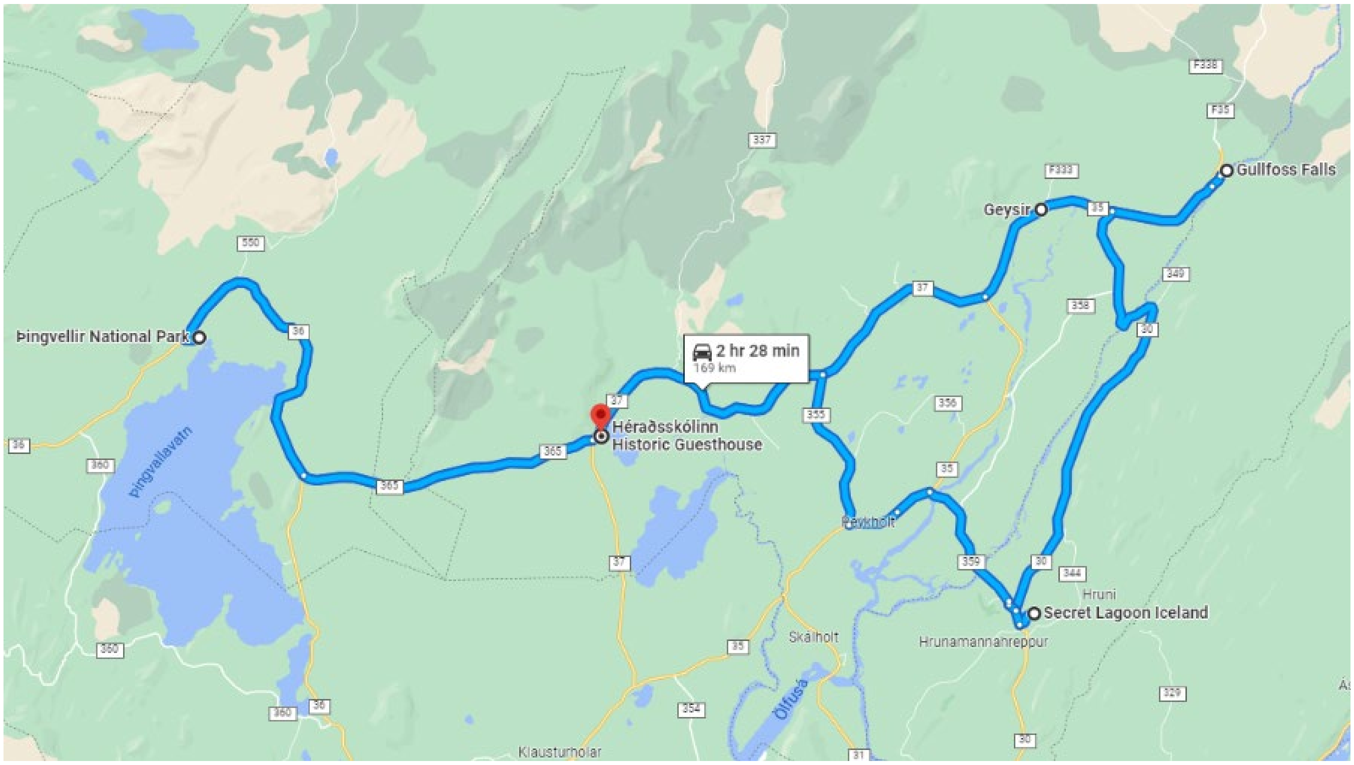


The rocks that constitute the cliffs, here as in much of the exposed parts of Eyjafjallajokull, are of hyaloclastite, that is, basaltic breccia, formed during eruptions under ice sheets - during the ice periods - and, possibly, also (the lowermost parts) in eruptions in the sea. Seljalandsfoss is well-known for being a waterfall that can be viewed not only from the front, but also from the back, from the footpath behind the waterfall, Some people walking along that path are seen in Figure 5.6.2. The water in the cascade is beautifully clear and clean and constitutes the small river Seljalandsa (Figure 5.6.3).

Figure 5.6.3. Seljalandsfoss is in the river Seljanlandsa, here seen on the ground in front of the waterfall.

Day 6: Thursday, March 9th, 2023 – Þingvellir, Geysir, Gullfoss, and Hot Springs

7:00AM: Wake-up, breakfast at the guesthouse
8:30AM: Depart for Þingvellir National Park
9:00AM: Arrived at Þingvellir National Park
9:30AM: Walk to the Law Rock and through the rift valley
11:00AM: Depart for Geysir
12:00PM: Arrive at Geysir, have lunch at the café (Our guesthouse will provide box lunches to take with us)
1:00PM: Walk the hydrothermal spring and geyser trail
1:45PM: Leave for Gullfoss (Golden Waterfalls)
2:00PM: Arrive at Gullfoss visit the fall and visitor's center
2:30PM: Depart for Secret Lagoon Hot Springs, Fludir (https://secretlagoon.is/)
3:00PM: Arrive at Secret Lagoon Hot Springs
5:00PM: Depart for the guesthouse or Dinner in Fludir? (https://minilik.is/)
6:00PM: Arrive at the guesthouse
6:30PM: Group dinner



STOP 6.1 – *Þingvellir National Park*

Þingvellir National Park is one of the most popular tourist attractions in Iceland and a UNESCO World Heritage site. It has numerous attractions including the historic parliament site, numerous geologic features, and Iceland's largest lake, Þingvallavatn. The park lies on a rift valley of the Mid-Atlantic ridge. The Icelandic parliament, known as Alþing (or Law Rock) was established in the area in 930 C.E. and remained there until 1789. The site was chosen for its accessibility to chieftains from around the country; no person had to travel for more than 17 days to attend. The area was also used as a location to hand out punishment to those found guilty of crimes. One pool on the river Öxará, known as Drekkingarhylur, was used to drown guilty women in sacks. Guilty men were simply beheaded. The pool remained in use until 1838.

We hiked along a fissure through a small forest to the Öxarárfoss waterfall. And then further to the parliament site on the shores of Lake Þhingvallavatn. Near Lögberg is a church, originally built after Iceland accepted Christianity in 1000 B.C.E. from timber sent by the king of Norway. The current church was consecrated in the same location in 1859. Also nearby is Peningagjá, a water-filled branch of a fissure.

The following is from: Gudmundsson, A., 2017, The Glorious Geology of Iceland's Golden Circle. Springer International Publishing, Cham, Switzerland, pgs. 48-71.

Thingvellir (Þingvellir)

Thingvellir is perhaps the best place on this planet to understand the process of rupturing of the crust in response to the pulling forces of plate movements. You will be driving to, and most likely walking inside, the most spectacular example of the effects of the enormous plate-tectonic forces tearing the crust apart. While it is easy to see the open fractures on the ground - and you will see the large ones while walking in the Thingvellir National Park - it is perhaps easier to explain the processes and forces by looking at the area and some of the sites we visit from aerial photographs (Figure 6.1.1). I, therefore, include many aerial photographs in this chapter.

Thingvellir constitutes a graben that forms a part of the West Volcanic Zone. More specifically, the Thingvellir Graben is located in the northern part of the Hengill Volcanic System (Figure 6.1.2). Although the area is geologically a wonderland, and all the sites are spectacular, it is worth mentoring that great care is needed while walking among the fractures. There are, as we shall see, numerous small fractures adjacent to the larger ones, and many of the fracture walls are unstable. So my strong recommendation is never ever go to the edge of a large fracture.

Almannagja

The fourth stop (4) on the Circle is normally at the entrance to the largest fracture of the Thingvellir area, Almannagja, which means the fracture or fissure for or belonging to the general public. It certainly does so today - and you are likely to see many people walking the path along Almannagja. At this stop the classic view is the one from Figure 6.1.3. For comparison, Figures 6.1.1 and 6.1.2 show a larger part of Almannagja from the air. More detailed aspects of this part of Almannagja are in Figures 6.1.4, 6.1.5, 6.1.6, 6.1.7, and 6.1.8. In particular, Figure 6.1.8 indicates some of the main geological structures associated with Almannagja. The main geological points regarding Almannagja may be summarized as follows (with references to Figures 6.1.1, 6.1.2, 6.1.3, 6.1.4, 6.1.5, 6.1.6, 6.1.7, and 6.1.8.

Figure 6.1.1. Aerial photograph showing the location of the four main sites visited at Thingvellir. View southwest, the fourth stop (4) is at the entrance to the main fracture in Thingvellir, namely Almannagja. The fifth stop (5) is along the path down Almannagja where the west wall is very high and clear for observations of flow units and related aspects. The sixth stop (6) is at Loberg, the site for parliamentary meetings when Iceland's parliament was located at Thingvellir, but also geologically and interesting place. The seventh stop (7) has two sites. The first popular water-filled fracture Peningagja and its extension Nikulasargja. Both of these, however, are just segments of the main fracture, referred to as Flosagja, which is the second site for the seventh stop. The Oxara flows to the southwest along part of Almannagja, from the waterfall Oxararfoss.

- The fracture is formed through two main processes: opening and subsidence (vertical displacement). The maximum opening is just over 60 m; the maximum subsidence of vertical displacement is about 40 m (Figure 6.1.9). Both processes relate to the plate-tectonic forces that tear the crust apart.
- The opening of 60 m by this single fracture gives spreading rate of about 0.6 cm per year. How do we know this? Simply by considering that the fracture is located in a lava flow that is about 10,000 years old. So if the fracture opens by 60 m in 10,000 years, then we have 60/10,000 or 0.006 m or 0.6 cm per year. When the openings of all the fractures along a line or profile (or section) across the Thingvellir Graben are added up, we obtain 100 m, so that the spreading rate in the past 10,000 years is, on average, about 1 cm per year. This result is generally in good agreement with the spreading rate at Thingvellir measured by other means (such as by satellites) during the past decades.
- The elevation difference between the top of the western wall to the lowest ground of the eastern wall, is about 40 m (Figure 6.1.9). It follows that during the past 10,000 years the average rate of vertical displacement, primarily subsidence, across Almannagja has been about 0.4 cm per year. We see therefore that the rate of vertical displacement is about half the rate of opening of spreading in the Thingvellir area.

Figure 6.1.2. The fractures of Thingvellir, including Almannagja, are part of the Hengill Volcanic System, whose central (main) volcano, Hengill, is seen here south of Lake Thingvallavatn. View southwest, this close-up aerial photograph of the southwestern part of Almannagja is taken about a decade later than the one in Figure 6.1.1, and the hotel (with a red roof close to the fourth stop) in Figure 6.1.1 is no longer seen in Figure 6.1.2 (it burned down in 2009). Stops 4, 5, and 6 in Figure 6.1.1 can be seen closer here (although not located again). The elevation difference between the western (right) and eastern (left) wall of the normal fault Almannagja is about 40 m, which is the subsidence across the fault in the past 10,000 years. The last major subsidence was during earthquake in 1789 when the northern shore of the lake, part of which is seen here, subsided by as much as 2.5 m. The maximum opening or aperture of the fault is about 60 m, close to Logberg (the sixth stop in Figure 6.1.1)

- While the plate movements are continuous, opening and vertical displacement across fractures such as Almannagja occur in discrete events. During such events, the eastern (lower) fracture wall of Almannagja suddenly subsides relative to the western (higher) wall (Figure 6.1.9). Such abrupt displacements normally give rise to earthquakes. The last major subsidence, by close to 1 m at Almannagja, took place during earthquakes in 1789. The earthquakes lasted many days, during which part of the land on the north shore of the lake subsided beneath the water. In the center of the Thingvellir Valley or Graben, the subsidence may have been greater, or as much as 2.5 m. As a result of this subsidence, the Parliament of Iceland was moved from Thingvellir to the capital, Reykjavik.
- All large fractures such as Almannagja - a large normal fault - are formed of smaller parts or segments. As the tearing apart of the crust continues, that is, the spreading continues, the parts or segments of the fracture link together. But the original segments and the linkage between them are normally marked by offsets (Figure 6.1.8). When you walk down the road or path inside Almannagja towards the fifth stop, you start your walk at the south end of one of the main segments of Almannagja. And at that lateral end, the fracture does not reach great depth and is made of pure opening - a tension fracture - so that there is no subsidence (Figures 6.1.2, 6.1.4, and 6.1.8).

Figure 6.1.3. Photograph of Almannagja from the fourth stop in Figure 6.1.1. View northeast, the surface of the eastern (right) fault wall is inclined by about 11º to the east, whereas the surface of the western (right) wall is horizontal (see Figures 6.1.8 and 6.1.9 for the geometric details). View northeast, the mountain Armannsfell is seen at the end of Almannagja, as well as part of the lava shield Skjarldbreidur.

Figure 6.1.4. The 'entrance' to Almannagja. This part can be seen on the aerial photographs (Figures 6.1.2 and 6.1.8) as being the end of one of the segments of Almannagja. Where the segments end, as here, they are pure tension fractures. That is, the walls on either side of the fracture are at the same elevation. Tension fractures are best seen in Figures 6.1.11, 6.1.12, and 6.1.15.

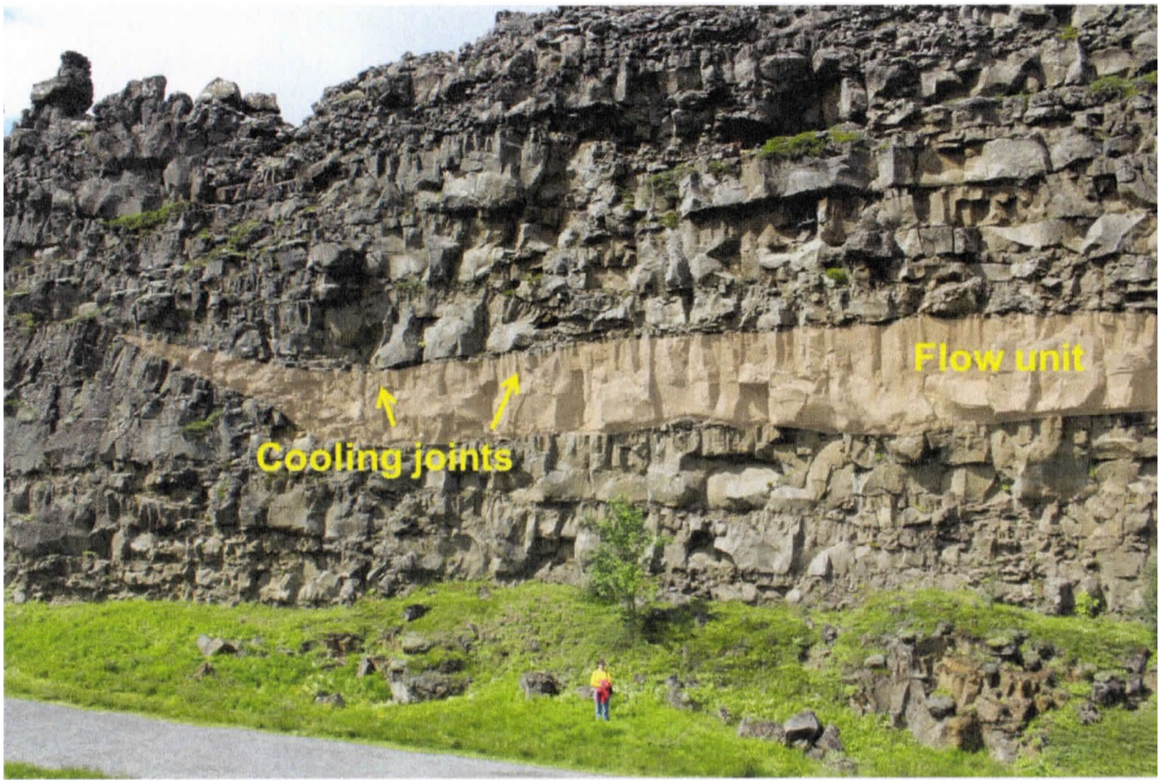


Figure 6.1.5. The lava flow that constitutes the walls of Almannagja is a pahoehoe lava flow. Such flows are basaltic and composed of numerous flow units, commonly with vertical cooling or columnar joints, and can reach thicknesses of several hundred meters, as does the present lava flow. For a vertical section through a thick pahoehoe lava flow, much older than the Thingvellir flow.

Walking down the path along Almannagja, we should make the fifth stop (5) so as to take a look at the fracture walls (Figures 6.1.5 and 6.1.6). We see that the walls are made of many layers, each one 0.5-2 m thick. All the layers belong to the same lava flow, which at Thingvellir has a thickness of several hundred meters. In the walls we see only the uppermost twenty meters or so (the maximum height of the western wall is about 28 m). The lava flow is about 10,000 years old and filled a valley, namely the graben that already existed at the time.

The flow is a thick pahoehoe flow of the type very common in the shield volcanoes of Hawaii and other basaltic edifices. Such flows are composed of numerous thin layers of the kind we see in the walls of Almannagja. The layers are called flow units (Figures 6.1.5 and 6.1.6). There may be many tens, sometimes hundreds, of flow units in a single thick pahoehoe flow. As mentioned in Chapt. 2, pahoehoe lavas are made of magma that is very hot (around 1300ºC). When erupted, the magma forms a flowing lava with a temperature of about 1200ºC at the surface (the lava, at the surface, is about one hundred degrees cooler than the magma in the magma chamber). Pahoehoe lava of this type of flows very easily, that is, it has a comparatively low viscosity or, more specifically, viscosity similar to that of tomato ketchup or mustard. Each flow unit normally comes from an underground tunnel or tube, a lave tube. When the tubes drain at the end of the eruption, they form caves, some of which may reach many kilometers in length.

When looking very closely at the flows units - which is perhaps best to do as you enter Almannagja where the walls are still low and little danger of rock falls (Figure 6.1.4) - you see a lot of cavities in them. Most of the cavities in them. Most of the cavities are wither circular of somewhat elliptical in shape, and with a common diameter between half and one centimeter. The cavities (named vesicles by geologists) are initially gas-filled swellings or bladders within the lava. When the gas escapes out of the hot but solidifying lava and into the air, a cavity is left. The shape of the cavity is an indication of the viscosity of the lava -

Figure 6.1.6. Close-up of some of the flow units and cooling or columnar joints seen in Figure 6.1.5. Here we see three main flow units (and part of the fourth one in the top left corner of the photograph). The cooling or columnar joints are best developed (more beautiful) in intrusions.

Figure 6.1.7. The surface of the eastern wall (left) of Almannagja is tilted by about 11º to the east. The tilting is most likely because of friction along the fault at depth (illustrated in Figure 6.1.9). The tilting of the eastern wall is along the greater part of Almannagja (Figures 6.1.1 and 6.1.8).

- and thereby the temperature of the lava. If the cavity cross-section is circular or somewhat elliptical, as in the walls of Almannagja, the lava flow had a high temperature and low viscosity. If the cross-section of the cavity is highly elongated or angular, the lava flow had a comparatively high viscosity and lower temperature. The lowest temperatures of basaltic lavas are around 1050ºC. These are **aa** lavas flows and easily ten times more viscous that the lava flow seen in the walls of Almannagja.

The **sixth stop (6)** is at the site of Logberg, which was the main site for the parliament meetings while the parliament still met at Thingvellir (Figures 6.1.1, and 6.1.2, and 6.1.8). The reason for the choose of this site soon after the settlement of Iceland is partly that the western wall of Almannagja is ideal for projecting the speaker's voice. One thing that is particularly clear at this site is that the surface of the eastern wall of Almannagja is inclined for tilted down to the east by about 11º. This is clearly seen on the ground (Figure 6.1.7) and also from the air (Figure 6.1.8). We could also see the sloping eastern wall from the first stop (Figure 6.1.3) but perhaps less clearly. By contrast, the surface of the western wall is perfectly horizontal (Figures 6.1.2 and 6.1.8).

So why is the eastern wall tilted while the western wall is not? The primary reason is friction between the walls at a certain depth (Figure 6.1.9), Almannagja and other fractures in the volcanic zones of Iceland are open or gaping only to shallow depths. At depths of several tens of meters the walls are closed, that is, in contact with each other. Friction is here a measure of the resistance to relative movement of the closed fracture walls of Almannagja. The part of the eastern wall away from the contact with the western wall can subside through bending of the rocks (Figure 6.1.9). At the contact between the walls, however, there is so

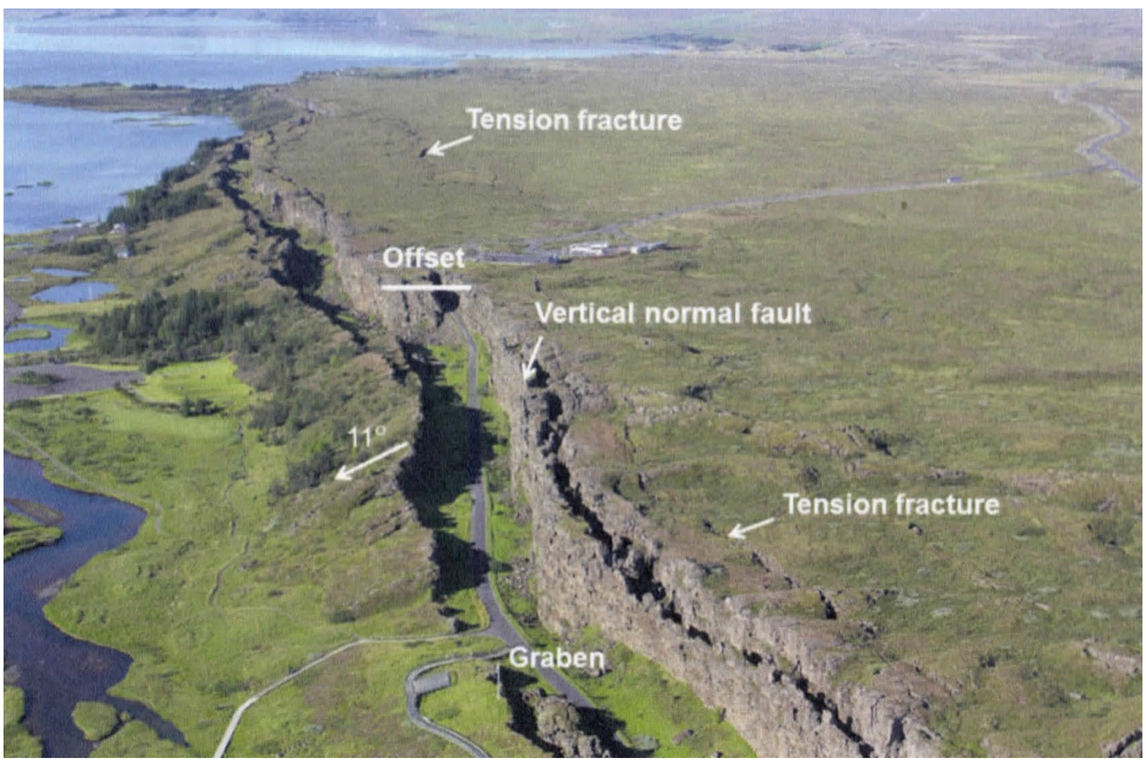


Figure 6.1.8. Aerial photograph showing some of the main structures associated with Almannagja. Around Almannagja itself there are many smaller structures. These include small tension fractures (discussed in detail in connection with Figures 6.1.11, 6.1.12, and 6.1.15) and the inclined eastern fault wall (its surface is inclined by 11º to the east, as shown here). By contrast the surface of the western fault wall is horizontal. Where you enter and start your walk down Almannagja, one segment of part of Almannagja is ending laterally (as a tension fracture). Then there is an east-west offset (indicated) and a new segment takes over and continues to the southwest. While Almannagja is a gaping or open normal fault, its opening is so large (more than 60 m in places) that it resembles a narrow graben (indicated). Compare the vertical section in Figure 6.1.9.

much friction that movement can only happen when large forces or stresses make it possible for slip to occur. And when slip occurs, there is an earthquake. The slip along the contact between the walls thus normally lags behind the general subsidence of the Thingvellir Graben, hence the bending or tilting of the eastern wall.

