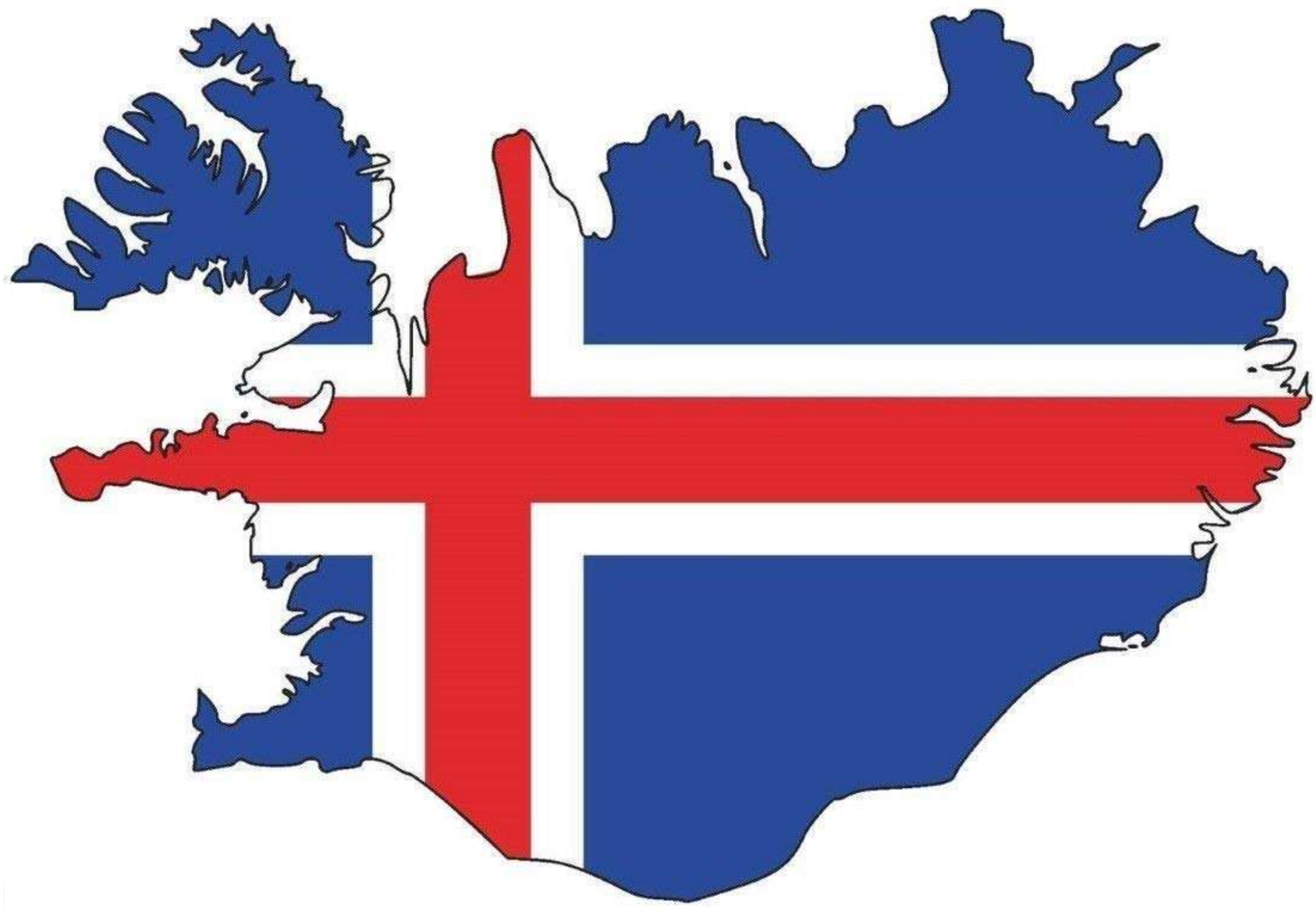
ICELAND SPRING BREAK TRIP 2020

UNIVERSITY OF PITTSBURGH AT JOHNSTOWN
DEPARTMENT OF ENERGY AND EARTH RESOURCES




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

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LOGISTICS, BASICS, AND TRIP RULES

Flights

Departing Flight
Departure: Sat 7 Mar 2020, 19:40, Washington Dulles International (IAD)
Icelandair (FI 644), Duration: 05:45
Arrival: Sun 7 Mar 2020, 06:30, Reykjavik Keflavik International (KEF)

Return Flight
Departure: Sun 15 Mar 2020, 16:50, Reykjavik Keflavik International (KEF)
Icelandair (FI 645), Duration: 06:30
Arrival: Sun 15 Mar 2020, 19:25, Washington Dulles International (IAD)

Iceland Basics

Emergency Number: 112
USA embassy: 595-2200

- *Currency:* Icelandic króna (IKR)
- *Exchange Rate:* 1 USD = ~130 IKR ($10 = 1,300)
- *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)

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.**

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.

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

Equipment:
• Universal Adapters
• Field Notebook
• Pencils/Pens
• Headlamp/Flashlight (you may want this for the lava tube)
• Water Bottles (or buy in Reykjavík)
• Rock Hammer (must be packed in checked luggage)
• Hand lens

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.

BRIEF ITINERARY

Day 1: Saturday, March 7th, 2020 – 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 8th, 2020 – Reykjanes Peninsula

6:30: 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: I think it will be best to have breakfast at the airport

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

Guðmundur Jónasson Travel (gjtravel@gjtravel.is)
Vesturvör 34, 200 Kópavogur, Iceland
Emergency number travel agency: +354-895 2007
Emergency number bus department: +354-893 5740

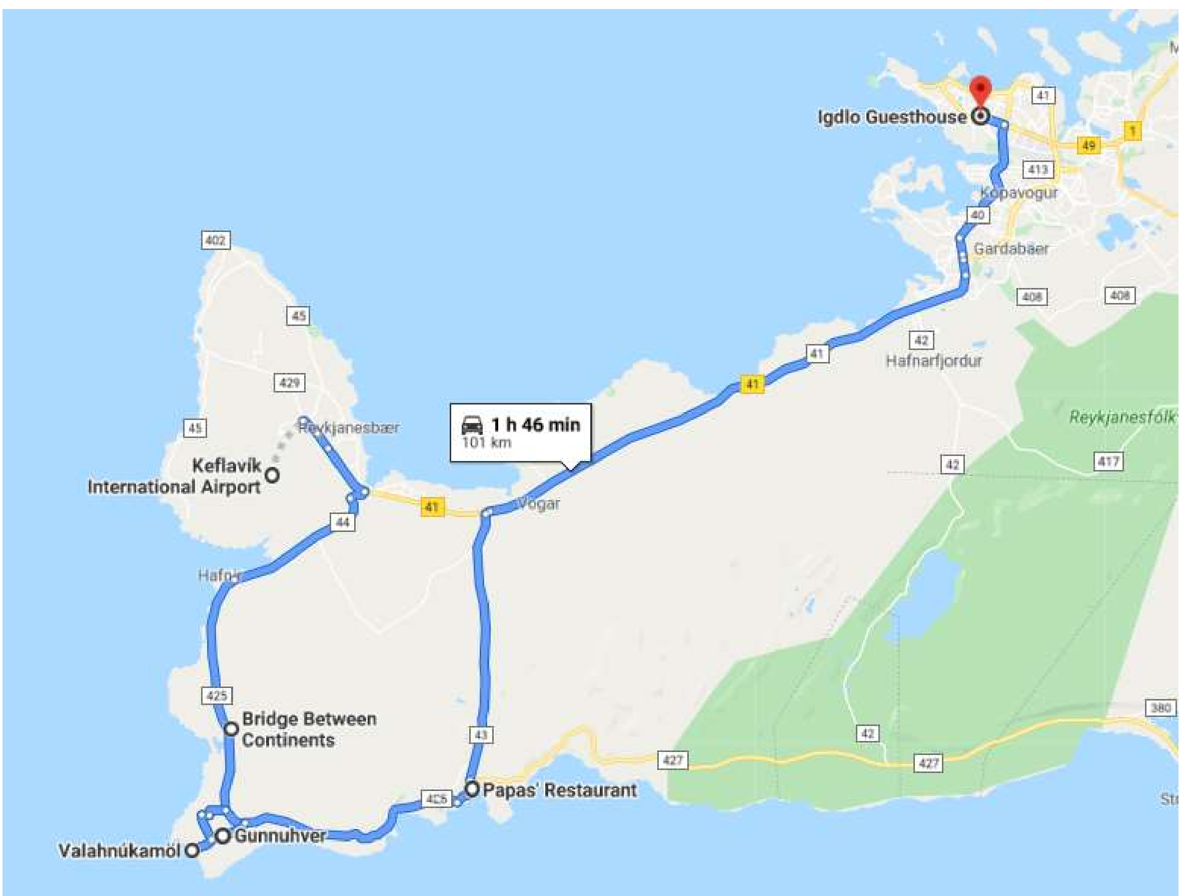
9:00: Stop at Bridge between Two Continents near Sandvik. We'll talk about Mid Atlantic Ridge, the boundary between the North American Plate and the Eurasian Plate.

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

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

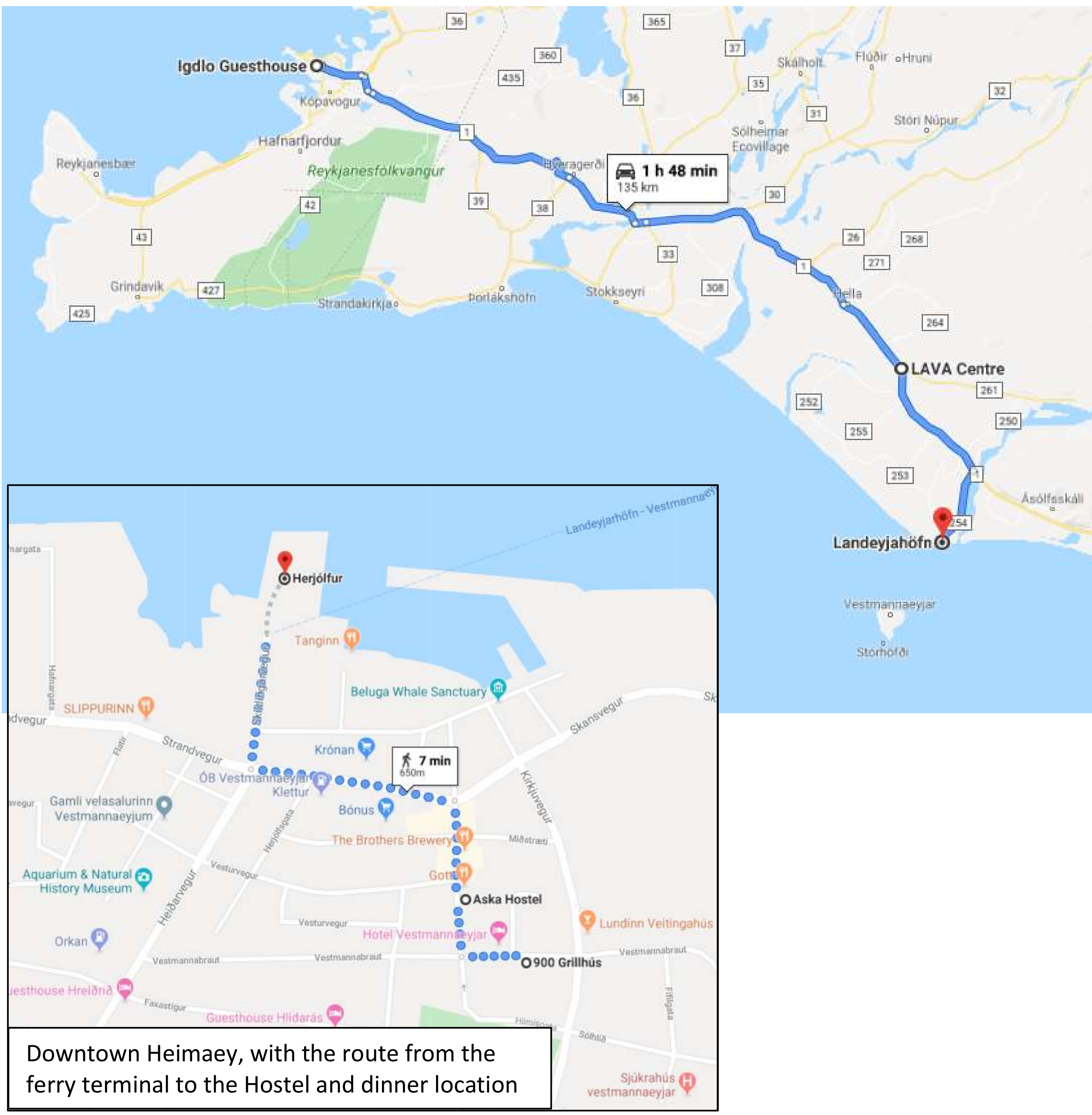
12:30: Lunch in Grindavik – There is a café called Papas' Restaurant (Hafnargata 7a, 240 Grindavik, Iceland) that might be fine….

2 PM: Get to the hostel (Igdlo Guesthouse, Gunnarsbraut 46, 105 Reykjavík). Stay there for one night. Fend for yourself for dinner. You could out or cook, the hostel has a kitchen.



Day 3: Monday, March 9th, 2020 – Reykjavik to Heimaey

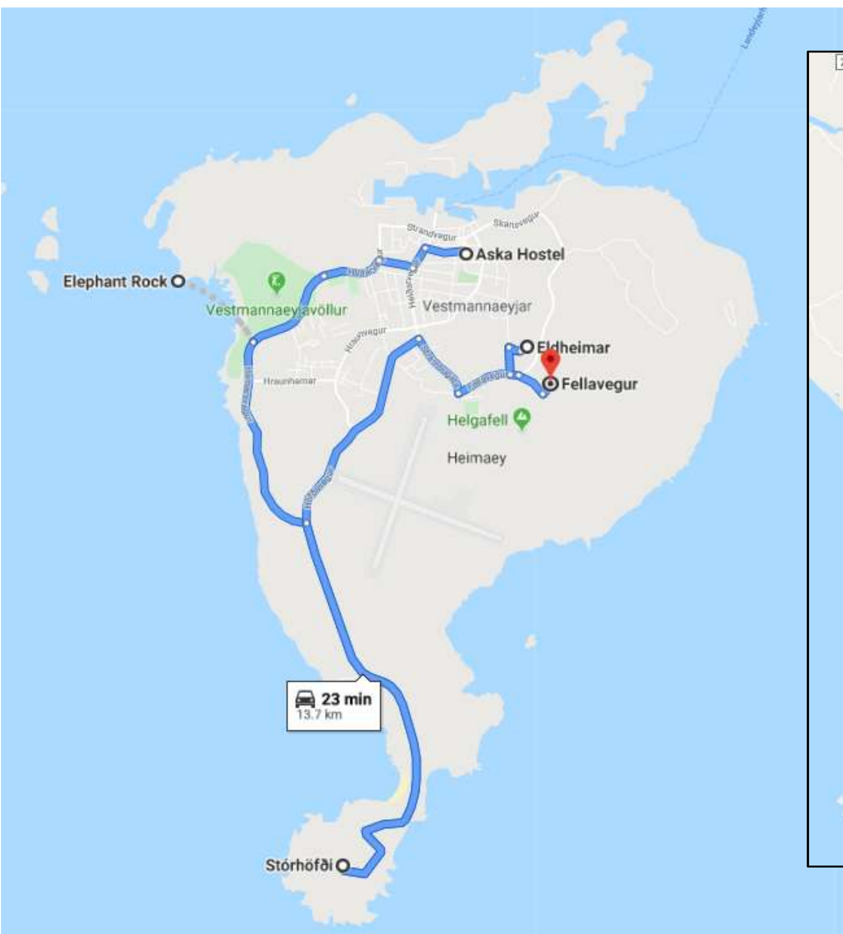
7:30AM: Wake up, pack up, breakfast is provided at the hostel.
8:30AM: Load the bus and leave the hostel
10:00AM: Arrive at LAVA Centre and tour the museum, people can buy lunch here or on the ferry to Vestmannaeyjar Islands
12:30PM: Depart from the LAVA Centre
1:00PM: Board the ferry and depart for Vestmannaeyjar, Heimaey.
2:30PM: Arrive Vestmannaeyjar, Heimaey and check in with the hostel (Aska Hostel, Bárustígur 11, 900 Vestmannaeyjabær, Iceland, http://askahostel.is/aska/)
Rest of the day: Walk around, hang out, relax, whatever…
6:00PM: Group dinner at 900 Grillhouse, Vestmannabraut 23, 900 Vestmannaeyjar, Iceland, http://www.900grillhus.is/

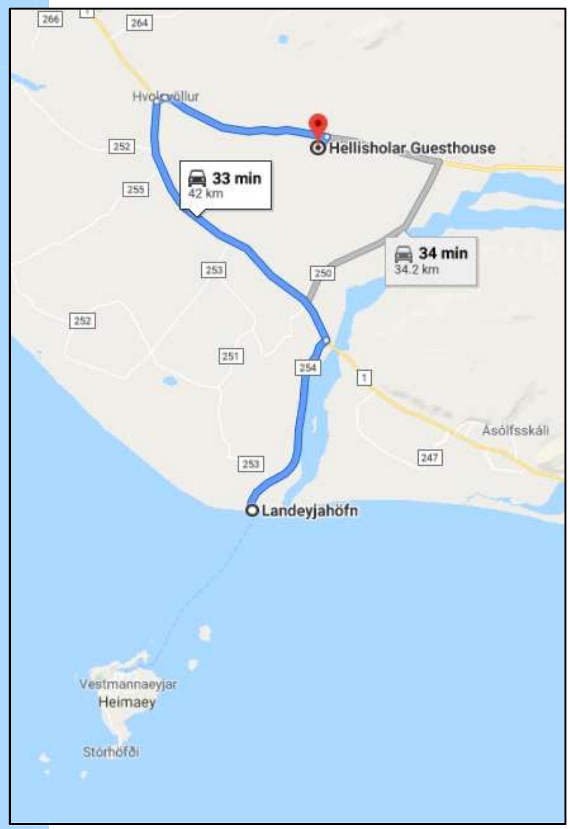


Downtown Heimaey, with the route from the ferry terminal to the Hostel and dinner location

Day 4: Tuesday, March 10th, 2020 – Heimaey to the Rift Valley

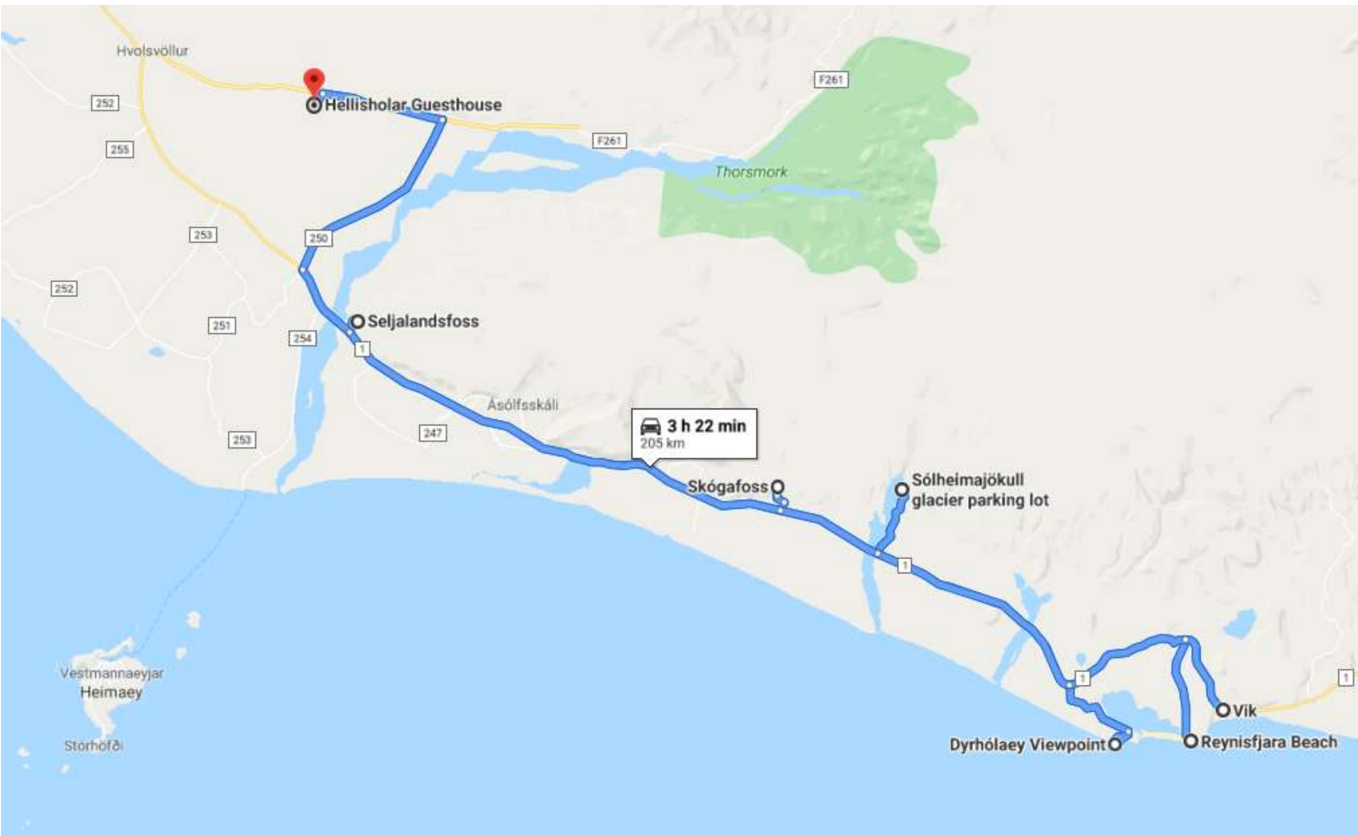
8:00AM: Breakfast in the hostel, pack up, and load into the buses.
9:00AM: Leave the hostel and drive around the island, first stop Elephant Rock
10:00AM: Pirate Cove & Storhofdi - south edge of the island, hike around and get a view of Surtsey
11:00AM: Eldheimar Volcano Museum (10, Gerðisbraut, Vestmannaeyjabær, opens at 11AM)
1:00PM: Climb Eldfell Volcano
2:00PM: Board the ferry and depart for the main land
3:30PM: Reach Landeyjahofn and drive to the Guesthouse
4:30PM: Get to Hellishólar Guesthouse, Öldubakki 5, Hvolsvöllur, Iceland, https://hellisholar.is/
6:00PM: Group dinner at the hostel
That evening: I am hoping this location will give us a good shot at seeing the Aurora Borealis, the Northern Lights





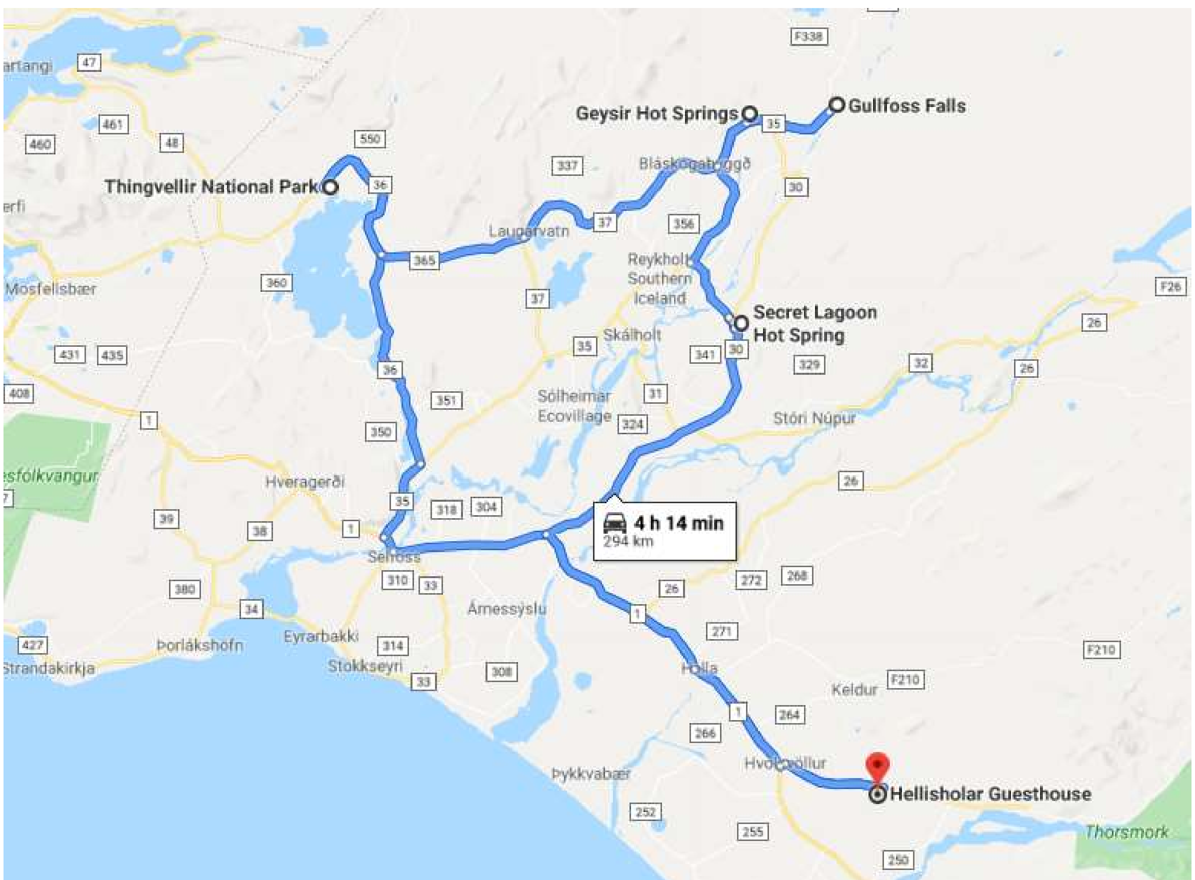
Day 5: Wednesday, March 11th, 2020 – Waterfalls, Glaciers and Vik Beaches

7:00AM: Wake-up, breakfast is provided by the hostel.
8:30AM: Depart from the hostel
9:00AM: Arrive at Seljalandsfoss waterfall.
10:30AM: Arrive at Skogafoss waterfall.
11:45AM: Sólheimajökulsvegur Glacier, A pack lunch will be provided by the hostel, we can eat at the glacier
2:30PM: Arrive at Dyrholaey Viewpoint
3:30PM: Arrive at Renisfjara Beach
4:15PM: Arrive at Vik
5:45PM: Arrive back at the hostel
6:30PM: Group meal at the hostel



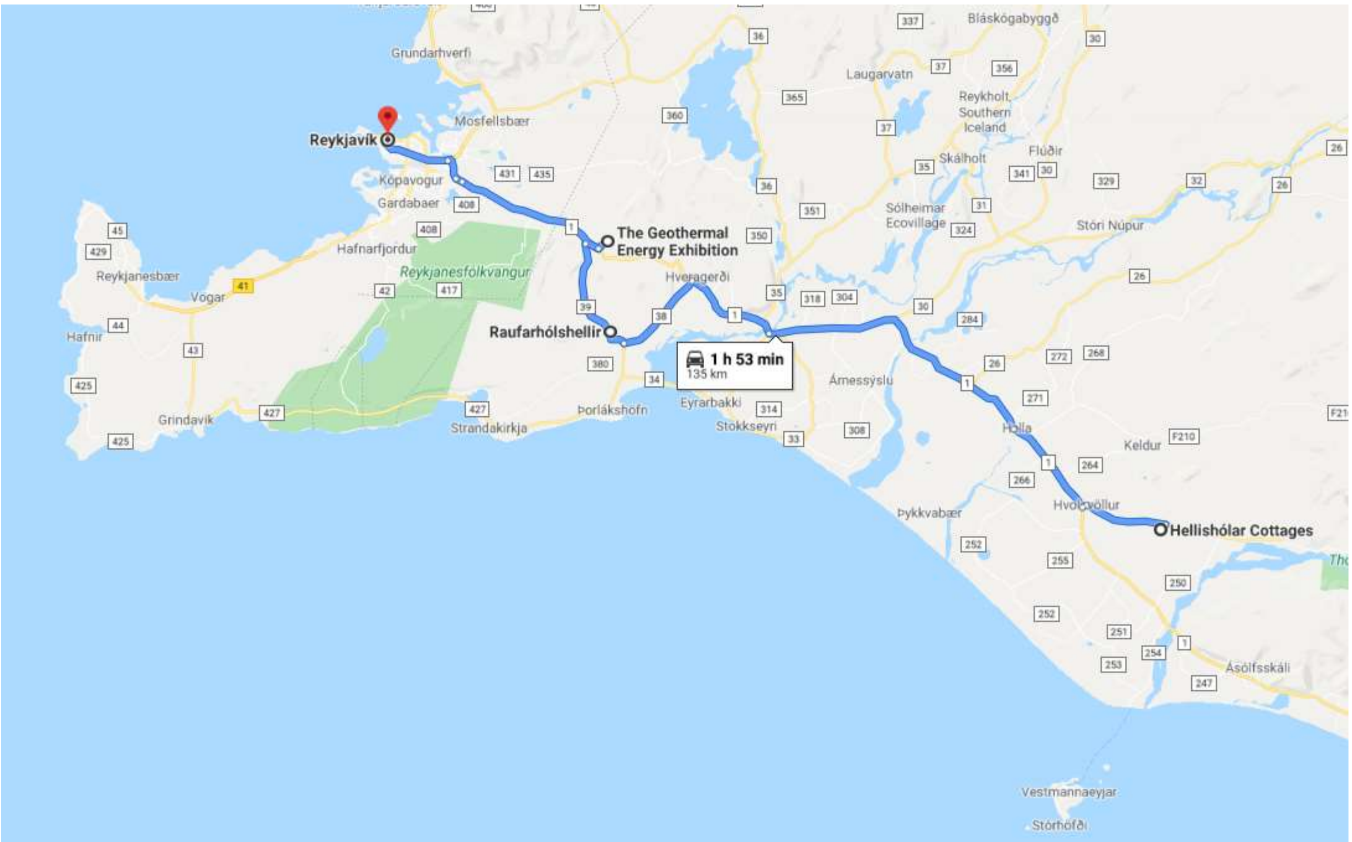
Day 6: Thursday, March 12th, 2020 – Þingvellir, Geysir, Gulfoss

7:00AM: Wake-up, breakfast at the hostel
8:00AM: Depart for Þingvellir National Park
9:30AM: Arrived at Þingvellir National Park
10:00AM: Walk to the Law Rock and through the rift valley.
11:30AM: Depart for Geysir
12:30PM: Arrive at Geysir, have lunch (the hostel will be providing packed lunches, but there is also a café there).
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 Hellisholar Guesthouse
6:00PM: Arrive at hostel
6:30PM: Group dinner at the hostel



Day 7: Friday, March 13th, 2020 – Hellisheiði Power Plant, Raurfarholshellir Lava Tube, and back to Reykjavik

6:00AM: Wake-up, have breakfast, pack our things, and load the vans.
7:30AM: Depart for Raurfarholshellir Lava Tube
9:00AM: Take a tour of the Raurfarholshellir Lava Tube (http://thelavatunnel.is/) THIS REQUIRES STURDY BOOTS
10:30AM: Take a tour of the Hellisheiði Power Plant geothermal museum and a "behind-the-scenes" tour of the power plant
12:00PM: Finished tour. Have lunch.
1:30PM: Returned to the van and head into Reykjavik. We will be staying in the same accommodations (Igdlo Guesthouse, Gunnarsbraut 46, 105 Reykjavík).



Day 8: Saturday, March 14th, 2020 – 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 15th, 2020 – Reykjavik and return home

8:00: Wake-up and have breakfast (provided by the hostel)
9:00: Load the vehicles
10:00: Hang out in Reykjavik

We have to be checked out of the hostel by 11AM

2:00PM: Load up in the van and head to the airport
3:00PM: Arrive at the airport
4:50PM: Boarding Icelandair Flight 645
7:25PM: Arrive 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 $63^{o}24$'N and $66^{o}33$'N and between longitudes $13^{o}30$'W and $24^{o}32$'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^{o}C (51^{o}F) in July, with average highs of 24.3^{o}C (76^{o}F). The average winter temperature in Reykjavík is about 0^{o}C (32^{o}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 2008, the population was 313,000 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 12^{th} century. The literacy rate is 99.9%, the highest in the world.

Iceland's currency is the krona, which in September 2010 traded at 114 krona to the dollar. Iceland's economy had an estimated GDP of $12.2 billion in 2009, with a GDP per capita of $39,800. 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 70% of its primary energy and 99.9% of their electricity from renewable energy sources. Their goal is to be completely energy independent, using 100% renewable energy by 2050.

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.

References:

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National Public Radio (2007), "Many Icelanders believe in Elves". http://www.npr.org/templates/story/story.php?storyId=17563875

Unknown Author (c. 1245), Laxdaela Saga, translated by M. Magnusson and H. Pàlsson (1969), 270 pp., Penguin Books, New York.

GEOLOGIC OVERVIEWS

Ridge-Hotspot Interaction – The Origin of Iceland

Contributed by Shuoshuo Han

Mid-ocean ridges and hotspots are two major surface manifestations of mantle upwelling and magma generation on the Earth. Mid-ocean ridges are linear features of 70,000km in total length around the globe, constituting most of Earth's divergent boundaries. Hotspots are localized regions of abundant magmatism and distinct geochemical anomalies. When a hotspot is located close enough to a mid-ocean ridge, the two volcanic systems may interact, resulting in unique geophysical and geochemical features[1]. At least 21 of the 30–50 identified present-day hot spots appear to be interacting with mid-ocean ridges[2]. Of them, Iceland is a classic example of a ridge above- hotspot interaction.

Iceland has been formed by the interaction of the Mid-Atlantic Ridge and the proposed Iceland mantle plume during the Cenozoic. The MAR is a slow spreading ridge that lies on the floor of the Atlantic Ocean and extends from Bouvet Island near South Africa to just 330 km south of the North Pole, with a total length of nearly 10,000 km. The section of MAR near Iceland is called the Reykjanes Ridge and has a spreading rate of 20 mm/yr. The Iceland Hotspot is fed by the upwelling of hot material from the deep mantle[3]. Seismic studies have shown that the mantle plume beneath Iceland has a radius of ~150 km and extends from 100 km to at least 400 km depth beneath central Iceland (Fig. 2).

Rifting along the Mid-Atlantic Ridge (MAR) began with the separation of the North American and Eurasian plates ~200 Ma (Palisades Sill is part of that initial rifting). To the north, rifting occurred later, splitting Greenland from Eurasia ~90-150 Ma. Evidence in southern Greenland suggests that the Iceland plume became active ~64 Ma (oldest volcanic rocks from the plume are between 58 and 64 Ma) and was located under western Iceland by ~24 Ma as the ridge moved westward[4,5], thus making the plume considerably older than Iceland. As the northern Atlantic opened to the east of Greenland during the Eocene, North America and Eurasia drifted apart and Greenland moved westwards above the Iceland plume. Upon further plate drift and opening of the ocean basin, the plume and the mid-Atlantic Ridge approached each other. Around 24-20 Ma, part of the plume head reached the region of thinned lithosphere at the ridge. The interaction led to increased melt that eventually became subaerial, forming the Icelandic crust. The Greenland-Iceland Ridge and the Faroe-Iceland Ridge are traces of the plume head preceding the formation of Iceland.

The current configuration of the Iceland plume and MAR indicate that extensive interactions between these two geologic phenomena are ongoing. These interactions between the MAR and Iceland Hotspot produce distinct geophysical and geochemical characteristics of Iceland. The bathymetric features include the elevated topography, which is the direct result of thickening of the oceanic crust both by erupting magmas on top of it and intruding magmas near its base; V-shape ridges pointing away from Iceland are associated with slightly thickened crust. The main feature of the gravity field is a clear, negative Bouguer anomaly over Iceland with a minimum around -200 mGal near 11 central Iceland. Seismic studies have provided better constrains on the crustal thickness of Iceland. The crustal thickness in the coastal areas is ~ 15 km and increases to ~40 km under central Iceland[6,7]. Geochemical anomalies centered over Iceland include elevated $^{87}Sr/^{86}Sr$ and $^{3}He/^{4}He$ ratio isotopic ratios (Fig. 3), as well as an excessive La/Sm ratio [further discussion of geochemistry in the following section].

In short, Iceland is an island generated by the interaction between the Mid-Atlantic Ridge and Iceland hotspot. The hot mantle material directly feeds the ridge, resulting in a major thermal anomaly, abundant magma production, and distinct geochemical signatures.

References:

[1]Dyment, J. Lin, and E.T. Baker, (2007). Ridge-hotspot interactions - How mid-ocean ridges tell us about deep Earth processes, Oceanography, Vol. 20, No. 1, 102-115.

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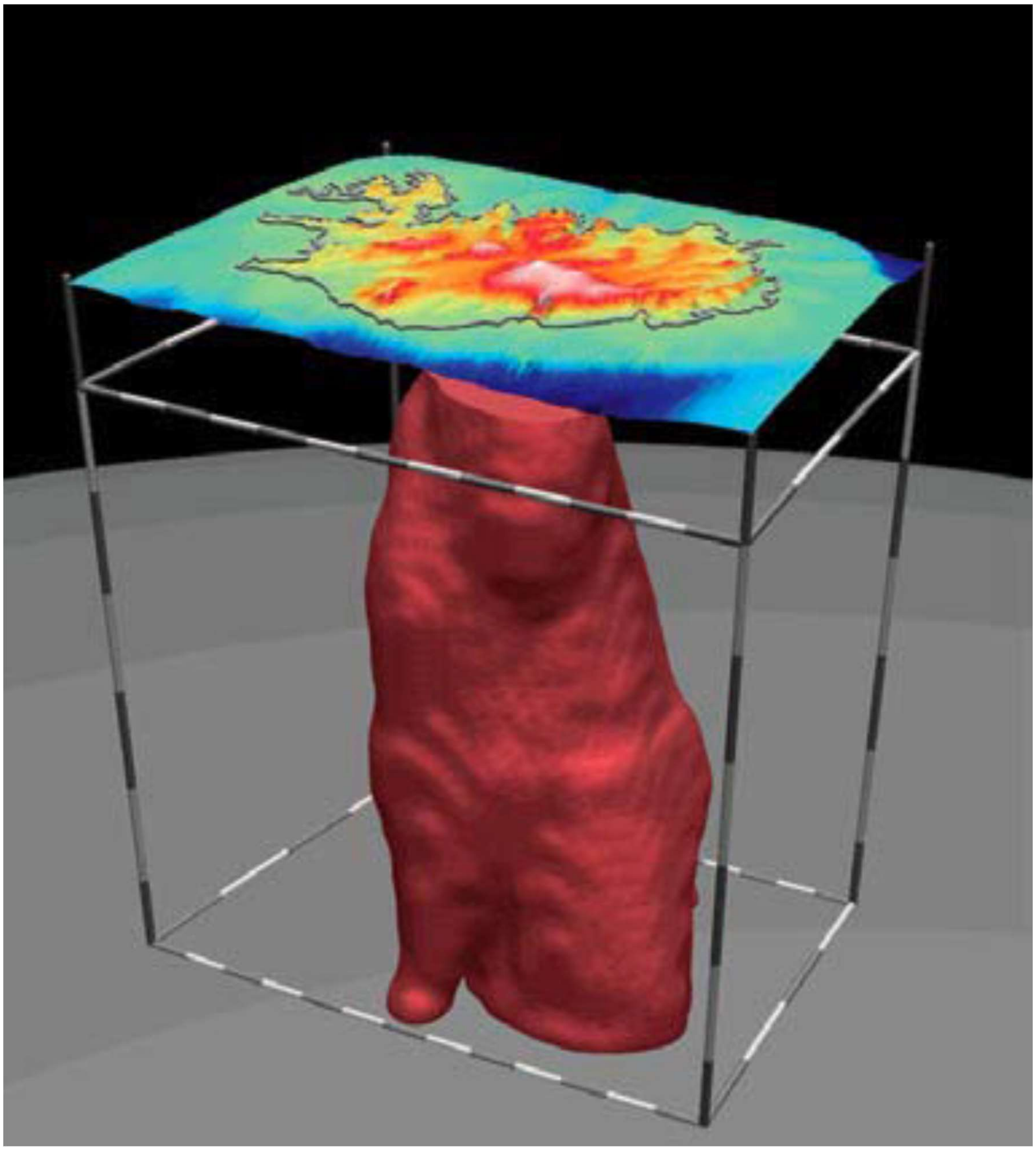

Figure 2. Seismic image of the upper mantle beneath the Iceland hotspot (Wolfe et al, 1997).

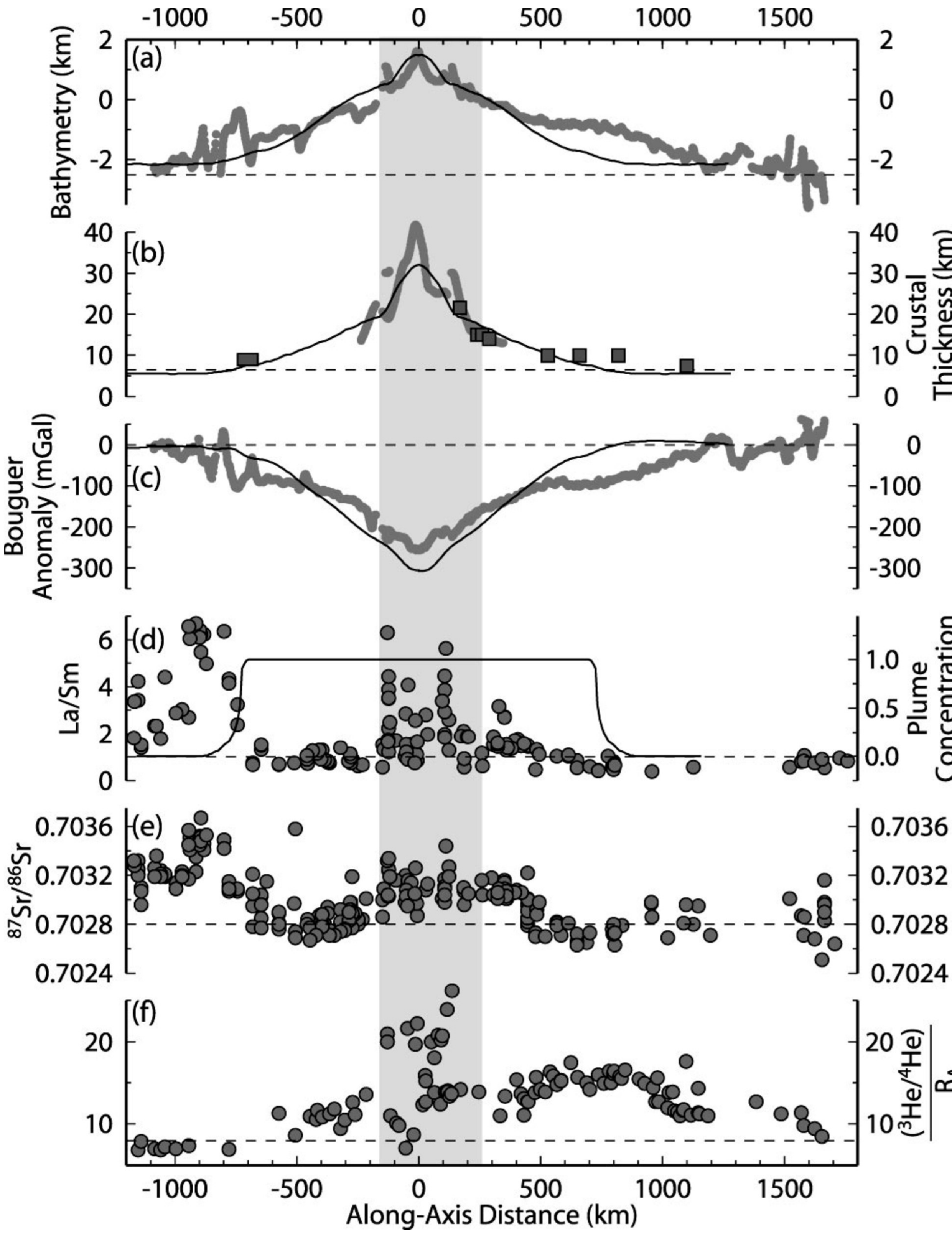

Figure 3. Profiles along the Mid--Atlantic ridge centered on Iceland of (a) bathymetry, (b) crustal thickness, (c) Bouguer gravity, (d) La/Sm ratio, (e) $^{87}Sr/^{86}Sr$ ratio, and (f) $He/^4He$ normalized by atmospheric ration. From Ito et al (2003).

Seismicity

Contributed by Pritwiraj Moulik

The relative motion of the MAR ridge (spreading ~18 mm/yr at 105º azimuth) over a hotspot moving westwards at about 9-13 mm/yr gives rise to many unique seismic and tectonic signatures in Iceland (Fig. 4). This tectonic configuration generates seismicity, which can fit into the following categories: 1) Plate boundary events in fracture zones, 2) Volcanic Zone events, 3) Earthquake swarms, and 4) Intra-plate events. These seismic signatures, apart from tele-seismic waveforms, have been exploited using various regional broadband experiments such as 'ICEMELT'[1] and in global elastic and an elastic tomography models[2,3,4] but the origin of the hotspot in the deep or shallow mantle has been a subject of debate[5,6]. The primary bone of contention in the deep mantle plume hypothesis for Iceland has been the lack of a high heat flow, a volcanic track or a seismic anomaly in the lower mantle. It may be expected that with progressively better resolutions in tomographic models, this hypothesis may be tested in the future.

The relative motions of a ridge in the hotspot frame results in ridge jumps between parallel rift zones with associated transform zones. A ridge-jump is currently in progress as the WVZ is gradually replaced by the EVZ. The volcanic zones of Iceland (Figs. 5), with the exception of the Reykjanes peninsula, are characterized by low seismicity with no observed earthquakes of magnitude larger than 5.0. The seismic zone in the Reykjanes peninsula extends from its tip to the mountain Hengill and is the seismically most active zone in Iceland[7]. The WVZ is expected to be a dying rift zone with the volcanic activity progressively more in the EVZ, but this is not evident from the seismicity (Fig. 5) as it is still active over the time scale of decades. There is evidence of a decline in volcanic productivity in the WVZ over thousands of years, but there has also been a considerable amount of rifting[8], leading to graben subsidence such as in the Þingvellir.

The volcanic zones consist of structural units called volcanic systems and each system consists of a central volcano and a transecting fissure swarm[9]. The seismicity of the volcanic zones is spatially clustered around central volcanoes while rifting structures such as fissure swarms are mostly aseismic. The activity in the Krafla volcano in the Northern Volcanic Zone has been widely studied and each phase in the magma chamber is accompanied by characteristic seismic activities: Inflation earthquakes ($M<4$), deflation earthquakes ($M<5$), rifting earthquake swarms, and tremors associated with dike intrusion and eruption at the surface. The volcanoes in central Iceland (Vatnajökull area), however, have been poorly understood owing to the thick ice sheet. Among the different central volcanoes in this belt, Bárdurbanga is the most seismically active and clusters of earthquakes preceding large, subglacial, volcanic flank eruptions have occurred there since 1974. There seems to be a temporal correlation of the earthquakes in Bárdarbunga with magmatic activity at Krafla[10], but this is debated11 and local earthquake and volcanic activity may be driving forces for the 1996 earthquakes. It has been proposed that the observations are consistent with earthquakes being generated from inflation of the shallow magma chamber along with the associated stress loading on the outward dipping cone-shape ring fault beneath the Bárdurbanga caldera[11].

The motion between these eastward-displaced volcanic rift zones and the MAR is also accommodated by the development of complex fracture zones in the north (Tjörnes Fracture Zone, TFZ) and in the south (South Iceland Seismic Zone, SISZ). The largest earthquakes ($M>7$) in Iceland tend to occur along these zones of transform motion (locations in Fig. 4) where large horizontal shearing stresses can build up. The left-lateral transform motion along the SISZ is taken up by slip on numerous parallel faults by counterclockwise rotation of the blocks between them and is an example of bookshelf tectonics[10]. The SISZ crosses some of the most populated areas and has been extensively monitored using radon measurements, volumetric strain meters, a geodetic network and a seismic network as part of the South Iceland Lowland (SIL) project[12].

Apart from the usual seismicity associated with volcanic zones and transform fracture zones, the other types of observed seismicity in Iceland include some microearthquakes from glaciers in the regional network (pers. comm., Helgi Björnsson), swarms of earthquakes, with no predominant principal earthquake (e.g. at the tip of the Reykjanes peninsula), and intraplate events (i.e. not related to the plate boundary or volcanic zones). The two primary classes of intraplate events in Iceland include events in the lithospheric block between transform zones, which may be related to crustal extension above the hotspot, and off the east and southeast insular shelf, which may be related to differential cooling rate in the crust across the shelf edge[10]. These myriad types of seismic observations make Iceland an exciting place to study the governing geological processes as well as use the data for constraining the regional elastic and anelastic structure that may ultimately resolve many outstanding questions in geophysics.

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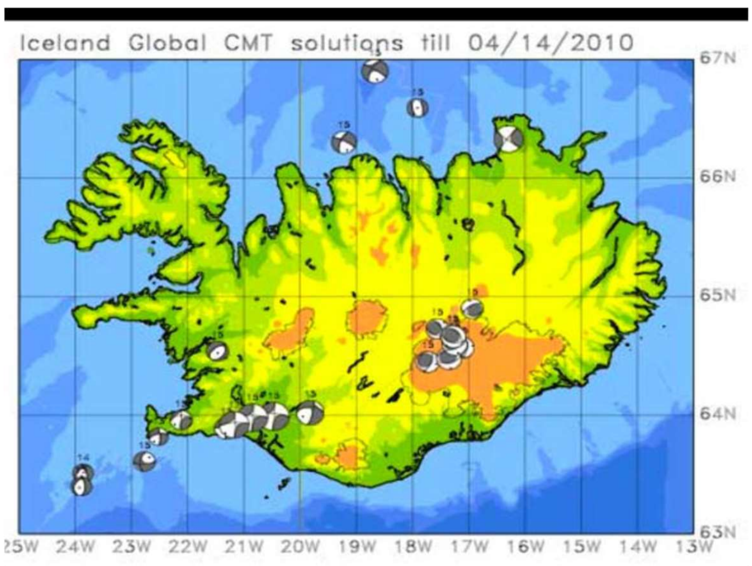

Figure 4. Iceland Global CMT solutions until 04/14/2010.

Petrology and Geochemistry

Contributed by Jason Jweda

Iceland consists of about 10% sediments and 90% igneous rocks. Most of the sediments of Iceland are typically derived from glacial advances and postglacial marine, lacustrine, and fluvial processes[1]. There are three main igneous rock formations including: 1) the voluminous Tertiary basalts which have been dated to 14 Ma and have stratigraphic thicknesses up to 10 km in eastern Iceland; 2) late Pliocene and Pleistocene basalts that are characterized by alternating hyaloclastites (ridges and table mountains erupted subglacially) and lava flows with pillows formed during interglacial periods; and 3) Holocene basalts erupted within active volcanic zones during this interglacial period[2]. Active volcanism, which occurs over ~30% of the area of Iceland, is concentrated along zones of neovolcanic rifting and two off-axis intraplate volcanic zones[3] (Fig. 5) [further discussion of volcanism in following section]. Although the majority of Icelandic lavas are basalts (~85%), rhyolites (~12%) and intermediate rocks (~3%) are present across the island, especially within large central volcanic complexes[4]. The distribution of different igneous rocks in Iceland is shown in Fig. 6.

The igneous petrology of Iceland is directly related to the volcanic zone in which lavas are erupted[5]. Basalts in Iceland can be categorized by genetic relationships called magma series that are inferred by chemical and mineralogical characteristics. The two main magma series are alkaline and subalkaline. As the names imply, alkaline rocks plot distinctly higher in $Na_2O + K_2O$ at a given SiO_2 content compared with subalkaline rocks. Based on crystallization experiments, it has been determined that to a first approximation alkaline rocks represent either very low degrees of partial melting and/or very deep sources of melting (>1 GPa ≈ 33 km depth). Subalkaline rocks can be further ubdivided into calc-alkaline and tholeiitic rocks, where tholeiites plot higher in FeO than calc-alkaline rocks on an alkali, FeO, MgO (AFM) ternary diagram[6]. In Iceland, tholeiitic basalts are almost exclusively produced at the active rift zones where there are higher degrees of partial melting whereas alkaline rocks are generally confined to the intraplate zones at the peripheries where temperatures are lower and lower extents of melting prevail. The fact that magma series are related to tectonic setting provides us with some clues as to the sources and processes that have generated the Icelandic rocks.

Isotopic ratios and elemental abundances of volcanic rocks serve as tracers of mantle processes and fingerprints of source contributions. Mid-ocean ridge basalts (MORBs) are characterized by relatively depleted incompatible element abundances (light rare earth elements, K, Rb, and Nb) and low but relatively homogeneous $^{87}Sr/^{86}Sr$ isotopic ratios. For this reason, MORBs are thought to be derived from melting of a homogeneous upper mantle depleted by repeated melt extraction. On the other hand, ocean island basalts (OIBs) not only have quite variable but also characteristically enriched incompatible and isotope values (such as Sr, Pb and He).