That abrupt slips and earthquakes are comparatively rare on Almannagja is known from recording of earthquakes, and is also indicated by Figure 6.1.10. Here we see a stone which poorly connected to the rest of the wall. In fact, the stone has been in exactly the same position for at least tens of years. During a moderate or strong earthquake the stone is almost certain to fall. But while the entire Thingvellir area is moving of spreading at the rate of close to a centimeter per year, no earthquake of these sizes have occurred on Almannagja for many decades.

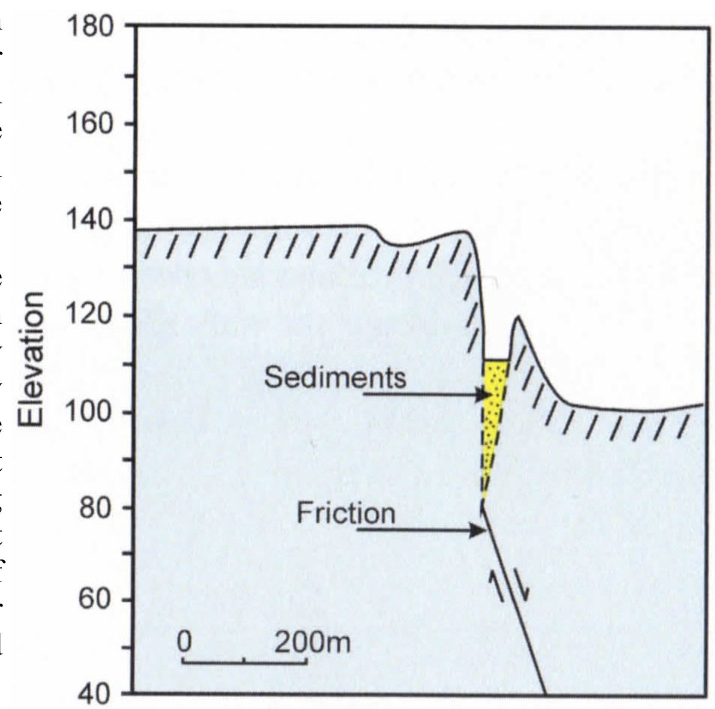


Figure 6.1.9. Vertical section through Almannagja (roughly the central part seen in Figure 6.1.2). The surface of the western (left) fault wall is at close to 140 m above sea level, whereas the lowest surface on the eastern (right) wall is about 100 m above sea level. The maximum vertical displacement ('subsidence') across Almannagja is thus about 40 m. The thickness of the 'sediments', which include fractured rocks from the fault walls and gravel, is unknown. Where the fault walls come together at depth, the fault changes from being vertical (originally a tension fracture) to an inclined fault where the eastern wall has moved down relative to the western wall. At this location, the friction between the walls is presumably the reason for the tilting of sloping of the eastern faut wall. The vertical scale is exaggerated about 8-times relative to the horizontal scale.

Peningagja and Flosagja

We now move on to the **seventh stop (7)**. This stop is split in two parts, as explained below, and indicated in Figure 6.1.1. It is easy to walk to this stop along the path from stop (6). Part of the path is seen in Figures 6.1.1 and 6.1.2. Alternatively, you may choose to walk back to your car up (south) along Almannagja and then drive to the seventh stop. The seventh stop is one of the most popular in Thingvellir and is at a water-filled fracture named **Peningagja**. The name means 'Money Fissure', the money in this case being coins thrown by tourists into the fissure, a tradition established in the early twentieth century, Peningagja is a pat of a larger fissure whose name is **Nikulasargja** which, in turn, is a part or segment of a larger fissure whose name is **Flosagja**. The latter, Flosagja, is the original name of the entire fissure, and Peningagja and Nikulasargja are just among its southernmost segments or parts (Figure 6.1.11).

Peningagja and Nikulasargja are very impressive structures (Figure 6.1.12). But in some ways the main fracture, Flosagja is the most spectacular of them all (Figure 6.1.13). Peningagja/Nikulasargja and Flosagja here count as the **seventh stop (7)** in two parts. Flosagja (Figure 6.1.13) can be reached through walking from Paningagja/Nikulasargja. Alternatively, if you drive into the Thingvellir Graben along Road 36 and then take Road 52 to the south to the parking place cloase to the waterfall **Oxararfoss**, seen in Figure 6.1.3, and walk from there to the fracture. In the previous section I explain how the fractures form, but first let us have a look at the water in the fractures.

The water is very clean and clear - it is a perfect example of high quality **groundwater**. In fact, the

Figure 6.1.10. View west, the uppermost part of the western fault wall of Almannagja at stop 6 (Figure 6.1.1). The little stone has been in this position for at least decades, indicating that despite gradual slow crustal movements at Thingvellir, as measured by geodetic instruments, no moderate to strong earthquakes have occurred on Almanngja for many decades and probably not since 1789.

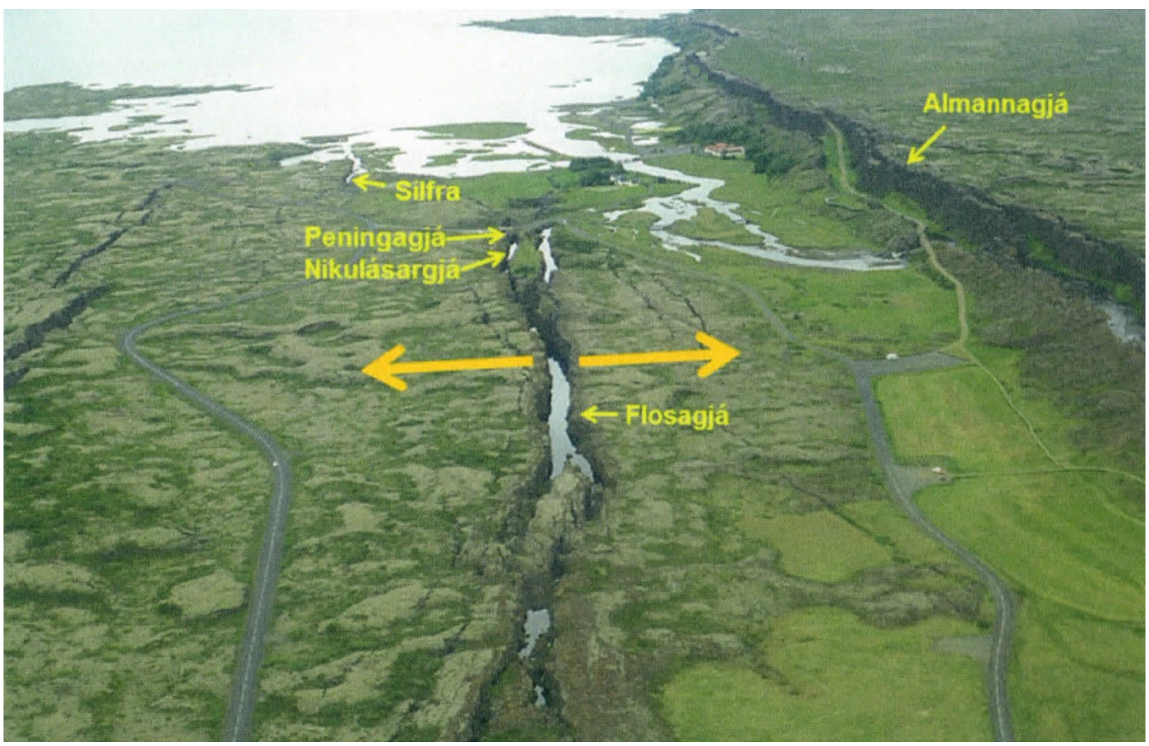


Figure 6.1.11. Aerial view of the tension fractures Peningagja, Nikulasargja, Flosagja, and Silfra, as well as the normal fault Almannagja. View southwest, the plate-tectonic forces, indicated schematically by orange arrows at Flosagja, tear the crust apart, rupture it, and form tension fractures and normal faults. Close to the road, at the east (left) margin of the photographs are normal faults.

Figure 6.1.12. Peningagja, the water-filled fissure with numerous coins at its bottom, is part of a tension fracture named Nikulasargja, most of which is seen here.

lava fields of Thingvellir and its surroundings are among the largest groundwater aquifer systems in Iceland. The water originally comes from precipitation, either directly from the rain and snow that falls on the area or, more indirectly, from melting of the glaciers in the north - in the highlands of Iceland - particularly the Langjokull ice cap. The groundwater migrates from the highlands surrounding the Thingvellir Graben through the lava flows which act as a sieve or filter for cleaning the water. When the water reaches the fractures it migrates into them and finally into **Lake Thingvallavatn** (Figures 6.1.1, 6.1.11, and 6.1.14). About 90% of all the water in the lake comes from groundwater springs, the rest being from surface water (rivers). And since much of the water comes from far away, from Langjokull and the surrounding highlands, it take many years - even tens of years - for the water to migrate the distance of about 50 km from the ice cap to the lake.

The surface elevation of the lake varies somewhat, but is at about 100 m above sea level on average (Figure 6.1.14) and is at the same elevation as the water level in the fractures (Figures 6.1.11, 6.1.12, and 6.1.13). This level is also the general elevation of the surface of the groundwater in the vicinity of the lake, so that the surface of the lake and the surface of the water in the fractures close to the lake are at the same elevation (Figures 6.1.1 and 6.1.11), named the **water table**. The lake itself exists because the valley or graben it occupies reaches below the water table - a common reason for the formation of lakes everywhere in the world. In fact, the lake is as deep as 114 m, so that its deepest parts reach below sea level (are at 14 m below sea level, to be accurate). The average or mean depth of the lake, however, is only 34 m. The lake covers an area of about 84 km^2, making it the largest natural lake in Iceland (Figure 6.1.14).

The fractures (Figure 6.1.11 and 6.1.12) were not in any way formed by the pressure of the water. All the fractures are formed directly by plate-tectonic forces or stresses (Figure 6.1.11) and are just conduits for the groundwater. The groundwater moves or circulates very slowly through the rock before it meets the fractures that conduct the water into the lake. Groundwater has close to the same temperature throughout the year, a temperature which is similar to the average annual temperature in the area. In the fracture the

Figure 6.1.13. Peningagja and Nikulasargja (Figure 6.1.11) are part of a larger tension fracture named Flosagja, part of which is seen here. View northwest, the maximum opening or aperture ('width') of the fracture is about 15 m. Tension fractures form by pure opening, where the forces of stresses causing the opening are directly related to the plate-tectonic forces. Flosagja, as well as Nikulasargja and Peningagja, are seen from the air in Figure 6.1.11.

the water temperature is mostly 3-4ºC (Figures 6.1.12 and 6.1.13). The water is thus very cold, yet warm enough so that it does not freeze. Thus, even in mid-winter, the water in the fractures does not become covered with ice.

The temperature of the lake (Figure 6.1.14), however, changes over the year. It is lowest in the winter months and highest in the summer months. In the winter months of January to March the average temperature is less than 1ºC, but 9-10ºC in July and August. The average temperature of surface water of the lake itself is somewhat higher than that of the water in the fractures. For the decades before the turn of the century, that is, before the year 2000, the water temperature in the lake was between 4 and 5ºC. In the present century, that is, after the year 200, however, the temperature has so far been above 5 ºC. That is, at least partly, related to the general warming of Iceland (and elsewhere) which has been most noticeable in the past two decades of so. Ice does form on the whole lake during the winter but the number of days with ice cover has been declining considerably in the past two decades. In fact, in some of the years during the past decade there were no days when the entire lake surface was frozen.

How Do the Fractures Form?

Coming back to the water-filled fractures (Figure 6.1.11 and 6.1.12), how do they form? The general answer is that they form when the tectonic plates on either side of the Thingvellir Valley are being separated or pulled apart, resulting in spreading. As we discussed above, Iceland is being pulled apart across the volcanic rift zones. In Thingvellir the rate of pulling apart, or spreading, is on average over thousands of years, about 1 cm per year. Far away from the volcanic zones, in particular Thingvellir itself, the spreading

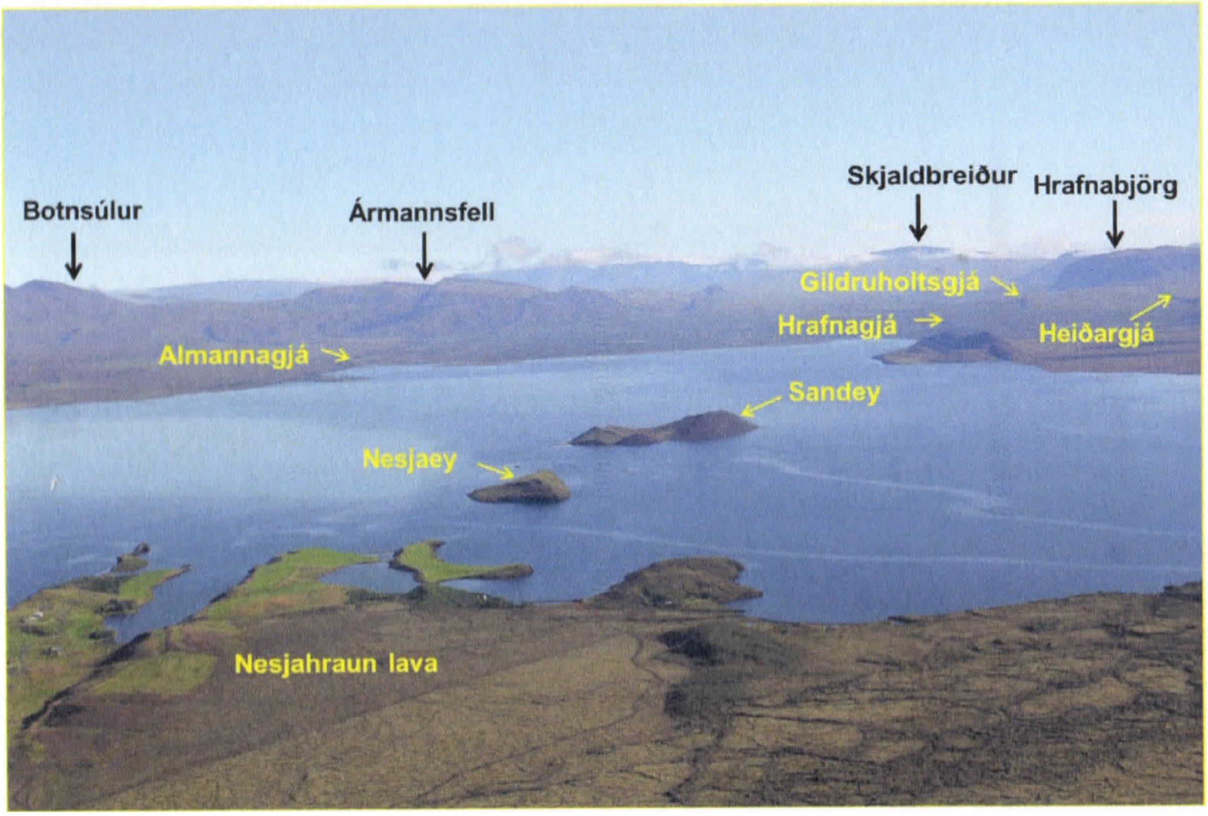


Figure 6.1.14. The greater part of Lake Thingvallavatn. This aerial photograph shows the from the southwest. Most of the water in the lake originates in groundwater springs. The surface elevation of the lake is about 100 m above sea level, whereas its deepest part reaches a depth of 114 m, so that it extends below sea level. Lake Thingvallavatn, with an area of 84 km^2, is the largest natural lake in Iceland. The largest faults at Thingvellir are Almannagja, Hrafnagja, Gildruholtsgja, and Heidargja. The lava flow Nesjahraun 2,000 year old lava flow Nesjahraum on the south shore of the lake and the island Sandey formed about 2,000 years ago.

is continuous, but its effects as regards fracture formation with the Thingvellir Graben is episodic. This means that centuries may pass between major **rifting events** with fracture formation or widening in Thingvellir. Recall that the last main rifting event in Thingvellir was in 1789, so more than two centuries ago.

So why does the rifting or rupture occur in separate events? Why is it not continuous like the spreading or plate movements themselves? The answer to both questions is that the plate-tectonic forces have to build up stress in the crust that is high enough to rupture the crustal rocks, to break the rocks. Gradually, as the forces move the plates apart, the Thingvellir Graben is stretched and its rocks become subject to higher and higher stress. As you know from tearing a sheet of paper, and existing rupture - a 'fracture' - makes it easier to tear the paper asunder. That is because the stress becomes raised or magnified at the rupture ends or tips, and these then propagate to the edges of the paper during the tearing. Similarly, the existing fractures (Figures 6.1.11, 6.1.12, and 6.1.13) raise or concentrate the plate-tectonic stress at their lateral ends of tips, so that a particular fracture is most likely to lengthen, become longer, when the stress is high enough for a rifting event to take place. Thus, during rifting events, existing fractures become larger, that is, become longer and also deeper (Figure 6.1.11). As rifting events continue, small offset fractures propagate and link up into larger fractures (Figures 6.1.15 and 6.1.16).

Flosagja (and Nikulasargja and Peningagja) are clearly different from Almannagja in that the fracture walls in Flosagja on either side of the fracture are at the same elevation (Figures 6.1.11, 6.1.12, and

6.1.13). By contrast, the eastern wall of Almannagja has subsided by as much as 40 m relative to the western wall (Figures 6.1.1, 6.1.2, 6.1.7, 6.1.8, and 6.1.9). In geological terms, Almannagja is a **fault**, and more specifically a **normal fault**, whereas Flosagja (and Nikulasargja and Peningagja) is a **tension fracture**. In a fault, much of the movement of the rock on either side of the fracture is parallel with the plane of the fracture, either up or down (vertical) the fault plane, or sideways (horizontal). Most **earthquakes** are related to sudden movements of the walls or slip on faults, and all large earthquakes are generated by such movements. On a tension fracture, by contrast, the movement is simple opening, pulling the fracture walls apart (Figure 6.1.11). There is thus no fracture-parallel movement during tension-fracture formation, and therefore no friction between the fracture walls (Figure 6.1.9). For tension fracture opening, the earthquakes that occur, if any, are normally small.