One of the most striking features of Icelandic basalts is that incompatible elements and Sr isotopes vary with latitude across Iceland[7]. Moving along the mid-ocean ridge toward the proposed mantle plume locality in central Iceland (currently under western Vatnajökull), incompatible elements and Sr isotope ratios generally become progressively enriched[8,9] (Fig. 3d,e). Fractionation-corrected major elements Fe and Na indicate that pressure and degree of partial melting also anomalously increase toward central Iceland[10,11]. This unique geochemistry has led to the conclusion that there exists a basic binary mixing relationship between “depleted, MORB-like” and “enriched, OIB-like” endmembers in erupted lavas[7]. Seismic indicators and geo-barometers, as well as the high incompatible abundances and isotope (especially $^3He/^4He$, Fig. 3f) ratios, suggest that “enriched” magmas sample a deep, high temperature, enriched (or at least un-depleted) mantle source whereas the “depleted” magmas are derived from extensional melting along the ridge.

Recent Pb isotope studies have furthered our understanding of Icelandic mantle heterogeneity and suggest that the simple paradigm of a binary mixing between depleted mantle MORB sources and the enriched mantle plume is actually more complicated. Pb isotopes (Fig. 7) show that there is a third component, probably recycled oceanic crust dispersed throughout the mantle below Iceland, that is incorporated into the Icelandic basalts[12]. The recycled oceanic crust appears to consist of abundant but variable ecologites and garnet-bearing pyroxenites that undergo decompression and/or small degrees of partial melting. Interestingly, different volcanic systems produce homogeneous but distinct isotopic ratios suggesting that either the mantle is heterogeneous at a scale sampled by volcanoes or melts from variable mantle components are homogenized in magma chambers below volcanic edifices.

The origin of silica-rich rocks in Iceland such as rhyolites have confounded researchers for decades. Although it was once thought that rhyolites were formed by partial melting of older granitic basement rocks, Sr isotopes of rhyolites are nearly indistinguishable from those of basalts. Since there is relatively little time difference between eruptions of basalts and rhyolites at some Icelandic central volcanoes, the same Sr isotope values indicate that lavas originated from either the same magma source (fractional crystallization) or from different sources with the same Sr isotopic ratio[13]. The most likely explanation for the origin of rhyolites is the reprocessing of Icelandic crust below thick crust central volcanoes. Silicic rocks are produced by melting of gabbroic intrusions and other buried portions of the Icelandic crust at large central volcanoes and enriched by fractional crystallization, crustal assimilation, and hydrothermal alteration[4]. Central volcanoes occur in regions of thicker crust and elevated crustal temperatures (due to high magma supply) thus providing ample opportunity for magma pooling, crustal melting, and survival of long-lived crystal mushes [4,13].

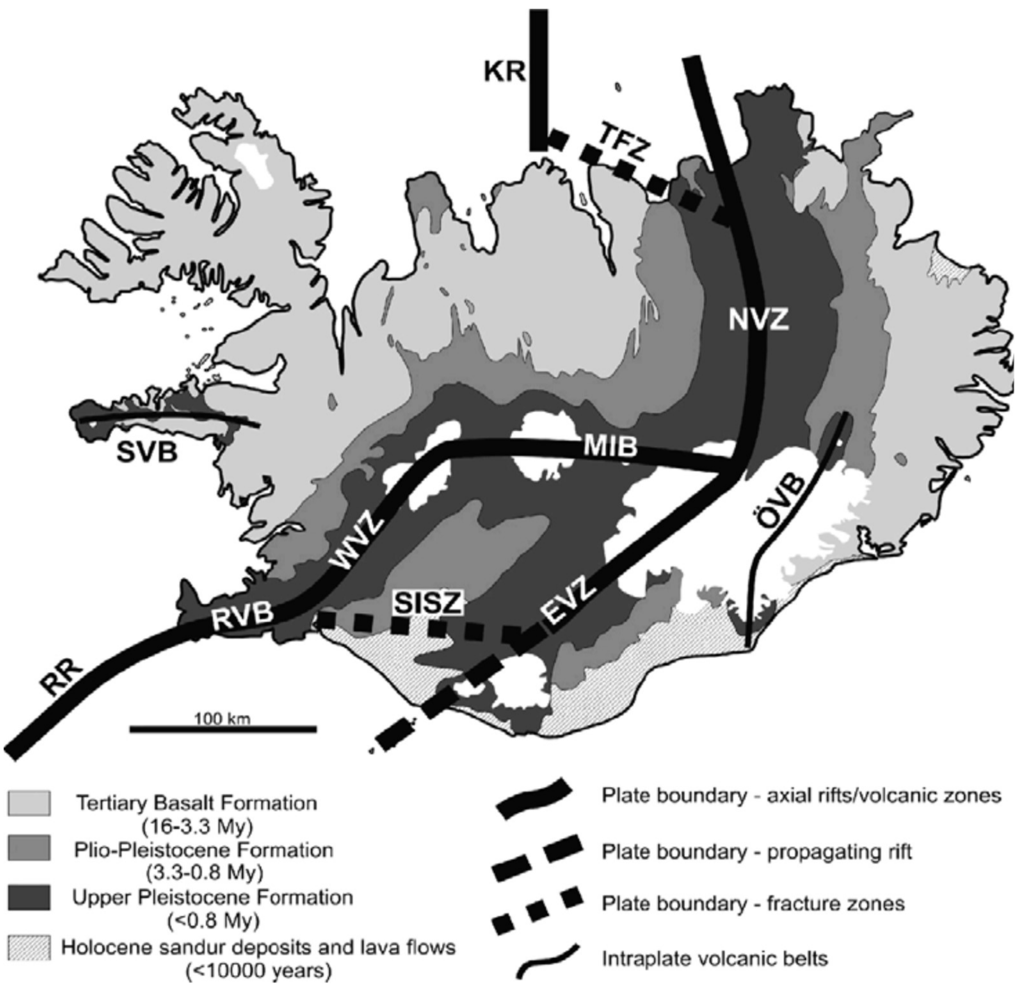

Figure 5. General Areas of Icelandic Volcanism (from Thordarson and Larsen, 2007).

RR – Reykjanes Ridge, RVB – Reykjanes Volcanic Belt, SISZ – South Iceland Seismic Zone, WVZ – West Volcanic Zone, MIB – Mid Iceland Belt, EVZ – East Volcanic Zone, NVZ – N

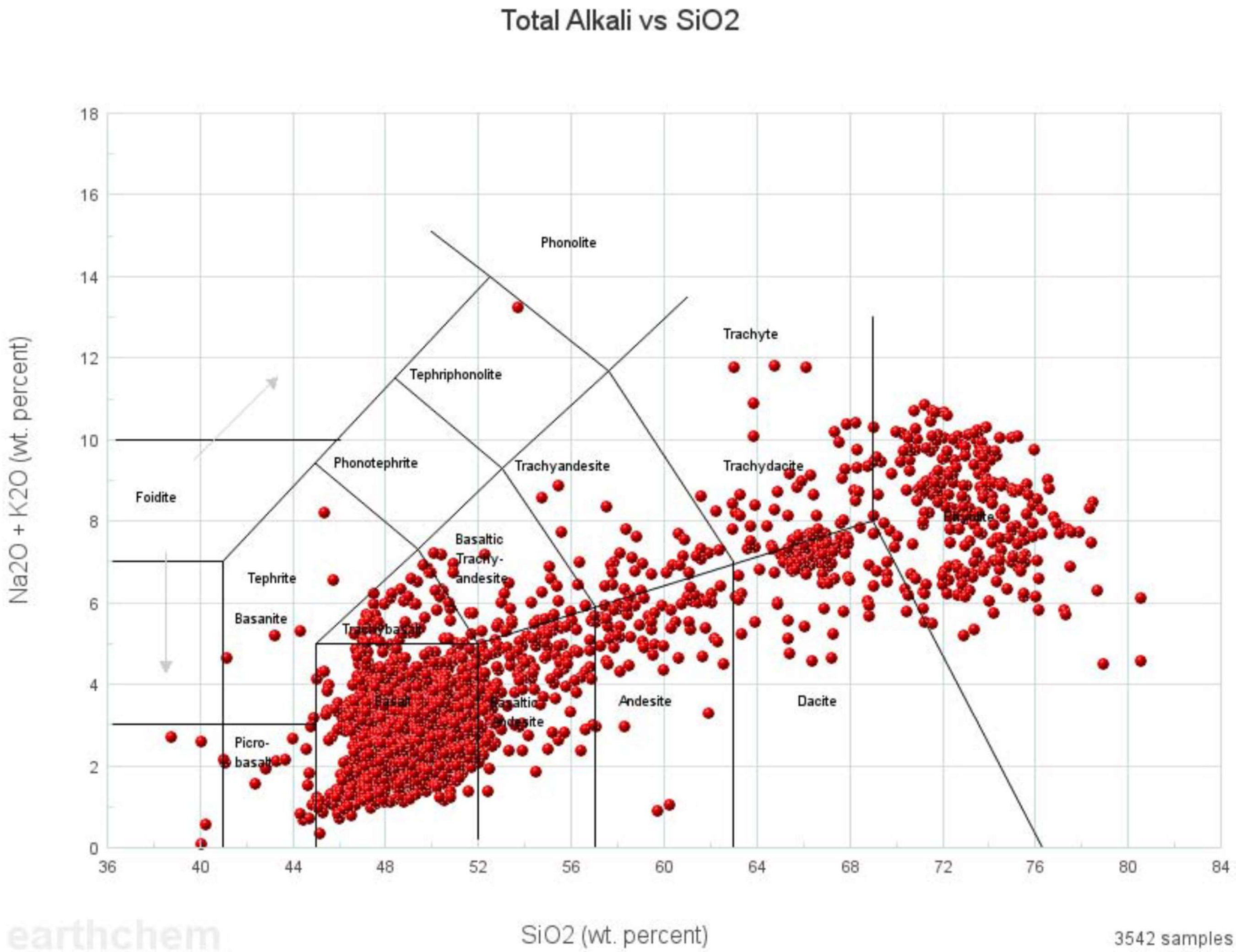

Figure 6. Classification and distribution of igneous rocks from Iceland (from Earthchem).

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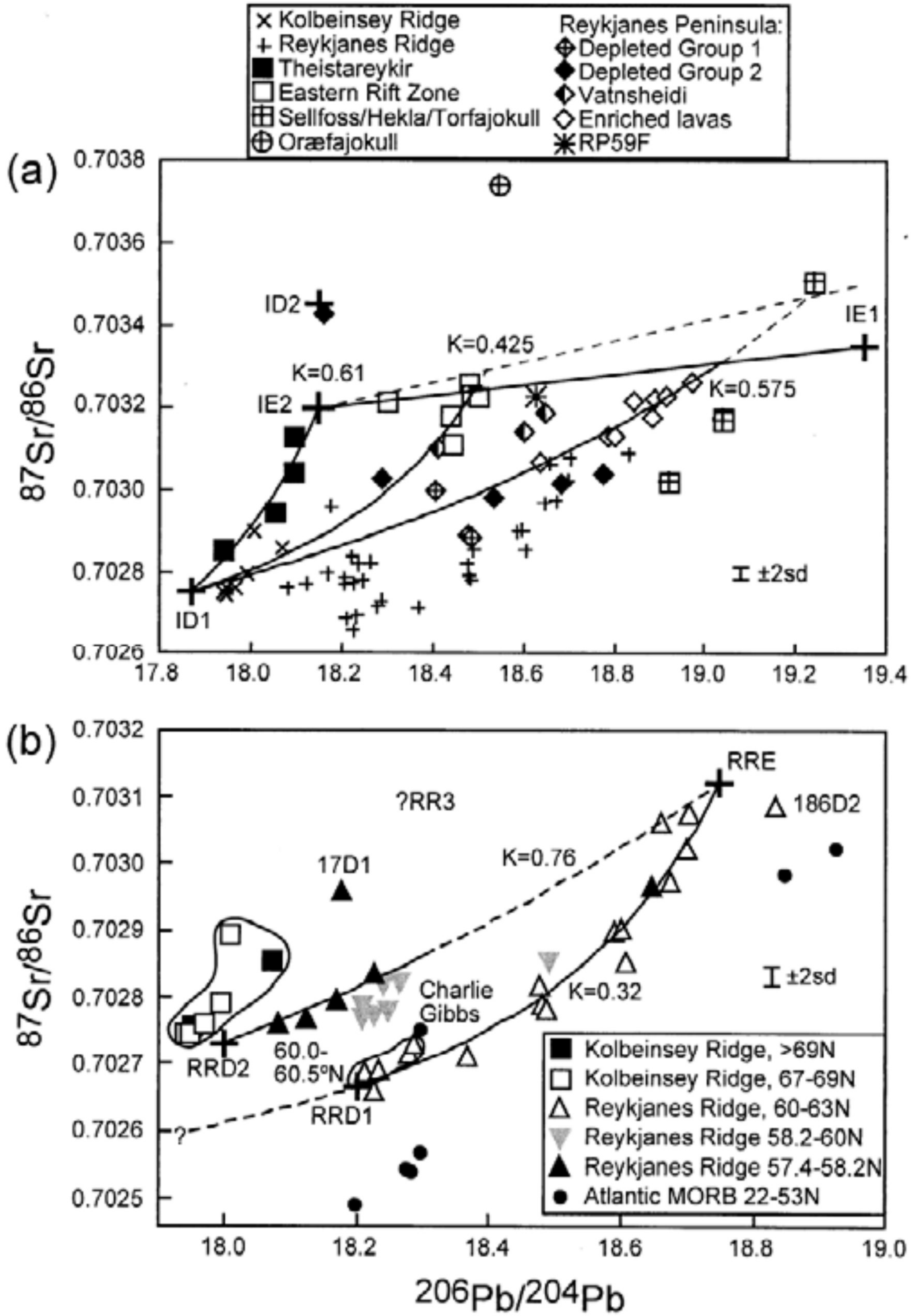

Figure 7. $^{206}Pb/^{204}Pb$ vs. $^{143}Nd/^{144}Nd$ showing mixing components for Icelandic magmas. Mixing endmembers include the enriched plume source IE1, a low Pb enriched endmember IE2, and the widespread depleted upper mantle endmember ID1. (from Thirwall et al., 2004).

Icelandic Mineralogy and Geochemistry

Contributed by Danielle Sumy

Volcanic rocks cover about 8% of the world's surface, and about half of that is basalt. Areas like central Iceland, which has a lot of exposed basalt and few inhabitants, are ideal to study the chemical weathering of Ca-Mg silicates. The weathering of Ca-Mg silicates is important for studying the CO_2 budget, and the weathering of basalts is important to understanding early Earth environments (Gisalson & Armannsson 1994).

Mars, like early Earth, is covered in volcanic rocks. The signature red dust that coats the surface of Mars is likely to be an alteration product of basalt, not rhyolite. The palagonitization of basalt has been suggested as a means to produce the red soils of Mars (Bishop et al. 2002). Palagonite is the product of alteration of basalt by water. Palagonitized tuff is very common on Iceland as a subglacial deposit. It is found as a resin-like red orange coating surrounding basaltic glass (Stroncik & Schmincke 2002).

The large amount of palagonite-like dust of Mars suggests that it may be widely altered, and its presence is used to argue that large amounts of water were present on Mars, although the relative lack of clay minerals suggests that water-rock interactions may have been limited (Michalski et al. 2005).

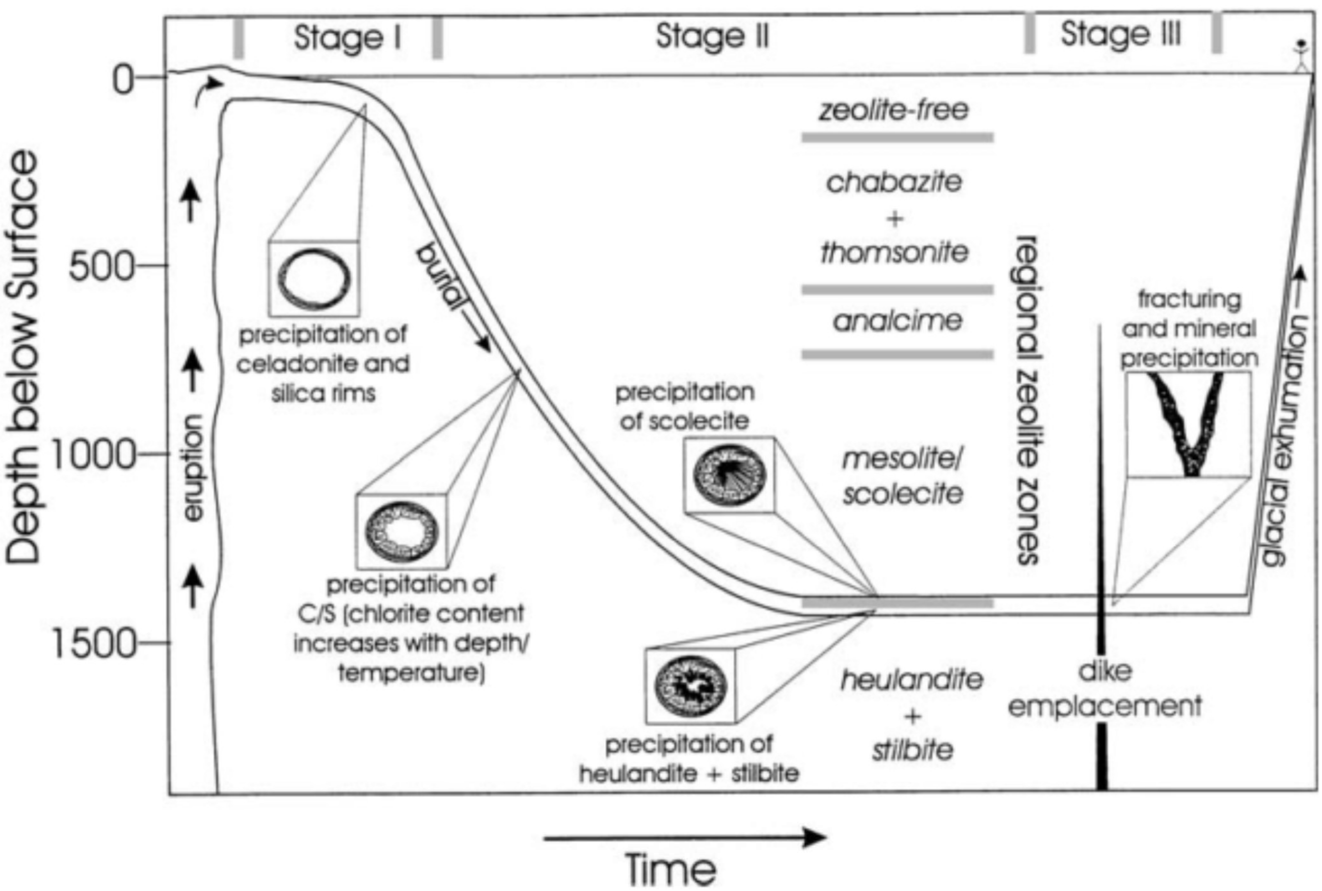

Fig. 13. Spatial and temporal development of pore-filling mineral assemblages at Teigarhorn. The vertical axis depicts depth below land surface at the time of each event depicted in the figure. Time elapsed after eruption increases to the right. No scale is implied on the horizontal axis. The parallel curves on the figure are boundaries of the lavas exposed at Teigarhorn in space and time. Note that the timing of dike emplacement is meant to infer only the timing of dikes associated with Stage III alteration at Teigarhorn.

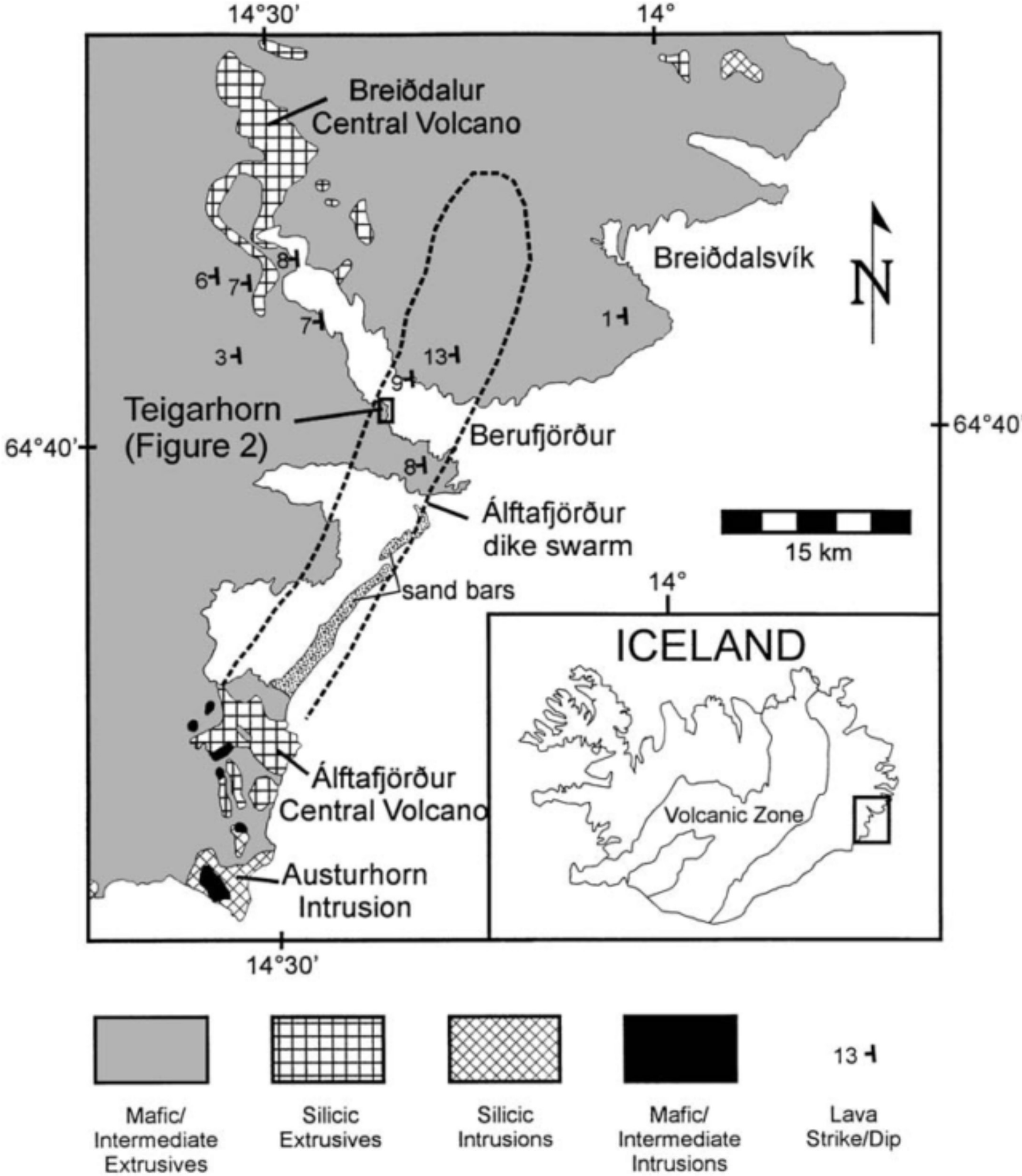

Fig. 1. Generalized geological map of a portion of eastern Iceland (after Jóhannesson and Sæmundsson, 1989) showing the distribution of major rock types, locations of intrusions and central volcanoes, and selected lava orientations from Walker (1963, 1974). Dashed curve outlines the Álftafjördur mafic dike swarm where dikes make up greater than 8 percent (by volume) of the crust (Walker, 1963).

Another famous alteration product is found in eastern Iceland. Zeolites are tectosilicate minerals with hydrated aluminosilicate frameworks that are loosely bonded to alkali and alkali earth cations. The water molecules and large cations occupy the large channels and cages present in all zeolite structures. Zeolites are a highly variable group of minerals, as up to 50% of silicon and aluminum can be replaced by phosphorus and beryllium. Exchange of cations and dehydration can be induced at relatively low temperatures (below 100°C for exchange and between 250°C and 400°C for dehydration) (Tschernich 1994). Once dehydrated, zeolites will absorb water at room temperature. This property is extensively utilized as an industrial desiccant.

Zeolites are formed in a range of environments, from dry lakebeds to cooling basalt flows. They are also formed as a result of low-grade metamorphism. In Iceland, they are formed as the result of regional hydrothermal metamorphism and burial metamorphism (Tschernich 1994, Neuhoff et al. 1999). Often, basalt flows in Iceland are subject to multiple stages and types of alteration. At Teigarhorn, coastal erosion has exposed famous zeolite rich outcrops produced by a multistage process.

If you examine the amygdules at Teigarhorn, you may see green and white rims around the edges. This is the first alteration product, celadonite (a green layer silicate) and quartz. No zeolites have formed at this stage yet. As the flow is buried by another basalt flow, chlorite and smectite forms, then zeolites precipitate. The type of zeolite produced is very sensitive to depth, and the zeolites here can be used a barometer (Neuhoff 1999).

The large, euhedral zeolites for which Teigarhorn is famous were formed by hydrothermal alteration caused by the Álftafjörður mafic dike swarm after burial. The most common large crystals found here are stilbite, heulandite, mordenite, scolecite and laumontite. Iceland spar calcite and euhedral quartz crystals may also be found (Neuhoff et al. 1999). Zeolites formed by these dikes are found throughout most of the area where the dikes are, in a swath from Álftafjörður to Breiðdalsvík. Exposures along the coast of Berufjörður are particularly

Zeolites are often quite distinct in the field, although they are almost impossible to distinguish from one another. Their crystal habit, which ranges from fans and blades to fine needles to blocky, is quite distinct from quartz and calcite. But, each mineral species may be a variety of colors and forms, and the overlapping physical properties make it difficult to tell which zeolite is which without further analysis.

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Volcanism

Contributed by Danielle Sumy

The construction of Iceland began ~24 million years ago[1,2,3,4,5] as a result of the volcanism that has occurred due to the interaction between a mantle plume and the eastwest spreading Mid-Atlantic Ridge that runs through the island[6,7,8,9,10]. Volcanism in Iceland is diverse, and has featured nearly all volcano types and eruption styles known on Earth[11,12].

The current distribution and arrangement of active volcanism in Iceland can be described by six major neovolcanic zones, or discrete 15-50 km wide belts of active faulting and volcanism[2,3,5,6,13,14] (see Fig. 5 for locations). The West (WVZ) and North (NVZ) Volcanic Zones are linked by the Mid-Iceland Belt (MIB) and linked to the Mid-Atlantic Ridge by the Reykjanes Volcanic Zone (RVZ) in the south and the Tjornes Fracture Zone (TFZ) in the North. The East Volcanic Zone (EVZ) is currently the most volcanically active region in Iceland and hosts the four most active volcanic systems (Grimsvötn, Bárdarbunga-Veidivötn, Hekla, and Katla) which have produced ~80% of all verified eruptions. The EVZ is an axial rift in the making, and will eventually take over for the WVZ as the ridge jumps eastward. There are also two active intraplate volcanic belts (the Öræfi and Snæfellsness Volcanic Belts) that account for only ~1.5% of the verified eruptions in Iceland. Collectively, these regions cover ~30,000 km^3 or about one third of Iceland.