So how much stress must build up before we will have a new rifting event in Thingvellir? That is easy to calculate and turns out to be about 3 million pascals (3 mega-pascals). Now this may sound as something very great. However, the unit pascal (Pa), which measures stress or pressure as force over area - force per unit area (newtons per square meter) - is tiny. One pascal is equal to the fluid pressure of a film or layer of water that is about 0.1 or one-tenth of a millimeter thick. At the bottom of a 2-m deep swimming pool the pressure due to the water is about 20,000 pascal. At the bottom of Lake Thingvallavatn, at 114 m, the pressure due to the water is about one million pascal. Thus, the stress needed to form Flosagja and other tension fractures at Thingvellir (and in general in rift zones and at ocean ridges worldwide) is of the same

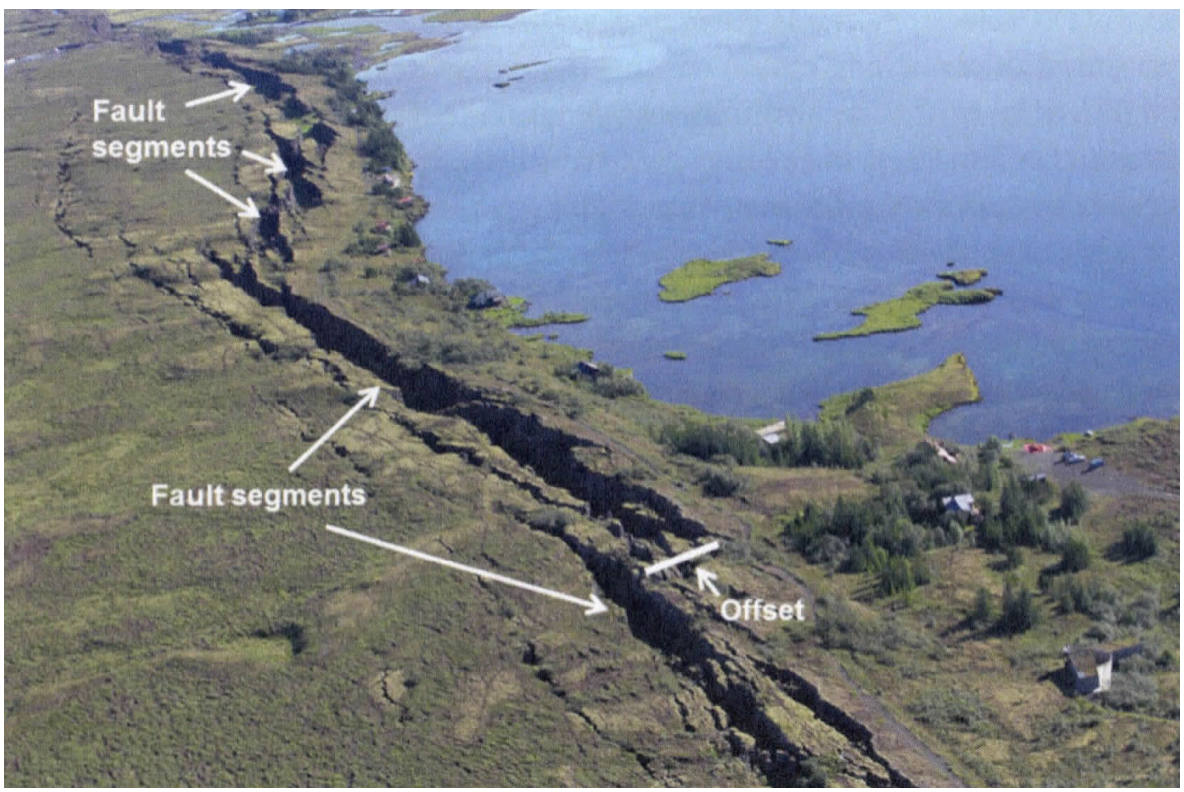


Figure 6.1.15. The southwestern part of Almannagja is highly segmented, that is, divided into many smaller fractures. This is partly because the old fault beneath the surface lava flow and which controls where the surface fractures occur is no longer perpendicular to the main plate-tectonic force (as shown in Figure 6.1.14). On a local scale, as here, the direction of the plate-tectonic force or spreading vector fluctuates ('wobbles' somewhat) so that a fracture that was initially oriented at right angle to the spreading vector or force may not be so for a while. The length of the offset indicates how much the fault shifts laterally when passing from one segment to another.

Figure 6.1.16. Close to its southernmost end, just as it enters into Lake Thingvallavatn, Almannagja changes into a set of tension fractures. View southwest, this set is seen here. The opening of the fracture to the right (west) of the white car is 12 m. The step-like oblique arrangement of the fractures seen here is known in geology by the French term én echelon.

magnitude as the pressure at the depth of about 300 m in a lake or the sea. Alternatively, it is of the same magnitude as the pressure or vertical compressive stress (due to the weight of the rocks) at the depth of 120-130 m in the Thingvellir lava flow, the one seen in Almannagja (Figure 6.1.5). I say the same magnitude because pressure or compressive stress seeks to compress an object, whereas tension or tensile stress (which may be of the same magnitude as the compressive stress or pressure, but with an opposite sign), responsible for the fracture formation, seeks to expand of extend the object - here the rocks at the surface of Thingvellir. As regards sign, in geology the sign of tensile stress is normally minus (-) and that of compressive stress plus (+), whereas in physics and engineering the sign convention is exactly the opposite.

The tensile stress needed to form the tension fractures is thus high, but not very high in comparison with the compressive stresses that generally exist in the crust. The compressive stress increases with depth in the crust. For example, in the roofs of many shallow magma chambers in Iceland, at depths of one to three kilometers, the vertical stress is between about 24 million and 80 million pascal. The magnitude of the vertical stress in the roofs of shallow magma chambers is thus 8-27 times larger than the tensile stress needed to rupture the crust and form tension fractures at Thingvellir.

How Deep are the Fractures?

Now that we know the stresses required to form the impressive tension fractures (and similar stresses are needed for the large faults such as Almannagja), the next question is how deep are the fractures? These are really two questions. One question is: what is the visible depth of the fractures, that is, the part mostly filled with groundwater? The other question is: what is the depth of the fracture as a narrow crack in the crust? As for the first question, Flosagja reaches a maximum visible depth of some 25 m (Figures 6.1.11

and 6.1.13). There are other tension fractures nearby that reach even greater visible depths. The best known is **Silfra**, whose maximum visible depth is around 60 m. Silfra is on the north shore of, and extends into, Lake Thingvallavatn, a few hundred meters to the south of Peningagja (Figure 6.1.11). Silfra is very popular for diving.

The second question is to what depths in the crust do the tension fractures reach? Here I mean depth not as the widely open fractures seen at the surface, or with the openings that people can dive into, but rather the depths to which the fractures continue as narrow cracks down into the crust. You might ask how it is possible to find this depth. The answer is that all large tension fractures, such as Flosagja, Nikulasargja, and Peningagja, and Silfra can only reach a certain maximum depth. If (say during a rifting event) they attempt to exceed this maximum depth, they will automatically change into normal faults. That is, one of the fracture walls will then subside relative to the other wall - just like at Almannagja and the other normal faults at Thingvellir. Using this information, and general knowledge of how fractures form (a specific scientific field named **fracture mechanics**), it is possible to calculate the maximum depths of tension fractures such as Flosagja and Silfra as being between 300 and 400 m. They are thus most likely entirely within the thick pahoehoe lava flow that occupies the uppermost part of the Thingvellir Graben - namely the Thingvellir lava flow.

And then, of course, the next question would be: how deep is Almannagja? The answer is that there are no simple methods for calculating accurately the depths of large normal faults such as Almannagja. If Almannagja were highly active seismically - with numerous small earthquakes - then their depths would indicate the depth of the fault. But Almannagja has vey little seismic activity. One crude indication of depth of a fracture, including faults such as Almannagja, is its length at the surface: longer fractures tend to be deeper than shorter fractures.

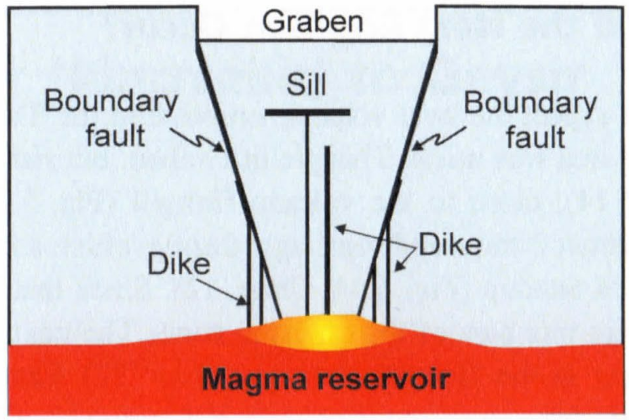
Almannagja is the longest continuous fracture of the Thingvellir Graben. By continuous fracture I mean that all the fracture segments of parts are physically connected or linked together - there is no strip of land in-between their nearby ends. Its total length as a continuous fracture is about 7.7 km. For comparison the shortest tectonic fracture in the Thingvellir Graben is about 60 m and the average or mean length of all the fractures about 620 m. The longer fractures are generally normal faults ad generate earthquakes when they slip, whereas the shorter fractures tend to be tension fractures with little earthquake activity when they grow.

But Almannagja, like all the larger fractures, is composed of parts or segments, many of which, even if comparatively close to each other, are not physically connected - they are disconnected and offset (Figure 6.1.8, 6.1.15, and 6.1.16). We know that in earthquakes segmented and disconnected faults commonly act as single faults, and the same would apply to all the segments of Almannagja during moderate to strong earthquakes (Almannagja cannot generate really major earthquakes of magnitude 7 or greater). And if all the segments of Almannagja are counted, then its length within Thingvellir is at least 15 km. Similar segments continue into the hyaloclastite mountains north of Thingvellir (Armannsfell), as well as to the southwest along Lake Thingvallavatn and towards the Hengill Volcano. If all these segments are regarded as parts of Almannagja, then its total length is easily 30-40 km. Similar lengths would be obtained for some other large faults in the area; their lengths may reach several tens of kilometers when all the segments, also in the older rocks, are considered parts of the same faults.

Then we come back to the question: how deep into the crust do Almannagja and the other large faults at Thingvellir extend. The answer is at least 10 km, and more likely about 20 km. Why not more than 20 km? Because at approximately that depth there is magma beneath the West Volcanic Zone, of which the Thingvellir Graben is a part. The large faults of the Thingvellir Graben, and their extensions to the southwest and northeast along the West Volcanic Zone, most likely reach to the bottom of the crust, into the roofs of deep-seated and very large magma reservoirs (6.1.17).

If so, why does the magma then not come up along the faults? The reason is their inclination and the unfavorable stresses generated temporarily in the graben following earthquake slip (Figure 6.1.17). In

Figure 6.1.17. Grabens are common in volcanic rift zones, such as in Iceland. Grabens can often act, temporarily at least, as barriers to dike propagation to the surface, and thus to fissure eruptions. Graben acts as a barrier to vertical dikes when the boundary faults deflect or stop or arrest the dikes and also when temporary compression inside the graben wedge stops or arrests dikes or deflects them into sills. When the graben wedge subsides, it enters into a narrower 'gap', so to speak, and may then become subject to horizontal compression for a while. Horizontal compression arrests vertical dikes or deflects them into sills; in both cases stopping the dike from reaching the surface to erupt.



a volcanic rift zone such as Thingvellir, the magma almost always travels to the surface through vertical magma-filled fractures, that is, **dikes**. The magma very rarely uses existing inclined fractures, such as normal faults, for the simple reason that it requires much more energy to push the inclined fracture walls aside to make room for the magma, the dike, than to use the numerous vertical cooling fractures, columnar joints (Figures 6.1.5, 6.1.6, and 6.1.10) to generate its own path to the surface. This follows because the plate movements are horizontal, so that it is easier for the magma to push the crust horizontally than in an inclined manner. Additionally, when the Thingvellir graben subsides along the main faults. Almannagja and Hrafnagja, the effect is to hinder magma movement to the surface. When the wedge-shaped crustal block of the graben subsides, it is forced into a gradually narrower 'gap' in the crust (Figure 6.1.17), so tht the effect is mechanically similar to pressing a cork into a bottleneck, namely temporary horizontal compression. This compression generates compressive stresses which tend to prevent vertical dike propagation; the dikes either become deflected into horizontal sills of stop altogether (Figure 6.1.17). In either case the dike is unable to reach the surface to erupt.

When Will the Next Eruption Occur?

When can we then expect the next volcanic eruption in the Thingvellir area? The last eruption in the area was not in Thingvellir Graben, but rather at the south end of the lake (Figure 6.1.14), close to the volcano Hengill (Figure 6.1.2). This eruption occurred about 2,000 years ago, during which a lava flow formed as well the island of Sandey (Figure 6.1.14). Since that time there has not been any eruption in this part of the volcanic zone. The next eruption is in fact more likely to occur in the Hengill Volcano than in the Thingvellir Graben. This follows from pure statistics. As we discussed I Chapt. 4, outside the main central volcanoes (such as Hengill) there is, at any given locality (such as Thingvellir), one new lava flow erupted every several thousand years - and occasionally there are tens of thousands of years between successive lava flows.

Given that the main lava flow in Thingvellir Graben is about 9,000 year old, however, we might expect a new flow to come in the geologically near future. In active areas such as Thingvellir, however, the 'near future' commonly means tens or hundreds, even thousands, of years from now. Whether tht eruption occurs inside the valley itself, or, as in the eruptions that formed the current lava flows in the graben, outside the graben, we do not know. But when the eruption occurs, it is likely to be much larger than the recent small eruptions in central volcanoes such as Grimsvotn, Hekla, and Eyjafjallajökull. In fact, an eruption in the Thingvellir area, when it occurs, is not unlikely to be of the order of several cubic kilometers.

STOP 6.2 – *Geysir*

A road out of the windy Þingvellir campsite follows the western rift zone, which stretches from the Reykjanes peninsula in the south to the Langjökull glacier in the north[1]. The drifting apart of the North American and European plates created the Þingvellir valley, a graben bounded by normal faults and split by long, linear fissures. Volcanic shields and hyaloclastite hills are visible along the road toward Geysir. Shields are formed by repeated subaerial or submarine lava flows, resulting in a perfectly round, gently sloped hill or mountain. Mt. Skjaldbreiður is a shield volcano located in the northern end of the graben[1]. Hyaloclastites, on the other hand, are smaller and more jagged formations, consisting of chunks of glassy basalt (rapidly cooled/extrusive rocks). They are formed under glacial ice, building up to high and sharp structures easily visible along the road.

A short drive away is the geyser field at Haukadalur. Volcanic activity in the rift zone allows for heating of the water and gas emissions in the field of more than 30 hot springs and pools, some of which erupt and are thus known as geysers. The large amount of tourist buses and endless souvenirs in the visitor's center do not spoil the appeal of the short walk among the hot springs or the surprise brought by a geyser eruption. For the athletically inclined, this is not a major hiking spot, but a 20-30 minute hike to an overlook above the geyser field is possible.

The walk begins with a glimpse of what's to come – Litli Geysir (or 'Little Geyser') to the left of the path has a rustic label board and its hellish boiling waters are an omen of a much larger eruption cooking up further ahead. Strokkur (Icelandic for 'churn') erupts regularly every 4-8 minutes to the heights of up to 30 meters[2] and provides a textbook example of a fountain glacier and its eruption sequence. The water slowly boils at the surface, but reaches temperatures of 120° C at depth (the higher pressures cause superheating) until the water domes up and erupts. A larger eruption usually follows smaller ones and sometimes a secondary eruption arrives when the waters just start flowing back into the hole. Tourists can stand on one side of the geyser and get a hot shower of sulfide-smelling water. Above the Strokkur geyser, a few hot pools provide colorful views with their milky blue waters (likely dissolved gypsum) and yellow, green, and red colored deposits of iron and sulfur minerals, as well as mats of thermophilic bacteria.

Further away is Geysir, the Father of all Geysers. Today it is just a hole encrusted in amorphous, shiny siliceous deposits. Geysir is the tallest geyser in the world with eruptions over 70 meters tall. It is now dormant, unless tourists visit Iceland on the National Day when qualified geologists provoke an eruption of one of Iceland's national symbols. Geysir lent its name to all geysers in the world, being the first geyser known to Europeans (earliest accounts date back to 1294). Its own name comes from the Old Norse (and Icelandic) verb 'to gush'[3]. The activity of Geysir, as well as Strokkur, is intimately linked with seismic events. Eruptions of Strokkur started after an earthquake in 1789 that unblocked its plumbing system. Geysir, on the other hand, was nearly dormant until an earthquake in 1896 caused it to erupt again, but blocked the conduit of Strokkur. Geysir remained active until 1916, after which its eruptions all but ceased. Geysir was later reactivated only by human interventions (such as digging a hole through its silica rim or adding surfactants to the water), although an earthquake in 2000 did cause a short-lived resurgence of natural eruptions. Strokkur, on the other hand, has remained faithful to its eruption interval since the locals cleaned out its conduit in 1963.

The following is from: Gudmundsson, A., 2017, The Glorious Geology of Iceland's Golden Circle. Springer International Publishing, Cham, Switzerland, pgs. 92-103.

Geysir

Geysir (the Great Geysir) may be the most famous geyser in the world, and is our tenth stop (10). Geysir is the namesake of all erupting (gushing) hot springs: they are referred to as **geysirs**. The **Great Geysir** and the nearby **Strokkur** (and occasionally some other hot springs in the same area) are the only erupting hot springs in Europe. The Great Geysir is hardly active now; it erupts very rarely - only a few times each year - and the height of the fountain or water column during eruption is normally less than 10 m. This is considerably less, both as regards fountain height and, in particular, eruption frequency than that of the nearby geyser Strokkur.

Strokkur currently erupts on average once every 5-10 minutes, so if you stay for a while in the geothermal field, you are certain to see erupting (Figure 6.1.1). Each eruption is short, perhaps a few minutes, all counted. The height of the resulting fountain varies much. Occasionally, the fountains are as high as 30-35 m, but most commonly 10-20 m (Figures 6.2.1, 6.2.2, 6.2.3, and 6.2.4). By contrast in the late 19th century, there are reports that the fountains of Strokkur occasionally reached the height of 60 m.

That height, however, is less than the height to which the fountains of the Great Geysir were able to reach in earlier times. In the middle of the 19th century it is reported to have occasionally reached the height of 170 m. This may, however, have been an overestimate because about the same time exact measurements by the scientist who first explained, in general terms, how erupting geysers operate (Robert Bunsen) indicated maximum foundation height of only about 54 m. It is well confirmed, however, that the fountain of the Great Geysir commonly reached 60-70 m in the 20th century. Furthermore, following the earthquake in South Iceland in the year 2000, Geysir became reactivated and for some days reportedly erupted to heights of about 120 m.

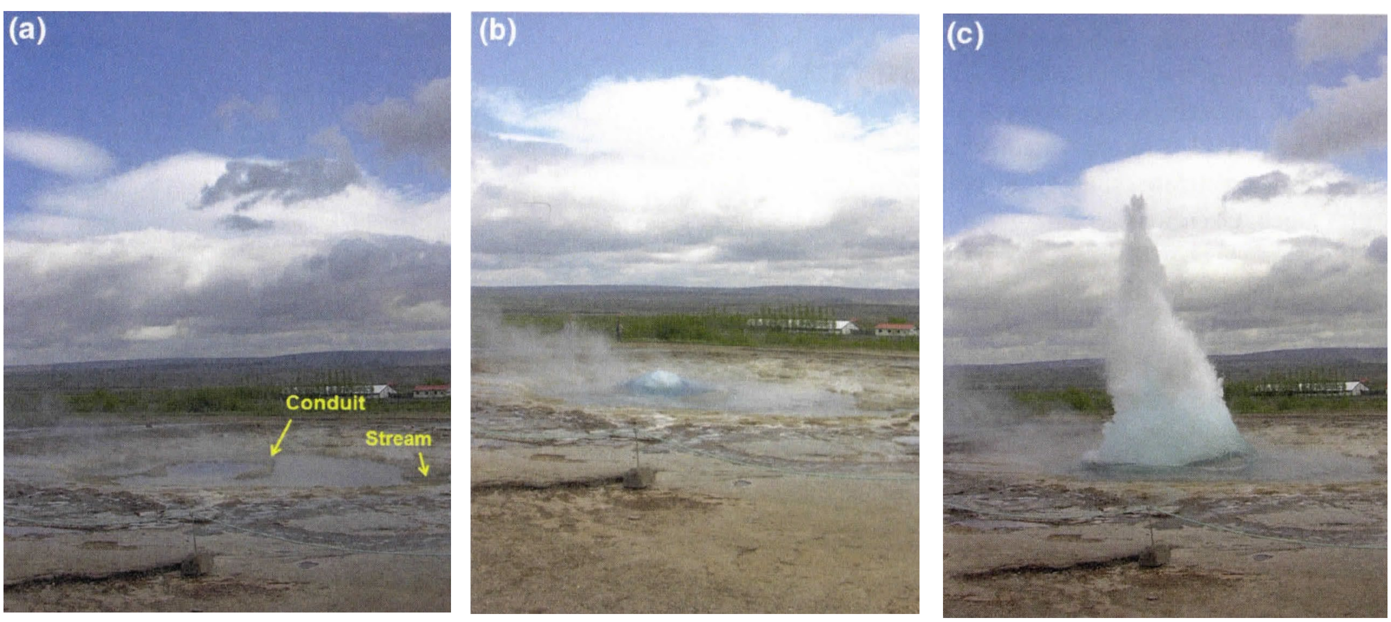


Figure 6.2.1. a, b, c Three stages in the eruption of the geyser Strokkur. **a.** The main conduit or pipe (indicated) is being filled with water. **b.** Swelling of the water surface, so as to form a half-sphere on the top of the conduit, indicating the beginning of the eruption. **c.** The eruption itself

Mechanism of Eruption

This brings us two questions. First, why is the activity in individual geysers so variable over time - in particular why does it relate to earthquake activity. Second, what is the general reason of the geyser eruptions or gushes. We start with the second question, the one broadly explained by Bunsen during the middle of the 19th century.

Eruptions in a geyser are driven by boiling of the geothermal water in the geyser pipe or conduit (Figure 6.2.5). The water is everywhere above 100ºC and its temperature gradually increases with depth. However, because the water pressure also increases with depth - as you know from being in a swimming pool or the sea - the temperature at which water boils (**boiling temperature**) and changes into steam also increases with depth. the boiling temperature is thus well above 100ºC at deep in the conduit or pipe of a geyser. For example, at the depth of about 20 m in the Great Geysir the normal water temperature is about 120ºC, which is still not enough to cause boiling. Overheating of the geothermal water is needed in order to reach boiling point. When that happens, for example when water enters the pipe at a certain depth at a higher temperature than the surrounding water at that depth, then boiling begins, which normally results in an eruption.

Figure 6.2.2. Some eruptions in Strokkur fail to reach their peak and remain very small. Here is an example of one such 'failed' eruption.

Figure 6.2.3. Example of a reasonably large eruption in Strokkur. The human-made stream, indicated, helps keep the water level in the conduit comparatively low so as to encourage boiling and eruptions.

In detail the process is then as follows. When the boiling begins in the conduit or pipe at a certain depth (Figure 6.2.5), the water above that depth must rise somewhat. Why? Because heating the already hot water increases the water volume while at the same time **bubbles** form and grow, resulting in further volume increase of the water.

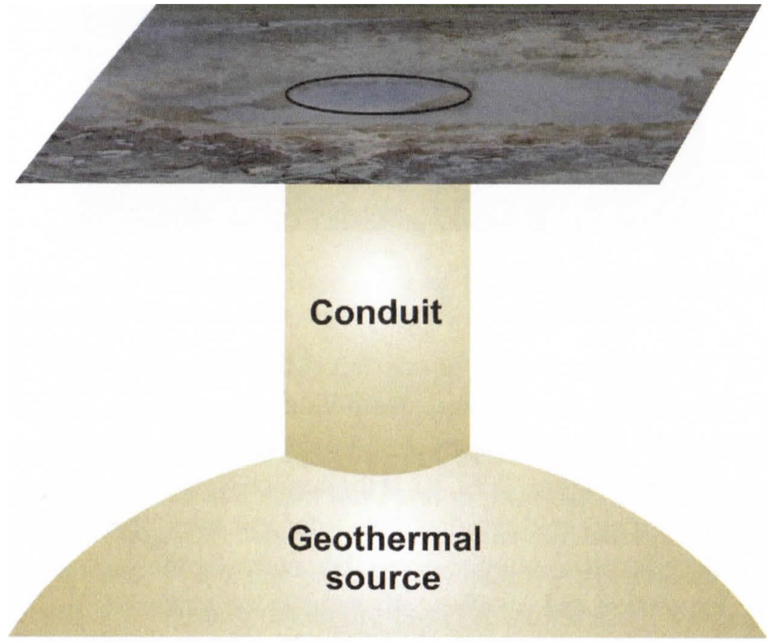
The volume of the cylindrical pipe or conduit is basically always the same, so the only way that the additional water and steam volume in the pipe can be accommodated is by **lifting the water surface**. And this is what you see happening during preparation for an eruption (Figure 6.2.1a,b). If the surface water cools very rapidly, such as when there is a strong, cold wind at the surface, it may be difficult for enough boiling to take place for an eruption to occur. But normally the pressure decrease due to the volume expansion and overflow of water at the surface (Figure 6.2.1b) triggers further boiling in the upper part of the pipe, resulting in an eruption (Figure 6.2.1c).

Figure 6.2.4. Large eruption in Strokkur

As the eruption starts, water is transferred out of the pipe (into the air), which further reduces the water pressure in the pipe. Consequently, boiling extends **deeper into the pipe**, generating more steam, and more water is shot up into the air. Thus, the eruption commonly occurs in several shots of gushes of water into the air in a rapid succession (Figures 6.2.3 and 6.2.4). Following these shots, the water left in the pipe is all overheated so that it boils into steam. The rest of the eruption is therefore primarily a noisy steam eruption. After the eruption is finished, the pipe gradually becomes filled with geothermal water again (water is continuously flowing into the pipe through fractures), and the story repeats itself (Figure 6.2.1). Much of the water that makes the fountain falls back into the pipe (Figure 6.2.6), or flows back into it from the surrounding bowl, but some leaks away along the tiny stream (Figure 6.2.1b and 6.2.3).

The story described above is the classic course of events from one major eruption to the next. But there are many factors that may affect the eruption scenarios. Thus, many eruptions are small and thus incomplete (Figure 6.2.2) and their size distribution presumably follows a power law. Then the pipe does not become anywhere close to being empty, so that the time to refill it so as to be ready for the next eruption is often very short. There are several other factors that affect eruption size and frequency. One, indicated above, is the weather. Rapid cooling of the surface water by wind may prevent the eruption from happening for a while. Another factor is the rate of inflow of water into the pipe (Figure 6.2.5), which is variable, and also the water temperature. Generally, geothermal fields, such as the Geysir area (the formal name is **Haukadalur**, the Haukur Valley), are continuously changing. For example, the inflow of water into the pipe depends on the openings of apertures of the fractures through which the water flows. The apertures gradually change because of mineralization, that is, particles or minerals from the hot water gradually fill and seal the fractures, thereby making them narrower and partly closed. Even a small change in the aperture or opening of a fracture has very large effects on its ability to transmit or conduct water. Which brings us to the question: why are there geothermal fields in Iceland, and why in the Geysir area or Haukadalur in particular?

Figure 6.2.5. Very schematic illustration of the conduit, the pipe, of a geyser. The pipe is normally a crude cylinder, into which hot water flows. Here we use the rim of the conduit of Strokkur as a model (Figure 6.2.1a). The geothermal source is shown in a generalized way. Water can flow into the pipe from all directions, not only from below, but also through the walls of the conduit, and mostly through narrow fractures. When conduit is subject to extra loading, such as during earthquakes, stresses concentrate, that is, become raised at and around the conduit/pipe resulting in forming or reopening of fractures, thereby, commonly, increasing the flow of hot water into the conduit at various depths.



gradually change because of mineralization, that is, particles or minerals from the hot water gradually fill and seal the fractures, thereby making them narrower and partly closed. Even a small change in the aperture or opening of a fracture has very large effects on its ability to transmit or conduct water. Which brings us to the question: why are there geothermal fields in Iceland, and why in the Geysir area or Haukadalur in particular?

Geothermal Fields

All geothermal fields, whether they have geysers or not, are related to rain (and in Iceland also snow) migrating to great depths in the crust, becoming hot, and then rising as hot water to the surface. (The general term for condensed atmospheric water - including drizzle, rain, sleet, snow, and hail - falling on Earth's surface is **precipitation**.) Part of the rain and snow that falls on the ground runs off in streams and rivers, but part migrates into the soil and the solid rock below the soil. The water that remains in the soil and uppermost few tens of meters of the solid rock (bedrock) is referred to as groundwater, the water which we see in the open fissures and the lake at Thingvellir. Some water, however, goes deeper, and in areas of volcanic activity, of recent volcanic activity, this water, if it migrates to great depths, becomes geothermal water.

How does the water migrate to great depths? Partly through numerous columnar or cooling fracutres (joints), cavities from expanding gas (vesicles), as we saw in the lava in the walls of Almannagja (Figure 6.15 and 6.1.6) and in the pillow lavas, Much of the water, however, migrates to great depths through earthquake fractures, namely faults. So here is the connection between earthquakes and geysers, as is clear in the Geysir area. Earthquakes generate, or reopen, fractures that increase the flow of geothermal water towards the geysers. Not only that, but new or reopened fractures are very likely to occur exactly at the main geysers. Why? Because these are fed by pipes, cylindrical conduits (Figures 6.2.1a and 6.2.5), and all such holes or cavities tend to **magnify stresses**, that is, concentrate stresses. It follows that when earthquakes occur, stresses become magnified at the geyser pipes (Figure 6.2.5), and new fractures form or older ones become reopened at and around the pipes.

And it does not matter if the earthquake fractures themselves do not reach to the Geysir area. All earthquakes, the quakes themselves, carry stresses (and strains) and these become magnified at the geyser pipes. The new and reopened or reactivated fractures at and around the pipes then contribute to the activities of the geysers in two main ways. First, they normally (but not always) allow more geothermal water to flow into the pipes, thereby refilling them more quickly. Second, they change the fluid-flow paths and commonly make it possible for hotter or warmer water to enter the pipe at a shallower depth, thereby encouraging eruptions in the way we discussed above. The fractures that supply the water into the pipes of erupting geysers, and of hot springs in general, are normally tiny. For example, the volumetric flow rate from Geysir (in other words, the volume of geothermal water flowing form the Great Geysir) is about 1.5 liters per second. A **single fracture** some tens of centimeters long and with an opening or aperture of about one millimeter could theoretically conduct all the water needed for the eruption activity of the Great Geysir.

Fracture reactivation normally results in increased activity of the geysers, but not always. While reactivation generally increases the ease of fluid transport through the rock, that is, the **permeability**, the fluid-flow paths also commonly change. This means that cooler water may be injected into the pipe than before. Alternatively, the hot water necessary to trigger eruptions may no longer be injected at a suitable depth into the pipe to cause boiling but at a greater depth where the pressure is too high for water of the given temperature to boil. And there are various other scenarios possible whereby earthquakes can change the situation at and around the geysers so as to hinder, rather than help, eruptions to occur. In most cases, however, earthquakes increase the chances of eruption in geysers, as is indicated by the following brief account.

Geysers and Earthquakes

The connection between earthquakes and the activities of the erupting springs in the Geysir field is well established. Based on written accounts, the Great Geysir seems to have **become active** following large earthquakes in South Iceland **in the year 1294**. It may of course have been active mach earlier, but these are the oldest written accounts (annals) describing its activity. Even if it was active earlier, it have been dormant for a long period before the large earthquakes in 1294 and thus not mentioned in the annals.

Later strong and major earthquakes in South Iceland have affected the activity of the Great Geysir. For example, Geysir was essentially dormant before the large earthquake in 1896, but following those earthquakes it produced long-lasting eruptions many times each day. The activity then declined over the next decades, while channels (for lowering the water level in the pipe) and the addition of soap to the water in pipe (to make it easier for the water to surface to rupture) where made to keep its eruptions going. However, Geysir had been essentially dormant for decades prior to 2000 earthquakes in South Iceland when, for a while, it became very active. Measurements suggest that in the days following the June 2000 earthquakes, the fountains may have reached the height of over 120 m. The activity soon declined, however, and, as indicated above, eruptions are currently very rare and small.

Figure 6.2.6. Much of the water that goes into an eruption of Strokkur falls again into the bowl around the conduit, as is seen here. Comparatively small amounts of water flows from the geyser, mostly along a human-made stream (Figures 6.2.1a and 6.2.3)

A similar story applies to Strokkur. Like the Great Geysir it is unknown when its eruption activity began. However, following large earthquakes in 1789 - the largest historical earthquakes in South Iceland - its eruptions became very noticeable after having been dormant for a considerable time. Following these earthquakes, Strokkur erupted frequently and with great force; in fact, its eruptions were more spectacular at that time than those of the Great Geysir. The 1896 earthquakes, which renewed the eruption activity of the Great Geysir, had the opposite effect on Strokkur, which became dormant. Strokkur remained largely dormant until a hole, tens of meters deep, was drilled into the bottom of its conduit in 1963. Since then Strokkur has been erupting on average once every 5-10 minutes.

Heat Sources

How is the geothermal water generated in the first place - why does the water become hot? The basic answer is that the **temperature** of the rocks in the Earth's crust everywhere **increases with depth**. ON average, worldwide, the temperature increases with depth by about 25ºC for every kilometer. But the temperature increase with depth in the crust is much faster in active volcanic areas, and at plate boundaries in general. For example, in parts of Germany, in the Rhine Graben, which is volcanically active (although not very active), the temperature at the depth of 1 km may be as high as 40ºC. In areas with great volcanic activity, such as Iceland, the temperature in the volcanic zones is commonly at or above 200ºC at the depth of one kilometer. In fact, that is the definition of a **high-temperature geothermal field** in Iceland: the water temperature is above 200ºC at the depth of 1000 m. By contrast, if the temperature at the depth of 1000 m is below 150ºC, the geothermal field is referred to as a **low-temperature geothermal field**. While there are over 250 low temperature area all over Iceland, there are only 32 well-defined high-temperature fields in the country, one of which is the Geysir area.

So why does the Earth become hotter at depths - what are the heat sources? For the Eath as a whole, the heat source is mainly **radioactive decay** of elements, accumulated when the Earth formed. Heat is generated in the crust though radioactive decay, but flows also from the **outer core**, which is molten, through the mantle (partly as **mantle plumes**, cylindrical conduits of partly molten material, on of which forms Iceland) and the crust to the surface. For volcanic areas such as Iceland, however, the main heat sources are much more local, and mostly **shallow magma chambers** and associated intrusions of the type we saw Stardalur in Esja in Chapt. 4. Thus, most of the high-temperature fields in Iceland are directly related to, and occur inside or close to, active **central volcanoes** - an excellent example being Hengill.

The Geysir or Haukadalur high-temperature field, however, is somewhat special in the sense that no eruption has occurred in the area for the past 10,000 years, so that it is not regarded as volcanically active. Rather, it is located at the **margin** of the active volcanic zone. It presumably was an active volcano, some tens of thousands of years ago, but appears to be either dormant or totally extinct by now. There may of course be some intrusions, cooling magma bodies, at depth below the Geysir area even if no eruption has occurred for the past 10,000 years. It is well known that most magma-filled fractures, dikes, never reach the surface to supply magma to eruptions, and some may have propagated under the Geysir area without erupting. It is, however, more likely that the water in the Geysir area becomes heated up while circulating through deep fractures, many of which may be related to earthquakes. The water can reach depths of several kilometers in such fractures, and then migrate to the surface, where it forms hot springs and geysers. When the water finally reaches the surface in the hot springs and geysers it has been migrating through the rocks for a long time - some geothermal waters in Iceland circulate through the crust for **thousands of years**, while others circulate only for tens to hundreds of years, before they reach the surface as hot springs.

As a final thought on the Geysir area (Great Geysir), it is worth emphasizing again the fracture network that allows the flow of geothermal water through the rocks in most geothermal fields worldwide is **maintained through earthquakes**. When there are no earthquakes in a geothermal field for some time, the fractures and cavities and contacts (between rock layers and units) and tend to become filled with secondary minerals (zeolites, calcite, quartz, etc.) and block the flow. Thus, for a geothermal field to maintain its fluid transport, to maintain its permeability, earthquakes are needed from time to time, and that is exactly what has been observed over centuries in the Geysir area.

STOP 6.3 – *Gulfoss*

The Gullfoss waterfalls are located a 15 min drive from the geyser field, along the Hvítá (White) river. The visitor's center is located at the head of a boardwalk trail that leads to the waterfalls, as well as to an overlook deck on a cliff above them. A splendid view of the mountains across a vast plateau can be enjoyed with a cup of coffee or lunch. Near the visitor's center, one can also pat a few scruffy, short Icelandic horses.

Hvítá has its source in the glacier lake Hvítávatn ('white river lake'), 40 km north of the falls, just under the Langjökull glacier[4]. The river carries glacial sediments, which under sunlight, render the waterfalls golden (thus the name 'golden falls') [4]. These are the most visited and one of the most voluminous waterfalls in Iceland (80-140 m^3/s) [5]. The falls start with a three-step cascade after a sharp left turn of the river, where tourists can appreciate foaming golden water. The river then takes two vertical plunges into a 30-meter deep crevasse and flows through a 2.5 km long steep-walled canyon [5]. The river seems to mysteriously disappear into the abyss, with steam rising high above and creating remarkable rainbows on a sunny day. The Hvítá was a subject of several hydroelectric development plans in the early 20th century when parts of its course were privately owned, but the plans failed to be realized due to the lack of money. Legend has it that Sigríður Tómasdóttir, a daughter of a local farmer who partly owned the falls, walked all the way to Reykjavík over the sharp rocks of Iceland, in order to prevent the destruction of the falls. She supposedly arrived in the capital, her feet bleeding, and threatened to throw herself into the Gullfoss, should the hydroelectric plant be built [4,5].

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[4]Gullfoss – Iceland's most famous waterfall. http://www.gullfoss.org/ <accessed Sep 12, 2010>

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The drive from Geysir to the waterfall Gullfoss along Road 35 is short. The waterfall, which constitutes the eleventh stop (11). The main features to see on the way are the hyaloclastite mountains north of Geysir and, if the visibility is good, the southern part of the ice cap **Langjokull** (the Long Ice Sheet). However, to really enjoy the glaciers of ice caps, one needs to approach them, and such a trip is beyond the present excursion. We therefore drive on to Gullfoss, the most famous waterfall in Iceland (Figure 6.3.1).

Why Has Gullfoss Two Oblique Steps?

Gullfoss (The Golden Waterfall) is in the glacier river **Hvita (White River)**. Part of the beauty of Gullfoss lies in the **two main steps** that constitute the waterfall whose total drop (waterfall height) is 32 m (Figure 6.3.1). These steps make an (acute) angle of about 60º - and thus a larger (obtuse) angle of about 120º (Figure 6.3.2). More specifically, the upper waterfall of step has a direction (trend, strike, azimuth) of about 75º (the angle is always referred to the geographical north), whereas the lower waterfall or step (into the main channel or gorge) has a direction of about 15º. Then main river channel to the southwest of Gullfoss has a general trend or azimuth of about 40º. All these fracture directions are indicated schematically in Figure 6.3.2.

The same main directions are seen at other locations southwest along the main river channel, that is, the main channel itself trends about 40º (always referring to azimuth, that is, east of north) and is dissected by fractures with the two other trends, the one at about 15º and the other at about 75º. These fracture trends are also seen in some of the nearby river channels and all over South Iceland. These directions clearly mark systems or sets earthquake fractures and are easy to explain.

Figure 6.3.1. General overview of the waterfall Gullfoss. View east, the waterfall consists of two main steps, with a total drop (waterfall height) of 32 m. The waterfall is located in the river of Hvita (Figure 6.3.2)

Fractures with the trend of about 40º, that is, trending northeast-southwest, characterize all the volcanic systems in the southern half of Iceland, as well as the West and East Volcanic Zones. As we already know from the Reykjanes Peninsula and Thingvellir the larger fractures with this trend are mostly **normal faults**, and that applies to the fracture forming the main channel southwest of Gullfoss (marked by B in Figure 6.3.2). Thus, the main canyon presumably developed along a normal fault zone, containing also tension fractures, which may originally have been partly similar to Almannagja.

The other two directions, 15º (marked by C in Figure 6.3.2) and 75º (marked by A in Figure 6.3.2) coincide with well-known fracture systems that produce earthquakes in entire South Iceland. These fracture systems are faults that are generated (slip, move) in the same stress field as controls the presently active **South Iceland Seismic Zone**. Everywhere in South Iceland there are faults with these two directions: one is north-northeast (about 15º at Gullfoss but somewhat variable), and the other one is east-northeast (about 75º at Gullfoss but also somewhat variable). In contrast to the normal faults at Thingvellir, such as Almannagja, where the movement of the fault walls is primarily vertical (up and down the fault plane), the movements of the walls of the faults are named **strike-slip faults** - San Andreas in California (the United States) is among the most famous examples of such a fault. Beautiful examples of these types of faults can be seen in some of the hyaloclastite mountains in South Iceland, perhaps the best examples in **Vordufell**, which we will discuss at the twelfth stop later today.

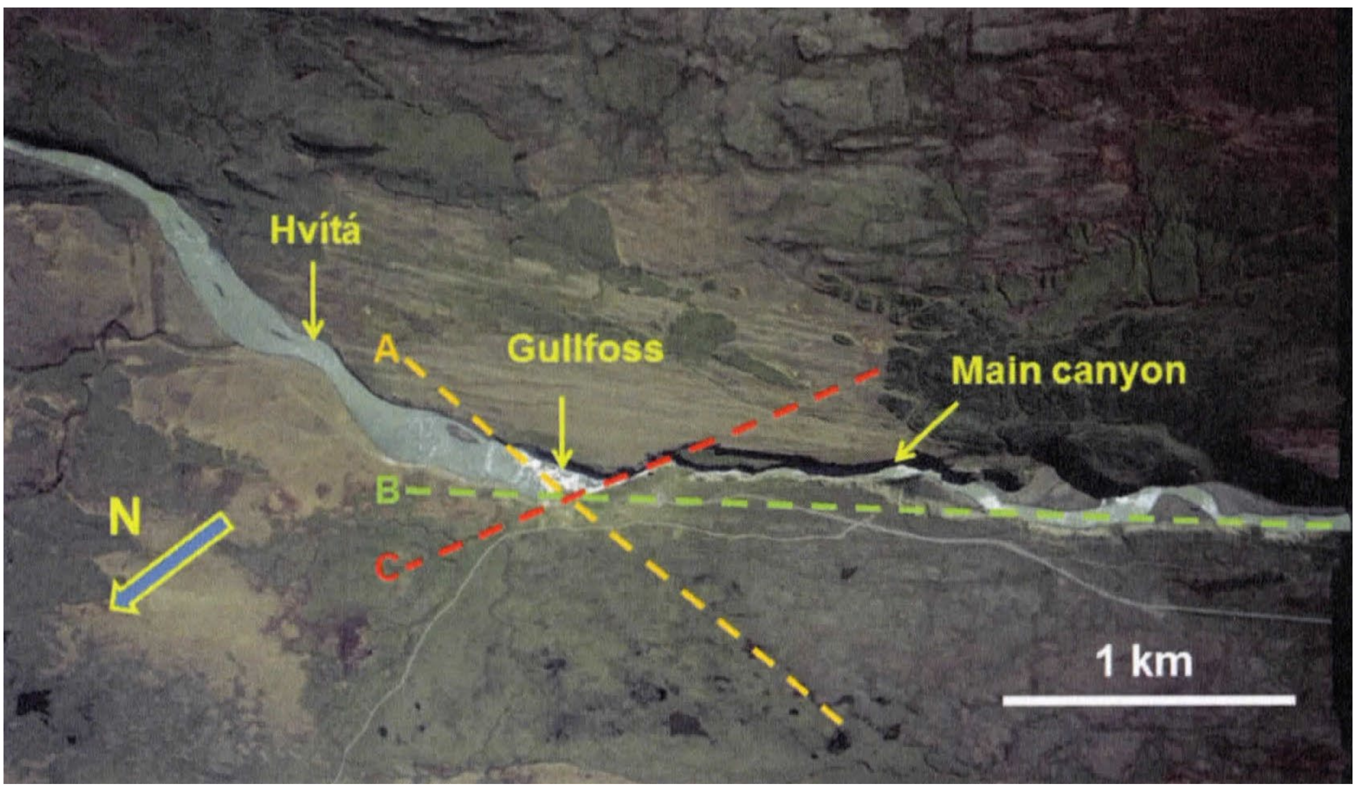


Figure 6.3.2. Aerial view of the canyon of the river Hvita, namely Hvitargljufur, and Gullfoss. The main steps that constitute Gullfoss have very different orientations, and are also different in orientation from the trend of the main canyon itself. All the three orientations are related to earthquake fractures, that is, faults. The main canyon, running parallel with the broken green line B, relates to a normal fault zone, perhaps originally similar to Almannagja, and trends about 40º. The upper step, running roughly parallel with the broken orange line A, is related to a fault, and so is the lower step, which runs parallel with the broken red line C. All the faults A, B, and C are typical for South Iceland. A is called a sinistral or left-lateral strike-slip fault, whereas C is called a dextral or right-lateral strike-slip fault. These technicalities need not concern us here, but are mentioned in you wanted to explore the fault pattern in greater detail - here and in later chapters. The direction of geographic north (N) is indicated with a thick arrow, and so is the scale, that is, the length of 1 km.