Most of the volcanic systems consist of a fissure (dike) swarm or a central volcano or both, and have a typical lifetime of 0.5-1.5 million years[1,2,15,16]. The fissure swarms are elongate features that tend to align sub-parallel to the volcanic zone, and the central volcano, when present, is the focus of eruptive activity and is typically the largest edifice within the system. Jóhannesson and Sæmundsson [1998] identified 30 volcanic systems within the active volcanic zones of Iceland; 20 of these systems feature a fissure swarm, while 23 central volcanoes crown another 19 volcanic systems[17]. Individual systems range in length from 7 to 200 km and 25 to 2500 km^2 in area. Volcanism on each of these systems is intrinsically related to plate spreading, which is not a continuous process. Rather plate spreading occurs as discrete events that are localized to a single volcanic system at any one time, although near-concurrent activity on two or more systems has been witnessed[18,19,20,21,22,23]. Normally, the whole system is activated in episodes that can last from several years to decades, and are called 'Fires' (e.g. the Krafla Fires of 1975-1984).

The overall architecture of a volcano is primarily determined by the type of magma erupted, its eruption behavior, the shape of the vent system, and the environmental setting (i.e. subaerial, subglacial, or submarine). Central volcanoes in Iceland are constructed by repeated eruptions from a central vent system that is maintained by a long-lived plumbing system. They are built by a succession of alternating lava flows and volcaniclastic deposits. 10 of the 17 presently active central volcanoes, i.e. those active during the Holocene (past ~10,000 years), are largely constructed by subglacial eruptions[16,24,25,26,27].

The basaltic volcanoes of Iceland are classified based on their vent form and the nature of their vent products[12]. Note that approximately 80% of the 87 km^3 of magma that has erupted over the past 1100 years has been basaltic in composition. The vent systems are categorized based on their geometry (either linear or point source) and their deposits (lava, clastogenic lava, spatter, scoria, or ash). The type of deposit is dependent on the eruption style (effusive or eruptive) and environment (subaerial, subglacial, or submarine). For central vent systems (point source), shield volcanoes, spatter rings, and scoria cones are common in the subaerial magmatic environment, while tephra cones and maars form in the subaerial phreatomagmatic environment. Tuyas or table mountains form in the subglacial or submarine environments. For linear systems, craters form in the subaerial magmatic case (e.g. Laki craters), and all other linear features are simply a row of their central vent system counterparts.

The volcanic systems of the EVZ are responsible for 137 of the 172 verified events, or 80% of all eruption activity. 132 of those 137 events were produced by the four most active volcanic systems on the EVZ, namely Grímsvötn, Hekla, Katla, and Bárdarbunga-Veidivötn. Here, we elaborate on these four volcanoes as well as the latest eruption of Eyjafjallajökull in the spring of 2010. Grímsvötn last erupted in 2004, and is Iceland's most active volcano. Grímsvötn is the central volcano of the Laki fissure system in the south of Iceland, beneath Iceland's largest ice cap, Vatanjökull. Hekla is a stratovolcano that is forming at a rift-transform junction. Hekla exhibits a 5.5 km long fissure that cuts across the volcano, and the fissure is often active during major eruptions, the last of which occurred in 2000. Katla is a subglacial volcano with a large caldera. It is extremely active with eruptions occurring from fissures inside the caldera. Katla is one of the largest tephra producers in Iceland during historical times, with the last major eruption occurring in 1918 and a possible event that did not break the overlying glacial ice in 1955. Bárdarbunga-Veidivötn is a stratovolcano with a subglacial caldera that exhibits large fissure eruptions, with the last known eruption occurring in 1910. An eruption between the Bárdarbunga-Veidivötn and Grímsvötn systems occurred in 1996. Anomalous seismic activity, recorded from 1976-1996, in this region show that earthquakes were generated during the inflation of the magma chamber. The last event coincided with the start of the eruption[28]. This seismicity suggests there is some degree of connectivity between the Bárdarbunga-Veidivötn and Grímsvötn volcanic systems.

Eyjafjallajokull, which translates to island-mountain-glacier, is an E-W trending elongated ice-covered stratovolcano with a 2.5 km wide summit caldera. The last historical eruption before the 2010 event was from 1821-1823. In 2010, prior to any eruption, measured deformation and increased seismic activity began. In March, a 500 m long fissure with lava fountains became active 9 km from the central caldera. In early April 2010, the eruption ceased from the original fissure; however, in mid-April, an eruption began from a new vent on the southern rim of the caldera. Meltwater from the overlying glacier flowed to the north and south, and caused flooding in the surrounding areas. On May 24, 2010, the Icelandic Meteorological Office indicated that the volcano was no longer emitting ash and that the eruption had stopped. This eruption may only be the first in a series of eruptions, however, and may have several eruption cycles not unlike those of the Krafla Fires of 1975-1984.

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Columnar Basalts: Morphology and Processes

Contributed by Sarah Slotznick

Columnar Basalts: Summary

Columnar basalts are found on every continent and throughout Iceland such as in Hreppholar/Hreppar area (Mattson et al. 2011, Bosshard et al. 2012, Almqvist et al. 2012, Forbes et al. 2014), Hjálparfoss and Gjáin (Lyle 2000, Forbes et al. 2014), Dverghamrar, Gerðuberg, Hljóðaklettar, Kirkjugólfíð, Reynishverfi (Hetényi et al. 2012) and Svartifoss (Guy 2010, Hetényi et al. 2012, Tanner 2013). In addition to tiers of long equal-sized parallel columns and regular polygonal fracture patterns, these sites exhibit smaller surface morphologies such as horizontal striations, plumose hackles, inscribed circles, and concentric ring features. Based on the morphological observations, petrography, in situ observation, experiments, and numerical modeling, there are four models for the formation of columnar basalts and their internal structures: 1) thermal contraction potentially with a) water interactions for entablature and/or b) pressure and crystallization-induced melt migration with viscous fingering 2) double diffusive convection or constitutional super-cooling.

Columnar Basalts: Morphology and Processes

Columnar joints consist of long colonnades/columns with locally parallel axes and regular polygonal fracturing. They regularly occur in subaerial basalt flows, but also can occur in lavas of other chemistries. The columns can range in scale from centimeters to meters in diameter and can extend through an entire flow unit up to ~ 30 meters, although usually they are in two or more tiers of jointed

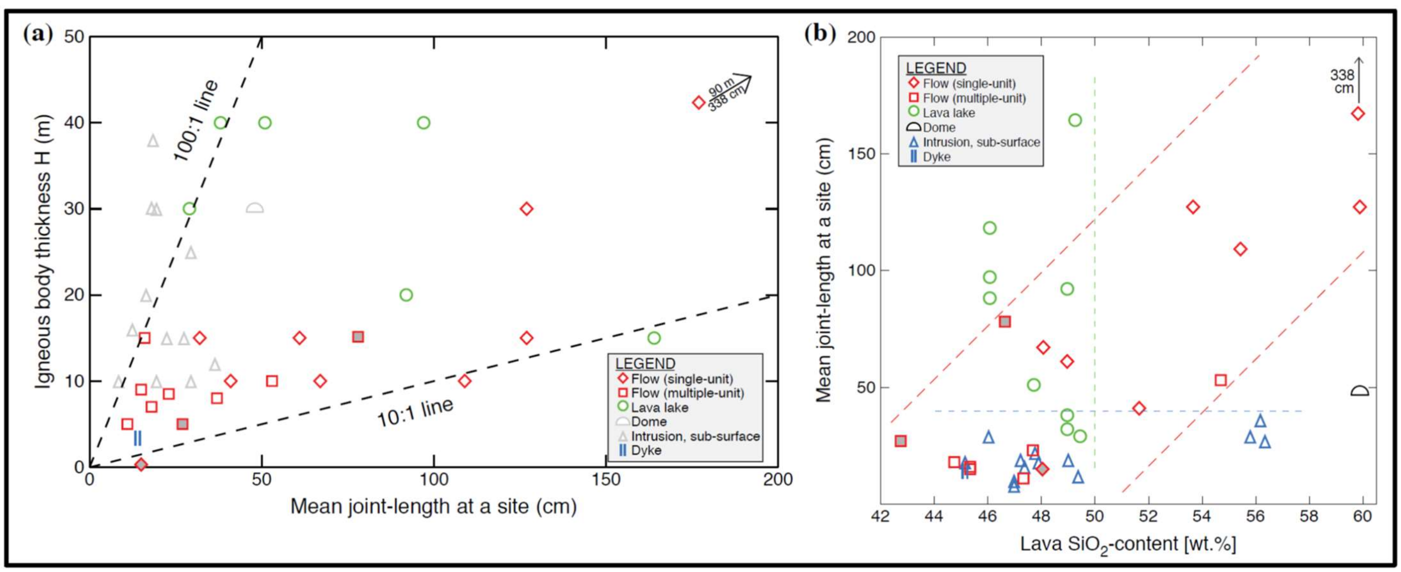


Figure 1: a) Igneous body thickness versus the average side length of columns at 50 different columnar jointing sites in 3 countries. Note that erosion and partial exposure might have reduced the thickness of H and the thickness of the dike site was divided by 1.5 to compare to free flows. Symbols filled with grey are sites where the flow type could not be readily established and guesses were taken. b) Mean side length of a column at each side and Lava SiO_2 content in wt%. Upper limits for intrusions and lava lakes is shown with dashed lines of corresponding colors. The long-dashed red lines are the best fit correlations between jointing side length and SiO_2 content. (from Hetényi et al. 2012)

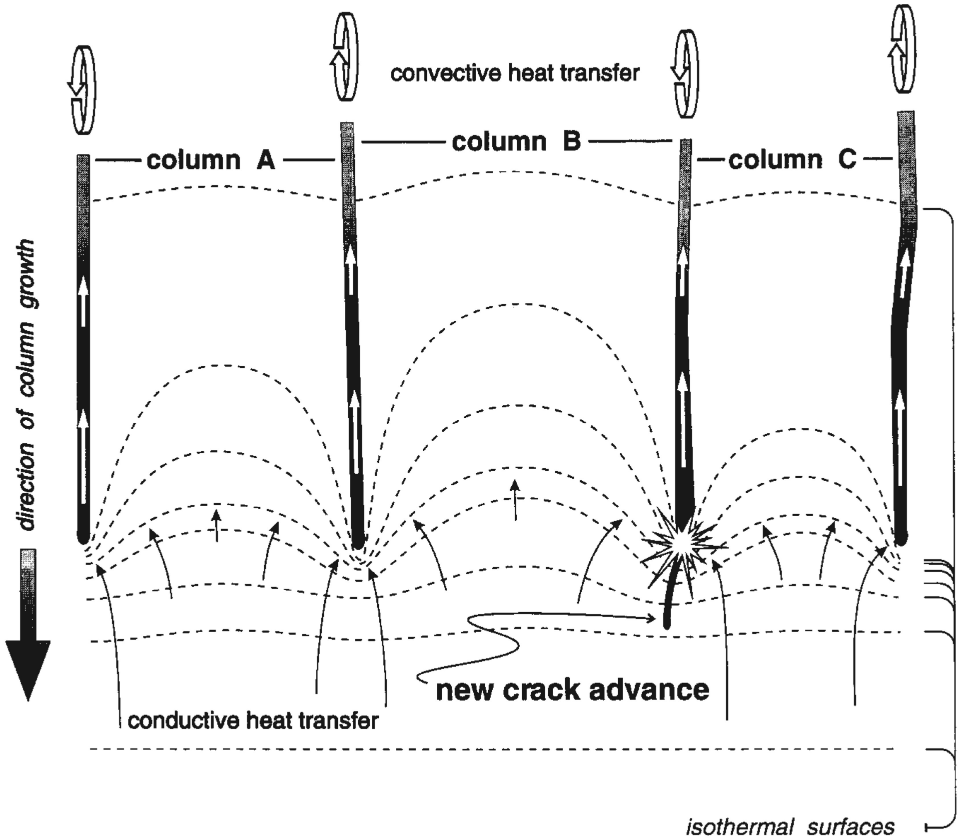


Figure 2: Sketch detauling hypothesis to explain equal-size distribution of columns within a flow unit. (from Budkewitsch and Robin 1994)

columns up to many 10s of meters (DeGraff and Aydin 1987, Grossenbacker and McDuffle 1995). The basic model for understanding how these columns form is through thermal volume contraction as the basalt cools from its two contact surfaces. Stress will accumulate as the temperature falls below that of elastic behavior. When this stress exceeds the tensile strength, tensional cracks will form at the margins of these flows perpendicular to their boundaries and propagating inward (DeGraff and Aydin 1987, Budkewitsch and Robin 1994). Isotropy of the crack pattern suggests that contraction occurs equally in all directions during the jointing (Budkewitsch and Robin1994).

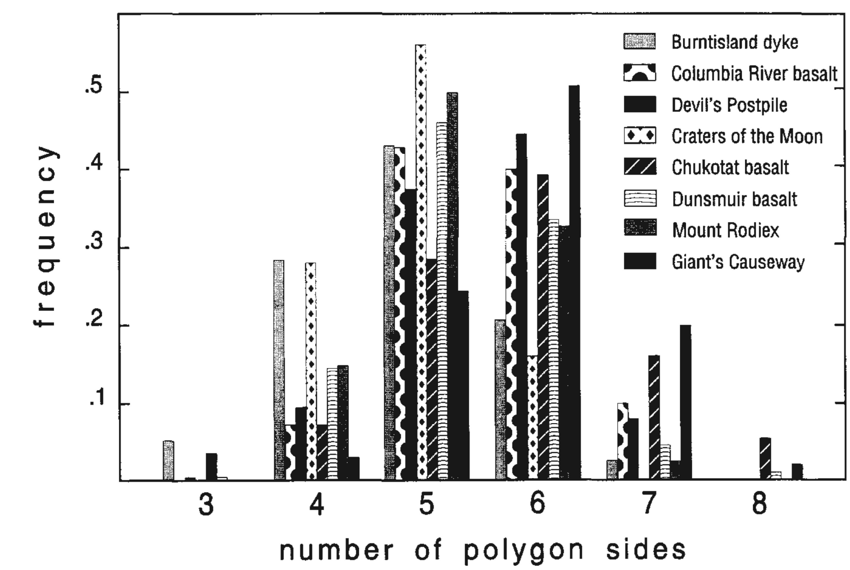


Figure 3: Distribution of number of sides on polygonal cross sections of worldwide columnar basalts. (from Budkewitsch and Robin 1994)

Most studies suggest the diameter of the columns is proportional to the cooling rate, i.e. large thick columns have slower cooling times (Ryan and Sammis 1978, Long and Wood 1986, Grossenbacker and McDuffle 1995). However, recently the column diameter/aspect ratio was linked instead to the geology setting and chemistry of the columnar bodies. When geology constrains the geometry emplaced body such as in dikes and intrusive bodies, columns are thinner; in unconstrained geometries such as lava flows, chemistry becomes important with increased SiO_2 content creating thicker columns (Figure 1, Hetényi et al. 2012). The diameter of the columns is fairly regular throughout a flow; one hypothesis is that while the cracks propagate downward, they deviate parallel to the highest thermal gradient to maintain and achieve an overall uniform size (Figure 2, Budkewitsch and Robin 1994).

Although normally pentagonal or hexagonal in cross section, the columns can have three to eight sides. Columnar basalts around the world contain slightly different, but overall similar, distributions of number of sides (Figure 3, Budkewitsch and Robin 1994, Hetényi et al. 2012). The most common joint intersections are those of T's, Y's, and X's; immature flows contain more T and X junctions – thus quadrilateral polygons. More mature flows contain more Y junctions – thus increasing the sides on the polygons (hexagonal being the maximum if all the Ys were perfect 120°) (Gray et al. 1976, Aydin and DeGraaf 1988). This joint evolution can be modeled by Voronoi tessellation around anticlustered centers (space-filling polygons with distant centers), crack propagation, and thermal gradients to show that any initial crack pattern will mature into a quasi-hexagonal pattern (Budkewitsch and Robin 1994). Although approaching perfect hexagons, the patterns do not mature enough to reach this stage (with average number of sides <6). The polygon column cross-sections also have smaller areas than regular polygons at all side numbers (aka their centroids are not the Voronoi center) (Figure 4). Based on numerical modeling, it is suggested that joint evolution slows down after a certain point and an increasing large number of cracks are needed to form a more regular hexagons, reaching a natural limit based on cooling rates (Budkewitsch and Robin 1994). It has also been suggested that the jointing process isn't in equilibrium and inertia, heterogeneities, or environmental constraints (such as cooling rate) prevent a perfect hexagonal network from forming (Hetényi et al. 2012).

Understanding the tiering pattern found in columnar basalt outcrops has also been of interest to scientists. As discussed before, singly tiered lavas can be up to 30m thick, normally any flows larger become multi-tiered systems. These systems often consist of an upper colonnade, entablature, lower colonnade and sometimes a basal pillow zone or breccia at the bottom (Figure 5, Long and Wood 1986). Entablature is a zone of irregularly oriented columnar joints, curved fracturing, and small cube-jointing. It is suggested that the interaction of columnar joints and pseudopillow fracture systems (with a master fracture and several smaller ones) creates the jointing seen in entablature (Forbes et al 2014). Some systems only have two tiers with colonnades that do not match up, and it is noted that the downward growing joints meet the lower colonnade well below the middle of the tier. This rapid cooling of the upper portions compared to the lower portions could be due to the convection of water from the surface through the columnar joints to aid in cooling (DeGraff and Aydin 1987). Several studies on the petrography of entablature show textural signs of quenching compared to the lower colonnade. In multitiered columnar basalts around the world, evidence of paleo-river valleys, damming of paleo-drainages, high rainfall/evidence of surface water, and associated lacustrine or fluvial sediments suggest that surface flooding of the cooling lava flow due to displaced drainages is the cause behind this multi-tiered architecture (Long and Wood 1986, Lyle 2000, Forbes 2014). Most of the water enters along the master fractures in the pseudopillow fracture system, and cube-jointing likely forms when more water enters the lava (Forbes et al. 2014).

In addition to these large-scale features, scientists have noted several other surface features on the faces and parting surfaces of columns to help understand the details of the processes forming columnar basalts. Horizontal striations or banding are often seen around the entire perimeter of the columns, although sometimes they are vertically offset between faces (Figure 6a,c). The striations are on the order of cms to 10s of cms. Two different mechanisms have been used to explain striation thickness: 1) Striation height varies inversely with the thermal gradient developed during cooling (Grossenbacher and McDuffle 1995), and 2) striation thickness correlates inversely with the velocity of the cooling front (Goehring et al. 2009). The horizontal striations are interpreted to be a stepwise propagation of the

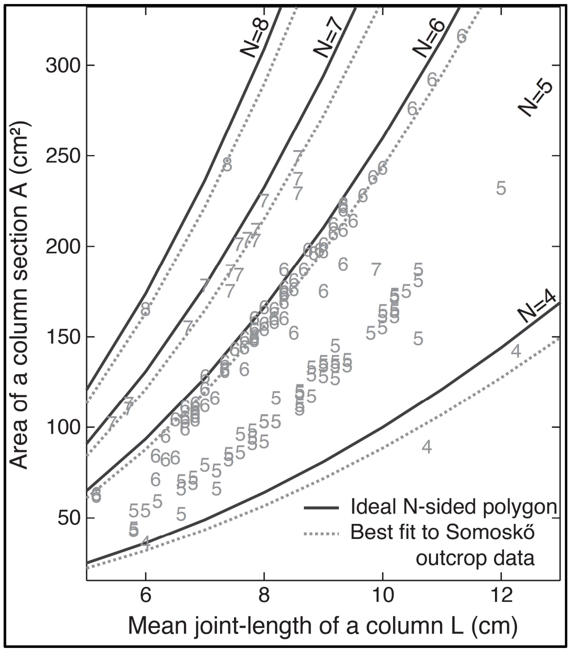


Figure 4: Cross sectional area of a column versus the mean side length of a column from one site. Each point is labeled by a number to indicate the number of sides on a column. Solid black curves show the theoretical curve for different n-sided regular polygons, while dotted grey curves show the best fit curves to the data (anchored at the origin). (from Hetényi et al. 2012)

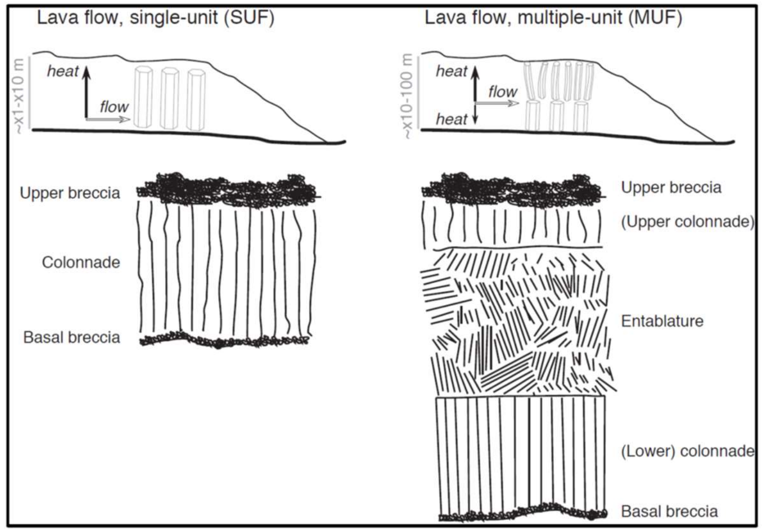
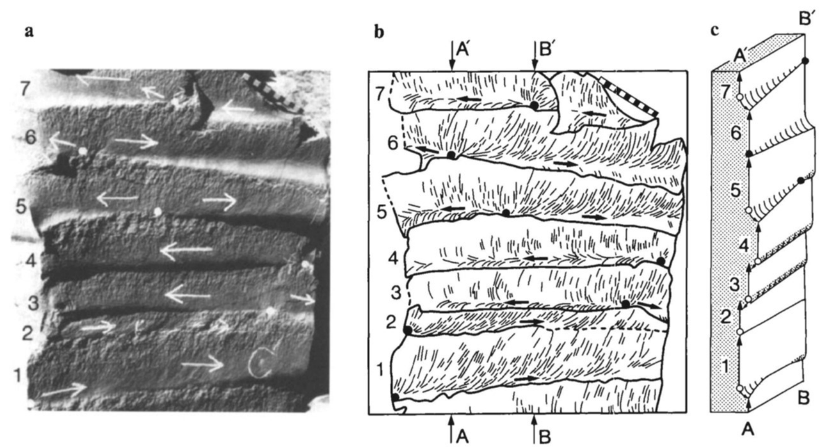


Figure 5: Diagram showing columnar basalt at the outcrop in single unit flows/single tiers and in multiple-unit flows. (from Hetényi et al. 2012).



polygonal fractures (Ryan and Sammis 1978, Budkewitsch and Robin 1994). Often each striation contains a smooth and a rough surface which is suggested to be formed by alternating brittle elastic and non-elastic incremental failure as the crack propagates into hotter regions which are more ductile but which then cool due to the new crack exposure (Ryan and Sammis 1978).

Within the horizontal striations, but rarely visible in the "rough" part, are crescent hackles also called a plumose structure (e.g. Figure 6b), which commonly reverses direction from one striation to the next. Originally interpreted to be relicts of rotational shear during thermal contraction (Ryan and Sammis 1978), DeGraff and Aydin (1987) reinterpreted them as having formed during crack propogation, starting at a point of weakness for the fracture origin and radiating away in the direction of propagation. Thus these plumose structures can also be used to aid understand the direction of growth in basalt columns.