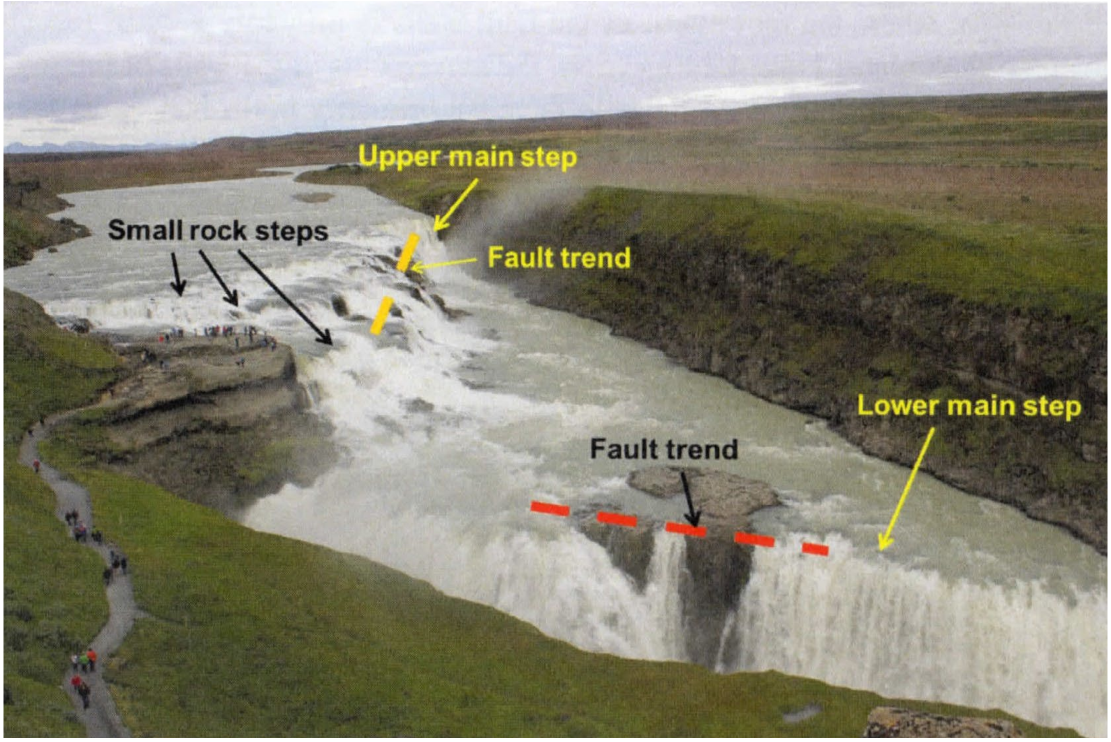


Figure 6.3.3. Details of Gullfoss. View east, the main upper step is composed of several smaller rock steps (forming a series of cascades). By contrast, the lower main step is a single one. The upper step is about 11 m in total, whereas the lower step is about 21 m. Also indicated, crudely, are the two fault trends that contribute to the formation of the oblique steps (Figure 6.3.2)

Figure 6.3.4. The part of the canyon that is parallel with the strike-slip fault, indicated by the red broken line in Figures 6.3.2 and 6.3.3. View south, at its south end, this canyon joins the main canyon at an acute angle of about 35^{o}.

So the earthquake fractures offer zones of weakness in the rocks that the water of the river Hvita can easily erode, forming a major gorge or canyon (Figures 6.3.2, 6.3.3, 6.3.4, and 6.3.5). The main canyon (Figure 6.3.2) follows the more fractured and thus more easily eroded normal fault zone. It is named for the river as Hvitargljufur (White River Canyon) has a maximum depth of about 70 m and a length of some 2500 m. The **zig-zag geometry** of the river channel (Figure 6.3.2), particularly close to and at Gullfoss, is, as discussed, the consequence of the two other main earthquake fault (strike-slip fault) directions (A and C in Figure 6.3.2) that make for fractured rocks and easy erosion.

How Did the Canyon Evolve?

How easily the **erodes** the rocks and expands the canyon depends on the properties of the rock layers themselves (Figure 6.3.1, 6.3.3, and 6.3.6). The lower step in the waterfall, and the associated canyon, is primarily composed of a thick basaltic lava flow with numerous columnar or cooling fractures (Figure 6.3.4 and 6.3.5). The upper step, however, is composed of various rock layers. The layers are primarily of two types: basaltic lava flows with columnar joints, and sedimentary layers. The **lava flows** were formed during interglacial (ice free) periods, whereas the **sediments** (rocks formed through erosion and transport of rock particles) were mostly formed during the glacial (ice) periods of the past several hundred thousand years.

How the rock layers respond to the flowing water and its pressure depends on many factors and is not always easy to forecast. We might think that the 'strong' basaltic lava flows would be very resistant to erosion, but that is not necessarily so. This follows because the vertical cooling fractures, **columnar or cooling joints**, make the lava flows weak in response to water pressure from above. The lava flow resistance to erosion also depends on the rock layer thickness: thin layers with numerous vertical fractures are generally more easily eroded by flowing water than thick layers.

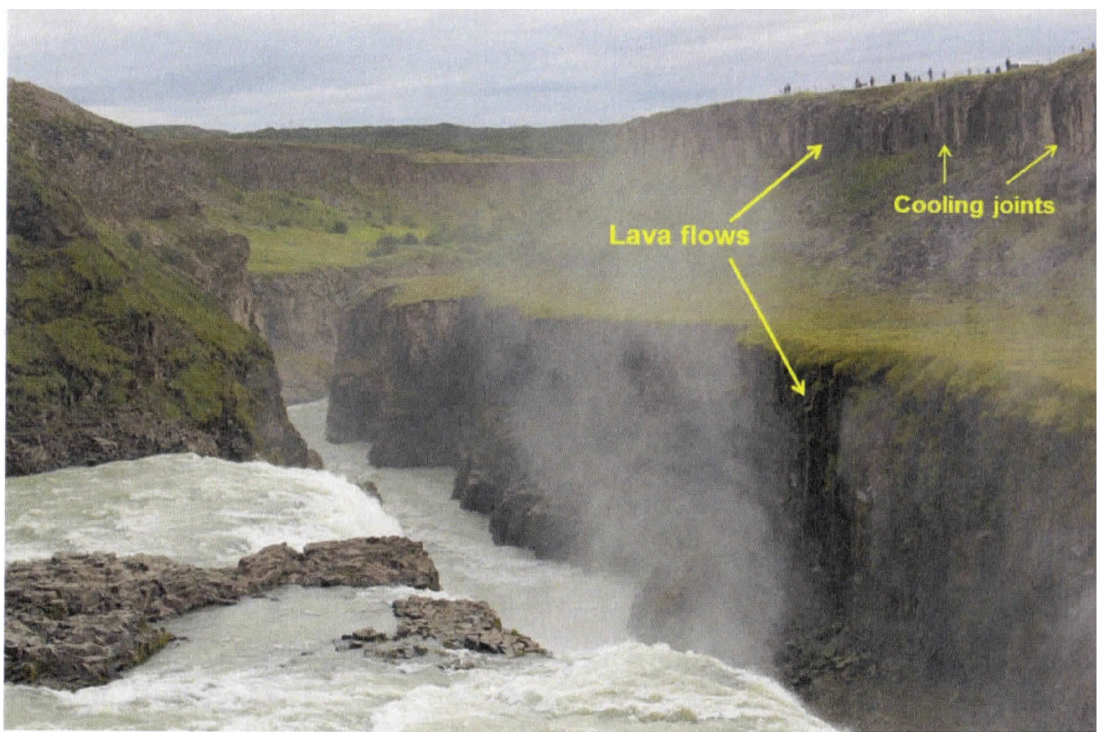


Figure 6.3.5. The same part of the canon as in Figure 6.3.4 but from a different perspective. The canyon is primarily composed of basaltic lava flows, indicated, with numerous vertical columnar joints. These are aa lava flows, and thus formed of a single unit, in contrast with the pahoehoe lava forms seen in the walls of Almannagja, which are composed of many thin flow units. The columnar joints are very well developed in these lava flows and made them comparatively easy to erode by the river.

Some sedimentary rock layers are comparatively strong, whereas others are weak; the strength depends on their grain size and other properties. What we see is that the top lava flow has been largely eroded whereas the topmost sedimentary layer (the one the people are standing on in Figure 6.3.6) is comparatively strong - and thus forming an overhang. The sedimentary layer below is easily eroded, whereas the lowermost sedimentary layer is comparatively strong. Below that layer is again a lava flow that is comparatively resistant to erosion. This layering of the upper step can be seen in the geometry of the waterfall itself. The layering results in the upper step not being a single one, but rather composed of four or five **small rock steps, cascades** (Figures 6.3.1 and 6.3.3), each of which corresponds to one of the layers in Figure 6.3.6.

Gradually, however, the layers become eroded and the canyons become longer. The main canyon, Hvitargljufur (Figures 6.3.4 and 6.3.5) and all the structural features associated with Gullfoss itself as seen today must be formed since the ice caps of the last ice period disappeared. This follows because glaciers always tend to change narrow river canyons and valleys into larger U-shaped valleys. this has not happened here - the canyon walls are clearly vertical (Figures 6.3.4 and 6.3.5) - so that the canyon and the entire associated landscape must be younger than the last glaciers in this part of Iceland. This part of Iceland became permanently ice free some 8-9 thousand years ago. If, as is likely, the entire 2500 m long Hvitargljufur was formed in the past 8-9 thousand years, then the rate of growth or expansion of the canyon must have been, on average, about 30 cm per year. And this is the same rate as Gullfoss itself is moving up the canyon. So every year, on average, the waterfall itself moves some 30 cm to the northeast, that is, further inland.

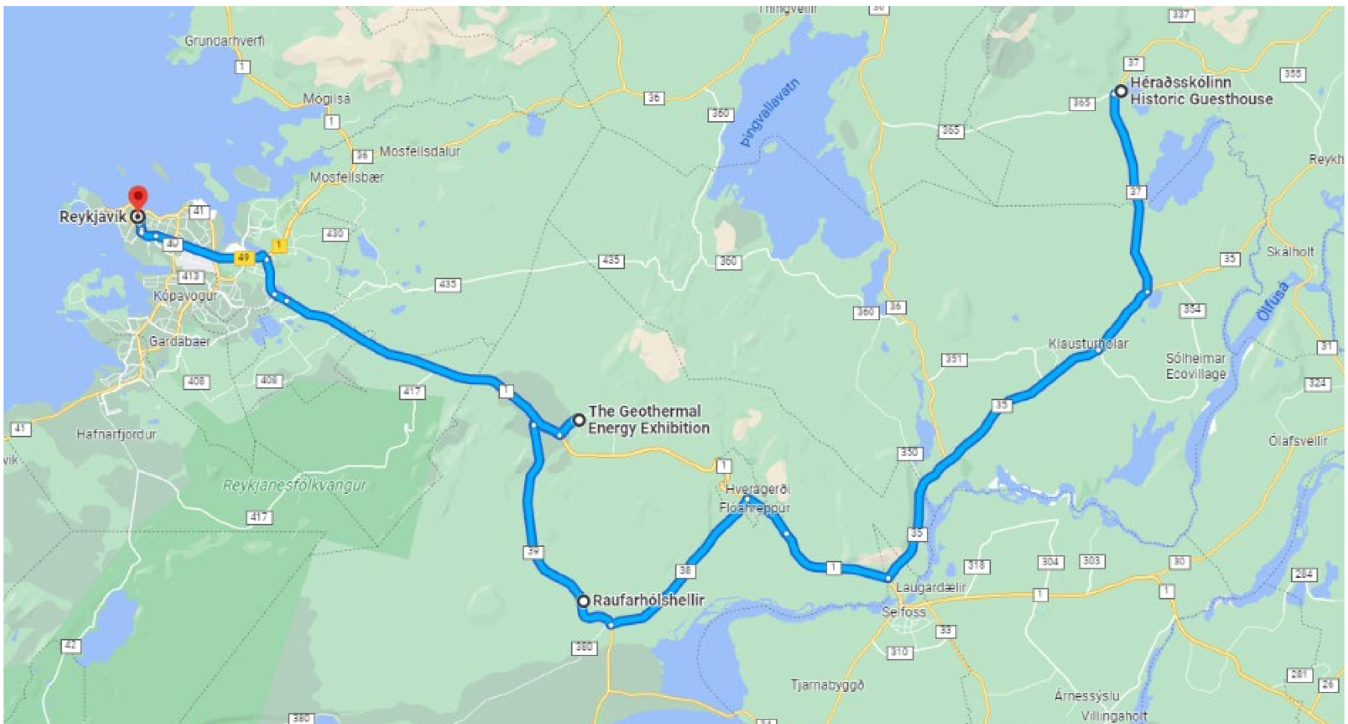
Figure 6.3.6. Gullfoss gradually moves inland as the erosion of the steps that constitute the waterfall continues. View east, the upper step, seen here, is composed of rock layers of different composition and strength. 'Strength' here means resistance to erosion. The lava flows are only moderately resistant to river erosion because they contain numerous fractures, columnar or cooling joints (Figure 6.3.5), that make the rocks more easily eroded, of 'weaker'. The sedimentary layers are of several types. Depending on the grain size and other factors, some of the layers are comparatively strong or resistant to river erosion, whereas others are weaker or less resistant to erosion, as indicated. The different layers are reflected in the small rock steps tha characterize the upper step (Figure 6.3.3).

STOP 6.4 – *Secret Lagoon Hot Springs*

Secret Lagoon natural hot springs are located in the small village called Fludir and are in the Golden Circle area. We have kept it natural and unique for our guests so they can get the true Icelandic feeling. The pool's natural surroundings and steam rising into the air gives the place a magical feeling. The warm water stays at 38-40 Celsius all year. In the whole area there are several geothermal spots and a little Geysir which erupts every 5 minutes, showing off for the guests relaxing in the hot spring. During winter, the northern lights often give a great lightshow above Secret Lagoon. What better way to view the spectacular light show overhead than relaxing in the pool's warm water?

Day 7: Friday, March 10th, 2023 – Raurfarholshellir Lava Tube, Hellisheiði Power Plant, and Reykjavik

7:00AM: Wake-up, have breakfast, pack our things, and load the vans.
8:00AM: Depart for Raurfarholshellir Lava Tube
9:00AM: Take a tour of the Raurfarholshellir Lava Tube (http://thelavatunnel.is/)
11:00AM: Take a tour of the Hellisheiði Power Plant geothermal museum and tour (https://www.on.is/en/geothermal-exhibition/)
12:30PM: Finished tour. Have lunch. (Our guesthouse will provide box lunches)
1:30PM: Arrive in Reykjavik. Check-in at the guesthouse
Guesthouse Aurora (https://www.aurorahouse.is/)
Freyjugata 24, 101 Reykjavík, Iceland
Email: book@aurorahouse.is, Phone: +354 899 1773
Rest of the Day: Enjoy Reykjavik, you are on your own.



Downtown Reykjavik

STOP 7.1 – *Raufarhólshellir Lava Tube*

The Raufarhólshellir lava tube is located about 20 km east of Reykjavík in the Leitahraun lava field on the Reykjanes peninsula. It was formed during a lava flow around 5 ka. The length of the tube is listed at 1,360 meters. About 40 minutes into the tube, we turned around (at a site where a collapse makes the tube veer upwards) because we didn't have enough time. While in the lava tube, Roger talked about bathtub rings. These are horizontal lines left on the wall of the tube. As the flow rate of the lava decreases with time, the top of the lava hardens forming one of these lines. Then the lava level drops, the top layer hardens, and another layer forms. This process continues until the lava has completely receded from the tube. Tim also explained the red color of some of the lava flows: the surface is exposed to the air and oxidizes, then new lava flows over the older surface and picks up oxygen at the interface, generating a red color.

STOP 7.2 – *Hellisheiði Power Plant*

Hellisheiði Power Plant is located on the southern part of the Hengill volcanic system to take advantage of the availability of high-grade heat in the area. The geothermal area includes two main regions, one upper region that is above Hellisskarð pass and a lower elevation region below the pass. The power plant is a combined heat and power plant, providing both heat and electricity to domestic and industrial sectors. When the plant is finished it will generate 300 MW of electrical power and 400 MW of heat, although it currently generates substantially less than that[3]. Drill sites are located in metallic geodesic domes dotting the geothermal regions (fig. 4). The borehole taps into a source of two-phase H_2O, as well as a small percentage of gaseous CO_2 and H_2S. Upon reaching the surface, the mixture enters a silencer to reduce noise and determine the quality of the steam. The steam is then separated from hot water for use in electricity generation. The hot water is then pressurized to generate more steam for electricity. The remaining hot water is used to generate thermal energy for heating purposes.

STOP 7.3 - *Reykjavik*

Reykjavik

Contributed by Miki Nakajima, 2014 Caltech Enrichment Trip Iceland

History

Reykjavik is the capital of Iceland and the largest city in Iceland. Its population is around 120,000, which is ~60% of the Icelandic populations. Reykjavik means "Smokey Bay", which is named after steam rising from geothermal vents [2]. The first permanent Icelander is believed to be Ingólfur Arnarson (AD 871). He decided to live in this location based on a Viking tradition: throwing his high-seat pillars into the ocean when he saw the coastline and settled wherever the pillars came to shore. Until the 18th century, Reykjavik was just a small farmland. In 1752, the king of Denmark donated Reykjavik to Innréttingar Corporation. This movement was led by Skúli Magnússon, as known as "Father of Reykjavik". He started wool factories, which became the major industry in Iceland. The Danish crown abolished the monopoly trading in 1786 and this date is recorded as the foundation of Reykjavik. Reykjavik boomed during World War II when British and American soldiers built camps there. The city kept growing until the financial crisis in 2008.

Geography

During the Ice Age, this region was partly covered by a large glacier and partly by sea water. At the end of the Ice Age, some hills in Reykjavik existed as islands. The sea level during this period could have been 43m (141 ft) higher than the current sea level as indicated by clam shells found in sediments.

Weather

Reykjavik is warm for its high latitude due to the Gulf Stream and Westerlies. The temperature in winter rarely goes below -15°C (5°F). In summer, it is between 10-15°C (50-59°F) (Figure 2). The length of the day can be as short as 4 hours in winter and as long as 21 hours in summer. On average, precipitation occurs 148 days per year.

Energy

Reykjavik is one of the greenest cities in the world. Space heating is provided completely by geothermal energy. Some buses in Reykjavik use public hydrogen fueling stations (The Ecological City Transport System, ECTOS, project, Figure 2).

- ***Perlan* –** The building has been used to store hot water. It has large space for exhibition/dining/shopping. The restaurant on the highest floor has a great view of the city and rotates every two hours. The Saga museum exhibits the early history of Iceland.
- ***Hallgrimskirkja* –** a Lutheran parish church named after a poet in 17's century, Hallgrímur Pétursson. This is the largest church in Iceland (73 meters, 244 ft). State Architect Gudjón Samúelsson's designed this building in 1937 inspired by columnar jointed basalt. The statute is Leif Erikson, who found the North American continent 500 years before Christopher Columbus. The elevator inside of the church brings you up to top of the building where you can enjoy the great view of the city.
- ***Höfdi* –** a house initially built for the French consul Jean-Paul Brillouin in 1909. It is best known as the location for the 1986 Reykjavík Summit meeting of presidents Ronald Reagan and Mikhail Gorbachev to take a step to end the Cold War.
- ***Bæjarins Beztu Pylsur (4 stores in/near Reykjavik)* –** a small chain of popular hot dog stands in Reykjavik. The British newspaper The Guardian selected this chain as the best hot dog stand in Europe in 2006. A number of celebrities have visited, including Bill Clinton, James Hetfield, and Charlie Sheen.
- ***More* –** Tjörnin (lake), Sun Voyager (Viking monument based on the myth), Laugardalur (spa)[9]

References & Further Reading

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[10] *Laugardalur* http://www.holidaym.ru/iceland/gid_laugardalur_valley.php

Reykjavik Maps (these maps are from the Lonely Planet Guidebook, 2022)

Reykjavík

Top Sights
1 Laugardalur ... G4
2 National Museum ... B4
3 Reykjavík Art Museum – Ásmundarsafn ... F4
4 Tjörnin ... C3

Sights
5 Ásgrímur Jónsson Collection ... C4
6 Hljómskálagarður Park ... C4
7 Landakotskirkja ... B3
8 Miklatún Park ... D4
9 Nordic House ... B4
10 Peace Tower ... H1
11 Perlan ... D5
12 Reykjavík Botanic Gardens ... G4
13 Reykjavík University ... D6
14 Reykjavík Zoo & Family Park ... G4
15 Sigurjón Ólafsson Museum ... F2
16 University of Iceland ... B4
17 Viðey Church ... H1
18 Viðeyarstofa ... H1
Wonders of Iceland: Glaciers & Ice Cave ... (see 11)

Activities, Courses & Tours
19 Air Iceland Connect ... C5
Atlantsflug ... (see 19)
Eagle Air Iceland ... (see 19)
20 Laugar Spa ... F3
21 Laugardalslaug ... F3
22 Nauthólsvík Geothermal Beach ... C6
23 Norðurflug ... C5
24 Reykjavík Excursions ... C4
25 Reykjavík Helicopters ... C5
26 Reykjavík Skating Hall ... G4
27 Vesturbæjarlaug ... B3

Sleeping
28 Embassy Apartments ... C3
29 Ferðafélag Íslands ... G5
30 Guesthouse Butterfly ... C3
31 Hilton Reykjavík Nordica ... F4
32 Icelandair Hotel Natura ... C5
33 Oddsson Hostel ... B2
34 Reykjavík Campsite ... G3
35 Reykjavík City Hostel ... G3
36 Three Sisters ... C2

Eating
37 10-11 ... E4
38 Bónus ... E5
39 Café Flóra ... G4
40 Frú Lauga ... F3
41 Kaffihús Vesturbæjar ... B3
42 Le Kock ... G5
43 Nauthóll ... D6
Viðeyarstofa Café ... (see 18)
44 Viðeyjarnaust Day Hut ... G1
Vox ... (see 31)

Drinking & Nightlife
45 Bike Cave ... B5
46 Stúdentakjallarinn ... B4

Entertainment
47 Football Association of Iceland ... F3
Icelandic Dance Company ... (see 50)
48 Laugardalshöllin ... F4
49 Laugardalsvöllur National Stadium ... F3
50 Reykjavík City Theatre ... E5

Shopping
51 Kringlan ... E5

Old Reykjavík

Top Sights
1 i8 ... A1
2 Old Reykjavík ... B4
3 Reykjavík Art Museum – Hafnarhús ... B2
4 Settlement Exhibition ... A4

Sights
5 Aðalstræti 10 ... A3
6 Alþingi ... B4
7 Austurvöllur ... C4
8 Dómkirkja ... C4
9 Gröndalshús ... A2
10 Ingibjörg H Bjarnason Statue ... B4
Jón Sigurðsson Statue ... (see 7)
11 Ráðhús ... A5
12 Reykjavík Museum of Photography ... B1
13 Skúli Magnússon Statue ... A4
14 Volcano House ... A1

Activities, Courses & Tours
15 Free Walking Tour Reykjavík ... D4
16 Grayline Iceland ... D3
17 Haunted Walk ... B2
18 Literary Reykjavík ... B1

Sleeping
19 Apotek ... C4
20 Black Pearl ... A1
21 CenterHótel Plaza ... B3
22 Consulate Hotel Reykjavík ... D3
23 Hótel Borg ... C4
24 Hótel Reykjavík Centrum ... A4
25 Kvosin Downtown ... C5
26 Radisson Blu 1919 ... C3
27 Reykjavík Downtown Hostel ... A1

Eating
28 10-11 ... C3
Apotek ... (see 19)
29 Bæjarins Beztu ... C3
30 Bergsson Mathús ... B5
31 Bio Borgari ... A1
32 Fiskfélagið ... B2
33 Fiskmarkaðurinn ... A3
34 Grillmarkaðurinn ... D4
35 Hornið ... C3
36 Icelandic Fish & Chips ... A1
37 Icelandic Street Food ... C5
38 Jómfrúin ... D4
39 Lobster Hut ... D3
40 Matarkjallarinn ... B2
41 Messinn ... C5
42 Stofan Kaffihús ... B2
43 Tapas Barinn ... A2
44 Torfan Lobsterhouse ... D5

Drinking & Nightlife
45 Frederiksen Ale House ... C2
46 Loftið ... B3
47 Micro Bar ... B2
48 Pablo Diskobar ... B3
49 Paloma ... B2
50 Sæta Svínið Gastropub ... B2
51 Skúli Craft Bar ... B3

Entertainment
52 Gaukurinn ... B2
Húrra ... (see 52)
53 Tjarnarbíó ... A5

Shopping
Akkúrat ... (see 55)
Eymundsson ... (see 19)
54 Fischer ... A2
55 Iceland Design Centre ... B2
56 Kirsuberjatréð ... A2
57 Kogga ... A2
58 Kolaportið Flea Market ... C2
59 Nordic Store ... D4
60 Vínbúðin – Austurstræti ... C3

Highlight - Best Hot Dog in Europe?