On the flat cross-sections of the columns, there is often an inscribed circle with relief of a few mm above or below the rest of the parting surface often only a small rim. Radiating hackles are seen within the circle coming from a central point (Figure 7, Tanner 2013, Guy 2010). Tanner (2013) suggests that these hackles are similar to the plumose structures described earlier formed by tensile stresses in the column and that the circle and periphery are due to differences in tensile strengths of the early crystallized outer column and slower cooling interior of the column. Guy (2010) doesn't believe that these hackles come

Figure 8: Example of the internal compositional rings and fingers found in basalt columns from photos and sketches of the photos. Scale bar is b) 15mm, c) 5mm, f) 52cm. (from Mattson et al. 2011)

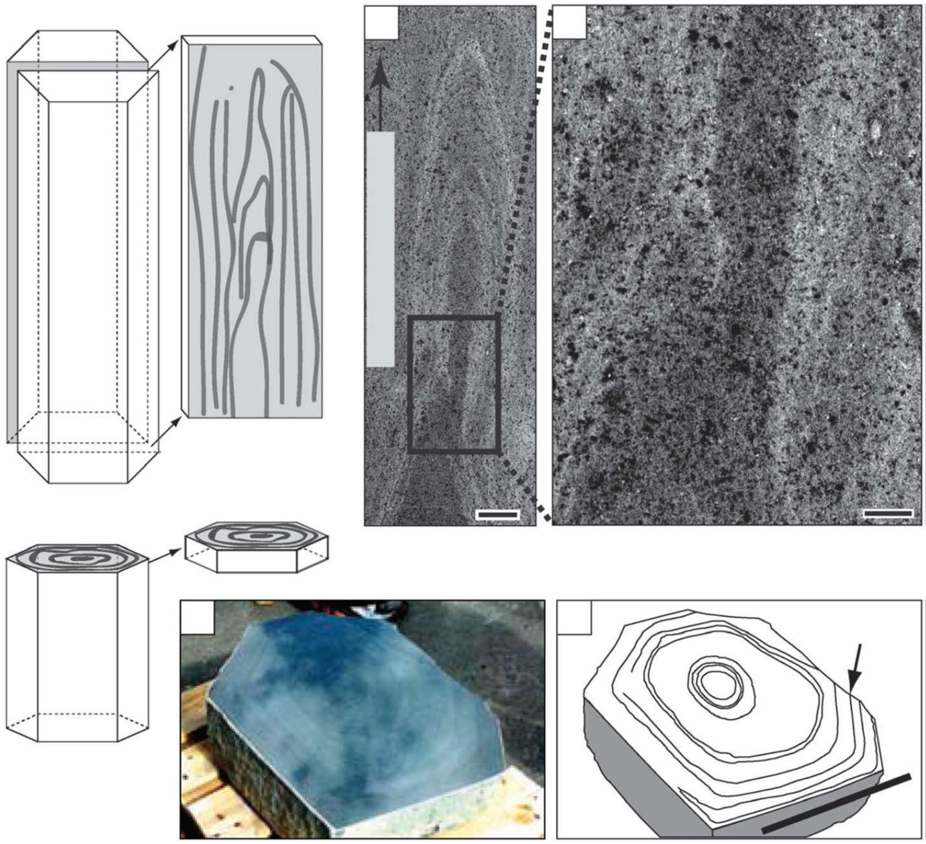
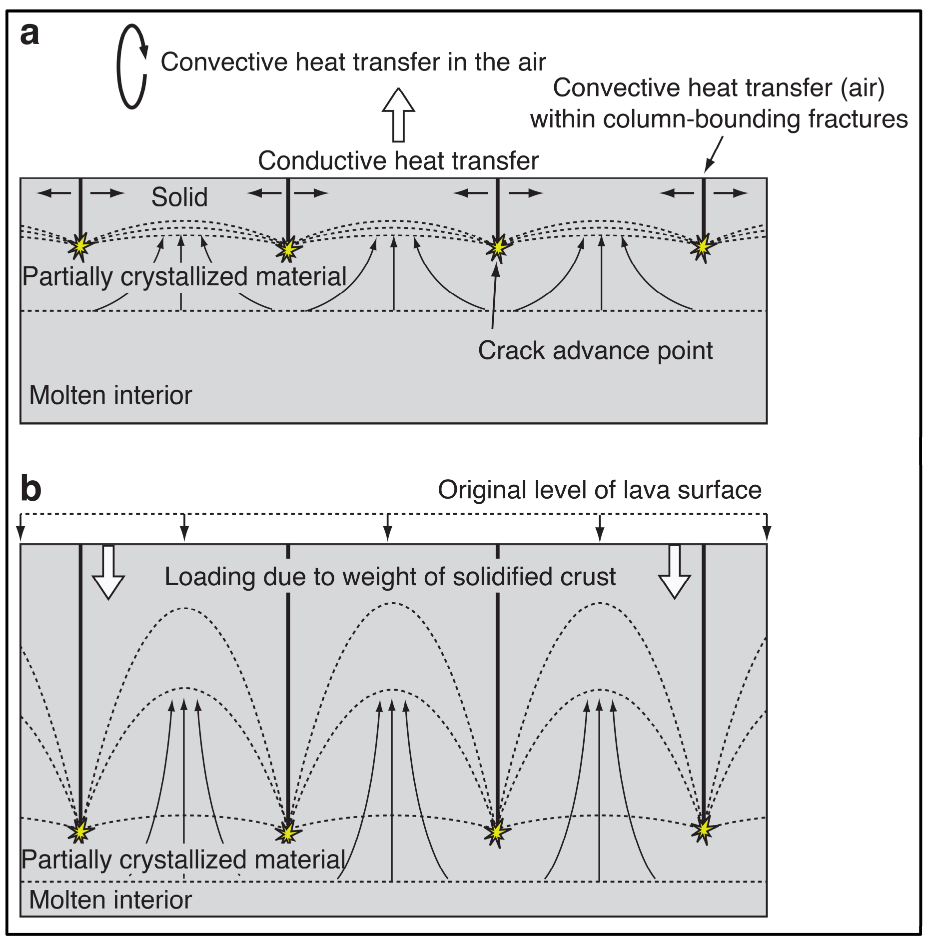


Figure 9: Diagram of how crystallization and pressure loading can force melt-migration in the interior of columns resulting in viscous fingers in the partially crystallized columns. (from Mattson et al. 2011)



from thermal stress due to their central starting point (fractures could start on a corner) and termination in a perfect circle. He instead thinks that they are from a directional growth of minerals guided by the geometry of solid fingers within the sample as it cools. This is one piece of evidence used to support his hypothesis that columns form by constitutional supercooling instead of by thermal contraction. In this model, a slight heterogeneity in the melt will cause the formation of non-planar conditions between the crystals and the melt. Gilman (2009) suggested that early minerals with high melting points will crystallize first slowly moving to crystals with low melting points. Guy (2010) thought basaltic melts were fairly homogeneous in composition, but that increased H_2O content of the melt as solidification occurs could drive constitutional supercooling, based on rings of small bubble circles on the rims of the columns. This new model for columnar jointing could also explain multi-tiered flows and entablature as being due to a higher degree of supercooling with poorly defined smaller thermal gradients in the middle of these larger units.

Other columns have concentric ring features of alternating dark and light bands resulting from slightly different proportions of the main minerals (e.g. plagioclase versus olivine). In polished cut slabs, one can see that these bands are pseudohexagonal on the rims becoming more circular toward a central point (Mattson et al. 2011, Guy et al. 2010). Cuts parallel to the column axis show that these rings are part of larger elongate finger shapes of slight compositional difference within the basalts (Figure 8). These rings are used to support the idea of constitutional supercooling (Guy 2010). Another explanation for this fingering is double diffusive convection in which thermal or compositional variations within the lava could result in instabilities forming basalt fingers which eventually develop into 3 layered structures with strong convection in the center and fingers on the edges (Kantha 1981). Although similar to constitutional supercooling where a compositional difference (or increasing gas bubbles) should be seen from the center to edge of a column, this additionally suggests differences should be seen from the top to the bottom of a columnar basalt flow. Testing these hypotheses, Bosshard et al. (2012) found that similar crystallization temperatures of magnetic minerals, similar compositions of plagioclase, and lack of down-warped material did not suggest convective motions or constitutional supercooling. Instead a new model was proposed in which steep isotherms are created inside the columns when cooling on crack and joint surfaces becomes locally dominate over heat transfer to the air at the top of the flow. Crystallization of titanomagnetite will cause a volume decrease (15% is observed) and sinking of the solidified upper portions forcing convection on the interior of columns and flows (Figure 9, Mattson et al. 2011). Systematic variations of plagioclase lath orientation/size across the column diameter and of the anisotropy of magnetic susceptibility (measuring orientation of titanomagnetite and paramagnetic grains) support the idea of vertical melt migration in the interior of the columns (Bosshard et al. 2012, Almqvist et al. 2012).

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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 slow down 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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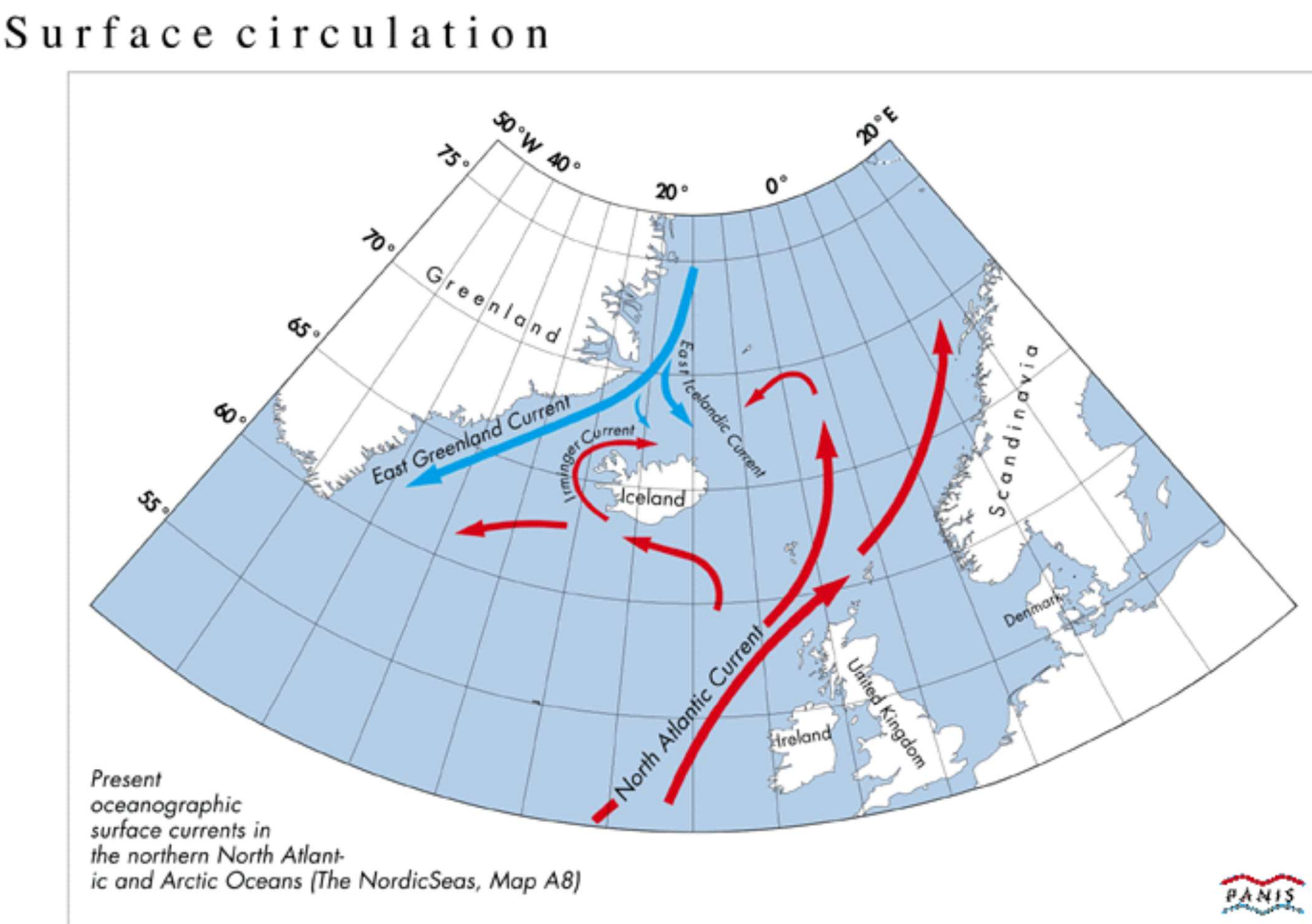


Figure 11. Present oceanographic surface currents around Iceland. Image source: http://www.hi.is/~jeir/panis_currents.html

Aurora Borealis

Copied Wikipedia Article on Aurora

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

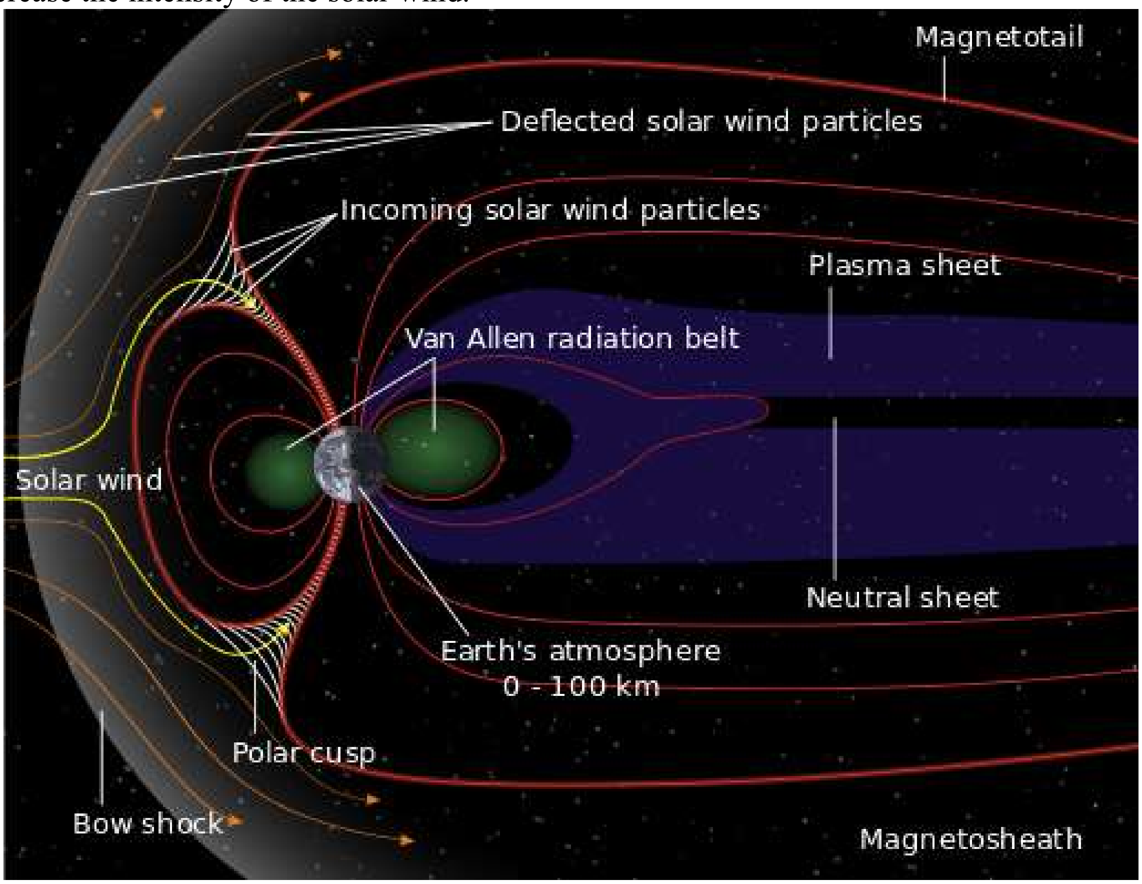
Bright auroras are generally associated with Birkeland currents (Schield et al., 1969;[32] Zmuda and Armstrong, 1973[33]), which flow down into the ionosphere on one side of the pole and out on the other. In between, some of the current connects directly through the ionospheric E layer (125 km); the 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 7th, 2020 – Board flight

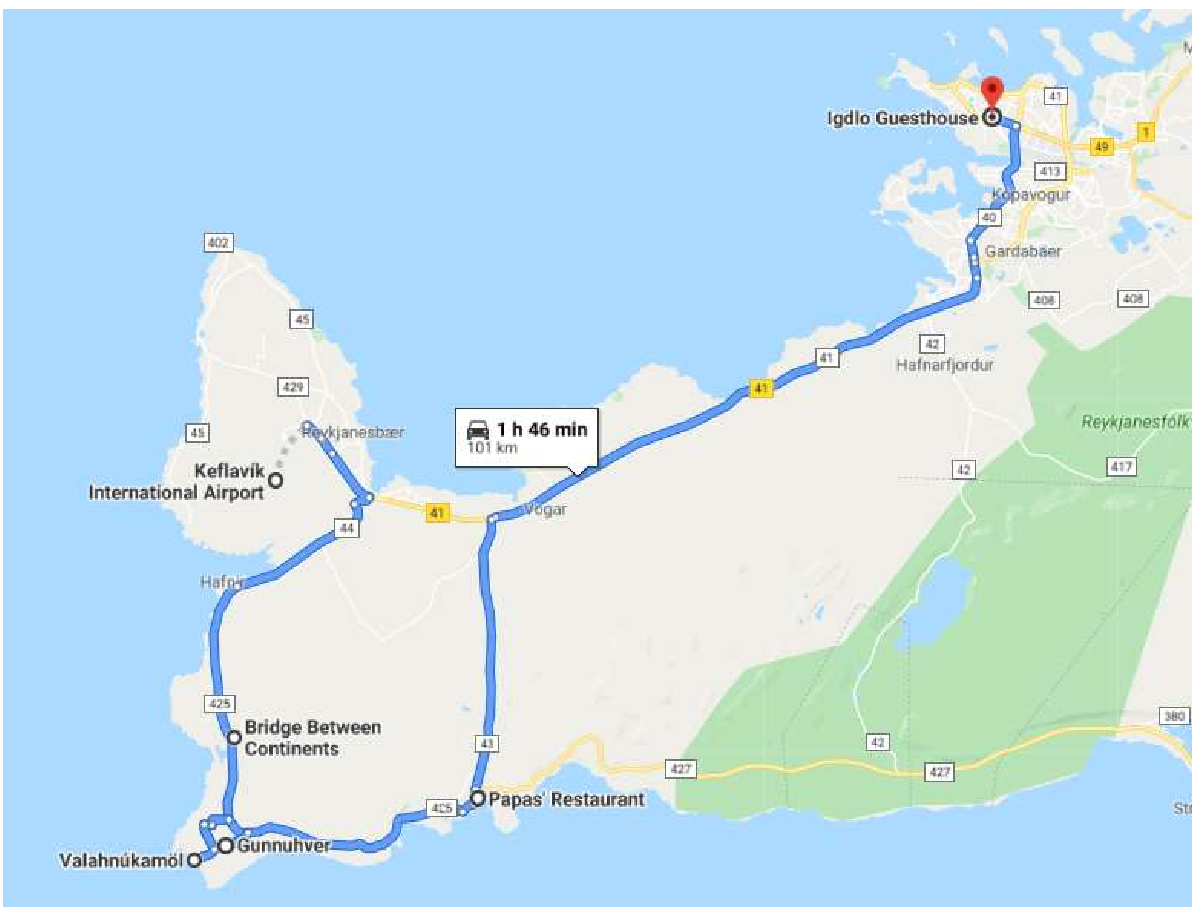
7:45PM: Depart from Dulles, Washington, DC (IAD) Icelandair – Flight 644 (economy)

Day 2: Sunday, March 8th, 2020 – Reykjanes Peninsula

6:30: 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: I think it will be best to have breakfast at the airport
8:30: Load into the bus. Here is the info for the bus company:

Guðmundur Jónasson Travel (gjtravel@gjtravel.is)
Vesturvör 34, 200 Kópavogur, Iceland
Emergency number travel agency: +354-895 2007
Emergency number bus department: +354-893 5740

9:00: 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. Check 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 Papas' Restaurant (Hafnargata 7a, 240 Grindavik, Iceland) that might be fine….
2 PM: Get to the hostel (Igdlo Guesthouse, Gunnarsbraut 46, 105 Reykjavík). Stay there for one night. Fend for yourself for dinner. You could out or cook, the hostel has a kitchen.



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.

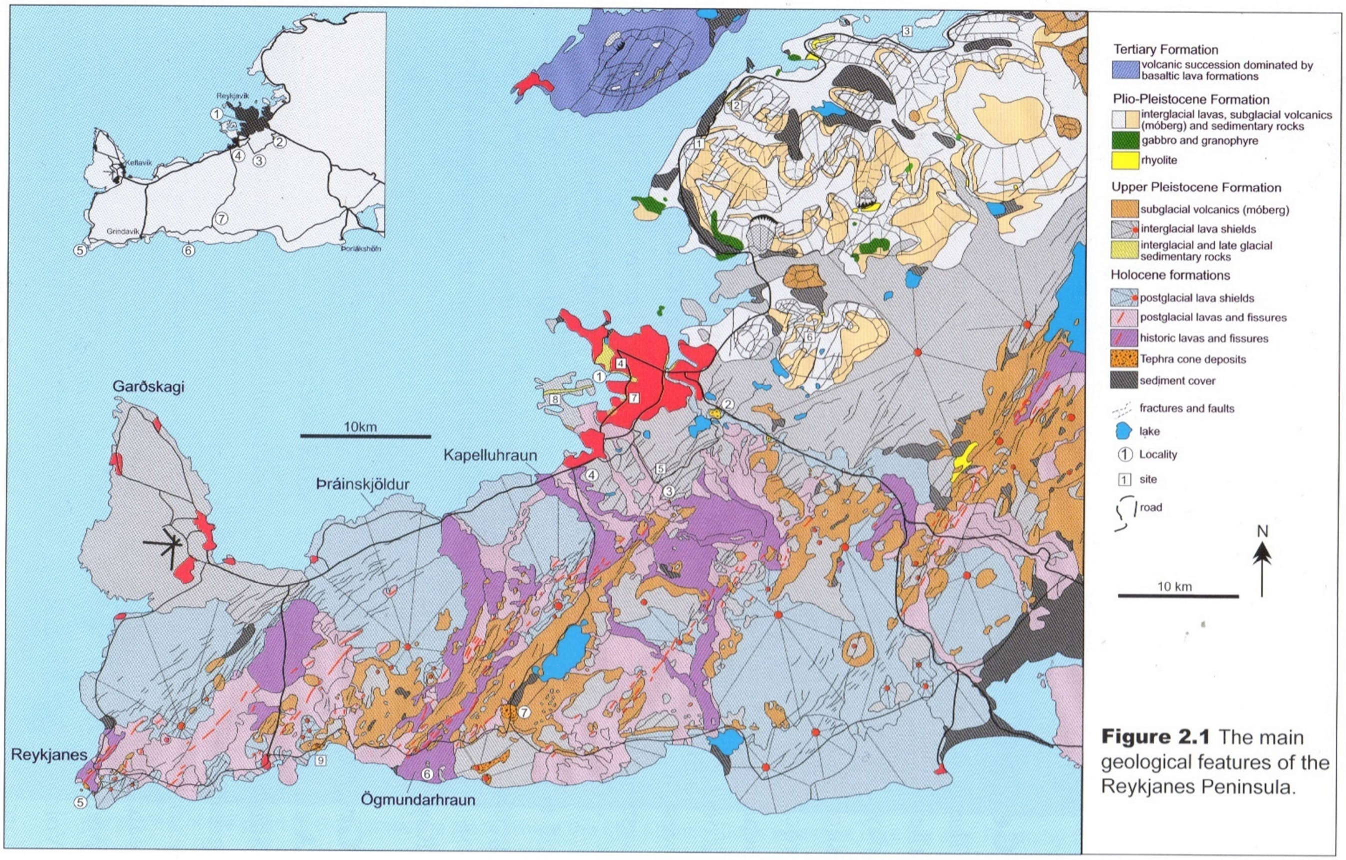


Figure 2.1 The main geological features of the Reykjanes Peninsula.

(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.

13.15 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 crater 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** (Fig. 13.37). The fracture is formed by the same plate-tectonic tensile forces or stresses as the tension fractures at Thingvellir (Figs. 5.11–5.13; Chap. 5).

However, the present fracture is not filled with ground water as are the fractures at Thingvellir, but rather by 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 (Chap. 5). Like most other large tension fractures in Iceland, this one is located in a pahoehoe lava flow which, in this case, derives from the lava shield **Langholl (Langhóll)**. 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 (Fig. 13.38). You may recall seeing lava tumuli at the surface of some of the pahoehoe flows on your way from Keflavik to Reykjavik (Fig. 2.8; Chap. 2).

Fig. 13.37 Tension fracture seen from the 'Bridge between two continents'. View southwest the maximum opening or 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

Does the bridged tension fracture really mark the separation between two continents? Hardly, because Iceland is not a continent or a part of a continent. The tension fracture is, however, without 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-ocean Reykjanes Ridge. You saw the southeastern boundary fault of that graben from Valahnukur (Fig. 13.29), 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 Fig. 13.39, 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 Fig. 13.37 extend? Using the theory explained in Chap. 5, the maximum depth of this tension fracture is **several hundred metres**. If the fracture tried to extend to greater depths it would change into a normal fault such as the one in Fig. 13.39. The stresses forming the tension fracture in Fig. 13.37 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 Figs. 13.38 and 13.39 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 (Chap. 5).

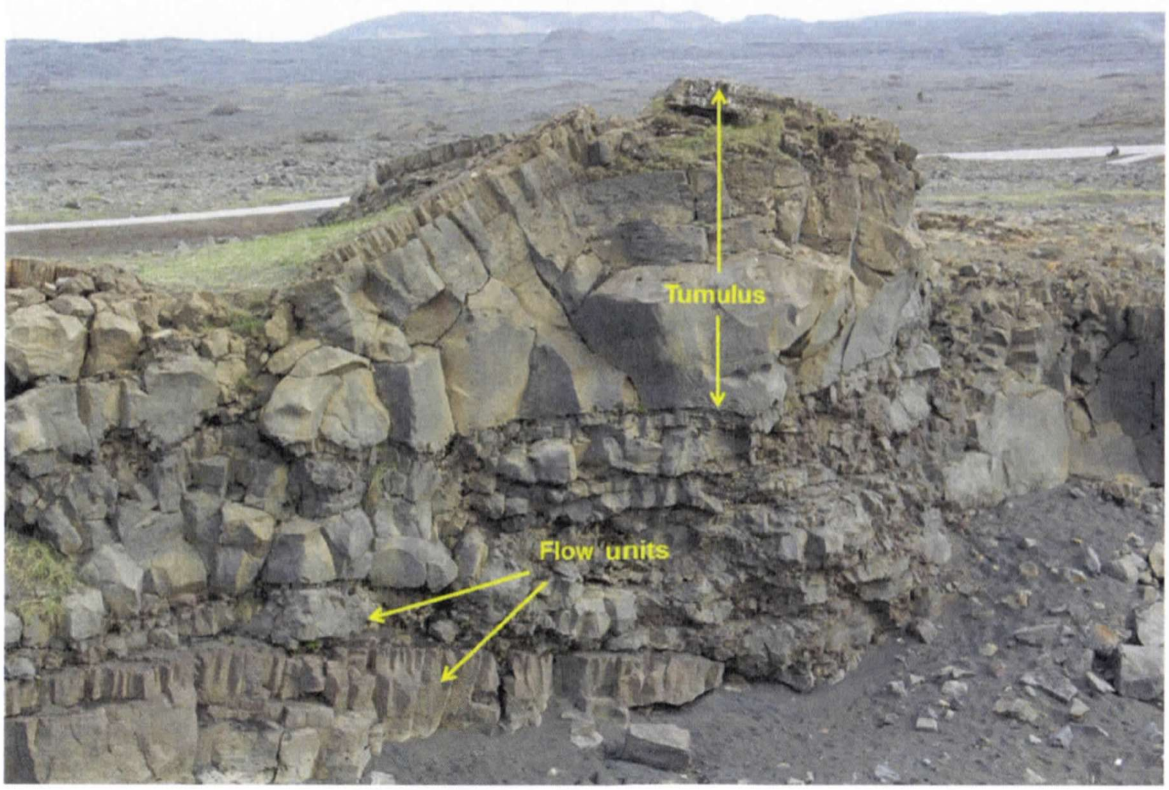


Fig. 13.38 View south of a tumulus and pahoehoe flow units seen in a vertical cross-section in the southeastern wall of the tension fracture in Fig. 13.37. Compare the flow units in the walls of Almannagja (Figs. 5.5 and 5.6) and the tumulus, seen at the surface, in Fig. 2.8 and in a cross-section in Fig. 13.39

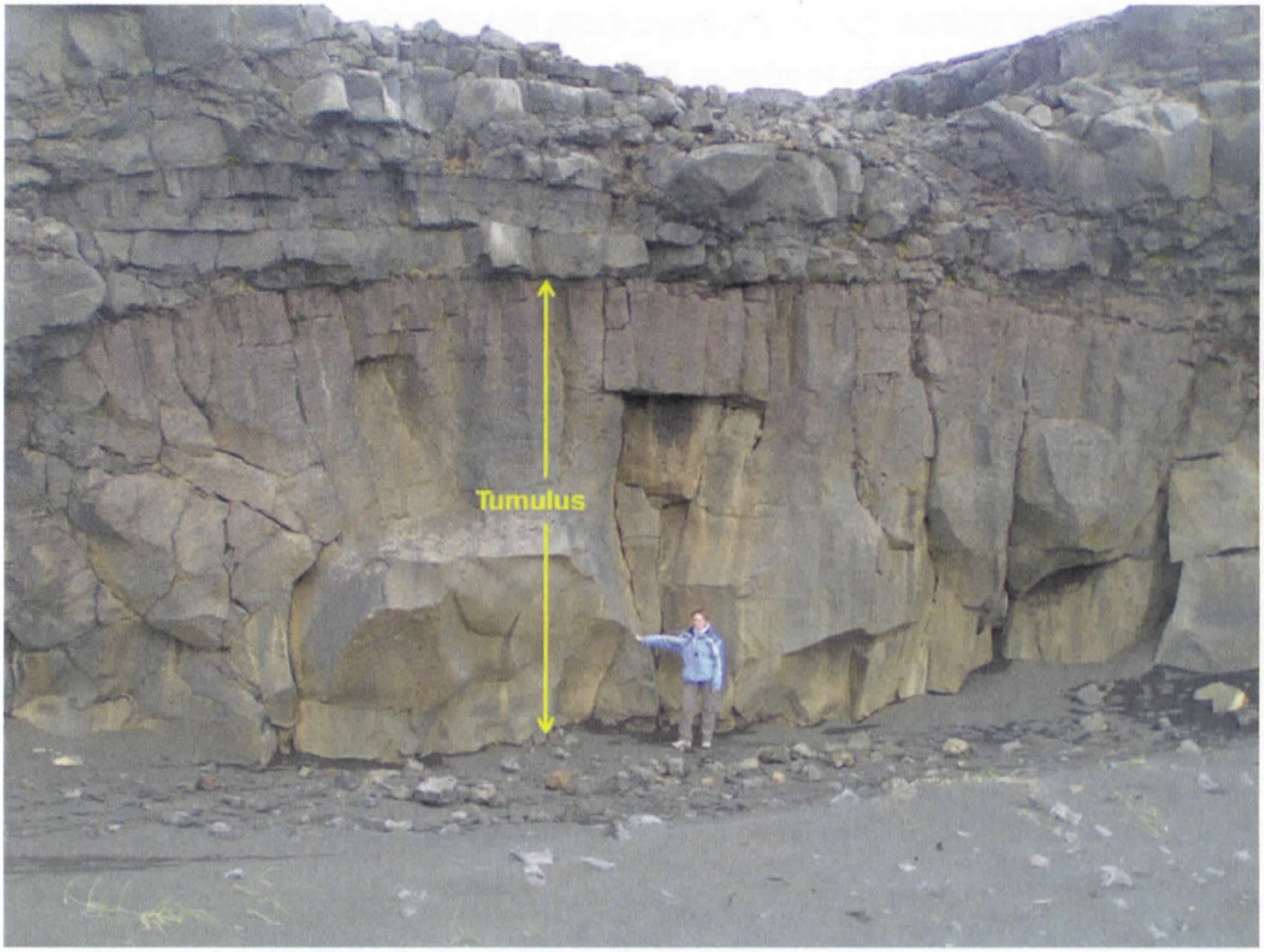


Fig. 13.39 Main northwestern boundary fault of the 5–6 km wide graben on Reykjanes, an on-land continuation of the mid-ocean Reykjanes Ridge (the southeastern boundary fault of the graben is seen in Fig. 13.29). Also seen is a vertical cross-section through flow units and a large tumulus (compare Figs. 2.8 and 13.38). The person provides a scale

This is our last formal geological stop in this excursion. We now return to Road 425 and drive first north along the edge of the Reykjanes Peninsula, to the village of **Hafnir** and from there along Road 44 to the northeast until it meets Road 41 close to the town of **Njardvik (Njarðvík)**. We are then on the same road as on the first day, namely the road from the Keflavik Airport to Reykjavik. All the main geological features along that road are already described and discussed in Chap. 2.