The Bæjarins beztu pylsur hot dog stand is not only the most famous hot dog stand in Reykjavik, and not only the most famous hot dog stand in Iceland, but in 2006, a British newspaper named it the best hot dog stand in Europe! Former U.S. President Bill Clinton has eaten here. The secret's in the sauce, apparently, a confection called remoladi, which tops off the usual staples of fried onions, raw onions, steaming dog, ketchup and mustard.

There is a cool local flea market close to the hot dog stand too.

Old Harbour

Old Harbour

Top Sights
1 Old Harbour C5

Sights
2 Aurora Reykjavík A4
Kling & Bang .... (see 7)
3 Nýló D2
4 Omnom Chocolate D1
5 Reykjavík Maritime Museum A4
6 Saga Museum A4
7 Stúdíó Ólafur Eliasson D2
8 Whales of Iceland B2

Activities, Courses & Tours
Bryggjan Brugghús .... (see 33)
9 Dive.is D1
10 Elding Adventures at Sea C5
11 Reykjavík Bike Tours C4
12 Reykjavík By Boat C5
13 Reykjavík Sailors B4
14 Reykjavík Sea Adventures C5
15 Special Tours C5
16 Whale Safari C5

Sleeping
17 Icelandair Hotel Reykjavík Marina B5
18 Reykjavík Marina Residence B5

Eating
19 17 Sortir A3
20 Bergsson RE C3
21 Coocoo's Nest B3
22 Fish & Chips B4
23 Flatey Pizza A3
24 Forréttabarinn B5
25 Grandi Mathöll C3
26 Hamborgara Búllan B5
27 Kaffivagninn B3
28 Lamb A4
29 Matur og Drykkur A4
30 Messinn Granda B3
31 Sægreifinn C5
Salt .... (see 31)
32 Valdís A3

Drinking & Nightlife
33 Bryggjan Brugghús A4
Marshall .... (see 3)
34 Slippbarinn B5

Entertainment
35 Cinema at Old Harbour Village No 2 .... C5

Shopping
36 Farmers & Friends D1
37 Jen's B3
38 Kjötkompaní B3
39 Steinunn A3

Highlight - Iceland Phallological Museum

The Icelandic Phallological Museum, located in Reykjavík, Iceland, houses the world's largest display of penises and penile parts. As of early 2020 the museum moved to a new location in Hafnartorg, three times the size of the previous one, and the collection holds well over 300 penises from more than 100 species of mammal. Also, the museum holds 22 penises from creatures and peoples of Icelandic folklore.

This is VERY unique!

Laugavegur

Top Sights

1 Culture House ... D3
2 Hallgrímskirkja ... F8
3 Harpa ... D1
4 National Gallery of Iceland ... A6

Sights

5 Árnarhóll ... C3
6 Einar Jónsson Museum ... E8
7 Einar Jónsson Sculpture Garden ... E8
8 Fríkirkjan í Reykjavík ... A6
9 Hverfisgallerí ... C3
10 Leifur Eiríksson Statue ... E7
11 Sun Voyager ... G3

Activities, Courses & Tours

12 Borgarhjól ... E4
13 Mink Viking ... D4
14 Sterna ... D1
15 TukTuk Tours ... D1

Sleeping

16 101 Hostel ... G6
17 101 Hotel ... C3
18 Baldursbrá Guesthouse ... B8
19 Canopy by Hilton ... D4
20 Castle House Apartments ... A6
21 CenterHótel Arnarhvoll ... D2
22 CenterHótel Þingholt ... C4
23 Forsæla Apartmenthouse ... F6
24 Galtafell Guesthouse ... B8
25 Hótel Frón ... E5
26 Hótel Holt ... C7
27 Hótel Leifur Eiríksson ... E7
28 Hótel Óðinsvé ... D6
29 Loft Hostel ... C4
30 Nest Apartments ... F7
31 Óðinn ... D6
32 REY Apartments ... E5
33 Reykjavík Residence ... E4
34 Room With A View ... D5
35 Sandhotel ... F5
36 Sunna Guesthouse ... E7

Eating

37 Austur Indíafélagið ... F5
Bakarí Sandholt ... (see 35)
38 Block ... C5
39 Bónus ... G6
40 Bónus ... C5
41 Brauð & Co ... F6
42 Dill ... C3
43 Garðurinn ... E5
Geiri Smart ... (see 19)
Gló ... (see 89)
44 Grái Kötturinn ... D4
45 Hamborgara Búllan ... C4
Holt Restaurant ... (see 26)
46 Joylato ... D6
Julia & Julia ... (see 1)
47 Kolabrautin ... C1
48 Krambúð ... E7
49 Krua Thai ... D6
50 Lemon ... G6
Mat Bar ... (see 19)
Nostra ... (see 58)
51 Ostabúðin ... C4
Public House ... (see 25)
52 ROK ... E7
Snaps ... (see 28)
53 Súpa ... D5
54 Sushi Social ... C4
55 Þrír Frakkar ... C7
56 Torfan Lobsterhouse ... B4
57 Vitabar ... G7

Drinking & Nightlife

58 Artson ... G6
59 Bar Ananas ... E5
60 Bastard ... D5
Bravó ... (see 68)
61 Den Danske Kro ... C4
62 Dillon ... E5
63 Kaffi Mokka ... D4
64 Kaffi Vínyl ... G5
65 Kaffibarinn ... D5
66 Kaffifélagið ... C5
67 Kaldi ... E5
68 Kiki ... E5
69 Mikkeller & Friends ... C3
70 Petersen Svítan ... C4
71 Port 9 ... F4
72 Prikið ... C4
73 Reykjavík Roasters ... F6
74 Spánski ... C4
75 Veður ... E5

Entertainment

76 Bíó Paradís ... F5
77 Mengi ... D5
78 National Theatre ... D3

Shopping

79 12 Tónar ... D5
80 66° North ... C4
81 Aurum ... C4
82 Blue Lagoon Shop ... D4
83 Cintamani ... C4
84 Dogma ... F5
85 Eymundsson ... D5
86 Fjallakofinn ... D4
87 Fóa ... C4
88 Handknitting Association of Iceland ... D6
89 Heilsuhúsið ... E5
90 Hrím ... E5
91 Húrra Reykjavík ... G5
92 Kiosk ... C4
93 Kron ... G6
94 KronKron ... G6
Mál og Menning ... (see 34)
95 Ófeigur Björnsson ... D4
96 Orrifinn ... D5
97 Rammagerðin ... D5
98 Reykjavík Foto ... G5
99 Reykjavík Record Shop ... E5
100 Skúmaskot ... D6
101 Spúútnik ... E5
102 Stígur ... D5
103 Tulipop ... E7

Day 8: Saturday, March 11th, 2023 – Free Day in Reykjavik

All day – This is a free day, there is a lot to do in the city, enjoy!

6:00 PM: Group Dinner, location to be determined.

Day 9: Sunday, March 12th, 2023 – Reykjavik, Blue Lagoon, and return home

Morning: Wake-up and have breakfast (provided by the guesthouse), hang out in Reykjavik

11:00: Check out of the guesthouse, load the bus, head to Blue Lagoon

12:00: Lunch and spa at Blue Lagoon (you have to pay for this on your own, it's about $55 each)

2:30PM: Into the bus and head to the airport

3:00PM: Arrive at the airport

4:50PM: Scheduled Departure Icelandair Flight 645

7:10PM: Scheduled Arrival in Dulles, Washington DC

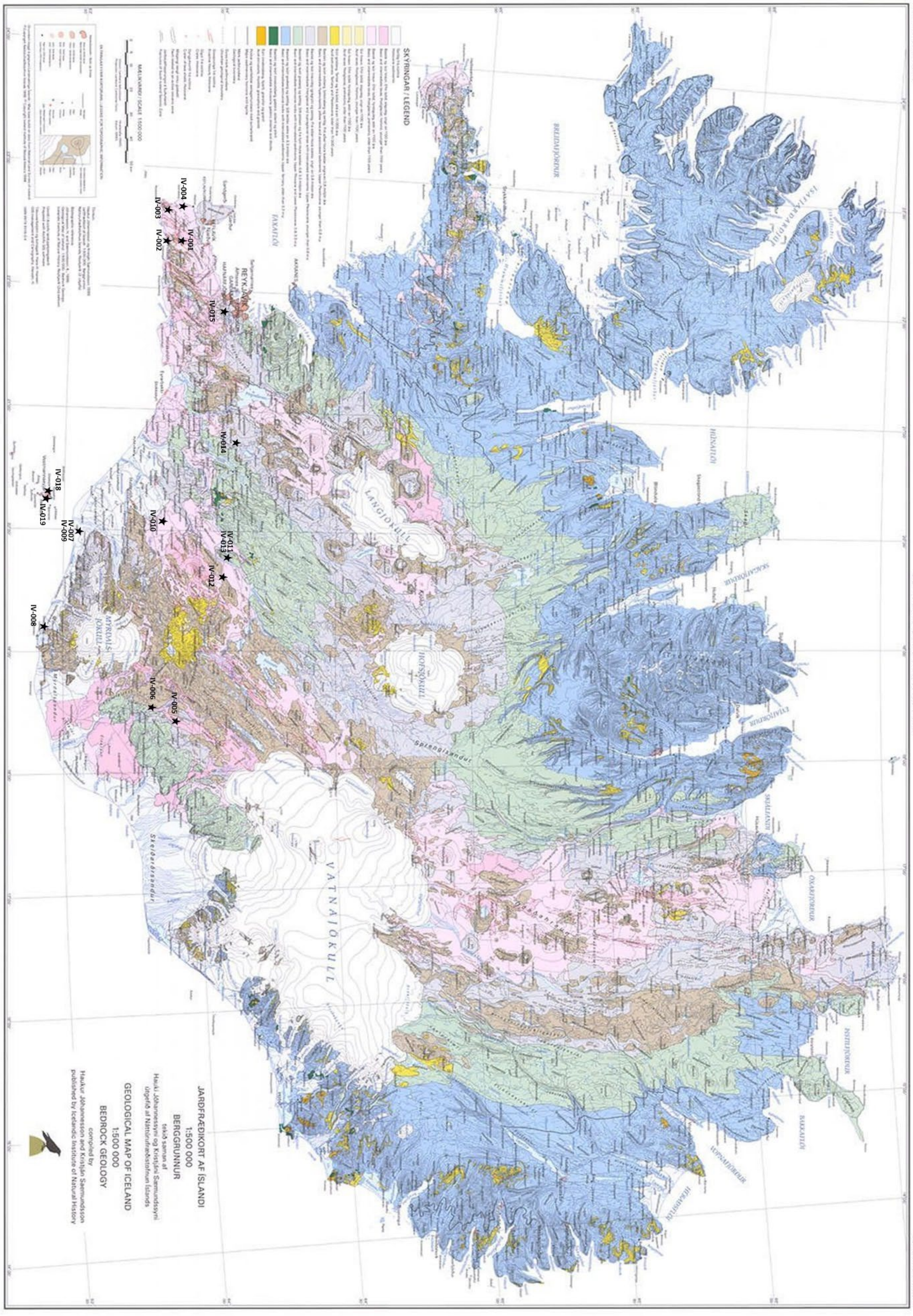
YOU WILL NEED TO GET YOURSELF HOME FROM DULLES AIRPORT

STOP 9.1 – *Blue Lagoon Geothermal Spa*

• ***The Blue Lagoon geothermal spa*** **–** the largest outdoor spa (5000 m2) and one of the most visited attractions in Iceland, located 20 minutes from Keflavik airport and 40 minutes from Reykjavik by car. It is an artificial lagoon and is fed by the water output of the geothermal power plant, Svartsengi. The water is rich in minerals (e.g. silica and sulfur) and the water temperature is controlled to 37-39°C (98-102°F). Facility hours: 9am-9pm, price: 40 EUR. Most crowded between 10am-2pm.

The Blue Lagoon, or "Bláa lónið", is one of the most popular attractions in Iceland. It is a geothermal spa located in a lava field just off the road between Keflavík and Grindavík. It is fed by the wastewater of the nearby geothermal power plant, Svartsengi. The six million liters of milky-blue water in the lagoon is 37-39° C (98-102° F) and is rich in silica and sulfur, along with the natural green blue algae. Tourists all around the world are attracted to Blue Lagoon for its proved healing power of skin diseases and the enhancement of wellness and beauty of the human body. The entrance fee is ~$55 for adults.

GEOLOGIC MAP OF ICELAND



GEOLOGIC SAMPLES IN THE PITT-JOHNSTOWN COLLECTION

<table>
<tr><th>Number</th><th>Sample</th><th colspan="6">Description & Location</th></tr>
<tr><td>IV-001</td><td>Vesicular Basalt</td><td colspan="6">7 km. S of Airport Highway about 6 km N of Grindavik (SW of Reykjavik</td></tr>
<tr><td>IV-002</td><td>Vesicular Olivine Basalt (picrite)</td><td colspan="6">approx. 2.5 km E of Grindavik</td></tr>
<tr><td>IV-003</td><td>Scoria (with phenocryst)</td><td colspan="6">From small cone 2 km E of road N to airport</td></tr>
<tr><td>IV-004</td><td>Vesicular Grey Basalt</td><td colspan="6">Top of Larghill Shield Volcano, This flow apparently extended from an upwelling which spread lava in all driections forming a shield. This, according to Iceland geologists, is the TYPE shield volcano which is very different in construction from Mauna Loa on Hawaii</td></tr>
<tr><td>IV-005</td><td>Porphyritic Tholeiite</td><td colspan="6">A marginal facies of the Laki Flow of 1783. Lakagigar Eruption of 1783. This eruption lasted about 4 months and disgorged about 12.3 km^3 of lava covering 565 km^2 to qualify as the world's largest modern lava flow.</td></tr>
<tr><td>IV-006</td><td>Transition Alkali Basalt</td><td colspan="6">Hrifunes, Skafta River</td></tr>
<tr><td>IV-007</td><td>Porphyritic Ankaramite (Dark green facies)</td><td colspan="6">Quarry at roadside about 5 km west of Holt farm (45 km West of Vik)</td></tr>
<tr><td>IV-008</td><td>Palaginite Breccia</td><td colspan="6">6 km west of Vik</td></tr>
<tr><td>IV-009</td><td>Porphyritic Ankaramite (light green facies)</td><td colspan="6">Quarry at roadside about 5 km west of Holt farm (45 km West of Vik) same locality as IV-007</td></tr>
<tr><td>IV-010</td><td>Basalt</td><td colspan="6">One of the Southern Hekla Flow, NE of Ginnarsholt</td></tr>
<tr><td>IV-011</td><td>Porphyritic Tholeiite</td><td colspan="6">(large plagioclase phenocrysts) 4 km south of new power station on Pjorsa River, NW of Hekla</td></tr>
<tr><td>IV-012</td><td>Andesite</td><td colspan="6">1970 Hekla andesite flow, 9km east of power station</td></tr>
<tr><td>IV-013</td><td>Pumice</td><td colspan="6">Sorry they are so small, but that is the way it is. We expected to find larger fragments but the locality turned out to be heaps of quite fine pieces. Collected just west of power station but found all over lower flanks of Hekla on the NE</td></tr>
<tr><td rowspan="7">IV-014</td><td rowspan="7">Tjnarkolar Lava</td><td colspan="6">Sample from outcrop 250 m west of southernmost Tjarnarkolar crater, Grimsnes area</td></tr>
<tr><td>SiO_2</td><td>47.39</td><td>MgO</td><td>8.63</td><td>TiO_2</td><td>1.80</td></tr>
<tr><td>Al_2O_3</td><td>15.08</td><td>CaO</td><td>12.49</td><td>H_2O^+</td><td>0.11</td></tr>
<tr><td>Fe_2O_3</td><td>1.53</td><td>Na_2O</td><td>1.99</td><td>H_2O^-</td><td>0.04</td></tr>
<tr><td>FeO</td><td>10.3</td><td>K_2O</td><td>0.32</td><td></td><td></td></tr>
<tr><td>MnO</td><td>0.18</td><td>P_2O_5</td><td>0.22</td><td>Total</td><td>100.08</td></tr>
<tr><td colspan="6">Ref. Jakobsson, 1966 Grimsnes Lavas p. 18</td></tr>
<tr><td>IV-015</td><td>Gray Basalt, porphyritic</td><td colspan="6">Quarry 5km south of downtown Reykjavik</td></tr>
<tr><td>IV-016</td><td>Zeolites</td><td colspan="6">Vesicular basalt (exact location unknown)</td></tr>
<tr><td>IV-017</td><td>Siliceous Sinter</td><td colspan="6">Hot springs, Iceland (exact location unknown)</td></tr>
<tr><td>IV-018</td><td>Porphyritic Basalt, vesicular with phenocrysts of sanidine?</td><td colspan="6">Golf Course on Vestmannaeyjabaer Island, (63° 26' 16.86" N, 20° 18' 05.59" W) From Spring break Trip in 2016</td></tr>
<tr><td>IV-019</td><td>Basalt</td><td colspan="6">vesicular, looks like a relatively fresh flow. From the summit of Eldfell, (63° 25' 55.52" N, 20° 14' 58.76" W) From Spring break Trip in 2016</td></tr>
</table>

Number	Sample	Description & Location
IV-020		
IV-021		
IV-022		
IV-023		
IV-024		
IV-025		
IV-026		
IV-027		
IV-028		
IV-029		

Number	Sample	Description & Location
IV-030		
IV-031		
IV-032		
IV-033		
IV-034		
IV-035		
IV-036		
IV-037		
IV-038		
IV-039		

GLOSSARY OF GEOLOGIC TERMS

Most of the definitions were taken from Wikipedia or random locations on the internet.

Aa: Hawaiian word used to describe a lava flow whose surface is broken into rough angular fragments.
Accessory: A mineral whose presence in a rock is not essential to the proper classification of the rock.
Accidental: Pyroclastic rocks that are formed from fragments of non-volcanic rocks or from volcanic rocks not related to the erupting volcano.
Accretionary Lava Ball: A rounded mass, ranging in diameter from a few centimeters to several meters, [carried] on the surface of a lava flow (e.g., 'a'a) or on cinder-cone slopes [and formed] by the molding of viscous lava around a core of already solidified lava.
Acid: A descriptive term applied to igneous rocks with more than 60% silica (SiO2).
Active Volcano: A volcano that is erupting. Also, a volcano that is not presently erupting, but that has erupted within historical time and is considered likely to do so in the future.
Agglutinate: A pyroclastic deposit consisting of an accumulation of originally plastic ejecta and formed by the coherence of the fragments upon solidification.
Alkalic: Rocks which contain above average amounts of sodium and/or potassium for the group of rocks for which it belongs. For example, the basalts of the capping stage of Hawaiian volcanoes are alkalic. They contain more sodium and/or potassium than the shield-building basalts that make the bulk of the volcano.
Andesite: Volcanic rock (or lava) characteristically medium dark in color and containing 54 to 62 percent silica and moderate amounts of iron and magnesium.
Ankaramite: is volcanic rock type of mafic composition. It is a dark porphyritic variety of basanite containing abundant pyroxene and olivine phenocrysts. It contains minor amounts of plagioclase and accessory biotite, apatite, and iron oxides. An ankaramite is a pyroxene-rich basalt and is the pyroxene equivalent of a picrite.
Ash: Fine particles of pulverized rock blown from an explosion vent. Measuring less than 1/10 inch in diameter, ash may be either solid or molten when first erupted. By far the most common variety is vitric ash (glassy particles formed by gas bubbles bursting through liquid magma).
Ashfall (Airfall): Volcanic ash that has fallen through the air from an eruption cloud. A deposit so formed is usually well sorted and layered.
Ash Flow: A turbulent mixture of gas and rock fragments, most of which are ash-sized particles, ejected violently from a crater or fissure. The mass of pyroclastics is normally of very high temperature and moves rapidly down the slopes or even along a level surface.
Asthenosphere: The shell within the earth, some tens of kilometers below the surface and of undefined thickness, which is a shell of weakness where plastic movements take place to permit pressure adjustments.
Aquifer: A body of rock that contains significant quantities of water that can be tapped by wells or springs.
Avalanche: A large mass of material or mixtures of material falling or sliding rapidly under the force of gravity. Avalanches often are classified by their content, such as snow, ice, soil, or rock avalanches. A mixture of these materials is a debris avalanche.
Basalt: Volcanic rock (or lava) that characteristically is dark in color, contains 45% to 54% silica, and generally is rich in iron and magnesium.
Basement: The undifferentiated rocks that underlie the rocks of interest in an area.
Basic: A descriptive term applied to igneous rocks (basalt and gabbro) with silica (SiO2) between 44% and 52%.
Bench: The unstable, newly-formed front of a lava delta.

Blister: A swelling of the crust of a lava flow formed by the puffing-up of gas or vapor beneath the flow. Blisters are about 1 meter in diameter and hollow.

Block: Angular chunk of solid rock ejected during an eruption.

Bomb: Fragment of molten or semi-molten rock, 2 1/2 inches to many feet in diameter, which is blown out during an eruption. Because of their plastic condition, bombs are often modified in shape during their flight or upon impact.

Caldera: The Spanish word for cauldron, a basin-shaped volcanic depression; by definition, at least a mile in diameter. Such large depressions are typically formed by the subsidence of volcanoes. Crater Lake occupies the best-known caldera in the Cascades.

Capping Stage: Refers to a stage in the evolution of a typical Hawaiian volcano during which alkalic, basalt, and related rocks build a steeply, sloping cap on the main shield of the volcano. Eruptions are less frequent, but more explosive. The summit caldera may be buried.

Central Vent: A central vent is an opening at the Earth's surface of a volcanic conduit of cylindrical or pipe-like form.

Central Volcano: A volcano constructed by the ejection of debris and lava flows from a central point, forming a more or less symmetrical volcano.

Cinder Cone: A volcanic cone built entirely of loose fragmented material (pyroclastics.)

Cirque: A steep-walled horseshoe-shaped recess high on a mountain that is formed by glacial erosion.

Cleavage: The breaking of a mineral along crystallographic weak lattice planes that reflect weaknesses in a crystal structure.

Composite Volcano: A steep volcanic cone built by both lava flows and pyroclastic eruptions.

Compound Volcano: A volcano that consists of a complex of two or more vents, or a volcano that has an associated volcanic dome, either in its crater or on its flanks. Examples are Vesuvius and Mont Pelee.

Compression Waves: Earthquake waves that move like a slinky. As the wave moves to the left, for example, it expands and compresses in the same direction as it moves.

Conduit: A passage followed by magma in a volcano.

Continental Crust: Solid, outer layers of the earth, including the rocks of the continents.

Continental Drift: The theory that horizontal movement of the earth's surface causes slow, relative movements of the continents toward or away from one another.

Country Rocks: The rock intruded by and surrounding an igneous intrusion.

Crater: A steep-sided, usually circular depression formed by either explosion or collapse at a volcanic vent.

Craton: A part of the earth's crust that has attained stability and has been little deformed for a prolonged period.

Curtain of Fire: A row of coalescing lava fountains along a fissure; a typical feature of a Hawaiian-type eruption.

Dacite: Volcanic rock (or lava) that characteristically is light in color and contains 62% to 69% silica and moderate a mounts of sodium and potassium.

Debris Avalanche: A rapid and unusually sudden sliding or flowage of unsorted masses of rock and other material. As applied to the major avalanche involved in the eruption of Mount St. Helens, a rapid mass movement that included fragmented cold and hot volcanic rock, water, snow, glacier ice, trees, and some hot pyroclastic material. Most of the May 18, 1980 deposits in the upper valley of the North Fork Toutle River and in the vicinity of Spirit Lake are from the debris avalanche.

Debris Flow: A mixture of water-saturated rock debris that flows downslope under the force of gravity (also called lahar or mudflow).

Detachment Plane: The surface along which a landslide disconnects from its original position.

Diatreme: A breccia filled volcanic pipe that was formed by a gaseous explosion.
Dike: A sheet-like body of igneous rock that cuts across layering or contacts in the rock into which it intrudes.
Dome: A steep-sided mass of viscous (doughy) lava extruded from a volcanic vent (often circular in plane view) and spiny, rounded, or flat on top. Its surface is often rough and blocky as a result of fragmentation of the cooler, outer crust during growth of the dome.
Dormant Volcano: Literally, "sleeping." The term is used to describe a volcano which is presently inactive but which may erupt again. Most of the major Cascade volcanoes are believed to be dormant rather than extinct.
Drainage Basin: The area of land drained by a river system.
Ejecta: Material that is thrown out by a volcano, including pyroclastic material (tephra) and lava bombs.
En Echelon: Set of geologic features that are in an overlapping or a staggered arrangement (e.g., faults). Each is relatively short, but collectively they form a linear zone in which the strike of the individual features is oblique to that of the zone as a whole.
Episode: An episode is a volcanic event that is distinguished by its duration or style.
Eruption: The process by which solid, liquid, and gaseous materials are ejected into the earth's atmosphere and onto the earth's surface by volcanic activity. Eruptions range from the quiet overflow of liquid rock to the tremendously violent expulsion of pyroclastics.
Eruption Cloud: The column of gases, ash, and larger rock fragments rising from a crater or other vent. If it is of sufficient volume and velocity, this gaseous column may reach many miles into the stratosphere, where high winds will carry it long distances.
Eruptive Vent: The opening through which volcanic material is emitted.
Evacuate: Temporarily move people away from possible danger.
Extinct Volcano: A volcano that is not presently erupting and is not likely to do so for a very long time in the future.
Extrusion: The emission of magmatic material at the earth's surface. Also, the structure or form produced by the process (e.g., a lava flow, volcanic dome, or certain pyroclastic rocks).
Fault: A crack or fracture in the earth's surface. Movement along the fault can cause earthquakes or--in the process of mountain-building--can release underlying magma and permit it to rise to the surface.
Fault Scarp A steep slope or cliff formed directly by movement along a fault and representing the exposed surface of the fault before modification by erosion and weathering.
Felsic: An igneous rock having abundant light-colored minerals.
Fire fountain: See also: lava fountain.
Fissures: Elongated fractures or cracks on the slopes of a volcano. Fissure eruptions typically produce liquid flows, but pyroclastics may also be ejected.
Flank Eruption: An eruption from the side of a volcano (in contrast to a summit eruption.)
Fluvial: Produced by the action of flowing water.
Formation: A body of rock identified by lithic characteristics and stratigraphic position and is map able at the earth's surface or traceable in the subsurface.
Fracture: The manner of breaking due to intense folding or faulting.
Fumarole: A vent or opening through which issue steam, hydrogen sulfide, or other gases. The craters of many dormant volcanoes contain active fumaroles.
Geothermal Energy: Energy derived from the internal heat of the earth.
Geothermal Power: Power generated by using the heat energy of the earth.
Graben: An elongate crustal block that is relatively depressed (down dropped) between two fault systems.

Guyot: A type of seamount that has a platform top. Named for a nineteenth-century Swiss-American geologist.

Hardness: The resistance of a mineral to scratching.

Harmonic Tremor: A continuous release of seismic energy typically associated with the underground movement of magma. It contrasts distinctly with the sudden release and rapid decrease of seismic energy associated with the more common type of earthquake caused by slippage along a fault.

Heat transfer: Movement of heat from one place to another.

Heterolithologic: Material is made up of a heterogeneous mix of different rock types. Instead of being composed on one rock type, it is composed of fragments of many different rocks.

Holocene: The time period from 10,000 years ago to the present. Also, the rocks and deposits of that age.

Horizontal Blast: An explosive eruption in which the resultant cloud of hot ash and other material moves laterally rather than upward.

Horst: A block of the earth's crust, generally long compared to its width that has been uplifted along faults relative to the rocks on either side.

Hot Spot: A volcanic center, 60 to 120 miles (100 to 200 km) across and persistent for at least a few tens of million of years, that is thought to be the surface expression of a persistent rising plume of hot mantle material. Hot spots are not linked to arcs and may not be associated with ocean ridges.

Hot-spot Volcanoes: Volcanoes related to a persistent heat source in the mantle.

Hyaloclastite: A deposit formed by the flowing or intrusion of lava or magma into water, ice, or water-saturated sediment and its consequent granulation or shattering into small angular fragments.

Hydrothermal Reservoir: An underground zone of porous rock containing hot water.

Hypabyssal: A relatively shallow intrusive consisting of magma or the resulting solidified rock.

Hypocenter: The place on a buried fault where an earthquake occurs.

Ignimbrite: The rock formed by the widespread deposition and consolidation of ash flows and nuees ardentes. The term was originally applied only to densely welded deposits but now includes non-welded deposits.

Intensity: A measure of the effects of an earthquake at a particular place. Intensity depends not only on the magnitude of the earthquake, but also on the distance from the epicenter and the local geology.

Intermediate: A descriptive term applied to igneous rocks that are transitional between basic and acidic with silica ($SiO2$) between 54% and 65%.

Intrusion: The process of emplacement of magma in pre-existing rock.

Intrusive: A term that refers to igneous rock mass formed at depth within surrounding rock.

Joint: A surface of fracture in a rock.

Jökulhlaup: is a type of glacial outburst flood. It is an Icelandic term that has been adopted in glaciological terminology in many languages. It originally referred to the well-known subglacial outburst floods from Vatnajökull, Iceland, which are triggered by geothermal heating and occasionally by a volcanic subglacial eruption, but it is now used to describe any large and abrupt release of water from a subglacial or proglacial lake/reservoir.

Juvenile: Pyroclastic material derived directly from magma reaching the surface. Also a term used to describe CM's approach to teaching Geology and life in general.

Kame: a steep-sided mound of sand and gravel deposited by a melting ice sheet.

Kipuka: An area surrounded by a lava flow.

Laccolith: A body of igneous rocks with a flat bottom and domed top. It is parallel to the layers above and below it.

Lahar: A torrential flow of water-saturated volcanic debris down the slope of a volcano in response to gravity. A type of mudflow.

Landsat: A series of unmanned satellites orbiting at about 706 km (438 miles) above the surface of the earth. The satellites carry cameras similar to video cameras and take images or pictures showing features as small as 30 m or 80 m wide, depending on which camera is used.

Lapilli: Literally, "little stones." Round to angular rock fragments, measuring 1/10 inch to 2 1/2 inches in diameter, which may be ejected in either a solid or a molten state.

Lava: Magma which has reached the surface through a volcanic eruption. The term is most commonly applied to streams of liquid rock that flow from a crater or fissure. It also refers to cooled and solidified rock.

Lava Dome: Mass of lava, created by many individual flows, that has built a dome-shaped pile of lava.

Lava Flow: An outpouring of lava onto the land surface from a vent or fissure. Also, a solidified tongue like or sheet-like body formed by outpouring lava.

Lava Fountain: A rhythmic vertical fountain like eruption of lava.

Lava Lake (Pond): A lake of molten lava, usually basaltic, contained in a vent, crater, or broad depression of a shield volcano.

Lava Shields: A shield volcano made of basaltic lava.

Lava Tube: A tunnel formed when the surface of a lava flow cools and solidifies while the still-molten interior flows through and drains away.

Limu O Pele (Pele Seaweed): Delicate, translucent sheets of spatter filled with tiny glass bubbles.

Lithic: Of or pertaining to stone.

Lithosphere: The rigid crust and uppermost mantle of the earth. Thickness is on the order of 60 miles (100 km). Stronger than the underlying asthenosphere.

Luster: The reflection of light from the surface of a mineral.

Maar: A volcanic crater that is produced by an explosion in an area of low relief, is generally more or less circular, and often contains a lake, pond, or marsh.

Mafic: An igneous composed chiefly of one or more dark-colored minerals.

Magma: Molten rock beneath the surface of the earth.

Magma Chamber: The subterranean cavity containing the gas-rich liquid magma which feeds a volcano.

Magmatic: Pertaining to magma.

Magnitude: A numerical expression of the amount of energy released by an earthquake, determined by measuring earthquake waves on standardized recording instruments (seismographs.) The number scale for magnitudes is logarithmic rather than arithmetic. Therefore, deflections on a seismograph for a magnitude 5 earthquake, for example, are 10 times greater than those for a magnitude 4 earthquake, 100 times greater than for a magnitude 3 earthquake, and so on. Energy release is roughly 27 times greater for each successive Richter scale increase.

Mantle: The zone of the earth below the crust and above the core.

Matrix: The solid matter in which a fossil or crystal is embedded. Also, a binding substance (e.g., cement in concrete).

Miocene: An epoch in Earth's history from about 24 to 5 million years ago. Also refers to the rocks that formed in that epoch.

Móberg Mountain: The Icelandic name for a flat-topped mountain produced by the subglacial eruption of a central vent volcano.

Moho: Also called the Mohorovicic discontinuity. The surface or discontinuity that separates the crust from the mantle. The Moho is at a depth of 5-10 km beneath the ocean floor and about 35 km below the continents (but down to 60 km below mountains). Named for Andrija Mohorovicic, a Croatian seismologist and wild blender aficionado.

Monogenetic: A volcano built by a single eruption.

Mudflow: A flowage of water-saturated earth material possessing a high degree of fluidity during movement. A less-saturated flowing mass is often called a debris flow. A mudflow originating on the flank of a volcano is properly called a lahar.

Myth: A fictional story to explain the origin of some person, place, or thing. Also a useful term to describe CM's technical publications.

Nuees Ardentes: A French term applied to a highly heated mass of gas-charged ash which is expelled with explosive force and moves hurricane speed down the mountainside.

Obsidian: A black or dark-colored volcanic glass usually composed of rhyolite.

Oceanic Crust: The earth's crust where it underlies oceans.

Pahoehoe: A Hawaiian term for lava with a smooth, billowy, or ropy surface.

Palagonite: an alteration product from the interaction of water with volcanic glass of chemical composition similar to basalt. Palagonite can also result from the interaction between water and basalt melt. The water flashes to steam on contact with the hot lava and the small fragments of lava react with the steam to form the light colored palagonite tuff cones common in areas of basaltic eruptions in contact with water. Palagonite can also be formed by a slower weathering of lava into palagonite, resulting in a thin, yellow-orange rind on the surface of the rock. The process of conversion of lava to palagonite is called palagonitization.

Palagonite soil is a light yellow-orange dust, comprising a mixture of particles ranging down to sub-micrometer sizes, usually found mixed with larger fragments of lava. The color is indicative of the presence of iron in the +3 oxidation state, embedded in an amorphous matrix.

Palagonite tuff is a tuff composed of sideromelane fragments and coarser pieces of basaltic rock, embedded in a palagonite matrix. A composite of sideromelane aggregate in palagonite matrix is called hyaloclastite.

Pali: Hawaiian word for steep hills or cliffs.

Pele Hair: A natural spun glass formed by blowing-out during quiet fountaining of fluid lava, cascading lava falls, or turbulent flows, sometimes in association with Pele tears. A single strand, with a diameter of less than half a millimeter, may be as long as two meters.

Pele Tears: Small, solidified drops of volcanic glass behind which trail pendants of Pele hair. They may be tearshaped, spherical, or nearly cylindrical.

Peralkaline: Igneous rocks in which the molecular proportion of aluminum oxide is less than that of sodium and potassium oxides combined.

Phenotypes: it is commonly impossible to determine a representative mineralogical mode of significantly aphanitic rocks, even in thin-section. If it is impossible to recognize the mineralogy of the matrix, a mode must be based on the phenocrysts. The IUGS recommends that rocks identified in such a manner be called phenotypes and have the prefix "pheno-" inserted before the name (e.g., pheno-latite).

Phenocryst: A conspicuous, usually large, crystal embedded in porphyritic igneous rock.

Phreatic Eruption (Explosion): An explosive volcanic eruption caused when water and heated volcanic rocks interact to produce a violent expulsion of steam and pulverized rocks. Magma is not involved.

Phreatomagmatic: An explosive volcanic eruption that results from the interaction of surface or subsurface water and magma.

Picrite Basalt (Picrobasalt): is a variety of high-magnesium olivine basalt that is very rich in the mineral olivine. It is dark with yellow-green olivine phenocrysts (20 to 50%) and black to dark brown pyroxene, mostly augite.

Pillow lava: Interconnected, sack-like bodies of lava formed underwater.

Pipe: A vertical conduit through the Earth's crust below a volcano, through which magmatic materials have passed. Commonly filled with volcanic breccia and fragments of older rock.

Pit Crater: A crater formed by sinking in of the surface, not primarily a vent for lava.
Plastic: Capable of being molded into any form, which is retained.
Plate Tectonics: The theory that the earth's crust is broken into about 10 fragments (plates,) which move in relation to one another, shifting continents, forming new ocean crust, and stimulating volcanic eruptions.
Pleistocene: An epoch in Earth history from about 2-5 million years to 10,000 years ago. Also refers to the rocks and sediment deposited in that epoch.
Plinian Eruption: An explosive eruption in which a steady, turbulent stream of fragmented magma and magmatic gases is released at a high velocity from a vent. Large volumes of tephra and tall eruption columns are characteristic.
Plug: Solidified lava that fills the conduit of a volcano. It is usually more resistant to erosion than the material making up the surrounding cone, and may remain standing as a solitary pinnacle when the rest of the original structure has eroded away.
Plug Dome: The steep-sided, rounded mound formed when viscous lava wells up into a crater and is too stiff to flow away. It piles up as a dome-shaped mass, often completely filling the vent from which it emerged.
Pluton: A large igneous intrusion formed at great depth in the crust.
Polygenetic: Originating in various ways or from various sources.
Precambrian: All geologic time from the beginning of Earth history to 570 million years ago. Also refers to the rocks that formed in that epoch.
Pumice: Light-colored, frothy volcanic rock, usually of dacite or rhyolite composition, formed by the expansion of gas in erupting lava. Commonly seen as lumps or fragments of pea-size and larger, but can also occur abundantly as ash-sized particles.
Pyroclastic: Pertaining to fragmented (clastic) rock material formed by a volcanic explosion or ejection from a volcanic vent.
Pyroclastic Flow: Lateral flowage of a turbulent mixture of hot gases and unsorted pyroclastic material (volcanic fragments, crystals, ash, pumice, and glass shards) that can move at high speed (50 to 100 miles an hour.) The term also can refer to the deposit so formed.
Quaternary: The period of Earth's history from about 2 million years ago to the present; also, the rocks and deposits of that age.
Relief: The vertical difference between the summit of a mountain and the adjacent valley or plain.
Renewed Volcanism State: Refers to a state in the evolution of a typical Hawaiian volcano during which --after a long period of quiescence--lava and tephra erupt intermittently. Erosion and reef building continue.
Repose: The interval of time between volcanic eruptions.
Rhyodacite: An extrusive rock intermediate in composition between dacite and rhyolite.
Rhyolite: Volcanic rock (or lava) that characteristically is light in color, contains 69% silica or more, and is rich in potassium and sodium.
Ridge, Oceanic: A major submarine mountain range.
Rift System: The oceanic ridges formed where tectonic plates are separating and a new crust is being created; also, their on-land counterparts such as the East African Rift of Africa or Southwest Rift of Hawaii.
Rift Zone: A zone of volcanic features associated with underlying dikes. The location of the rift is marked by cracks, faults, and vents.
Ring of Fire: The regions of mountain-building earthquakes and volcanoes which surround the Pacific Ocean.
Scoria: A bomb-size (> 64 mm) pyroclast that is irregular in form and generally very vesicular. It is usually heavier, darker, and more crystalline than pumice.