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.

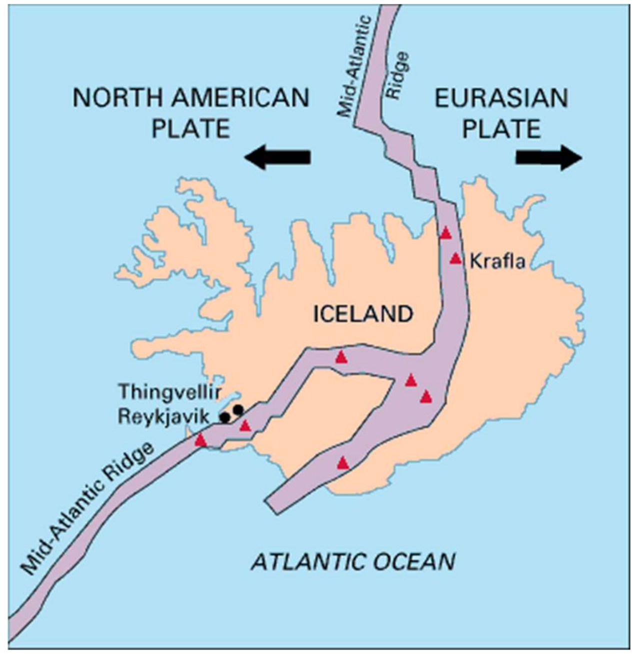


Figure 14. Valahnukur cliff: view south, showing the contact between laminated tephra and pillow basalts.

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.

Locality 2.5 Mid-ocean ridge rising out of the sea

If you travel west on Highway 41 towards the international airport at Keflavík, as you pass the town of Njarðvík 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 (see Fig. 2.1).

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 Vatnsleysuströnd. Along the centre of the rift is a series of 40–100 m-high steep móberg hills composed of pillow lava and hydroclastic tephra and breccia, including *Bæjarfell* [63.8155, −22.7043], where the present lighthouse stands, and *Valahnúkur* [63.8108, −22.7114], where the foundations of the old lighthouse can still be seen. On both sides, lava shields border the móberg hills, which in turn are partly covered by younger Holocene and historical lava flows (see Fig. 2.1). But not all of Reykjanes is volcanic. The cove south of Valahnúkur features a spectacular boulder beach formed by the rampant storms of the North Atlantic, and farther to the north the black sand dunes at Stóra-Sandvík 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 móberg mountains of *Sýrfell* [63.8369, −22.6598], Bæjarfell and Valahnúkur 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 móberg mountains consist of pillow lava, breccias and tuffs, which in the case of Sýrfell 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, Valahnúkur 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 the breccia units (Fig. 2.7a). The youngest tephra layers in the **regolith** that laps onto the eastern slopes of Valahnúkur 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 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 (see Fig. 2.1). 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] is a rather inconspicuous rise on the coast north of Valahnúkur, but is worth a visit for those interested in having a closer look at the internal make-up of tuff cones (Fig. 2.7). 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 (Fig. 2.7b). 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-century chronicles, that rose out of the sea of Reykjanes in 1211. The lavas of Yngri Stampar were formed either in the same eruption or 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 (Fig. 2.7c).

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 (Miðaldarlagið) and is found in soils all over the Reykjanes Peninsula, including Reykjavík and the Esja region. It forms an important time marker and has been used extensively for dating historical lava flows in the area. Eldey, 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

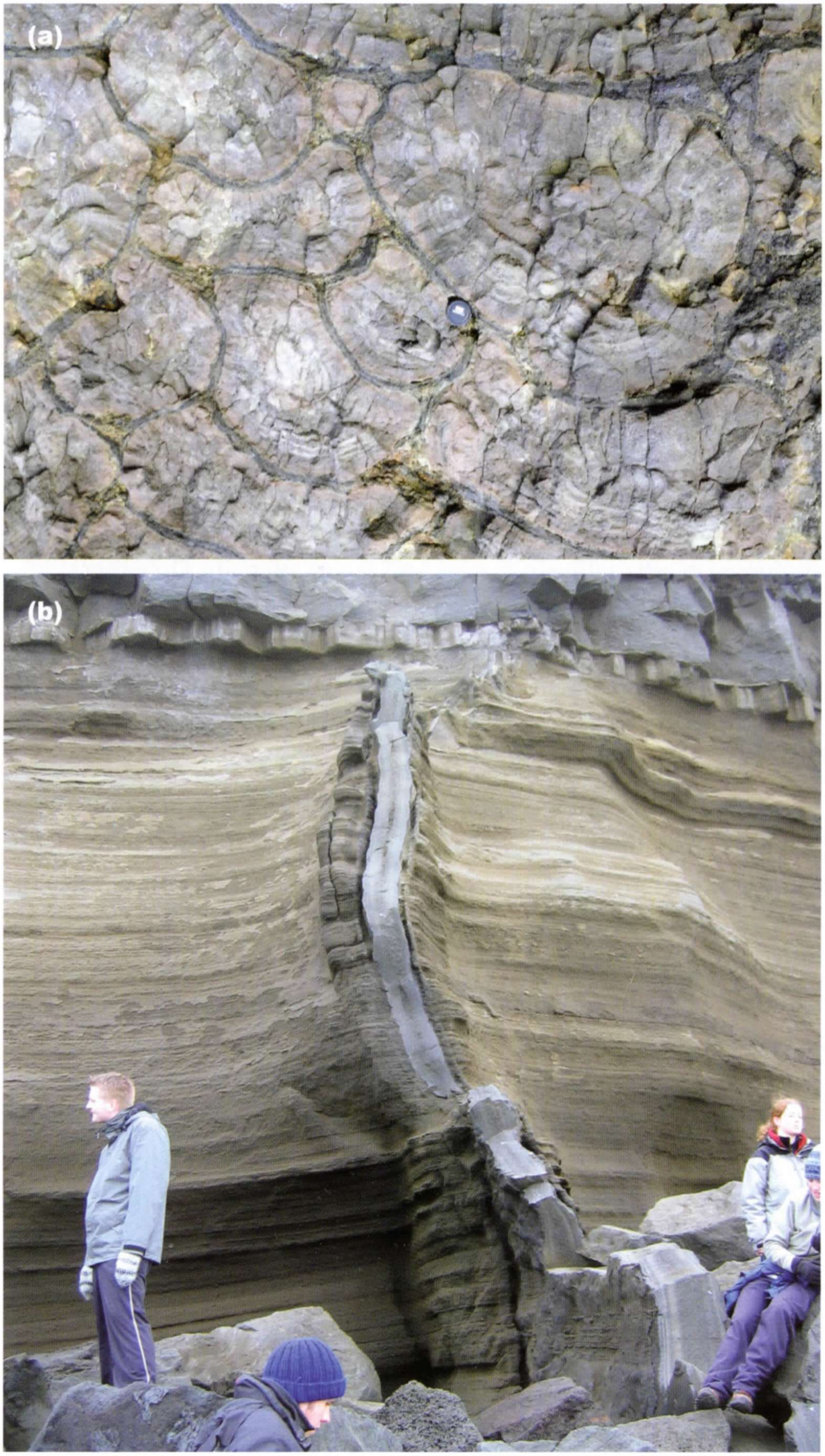
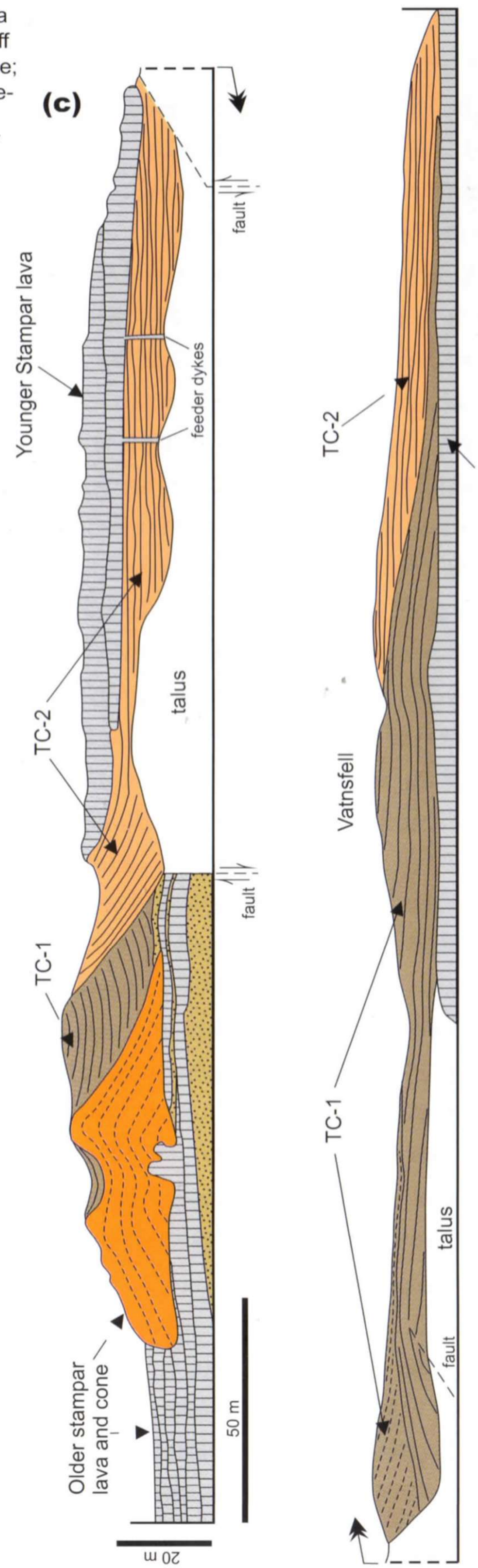

(a)
(b)

Figure 2.7 **(a)** *(opposite)* Pillow lava at Valahnúkur; **(b)** *(opposite)* 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.



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 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 (see Fig. 2.1). Tephrochronology 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 volcanic formations at Reykjanes are the *Eldri Stampar* [63.8250, −22.7172] and *Tjaldastaðargjá* [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 are the lava shields Sandfellshæð, *Skálafell* [63.8125, −22.6822] and *Háleyjarbunga*, [63.8166, −22.6510] which together are the largest lava formations in the area and solely composed of pahoehoe flows. Háleyjarbunga may hold a special interest for petrology enthusiasts, because it is composed of picrite basalt and is exceptionally rich in olivine phenocrysts. Some of the lava outcropping in the walls of the summit crater and the cliffs along the southern coast is green with olivine.

On the way

Continue on Road 425 along the southern coast towards the town of *Grindavík* [63.8453, −22.4351]. The route will take you through several older Holocene lava flows and, as you approach the putting greens of the Grindavík golf course, the mountain *Þorbjarnarfell* [63.8641, −22.4405] will appear on the skyline to your left. It is the highest (243 m) subglacial móberg 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 245 travelling east towards *Krýsuvík* [63.8869, −22.0651], which initially traverses the lavas of Sundahnúkar and Vatnsheiði. The former lava flowed into the sea to form the point Þórkötlunes and the inlet that hosts the harbour at Grindavík. 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 Vatnsheiði lavas are pahoehoe flows derived from three small picrite lava shields northeast of Grindavík that were constructed by eruptions during the early Holocene. The Vatnsheiði lavas host abundant gabbro xenoliths and large (2–3 cm) feldspar xenocrysts, which are readily discernible in the coastal outcrop at *Hrólfsvík* [63.8494, −22.3661] (Fig. 2.1: site 9).

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 Festarfjall 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

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[4]. 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[5]. 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 Grindavík, until reaching 63° 50′ 36.40″N/22° 26′ 09.70″W on the road no. 43, in which one is turning right north. After approximately 600 m, leave at 63° 51′ 03.00″N/22° 25′ 57.50″W to the left and turn onto road no. 425. Drive around Grindavík in the northwest and take the road no. 425 more or less parallel to the coast towards the west until it leaves at the branch at 63° 49′ 29.20″N/22° 39′ 43.70″W to the southwest. You have to drive a little more than 1 km to find a parking lot at 63° 49′ 08.70″N/22° 40′ 55.40″W or another small parking lot at 63° 49′ 30.06″N/22° 41′ 13.55″W. From there you can walk only on marked paths through the area with the mud springs and fumaroles of the high-temperature area Gunnuhver Fig. 6.51.

Fig. 6.51 Volcanic gases emitted in the high-temperature area of Gunnuhver © Wolfgang Fraedrich

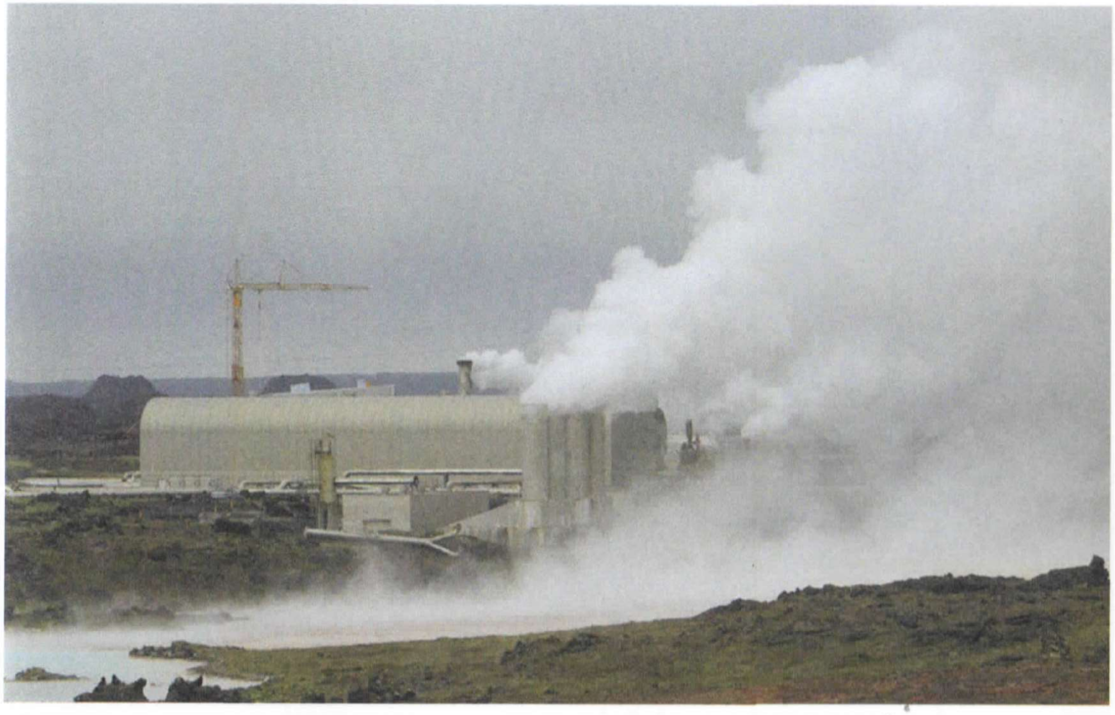


Fig. 6.52 View on Suðurnes Geothermal Power Plant © Wolfgang Fraedrich

Gunnuhver is a highly active volcano, which continues to the southwest in the Atlantic over the so-called Reykjanes Ridge (RR, Fig. 4.9). 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 circumstances block barriers. The high-temperature area Gunnuhver is the hottest in the southwest of Iceland with more than 300 °C. This fact forms the basis for the nearby Suðurnes Geothermal Power Plant. Worth mentioning is the name of the high-temperature area because Gunnuhverv is connected to the legend by the Gunna (by Guðrún Önun dardóttir). According to the legend, was a murderous poltergeist. The parishioner Eiríkur Magnússon finally succeeded in placing the ghost in the hot spring, which has been carrying the name Gunna since then.

The following is from: Gudmundsson, A., 2017, The Glorious Geology of Iceland's Golden Circle. Springer International Publishing, Cham, Switzerland, pgs. 239-243.

13.11 Volcanic Fissure and Flow Channelling

We now turn, and drive back, to the south along Road 43 until it meets Road 425. We drive onto Road 425, to the right, that is, to the west, on our way to the southwest edge or the toe of Reykjanes. We may make a short stop, then regarded as part of the seventh stop, just to view the Thorbjörn Graben from the southwest (Fig. 13.23), but then move on to the west along the road. On Road 425 we see many tectonic fractures, both tension fractures and normal faults, as well as volcanic fissures. One volcanic fissure erupted at about the same time—in the same 'fires'—those that generated Illahraun (at the Blue Lagoon), and we make a short stop where the road passes through the associated lava flow.

This is the **Eldvarpahraun (Eldvörp Lava)**, the **eighth stop**, which appears to have formed at a very similar time to that of Illahraun and Arnersetursharaun (Fig. 13.20a), and perhaps other lava flows. They are all formed at around 800 years ago probably during a volcanotectonic episode, fires, which lasted many years. At the eighth stop, the road passes through a broad lava stream that extends all the way to the coast. The volcanic fissure, also named Eldvörp, that issued this lava is discontinuous and composed of many offset segments, but its total length is close to **11 km**, one of the longest one on the Reykjanes Peninsula. Because of its length and location, the volcanic fissure and the associated crater cones are best seen from the air (Fig. 13.25).

The Eldvörp lava varies in character **between aa and pahoehoe**. Close to Road 425 it is a pahoehoe lava, whereas further inland parts of it are aa lava. The morphological characteristics of lava flows depend on many factors, such as volumetric flow rate (the amount of lava issued by the volcanic fissure over a given time period, say a second), viscosity (how easily the lava flows), temperature, and the slope of the land on which the lava is flowing. The lava composition has also strong effects. The same volcanic fissure can issue aa and pahoehoe, and commonly a pahoehoe lava may change into aa when the lava cools. Earlier we saw that the Nesjahraun lava also varies in character between aa and pahoehoe (Chap. 12).

The Eldvörp is a typical volcanic fissure or **crater row** (Fig. 13.25). It is composed of many segments or parts, whose nearby ends are separated by distances as long as 500 m. In addition, the segments are not in the same straight line, are **not collinear**, but rather out of line, that is, **offset**, either to the east or west of an (imagined) straight line by as much as 200 m. Earlier we saw normal faults and tension fractures composed of many offset segments (Chap. 5). There are many

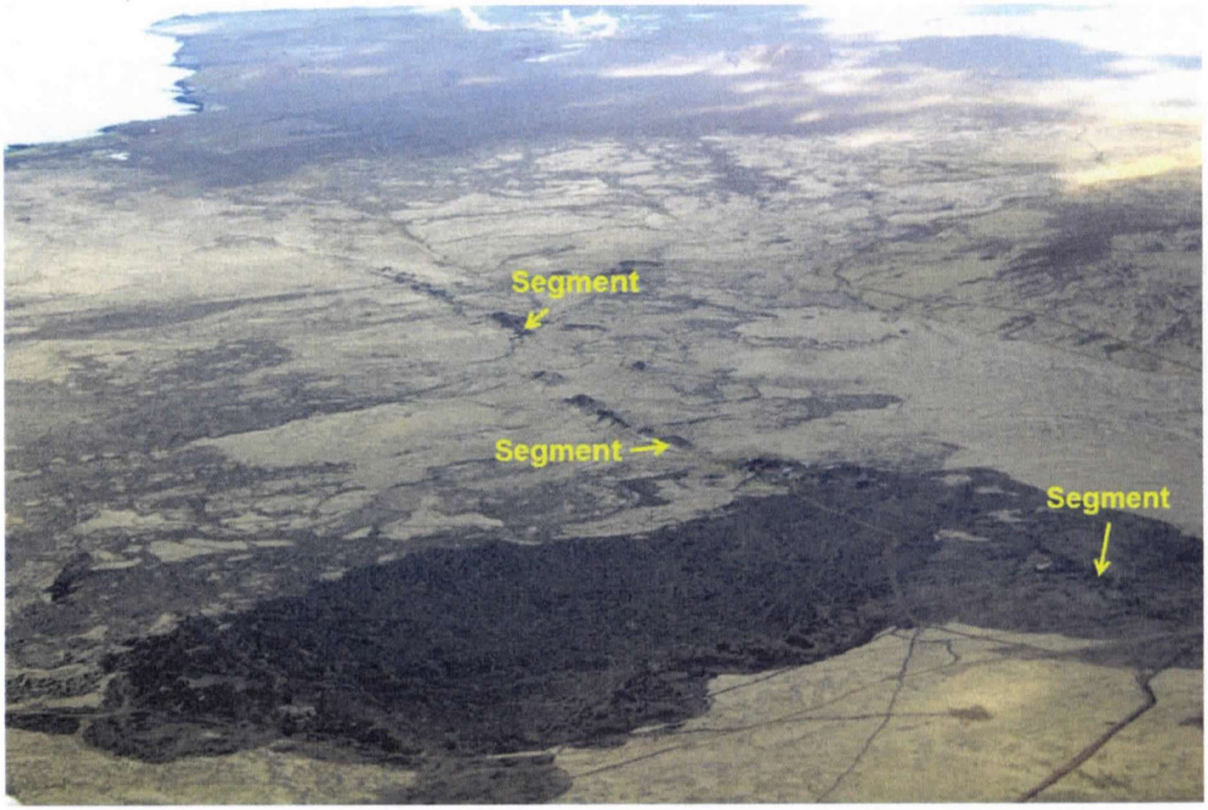


Fig. 13.25 Aerial view of part of the Eldvörp Volcanic Fissure, formed around 800 years ago. Like most volcanic fissures, it is composed of many segments, some of which are indicated here. The dark hillocks are crater cones. View southwest, Reykjanes and its geothermal fields are seen in the distance. The total length of the fissure is close to 11 km

small hills, or **crater cones**, along the fissure segments. Yet, only a fraction of the total length of the volcanic fissure is covered with crater cones.

There are several reasons for these geometrical features of volcanic fissures. First, they are segmented and offset because that is the way the **feeder-dikes** themselves (and, in fact, all dikes) are. Within the zone of high stress (concentrated or raised stress) in the crustal layers above an upward-moving or propagating dike, the layers rupture where they are weakest, that is, have the **least tensile strength**. Because of variations in the tensile strength within each layer, rupture normally occurs not along a straight line above the top of the dike at any time but rather at different points which may be far apart—resulting in the dike front being composed of many separated segments or '**fingers**' (Figs. 13.26 and 13.27). The eruption then begins when the first finger reaches the surface. Subsequent fingers are initially far apart, forming a discontinuous fissure composed of offset segments. As the eruption intensity increases, and more fingers reach the surface, some of the segments may link up to form longer segments. But it is very rare to see the entire volcanic fissure erupting at the same time—normally only parts of the fissure are active at any given time.