Seafloor Spreading: The mechanism by which new seafloor crust is created at oceanic ridges and slowly spreads away as plates are separating.
Seamount: A submarine volcano.
Seismograph: An instrument that records seismic waves; that is, vibrations of the earth.
Seismologist: Scientists who study earthquake waves and what they tell us about the inside of the Earth.
Seismometer: An instrument that measures motion of the ground caused by earthquake waves.
Shearing: The motion of surfaces sliding past one another.
Shear Waves: Earthquake waves that move up and down as the wave itself moves. For example, to the left.
Shield Volcano: A gently sloping volcano in the shape of a flattened dome and built almost exclusively of lava flows.
Shoshonite: A trachyandesite composed of olivine and augite phenocrysts in a groundmass of labradorite with alkali feldspar rims, olivine, augite, a small amount of leucite, and some dark-colored glass. Its name is derived from the Shoshone River, Wyoming and given by Iddings in 1895.
Silica: A chemical combination of silicon and oxygen.
Sill: A tabular body of intrusive igneous rock, parallel to the layering of the rocks into which it intrudes.
Skylight: An opening formed by a collapse in the roof of a lava tube.
Solfatara: A type of fumarole, the gases of which are characteristically sulfurous.
Spatter Cone: A low, steep-sided cone of spatter built up on a fissure or vent. It is usually of basaltic material.
Spatter Rampart: A ridge of congealed pyroclastic material (usually basaltic) built up on a fissure or vent.
Specific Gravity: The density of a mineral divided by the density of water.
Spines: Horn-like projections formed upon a lava dome.
Stalactite: A cone shaped deposit of minerals hanging from the roof of a cavern.
Stratigraphic: The study of rock strata, especially of their distribution, deposition, and age.
Stratovolcano: A volcano composed of both lava flows and pyroclastic material.
Streak: The color of a mineral in the powdered form.
Strike-Slip Fault: A nearly vertical fault with side-slipping displacement.
Strombolian Eruption: A type of volcanic eruption characterized by jetting of clots or fountains of fluid basaltic lava from a central crater.
Subduction Zone: The zone of convergence of two tectonic plates, one of which usually overrides the other.
Surge: A ring-shaped cloud of gas and suspended solid debris that moves radially outward at high velocity as a density flow from the base of a vertical eruption column accompanying a volcanic eruption or crater formation.
Talus: A slope formed at the base of a steeper slope, made of fallen and disintegrated materials.
Tephra: Materials of all types and sizes that are erupted from a crater or volcanic vent and deposited from the air.
Tephrochronology: The collection, preparation, petrographic description, and approximate dating of tephra.
Tholeiite: are a chemical sub-type of basalt defined on their silica content. Basalts that are silica saturated are known as olivine tholeiites, those that are silica oversaturated are termed quartz tholeiites. Tholeiites lack feldspathoids. Silica undersaturated basalts are termed alkali basalts.
Tilt: The angle between the slope of a part of a volcano and some reference. The reference may be the slope of the volcano at some previous time.
Trachyandesite: An extrusive rock intermediate in composition between trachyte and andesite.
Trachybasalt: An extrusive rock intermediate in composition between trachyte and basalt.

Trachyte: A group of fine-grained, generally porphyritic, extrusive igneous rocks having alkali feldspar and minor mafic minerals as the main components, and possibly a small amount of sodic plagioclase.

Tremor: Low amplitude, continuous earthquake activity often associated with magma movement.

Tsunami: A great sea wave produced by a submarine earthquake, volcanic eruption, or large landslide.

Tuff: Rock formed of pyroclastic material.

Tuff Cone: A type of volcanic cone formed by the interaction of basaltic magma and water. Smaller and steeper than a tuff ring.

Tuff Ring: A wide, low-rimmed, well-bedded accumulation of hyaloclastic debris built around a volcanic vent located in a lake, coastal zone, marsh, or area of abundant ground water.

Tumulus: A doming or small mound on the crest of a lava flow caused by pressure due to the difference in the rate of flow between the cooler crust and the more fluid lava below.

Tuya: a flat-topped, steep-sided volcano formed when lava erupts through a thick glacier or ice sheet. They are rare worldwide, being confined to regions which were covered by glaciers and had active volcanism during the same period.

Ultramafic: Igneous rocks made mostly of the mafic minerals: hypersthene, augite, and/or olivine.

Unconformity: A substantial break or gap in the geologic record where a rock unit is overlain by another that is not next in stratigraphic succession, such as an interruption in continuity of a depositional sequence of sedimentary rocks or a break between eroded igneous rocks and younger sedimentary strata. It results from a change that caused deposition to cease for a considerable time, and it normally implies uplift and erosion with loss of the previous formed record.

Vent: The opening at the earth's surface through which volcanic materials issue forth.

Vesicle: A small air pocket or cavity formed in volcanic rock during solidification.

Viscosity: A measure of resistance to flow in a liquid (water has low viscosity while honey has a higher viscosity.)

Volcano: A vent in the surface of the Earth through which magma and associated gases and ash erupt; also, the form or structure (usually conical) that is produced by the ejected material.

Volcanic Arc: A generally curved linear belt of volcanoes above a subduction zone, and the volcanic and plutonic rocks formed there.

Volcanic Complex: A persistent volcanic vent area that has built a complex combination of volcanic landforms.

Volcanic Cone: A mound of loose material that was ejected ballistically.

Volcanic Neck: A massive pillar of rock more resistant to erosion than the lavas and pyroclastic rocks of a volcanic cone.

Vulcan: Roman god of fire and the forge after whom volcanoes are named.

Vulcanian: A type of eruption consisting of the explosive ejection of incandescent fragments of new viscous lava, usually on the form of blocks.

Water Table: The surface between where the pore space in rock is filled with water and where the pore space in rock is filled with air.

Xenocrysts: A crystal that resembles a phenocryst in igneous rock, but is a foreign to the body of rock in which it occurs.

Xenoliths: A foreign inclusion in an igneous rock.

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Long, P. E., & Wood, B. J. (1986). Structures, textures, and cooling histories of Columbia River basalt flows. Geological Society of America Bulletin, 97(9), 1144-1155.

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BUDGET INFORMATION

(as of 02/01/23)

2023 - Iceland

Total Cost of the Trip: ……………………………………………………………$34,800.00

Cost per person for the trip (13 students)……………………………………….……….$1,400
Cost per person for the trip (2 faculty)………………………………………….……....$1,600
Cost per person for the trip (2 non-UPJ spouse)……………………………….……..$2,200
Contribution from Student Activities: ……………………………………………..$9,000

Breakdown

1.	Airfare – Iceland Air	$	11,836.25
2.	Transport - SBA - Norðurleið	$	6,279.00
3.	Lodging		
	a. Grindavik – 1 night at Grindavik Guesthouse	$	807.15
	b. Vestman – 1 night at Lava Guesthouse	$	700.00
	c. Laugarvatn – 3 nights at Héraðsskólinn Guesthouse	$	3,500.00
	a. Reykjavik – 2 nights at Aurora Guesthouse	$	1,905.70
4.	Miscellaneous		
	a. Guidebook (to be paid to the UPJ print shop)	$	750.00

Payments to be made during the trip

1.	Ferry to Vestmannjaey	$	527.00
2.	Eldheimar Museum	$	252.00
3.	Lava Centre	$	297.00
4.	Thingvellir Visitor Center	$	99.00
5.	Secret Lagoon Hot Springs	$	396.00
6.	Hellshiedi Power Plant	$	558.00
7.	Raurfarholshellir Lava Tube	$	900.00
8.	Group Meals	$	5,992.90

BOOKING RECEIPTS
AIRFARE

FLIGHT FI 644 - ICELANDAIR SAT 04 MARCH 2023

DEPARTURE: DULLES/WASH, DC (DULLES INTL) 04 MAR 19:40
ARRIVAL: REYKJAVIK, IS (KEFLAVIK INTL) 05 MAR 06:35
FLIGHT BOOKING REF: FI/3TPH33
RESERVATION CONFIRMED, ECONOMY (G) DURATION: 05:55

- -

BAGGAGE ALLOWANCE: 1PC
SEAT: 20A CONFIRMED FOR KERRIGAN/RYAN JASON
SEAT: 20B CONFIRMED FOR KOHLER/KAREN CLAIRE
SEAT: 20C CONFIRMED FOR MCCONNELL/TERESA KOHLER
SEAT: 20D CONFIRMED FOR MILLER/JESSICA LYNN
SEAT: 21A CONFIRMED FOR FREED/AVA
SEAT: 21B CONFIRMED FOR GALASSO/JOSEPH ALMANDO
SEAT: 21C CONFIRMED FOR GARRETT/HOLLY KATHERINE
SEAT: 21D CONFIRMED FOR HOWARD/CHRISTOPHER MICHAEL
SEAT: 21E CONFIRMED FOR KELLY/RYAN NICHOLAS
SEAT: 23A CONFIRMED FOR ROXBY/COURTNEY MARIE
SEAT: 23B CONFIRMED FOR SCELSI/NICHOLAS RAY
SEAT: 23C CONFIRMED FOR SCHAEFER/ANN MARIE
SEAT: 24A CONFIRMED FOR SHRECKENGOST/ALEYA GALE
SEAT: 24B CONFIRMED FOR SMITH/JADE ELAYNE
SEAT: 24C CONFIRMED FOR SMITH/NICHOLAS PATRICK
SEAT: 24D CONFIRMED FOR SMITH/TYLER MCALESTER
SEAT: 24E CONFIRMED FOR WEAVER/OLIVIA JANELLE
MEAL: ALCOHOLIC BEVERAGES FOR PURCHASE/FOOD FOR PURCHASE
NON-STOP DULLES/WASH, DC TO REYKJAVIK
AIRCRAFT OWNER: ICELANDAIR, FI
EQUIPMENT: BOEING 737 MAX 9

FLIGHT FI 645 - ICELANDAIR SUN 12 MARCH 2023

DEPARTURE: REYKJAVIK, IS (KEFLAVIK INTL) 12 MAR 16:50
ARRIVAL: DULLES/WASH, DC (DULLES INTL) 12 MAR 19:10
FLIGHT BOOKING REF: FI/3TPH33
RESERVATION CONFIRMED, ECONOMY (G) DURATION: 06:20

- -

BAGGAGE ALLOWANCE: 1PC

SEAT: 18A CONFIRMED FOR KERRIGAN/RYAN JASON
SEAT: 18B CONFIRMED FOR KOHLER/KAREN CLAIRE
SEAT: 18C CONFIRMED FOR MCCONNELL/TERESA KOHLER
SEAT: 18D CONFIRMED FOR MILLER/JESSICA LYNN
SEAT: 23A CONFIRMED FOR FREED/AVA
SEAT: 23B CONFIRMED FOR GALASSO/JOSEPH ALMANDO
SEAT: 23C CONFIRMED FOR GARRETT/HOLLY KATHERINE
SEAT: 23D CONFIRMED FOR HOWARD/CHRISTOPHER MICHAEL
SEAT: 23E CONFIRMED FOR KELLY/RYAN NICHOLAS
SEAT: 23F CONFIRMED FOR ROXBY/COURTNEY MARIE
SEAT: 24A CONFIRMED FOR SCELSI/NICHOLAS RAY
SEAT: 24B CONFIRMED FOR SCHAEFER/ANN MARIE
SEAT: 24C CONFIRMED FOR SHRECKENGOST/ALEYA GALE
SEAT: 24D CONFIRMED FOR SMITH/JADE ELAYNE
SEAT: 25A CONFIRMED FOR SMITH/NICHOLAS PATRICK
SEAT: 25B CONFIRMED FOR SMITH/TYLER MCALESTER
SEAT: 25C CONFIRMED FOR WEAVER/OLIVIA JANELLE

MEAL: ALCOHOLIC BEVERAGES FOR PURCHASE/FOOD FOR PURCHASE
NON STOP REYKJAVIK TO DULLES/WASH, DC
AIRCRAFT OWNER: ICELANDAIR, FI
EQUIPMENT: BOEING 737 MAX 9

FLIGHT TICKET(S)

TICKET: FI/ETKT 108 2412259818 FOR MILLER/JESSICA LYNN
TICKET: FI/ETKT 108 2412259819 FOR ROXBY/COURTNEY MARIE
TICKET: FI/ETKT 108 2412259820 FOR SCELSI/NICHOLAS RAY
TICKET: FI/ETKT 108 2412259821 FOR SCHAEFER/ANN MARIE
TICKET: FI/ETKT 108 2412259822 FOR SHRECKENGOST/ALEYA GALE
TICKET: FI/ETKT 108 2412259823 FOR SMITH/NICHOLAS PATRICK
TICKET: FI/ETKT 108 2412259824 FOR SMITH/TYLER MCALESTER
TICKET: FI/ETKT 108 2412259825 FOR SMITH/JADE ELAYNE
TICKET: FI/ETKT 108 2412259826 FOR WEAVER/OLIVIA JANELLE
TICKET: FI/ETKT 108 2412259827 FOR FREED/AVA
TICKET: FI/ETKT 108 2412259828 FOR GALASSO/JOSEPH ALMANDO
TICKET: FI/ETKT 108 2412259829 FOR GARRETT/HOLLY KATHERINE
TICKET: FI/ETKT 108 2412259830 FOR HOWARD/CHRISTOPHER MICHAEL
TICKET: FI/ETKT 108 2412259831 FOR KELLY/RYAN NICHOLAS
TICKET: FI/ETKT 108 2412259832 FOR KERRIGAN/RYAN JASON
TICKET: FI/ETKT 108 2412259833 FOR KOHLER/KAREN CLAIRE
TICKET: FI/ETKT 108 2412259834 FOR MCCONNELL/TERESA KOHLER

CHECK-IN: 3 HRS PRIOR TO DEPARTURE
THANK YOU FOR CHOOSING ICELANDAIR

TRANSPORTATION - BUS

Waiting for receipt from bus company…

TRANSPORTATION - FERRY

HERJÓLFUR
VESTMANNAEYJAR

Booking number
1977870

Confirmation

Booking Information

Journey header 1

Date	**06.03.2023**	
Departure	**Landeyjahöfn**	**13.15**
Arrival	**Vestmannaeyjar**	**13.55**
Product	**Standard Price**	
Farþegar	17 Adults	

Journey header 2

Date	**07.03.2023**	
Departure	**Vestmannaeyjar**	**14.30**
Arrival	**Landeyjahöfn**	**15.10**
Product	**Standard Price**	
Farþegar	17 Adults	

Payment

Customer WEB AGENT

Price excluding tax	74,800.00 ISK
VAT	0.00 ISK
Total price	74,800.00 ISK
Paid amount	74,800.00 ISK
To be paid	0.00 ISK

Check-in information

We would like to ask passengers to arrive for check in no later than 30 minutes before departure, both when travelling on foot and with a vehicle.

Please note that the confirmation note is not a boarding pass. Passenger can have their boarding passed on their phones , print them out at home or get them printed out at our office.

Passengers are asked to follow the departure schedule on www.herjolfur.is and other mediums, as the schedule can change with a short notice.

General terms for transport of passengers and luggage can be found on www.herjolfur.is.

HERJÓLFUR
VESTMANNAEYJAR

Boarding pass

Booking number	**1977870**	
Passenger		
	Adult	
Date	**07.03.2023**	
Departure	**Vestmannaeyjar**	**14.30**
Arrival	**Landeyjahöfn**	**15.10**

Check in 30 minutes before departure - herjolfur.is

HERJÓLFUR
VESTMANNAEYJAR

Boarding pass

Booking number	**1977870**	
Passenger		
	Adult	
Date	**06.03.2023**	
Departure	**Landeyjahöfn**	**13.15**
Arrival	**Vestmannaeyjar**	**13.55**

Check in 30 minutes before departure - herjolfur.is

GUESTHOUSES

Guesthouse Grindavik

Your Booking Reference:

GFGH-3082572-W

Lava House Guesthouse

From: Lava Guesthouse
To: Kerrigan, Ryan
Subject: RE: Group Accommodations - March 6th, 2023
Date: Thursday, December 8, 2022 6:51:23 AM
Attachments: 1651711176379000_265540721.png
1.png

Dear Ryan

Thanks for contact Lava Guesthouse and confirmation. I will book this so at this time you don't need to do anything. I will get back to you later for more information, payment and so on.

I will just clarify at we are a small guesthouse and for 18 people some will be together in double bed. Our guesthouse has 7 rooms and can accommodate up to 23 people, 15 beds.

The room we offer is:

Room			
R2	5 - person room	2 x 140cm bed and 1 x 90cm bed	Private bathroom
R3	4 - person room	1 x 140cm and 2 x 90cm bed	Shared bathroom
R4	2 - person room	1 x 140cm bed	Shared bathroom
R5	Small 2 - person room	2 x 90cm bed	Shared bathroom
R6	3 - person room	1 x 140cm and 1 x 90cm bed	Shared bathroom
R7	5 - person room	2 x 140cm and 1 x 90cm bed	Shared bathroom
R8	Small 2 - person room	1 x 140cm bed	Shared bathroom

For picture and information, you can look at https://lavaguesthouse.com/ and booking page like booking.com and airbnb.com

We are flexible about cancellation if that is needed, but of course let us know as soon as possible if any chances will be.

I hope this tells you something and you may have a good day and don´t hesitate to contact if any questions.

LAVA GUESTHOUSE

Best regards
Sigfus Johannsson
Phone: +354 659 5400

Heradsskolinn Guesthouse

Héraðsskólinn ehf.

Date: 2023-02-02
Kt: 700513-0680

Reference Number: 36653591
Voucher Number:

Name	Ryan Kerrigan University of Pittsburgh at Johnstown
Booking Reference	36653591
Check-in	Tuesday, 7 March, 2023
Check-out	Friday, 10 March, 2023
Number of Nights	3

Description	**Quantity**	**Price**	**Total**
Ryan Kerrigan University of Pittsburgh at Johnstown - 7 Mar 2023	3	105.00€	315.00€
Ryan Kerrigan University of Pittsburgh at Johnstown - 7 Mar 2023	3	115.00€	345.00€
Ryan Kerrigan University of Pittsburgh at Johnstown - 7 Mar 2023	3	115.00€	345.00€
Ryan Kerrigan University of Pittsburgh at Johnstown - 7 Mar 2023	3	105.00€	315.00€
Ryan Kerrigan University of Pittsburgh at Johnstown - 7 Mar 2023	3	105.00€	315.00€
Ryan Kerrigan University of Pittsburgh at Johnstown - 7 Mar 2023	3	105.00€	315.00€
Ryan Kerrigan University of Pittsburgh at Johnstown - 7 Mar 2023	3	115.00€	345.00€
Ryan Kerrigan University of Pittsburgh at Johnstown - 7 Mar 2023	3	105.00€	315.00€
Lunch Box (take away)	54	13.00€	702.00€
Grand Total			**3,312.00€**

We hope you enjoyed your stay with us.

Héraðsskólinn ehf, Laugarbraut 2, 840 Laugarvatn, P: 537-8060
email: booking@heradsskolinn.is, website: www.heradsskolinn.is
Bank: 526-26-700513

Account info:
Bank: Islandsbanki
Bank address:Sudurlandsbraut 14, 108 Reykjavik, Iceland
Account Holder: Heradsskolinn EHF

Aurora Guesthouse

We have sent an email notification to **kerrigan@pitt.edu**. If the email does not arrive in your inbox, please check it has not been put into your spam or trash folder.

Dear guest,

Thank you for choosing Guesthouse Aurora-Andrea. Please check your details:

Reference Number: 36728342
Room: Double or Twin Room with Shared Bathroom (7), Family Room with Shared Bathroom (1)
Name: Dr. Ryan Kerrigan
Email: kerrigan@pitt.edu
Arrival: Friday, 10 March, 2023
Departure: Sunday, 12 March, 2023
Nights: 2
Adults: 19
Children: 0
Rate: 2023-03-10 113.05 Non-Refundable 5%,
2023-03-11 113.05 Non-Refundable 5%

Description	Quantity	Price	Total
Double or Twin Room with Shared Bathroom - Friday, 10 March, 2023 - Sunday, 12 March, 2023 -	1	226.10	226.10
Double or Twin Room with Shared Bathroom - Friday, 10 March, 2023 - Sunday, 12 March, 2023 -	1	226.10	226.10
Double or Twin Room with Shared Bathroom - Friday, 10 March, 2023 - Sunday, 12 March, 2023 -	1	226.10	226.10
Double or Twin Room with Shared Bathroom - Friday, 10 March, 2023 - Sunday, 12 March, 2023 -	1	226.10	226.10
Double or Twin Room with Shared Bathroom - Friday, 10 March, 2023 - Sunday, 12 March, 2023 -	1	226.10	226.10
Double or Twin Room with Shared Bathroom - Friday, 10 March, 2023 - Sunday, 12 March, 2023 -	1	226.10	226.10
Double or Twin Room with Shared Bathroom - Friday, 10 March, 2023 - Sunday, 12 March, 2023 -	1	226.10	226.10
Family Room with Shared Bathroom - Friday, 10 March, 2023 - Sunday, 12 March, 2023 -	1	323.00	323.00
Grand Total			**1,905.70**

Best regards,

Guesthouse Aurora-Andrea

MISCELLANEOUS

PREVIOUS SPRING BREAK GROUPS

SPRING BREAK 2022 – HAWAII

Picture taken on top Papakōlea beach (Green Sand Beach)

L-R: Steve Lindberg, Marilyn Lindberg, Elliot Finney, Terry McConnell, Alex Kijowski, Aleya Shreckengost, Cian Williamson-Rea, Olivia Weaver, Ryan Kerrigan, Jessica Miller, Delaney D'Amato, Nick Scelsi, Holly Garrett, Courtney Roxby, and Avery Freed

SPRING BREAK 2021 – COVID STRIKES AGAIN!!!
SPRING BREAK 2020 – ICELAND (CANCELLED - STUPID COVID)

SPRING BREAK 2019 – ECUADOR

Picture taken in front of ash flow from Mount Chimborazo

L-R: Jen Hlivko, Kyle Molnar, Ryan Kerrigan, Jessica Miller, Abby Wess, Alex Hockensmith, Susan Ma, Kyle Sarver, Jake Marsh, Tyler Newell, and Kim Waltermire

SPRING BREAK 2018 – SCOTLAND

Picture taken in front of Edinburgh Castle

L-R: Ryan Kerrigan, Jessica Miller, Terry McConnell, Steve Lindberg, Marilyn Lindberg, Sam Louderback, Jake Marsh, Lauren Raysich, Kim Waltermire, and Katie Roxby

Not Pictured: Bill McConnell

SPRING BREAK 2017 – HAWAII

Picture taken at the rim of Mauna Ulu in Volcanoes National Park

L-R: Jacob Williamson-Rea, Tyler Norris, Kris Miller, Allie Marra, Luke Layton, Matt Leger, Katie Roxby, and Ryan Kerrigan

SPRING BREAK 2016 – ICELAND

Picture taken on columnar joints at Reynisfjara Beach, Iceland

Top Row: Tyler Norris, Lorin Simboli, Allie Marra, Luke Layton; *Bottom Row:* Catie Bert, Matt Leger; *Not Pictured:* Ryan Kerrigan, Terry McConnell, and Steve Lindberg

SPRING BREAK 2015 – NORTH CAROLINA

Picture taken at Ray Mine Pegmatite mine, Spruce Pine, NC

Left to Right: Kris Miller, Luke Layton, Leah Marko, Andrew Barchowsky, Matt Gerber, and Ryan Kerrigan

NOTES