So why is the eruption confined to parts of the fissure? The reason is that from the beginning the opening of the fissure, its **aperture**, differs somewhat from one measurement point to another along the fissure. This we know from simply observing tension fractures or open or gaping normal faults, such as at Thingvellir (Chaps. 5 and 6). All such fractures show significant variation in their opening along their lengths. Similarly, dikes followed laterally along their lengths show significant variations in thickness and thus in original opening or aperture of the dike-fracture. The volume of magma or lava issued through a part of the fissure/feeder-dike depends very strongly on the opening or aperture of that part. In fact, the volume of magma issued depends on the opening of the fissure in the 3rd power. This means that if one segment of the fissure has an opening of 1 m and the adjacent equally-long segment an opening of 3 m (everything else being the same),

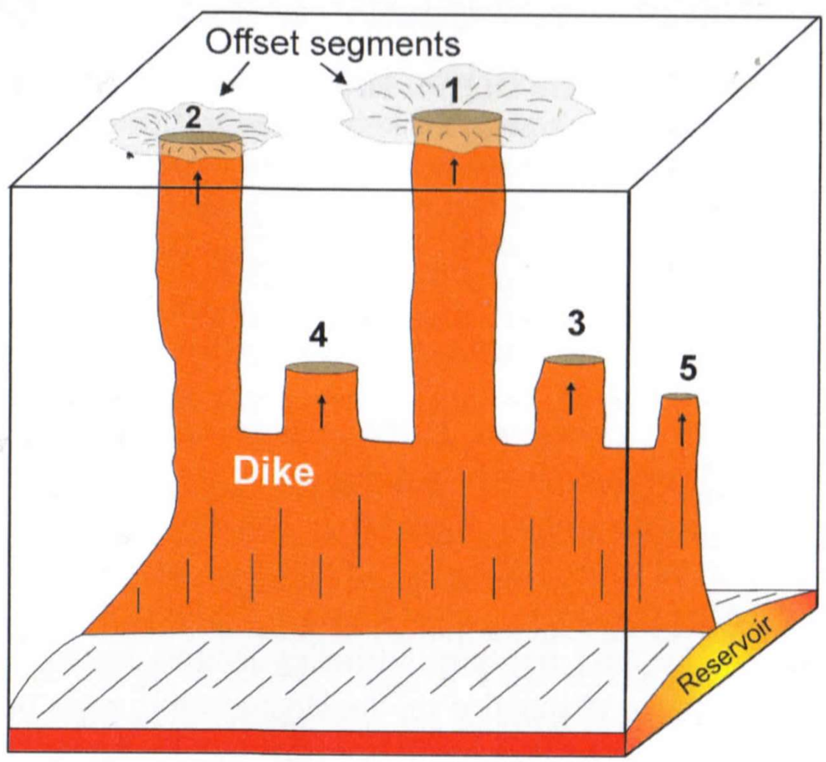


Fig. 13.26 Dike propagates as offset, separate segments, whose vertical propagation fronts are referred to as 'fingers'. Eventually, the fingers may or may not become laterally connected. In this schematic illustration, fingers or segments 1 and 2 have already reached the surface, whereas segments 3–5 are propagating towards the surface. Segments 3–5 may all reach the surface; alternatively, some or all of them may become arrested, stop their vertical propagation, at some crustal depth. This is a regional dike whose source is a large magma reservoir, as is appropriate for the Eldvörp feeder-dike (Fig. 13.25)

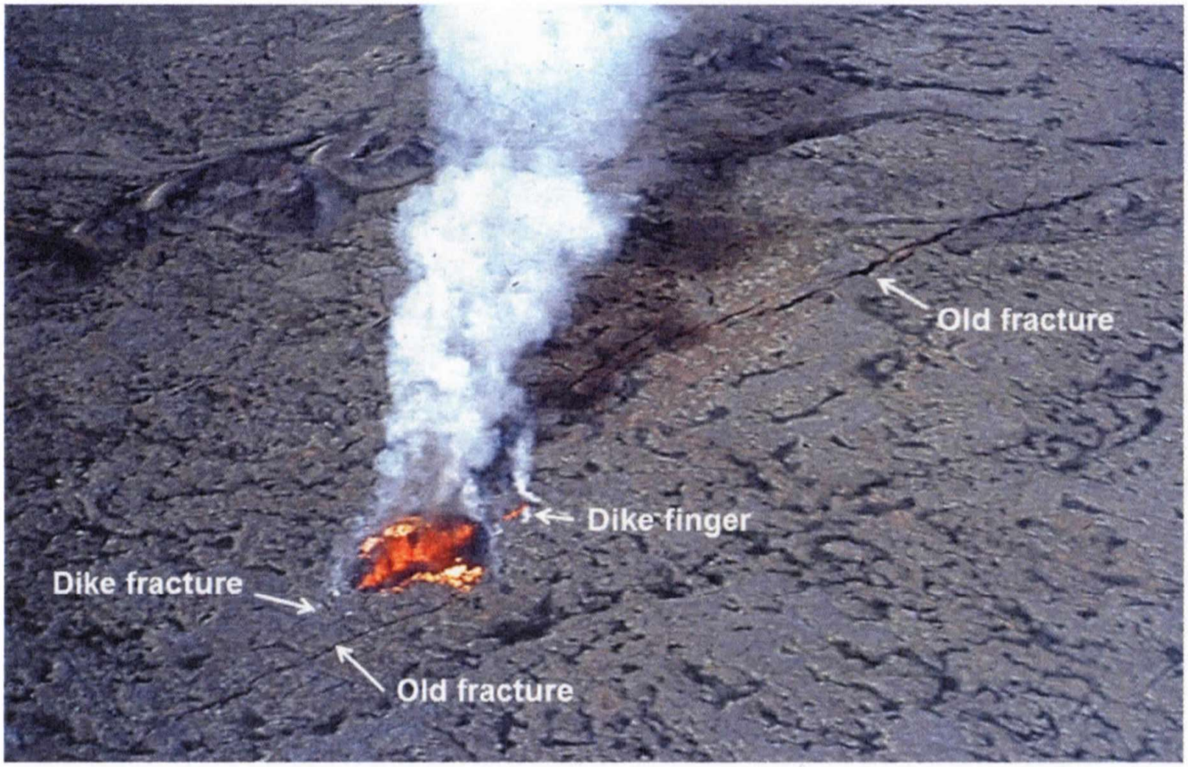


Fig. 13.27 Example of the first dike fingers to hit the surface, as seen here in the July 1980 eruption in the Krafla Volcanic System in the North Volcanic Zone (the zone is located in Fig. 2.2). The first dike finger or segment to reach the surface initiates the resulting fissure eruption. The first segments at the surface are commonly short, tens of metres, but they commonly propagate laterally at the surface and may eventually link up into larger fissure segments (Fig. 13.25). The indicated 'dike fracture' is a tension fracture forming ahead of a dike segment that has still not reached the surface as a finger

so that they differ by a factor of 3, then the second segment would issue $3^3 = 3 \times 3 \times 3 = 27$ times as much lava/magma as the first segment. This is a **universal law** that controls fluid transport in fractures, whether the fluid is groundwater, geothermal water, gas and oil, or magma. The law is named the **cubic law**, because a cube has the dimensions of length in the third power. The cubic law is the main reason why fluid transport, including magma transport, in fractures tends to be focused on, or channelled to, the large-aperture parts of the fracture. This process of channelling the flow to the large-aperture fractures of the fracture is referred to as **flow channelling**. Like the cubic law, flow channelling is a universal principle that applies to the flow of any type of fluids in crustal fractures.

How does the cubic law relate to the crater cones (Figs. 13.20d and 13.25; see also Fig. 12.21)? Answer: The crater cones tend to form along the segments, or those parts of the segments, where the opening is largest. Because of the cubic law, many times more magma is from the beginning issued through the **large-opening**

parts. It follows that these parts produce most of the lava and other eruptive materials. These are also the parts which the magma continues to flow through during the waning states of the eruption, when the magma pressure has decreased and the overall volumetric flow rate has fallen. Since the volume of hot magma flowing through the large-opening parts is much greater than through the adjacent narrower parts, the large-opening parts may somewhat increase their apertures through partial melting and removal of parts of the rock in the walls of the fissure. This melting and removal of wall rock is referred to as **thermal erosion** and may result in gradual increase in apertures during the course of the eruption of those parts of the fissure that had large openings from the beginning. All these factors contribute to much of the magma being transported through certain parts of the fissure; parts that develop into specific conduits that pile up lava, spatter, and scoria so as to become **crater cones** (Figs. 12.21, 13.20d and 13.25; Sect. 13.12).

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 - *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]

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[8] *Bæjarins Beztu Pylsur* http://en.wikipedia.org/wiki/B%C3%A6jarins_Beztu_Pylsur
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[10] *Laugardalur* http://www.holidaym.ru/iceland/gid_laugardalur_valley.php

Reykjavik Maps

Reykjavík

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

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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
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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

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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

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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

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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 Reykjavik

Old Reykjavik

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

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15 Free Walking Tour Reykjavík ... D4
16 Grayline Iceland ... D3
17 Haunted Walk ... B2
18 Literary Reykjavík ... B1

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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

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28 10-11 ... C3
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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 Nora Magasin ... C4
43 Stofan Kaffihús ... B2
44 Tapas Barinn ... A2
45 Torfan Lobsterhouse ... D5

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46 Frederiksen Ale House ... C2
47 Klaustur ... C5
48 Loftið ... B3
49 Micro Bar ... B2
50 Pablo Diskobar ... B3
51 Paloma ... B2
52 Sæta Svínið Gastropub ... B2
53 Skúli Craft Bar ... B3

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55 Tjarnarbíó ... A5

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

Old Harbour

Top Sights
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Sights
2 Aurora Reykjavík A4
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3 Nýló D2
4 Omnom Chocolate D1
5 Reykjavík Maritime Museum A4
6 Saga Museum A4
7 Stúdíó Ólafur Elíasson D2
8 Whales of Iceland B2

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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
Burið .... (see 39)
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 Kumiko C2
29 Lamb A4
30 Matur og Drykkur A4
31 Messinn Granda B3
32 Sægreifinn C5
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33 Valdís A3

Drinking & Nightlife
34 Bryggjan Brugghús A4
Café Haiti .... (see 36)
Marshall .... (see 3)
35 Slippbarinn B5

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

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


Laugavegur
Harpa
Sterna
Iceland By Bus
Small Cruise Ship Dock
Old Harbour
NORTH ATLANTIC OCEAN
Culture House
OLD REYKJAVÍK
National Gallery of Iceland
Hallgrímskirkja
Geirsgata
Kalkofnsvegur
Sæbraut
Faxagata
Skúlagata
Sölvhólsgata
Lindargata
Hverfisgata
Bankastræti
Laugavegur
Grettisgata
Njálsgata
Skólavörðustígur
Tjörnin
Austurvöllur
Hallargarðurinn
Hljómskálagarður Park
This Way to Our Hostel

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

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

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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 Loki 101 ... E7
31 Nest Apartments ... F7
32 Óðinn ... D6
33 REY Apartments ... E5
34 Reykjavík Residence ... E4
35 Room With A View ... D5
36 Sandhotel ... F5
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39 Block ... C5
40 Bónus ... G6
41 Bónus ... C5
42 Brauð & Co ... F6
43 Dill ... C3
44 Garðurinn ... E5
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45 Grái Kötturinn ... D4
46 Hamborgara Búllan ... C4
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Hverfisgata 12 ... (see 71)
47 Joylato ... D6
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48 Kolabrautin ... C1
49 Krambúð ... E7
50 Krua Thai ... D6
51 Lemon ... G6
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52 Ostabúðin ... C4
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54 Sushi Social ... C4
55 Þrír Frakkar ... C7
56 Torfan Lobsterhouse ... B4
57 Vitabar ... G7

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58 Artson ... G6
59 Bar Ananas ... E5
60 Bastard ... D5
61 Boston ... E5
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62 C is for Cookie ... D6
63 Den Danske Kro ... C4
64 Dillon ... E5
65 Kaffi Mokka ... D4
66 Kaffi Vínyl ... G5
67 Kaffibarinn ... D5
68 Kaffifélagið ... C5
69 Kaldi ... E5
70 Kiki ... E5
71 Mikkeller & Friends ... C3
72 Petersen Svítan ... C4
73 Port 9 ... F4
74 Prikið ... C4
75 Reykjavík Roasters ... F6
76 Spánski ... C4
77 Veður ... E5

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78 Bíó Paradís ... F5
79 Mengi ... D5
80 National Theatre ... D3

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81 12 Tónar ... D5
82 66° North ... C4
83 Aurum ... C4
84 Blue Lagoon Shop ... D4
85 Cintamani ... C4
86 Dogma ... F5
87 Eymundsson ... D5
88 Fjallakofinn ... D4
89 Fóa ... C4
90 Geysir ... D5
91 Geysir ... D5
92 Geysir Heima ... D5
93 Handknitting Association of Iceland ... D6
94 Heilsuhúsið ... E5
95 Hrím ... E5
96 Húrra Reykjavík ... G5
97 Kiosk ... C4
98 Kron ... G6
99 KronKron ... G6
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100 Ófeigur Björnsson ... D4
101 Orrifinn ... D5
102 Rammagerðin ... D5
103 Reykjavík Foto ... G5
104 Reykjavík Record Shop ... E5
105 Skúmaskot ... D6
106 Spútnik ... E5
107 Stígur ... D5
108 Tulipop ... E7

Laugavegur East

Laugavegur East

Sights
1 Gallerí Fold B2
2 Icelandic Phallological Museum A2
3 Reykjavík Art Museum – Kjarvalsstaðir B3

Activities, Courses & Tours
4 Sundhöllin A2

Sleeping
5 Alda Hotel A1
6 Eyja Guldsmeden C2
7 Fosshotel Reykjavík B1
8 Grettir Apartments A1
9 Hlemmur Square B2
10 KEX Hostel A1
11 Luna Hotel Apartments A1
12 OK Studios A1
13 Opal Apartments B2
14 Skuggi Hotel A1
15 Snorri's Guesthouse A3
16 Útivist D2

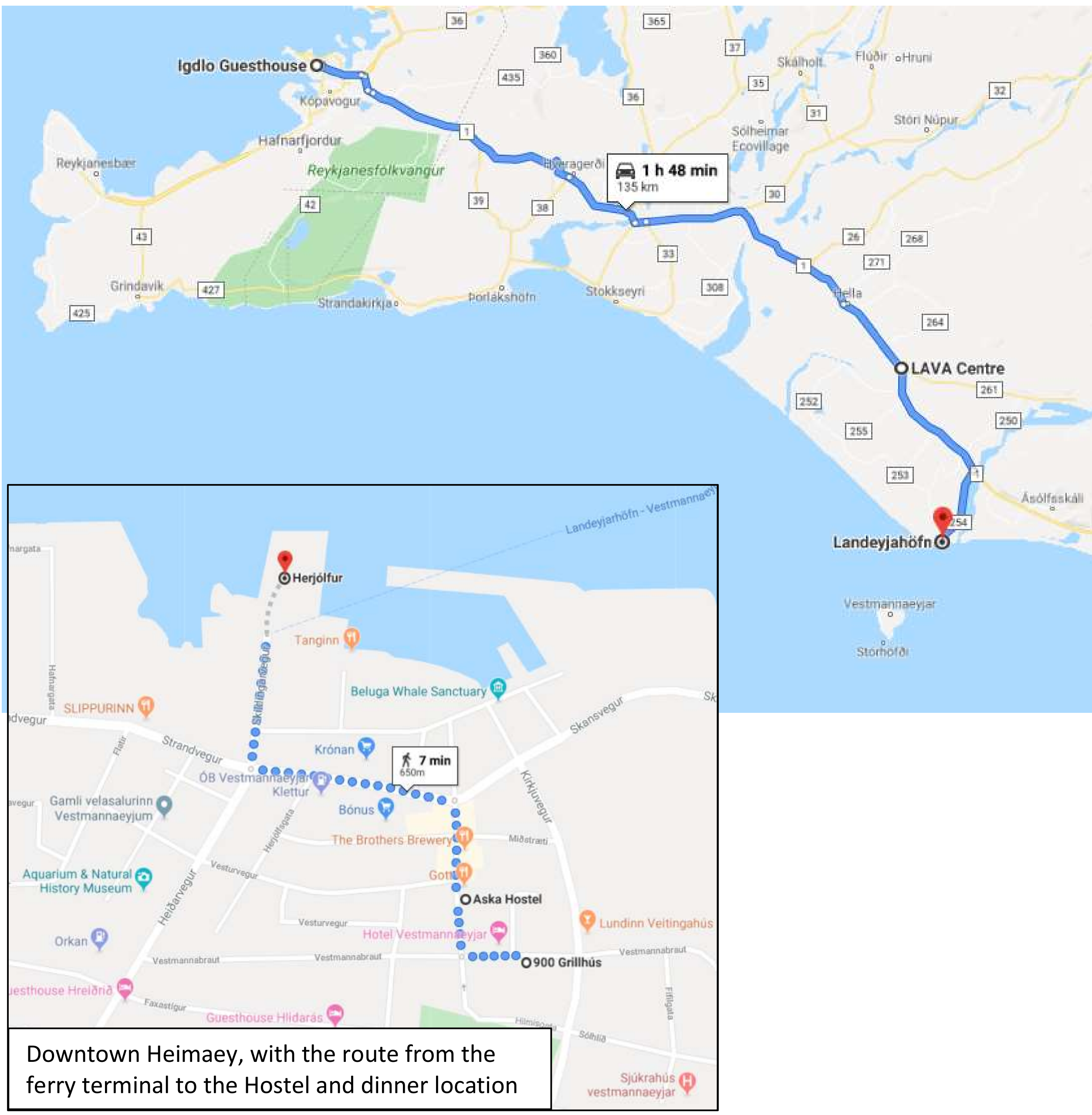
Eating
17 10-11 .... A1
18 10-11 .... D1
19 Argentína A1
20 Ban Thai B2
Hlemmur Mathöll .... (see 25)
21 Johansen Deli B1
22 Matwerk A2
23 Noodle Station A2
24 Restó B2
25 SKÁL! B2
26 Yummi Yummi B2

Drinking & Nightlife
KEX Bar .... (see 10)

Shopping
27 Handknitting Association of Iceland D1
28 Iceland Camping Equipment Rental A1
29 Iðnú Bookshop B2
30 Jokla Icelandic Design A2
31 Lucky Records B2
32 Orr A2

Day 3: Monday, March 9th, 2020 – Reykjavik to Heimaey

7:30AM: Wake up, pack up, breakfast is provided at the hostel.
8:30AM: Load the bus and leave the hostel
10:00AM: Arrive at LAVA Centre and tour the museum, people can buy lunch here or on the ferry to Vestmannaeyjar Islands
12:30PM: Depart from the LAVA Centre
1:00PM: Board the ferry and depart for Vestmannaeyjar, Heimaey.
2:30PM: Arrive Vestmannaeyjar, Heimaey and check in with the hostel (Aska Hostel, Bárustígur 11, Vestmannaeyjar, 900, Iceland).
Rest of the day: Walk around, hang out, relax, whatever…
6:00PM: Group dinner at 900 Grillhouse, Vestmannabraut 23, 900 Vestmannaeyjar, Iceland



Downtown Heimaey, with the route from the ferry terminal to the Hostel and dinner location

STOP 3.1 – *LAVA Centre*

This day is mostly a travel day but we will have one stop to 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 at 900 Grillhouse, a restaurant owned by the same owners of the Aska Hostel (they are giving us a discount to eat there).

Heimaey

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 10)
9 Heilsueyjan Spa C2
Rent A Bike .... (see 10)
10 Ribsafari B1
11 Swimming Pool A3
12 Viking Tours C1

Sleeping

13 Aska Hostel C2
14 B&B Hrafnabjörg B2
15 Gistiheimilið Hreiðrið B2
16 Hótel Eyjar C2
17 Hótel Vestmannaeyjar C2
Sunnuhöll HI Hostel .... (see 17)

Eating

18 Einsi Kaldi C2
Gott .... (see 13)
19 Krónan C2
20 Slippurinn B1
21 Stofan Bakhús C2
22 Tanginn C1

Shopping

23 Útgerðin C2
24 Vínbúðin C2

STOP 3.3 – *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.

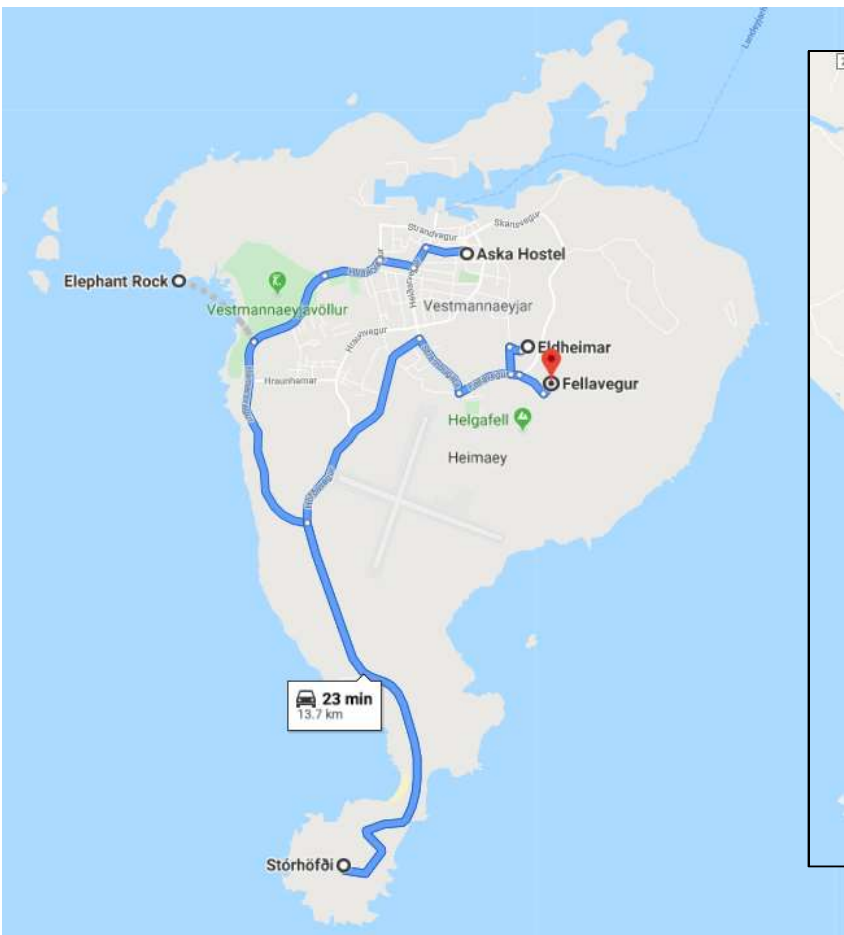
http://vestmannaeyjar.is/is/page/aeskulyds-og-ithrottamal

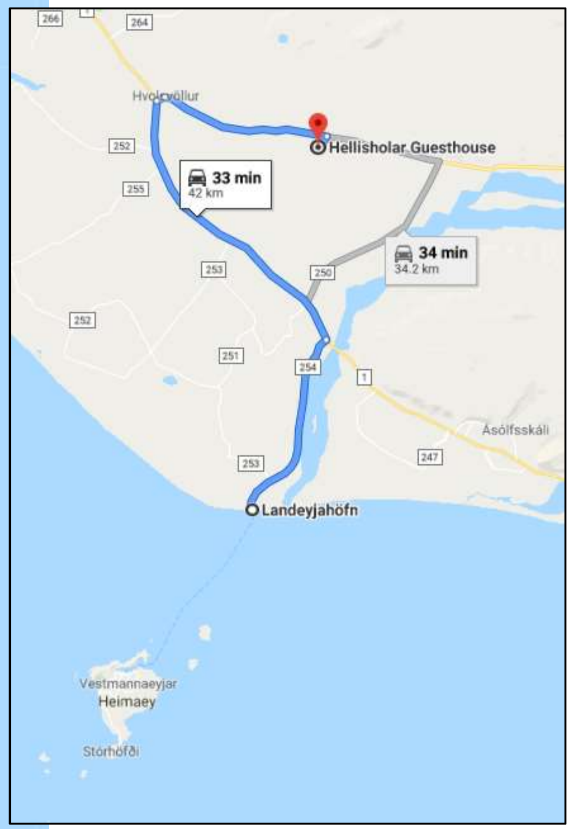
Swimming pool, Brimholalaut, 900 Vestmannaeyjar

It closes at 9:00PM

Day 4: Tuesday, March 10th, 2020 – Heimaey to the Rift Valley

8:00AM: Breakfast in the hostel, pack up, and load into the buses.
9:00AM: Leave the hostel and drive around the island, first stop Elephant Rock
10:00AM: Storhofdi - south edge of the island, hike around and get a view of Surtsey
11:00AM: Eldheimar Volcano Museum (10, Gerðisbraut, Vestmannaeyjabær, opens at 11AM)
1:00PM: Climb Eldfell Volcano
2:00PM: Board the ferry and depart for the main land
3:30PM: Reach Landeyjahofn and drive to the Guesthouse
4:30PM: Get to Hellishólar Guesthouse, Öldubakki 5, Hvolsvöllur, Iceland, https://hellisholar.is/
6:00PM: Group dinner at the hostel
That evening: I am hoping this location will give us a good shot at seeing the Aurora Borealis, the Northern Lights





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.

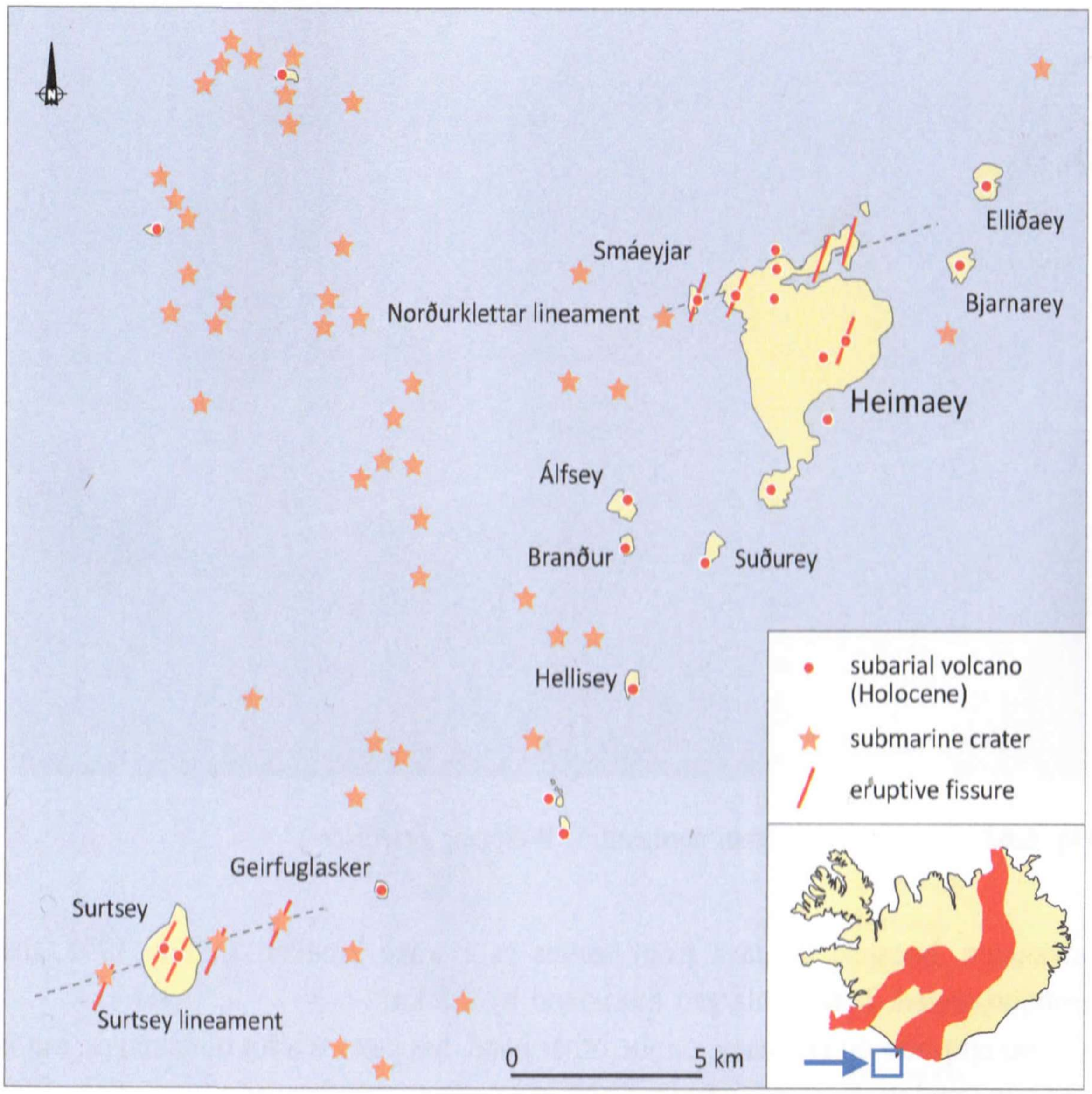


Fig. 6.62 The Westman Islands near Iceland's south coast © Wolfgang Fraedrich

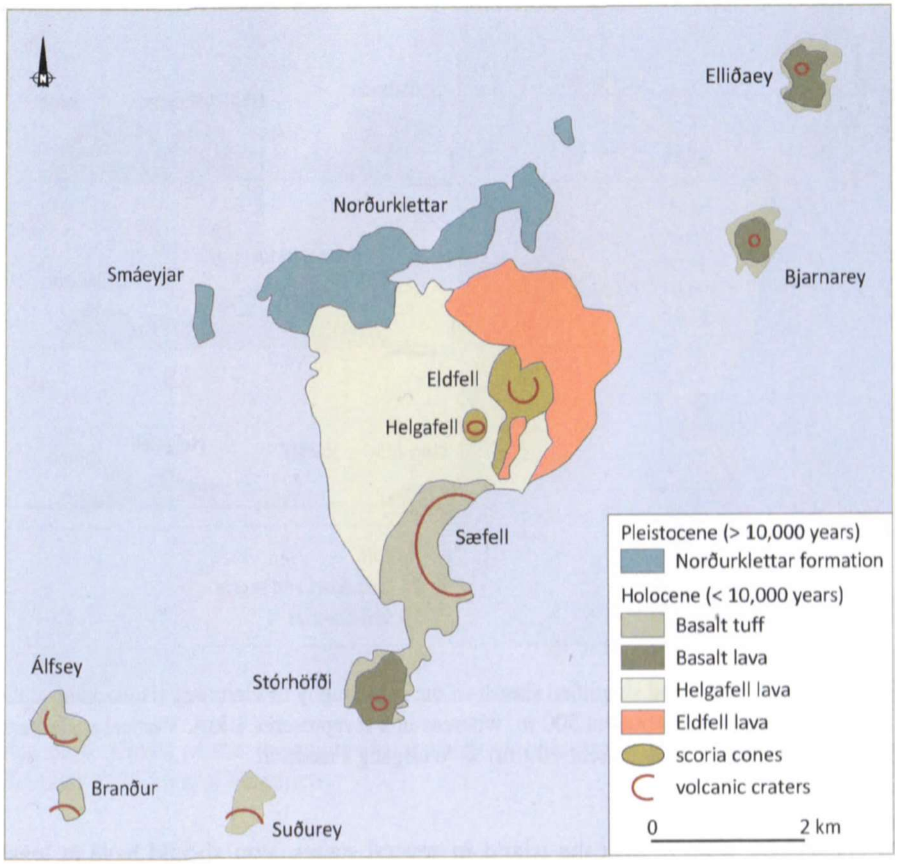


Fig. 6.64 Simplified geological map of des Vestman Islands © Wolfgang Fraedrich

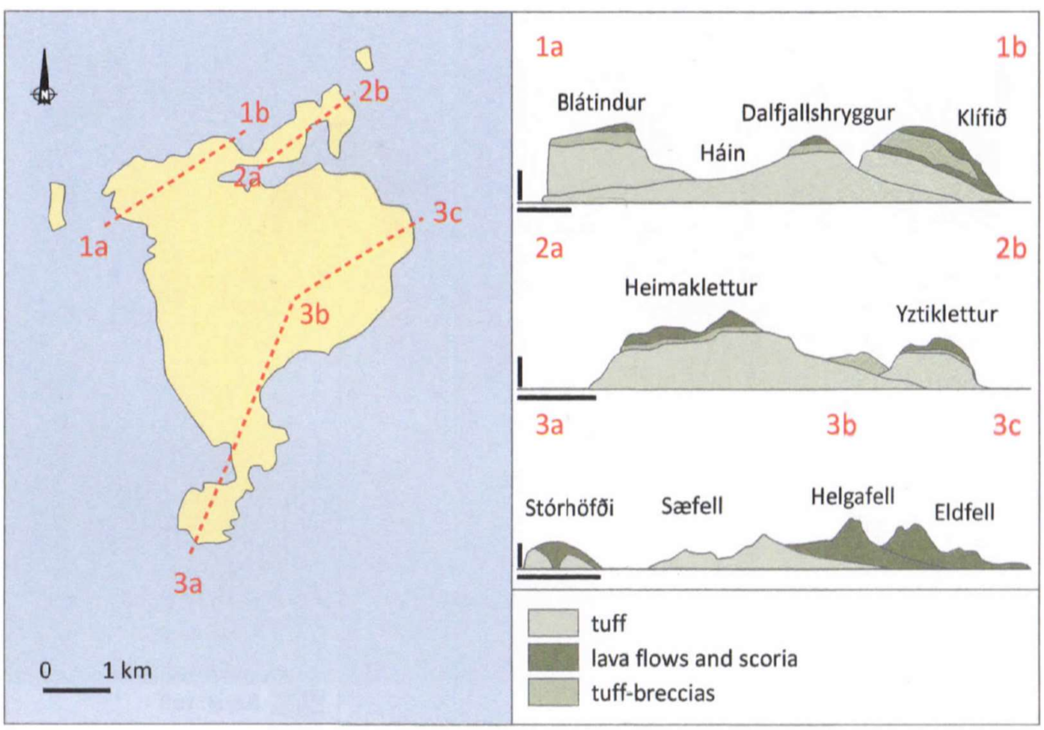
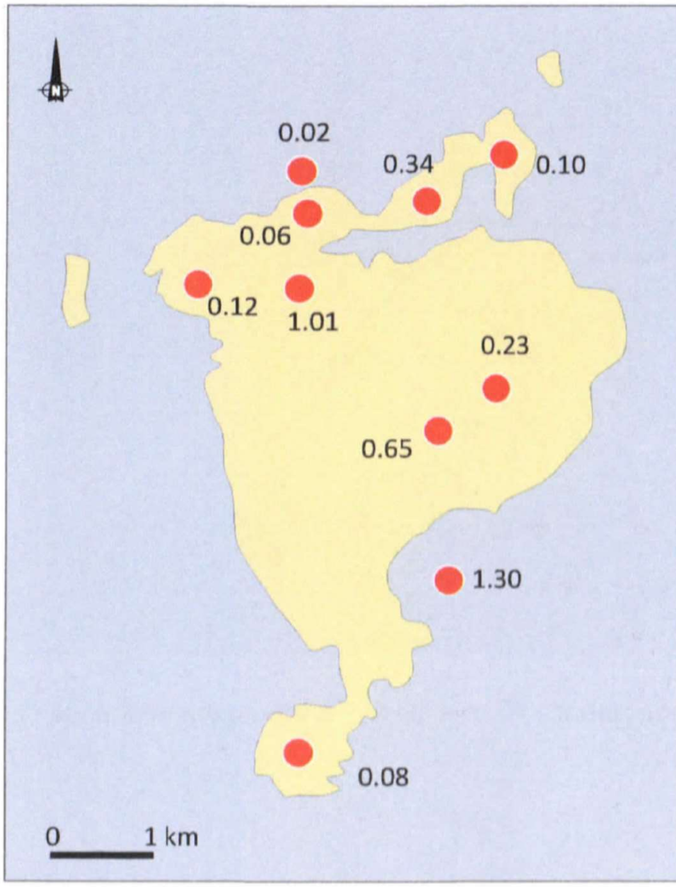


Fig. 6.65 Schematic and simplified sketch of the stratigraphy of Heimaey (Horizontal scale bars (black) in 1 and 2 represent 500 m, whereas in 3 it represents 1 km. Vertical scale bars (black) in 1, 2 and 3 all represent 100 m) © Wolfgang Fraedrich



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)

Fig. 6.66 Crowd of the volcanic material which was erupted by the different volcanoes on Heimaey © Wolfgang Fraedrich

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 coast line and go up to the towering cliffs of Norðurklettar. These basalts, formed at the end of the last Ice Age, make up the northwestern edge of Heimaey. 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. Norðurklettar 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 (63° 26′ 22.20″N/20° 18′ 23.90″W; Fig. 6.89).

Fig. 6.89 The elephant at Norðurklettar © Wolfgang Fraedrich

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.

– Sæfellcrater—Pirate Cove—Stórhöfði

It is also worthwhile to visit the southern tip of the island off Heimaey. Here you will find the remnants of previous eruptions. The Sæfell 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 63° 24′ 59.20″N/20° 16′ 52.30″W. You can climb to the ridge from there.

Sæfell 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 (Fig. 6.92). 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 Stórhöfði (63° 24′ 45.90″N/20° 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 (63° 24′ 52.20″N/20, 16′ 52.30″W).

Fig. 6.92 View from the south over the Pirate Cove to the Sæfell tuff ring © Wolfgang

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 (Fig. 6.93). Three ships with pirates from Algeria, under Turkish rule, reached Heimaey on July17, 1627. The fortifications built on Heimaey under Danish rule at the end of the 15th century did not help. The pirates forced their way through the coast and docked more south in the bay between Sæfell and Stórhöfði.

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 a 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.

A short beach walk is recommended along the west side of the island towards the north. Here, you have a good view of the Sæfell tuffs, on which you can walk

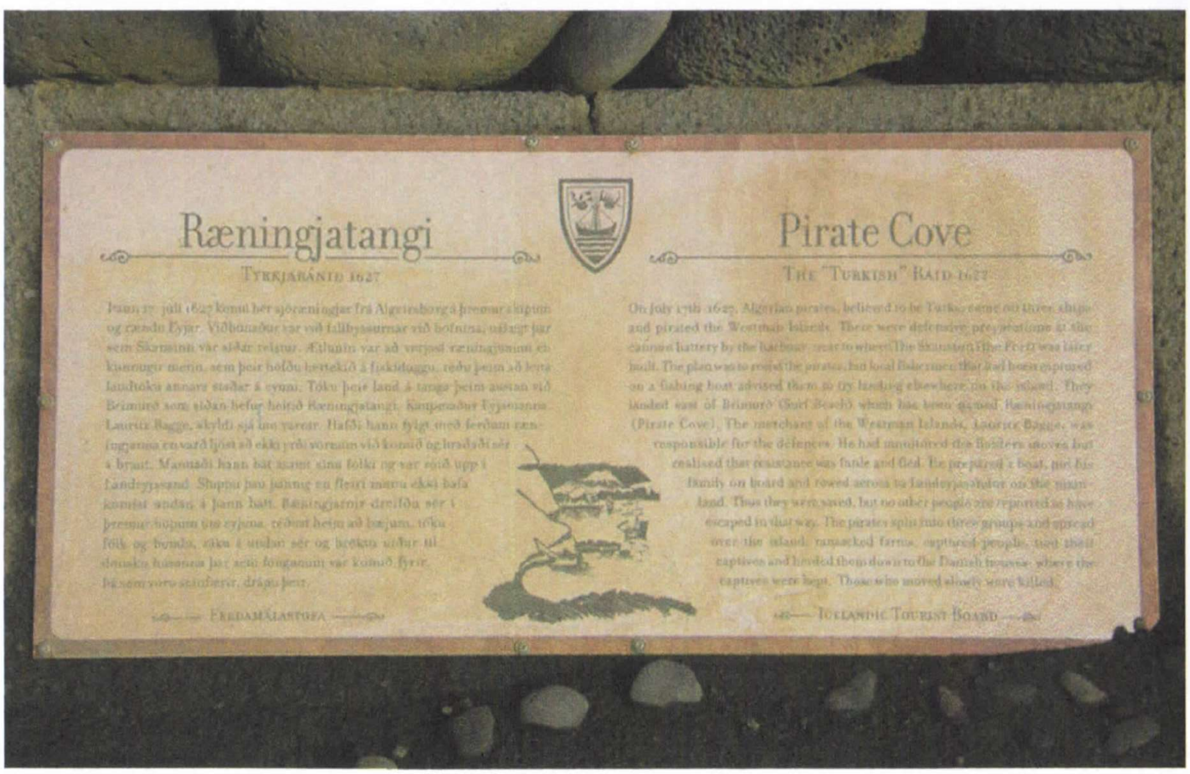


Fig. 6.93 Information board retelling the story of the pirate invasion of 1627 © Wolfgang Fraedrich

Fig. 6.94 Volcanic bomb embedded in Sæfell tuff © Wolfgang Fraedrich

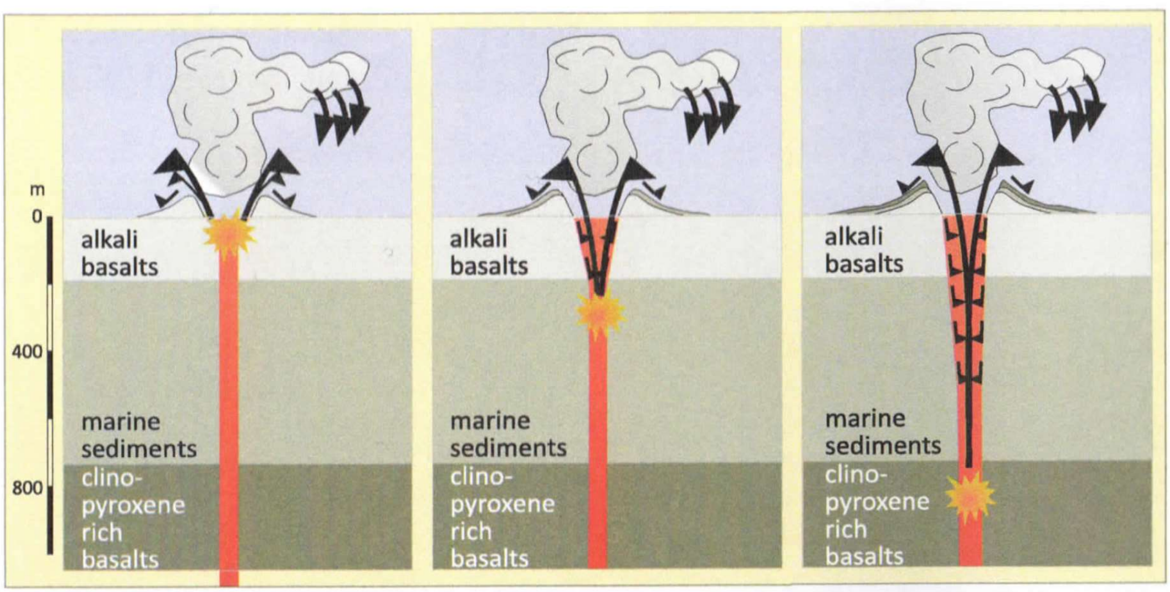


Fig. 6.95 Schematic sketch showing the growth of the diameter beneath Sæfell, (Left: The eruption begins and explosions are shallow-seated carrying alkali basaltic xenoliths (Type I) to the surface. Middle: Explosion focus moves downward into the sedimentary basement rocks and sedimentary xenoliths (Type 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) © Wolfgang Fraedrich

Fig. 6.96 View to the south of Heimaey with Stórhöfði © Wolfgang Fraedrich

Fig. 6.97 Lava flow at the north edge of Stórhöfði © Wolfgang Fraedrich

along. There are numerous volcanic bombs that have once been thrown out of the crater with fine material (Fig. 6.94). Due to their weight on the ground, they squeezed the loose materials together. As shown in Fig. 6.95, the ejected material is from different depths since the explosions occurred at increasing depth during the eruption.

The volcano Stórhöfði 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 Stórhöfði must have had a very low viscosity (Figs. 6.96 and 6.97).

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 (Fig. 4.2). 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 14 November 1963 by fishermen attending their nets 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 3½ 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.

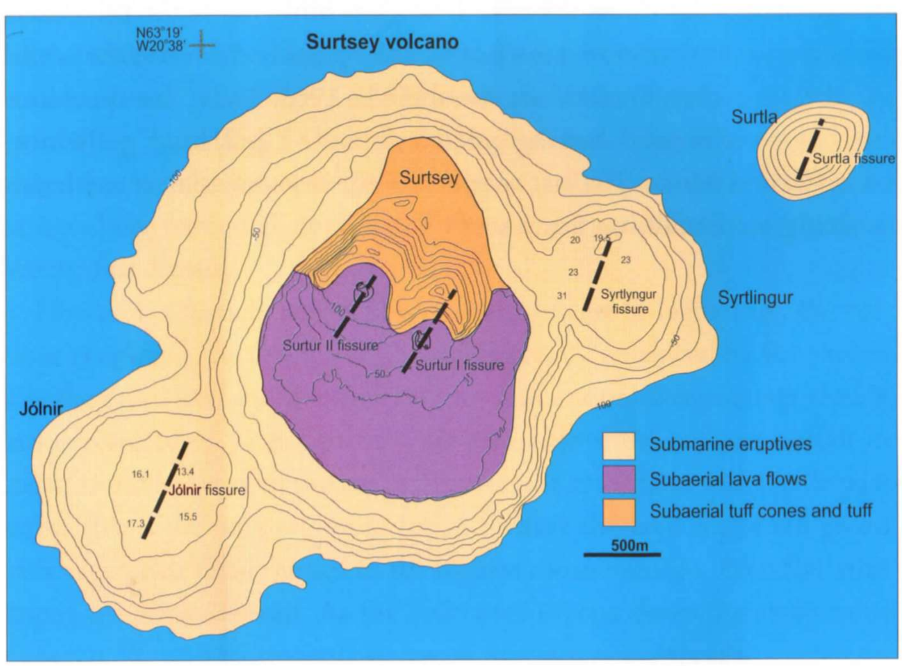


Figure 4.2 Geological map of the Surtsey volcano.

packed with people. The whole operation went remarkably smoothly and without mishaps, thanks to the decisive response from local authorities, favourable 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 3 July 1973. It covered most of the town with several metres 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 protruding 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 'Pompei of the North' began excavating some of the houses buried in the 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 *Páskahraun* branch of the lava [63.4300, –20.2401], which advanced into the sea during Easter 1973, as well as Vagabönd, which is a scoria mound representing a section of the Eldfell cone that broke off on 19 February and was then carried by the lava flow towards the sea. *Kirkjubæjarhraun [63.4393, –20.2430]*, the bulldozed sector of the lava flow field, is the site where it is thickest, or 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%.

STOP 4.3 – *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 Gerðisbraut and Austurgerði 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 (Fig. 6.82), 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 (Fig. 6.84). The story of the volcanic eruption and the fate of the inhabitants of Vestmannaeyjar are illustrated based on the example of Mrs. Gerður Sigurðardóttir and Mr. Guðni Ólafsson 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 Pompeji of the North, is worthwhile in any case (entrance ISK2300 = €18.50, $21.80, children up to 10 years free).

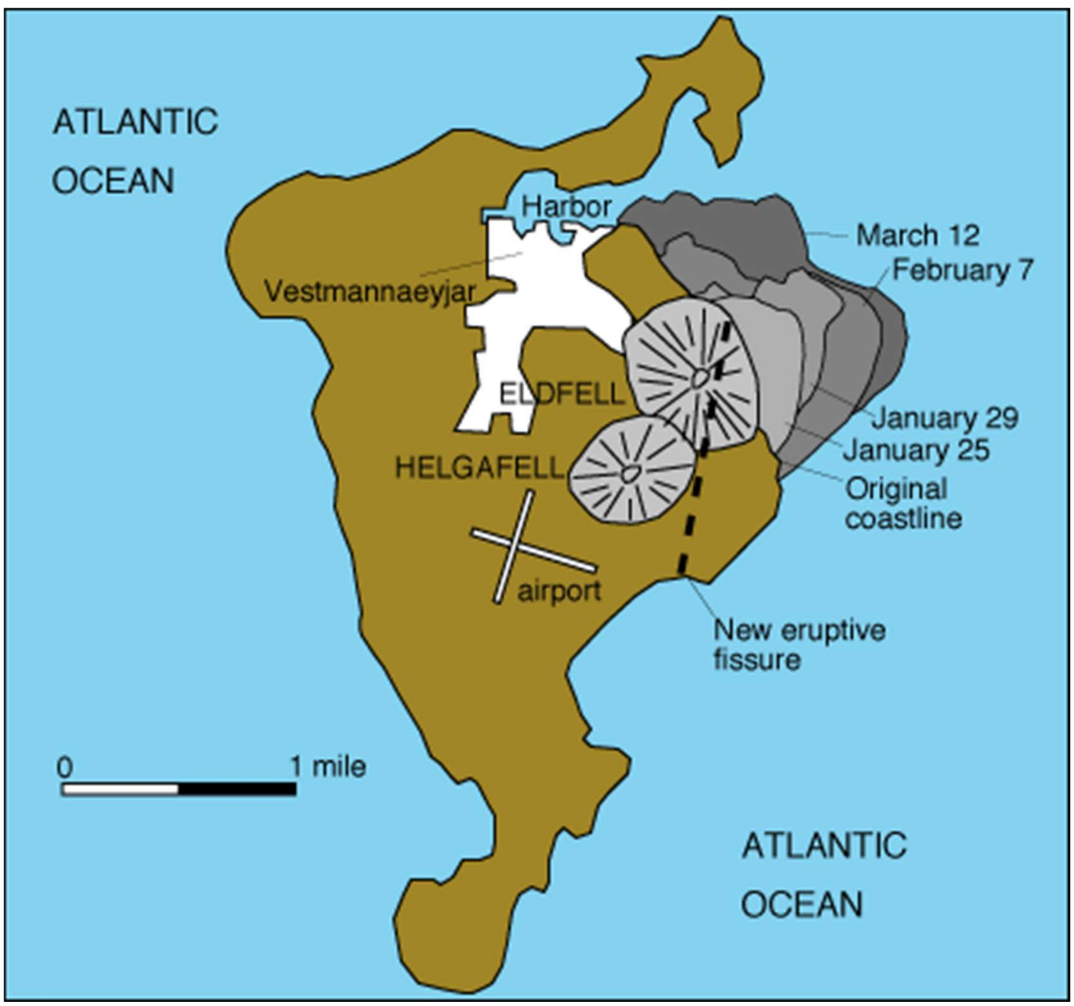
Fig. 6.84 View on the museum Eldheimar, 'Pompeji of the north' © Wolfgang Fraedrich

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.



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.

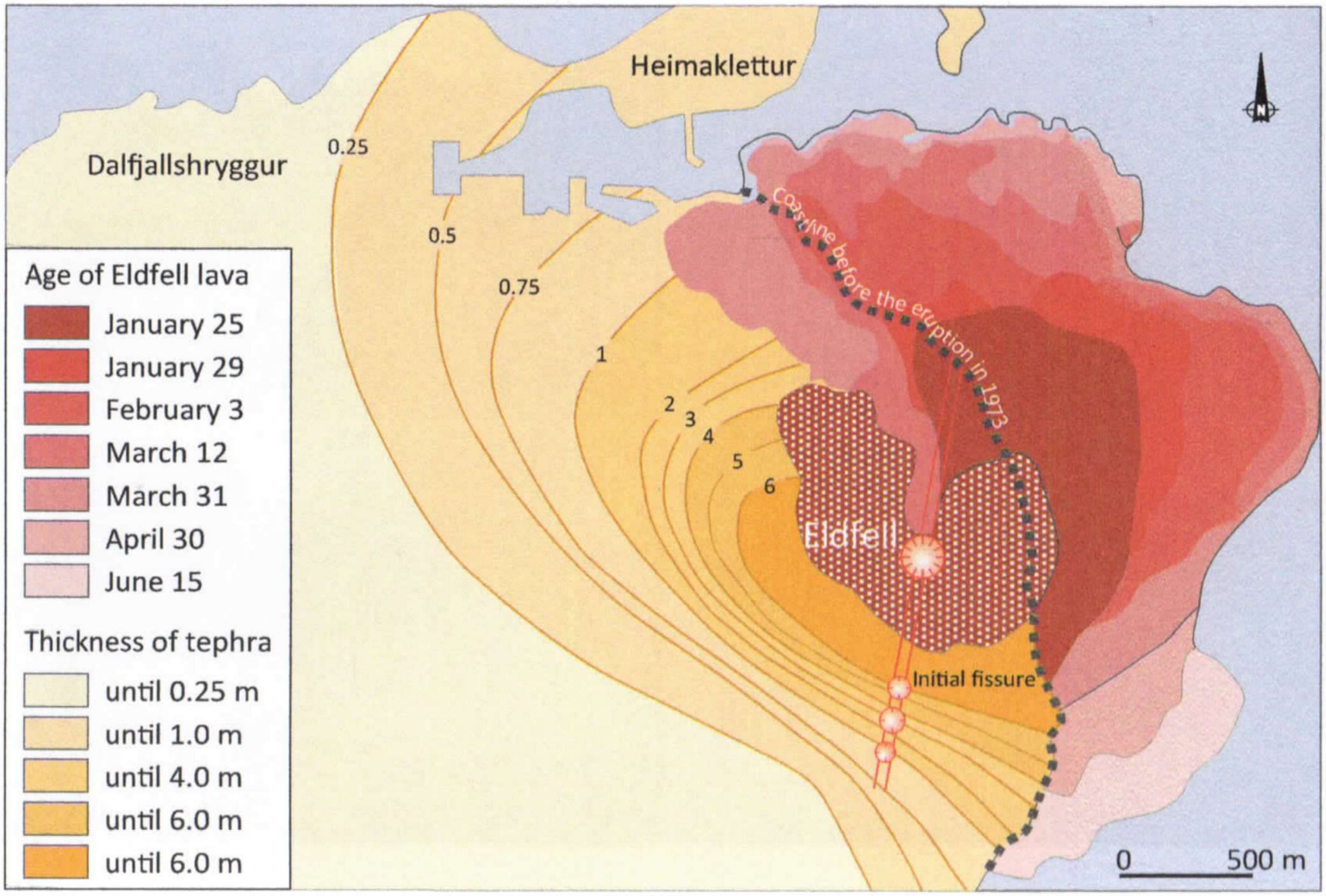
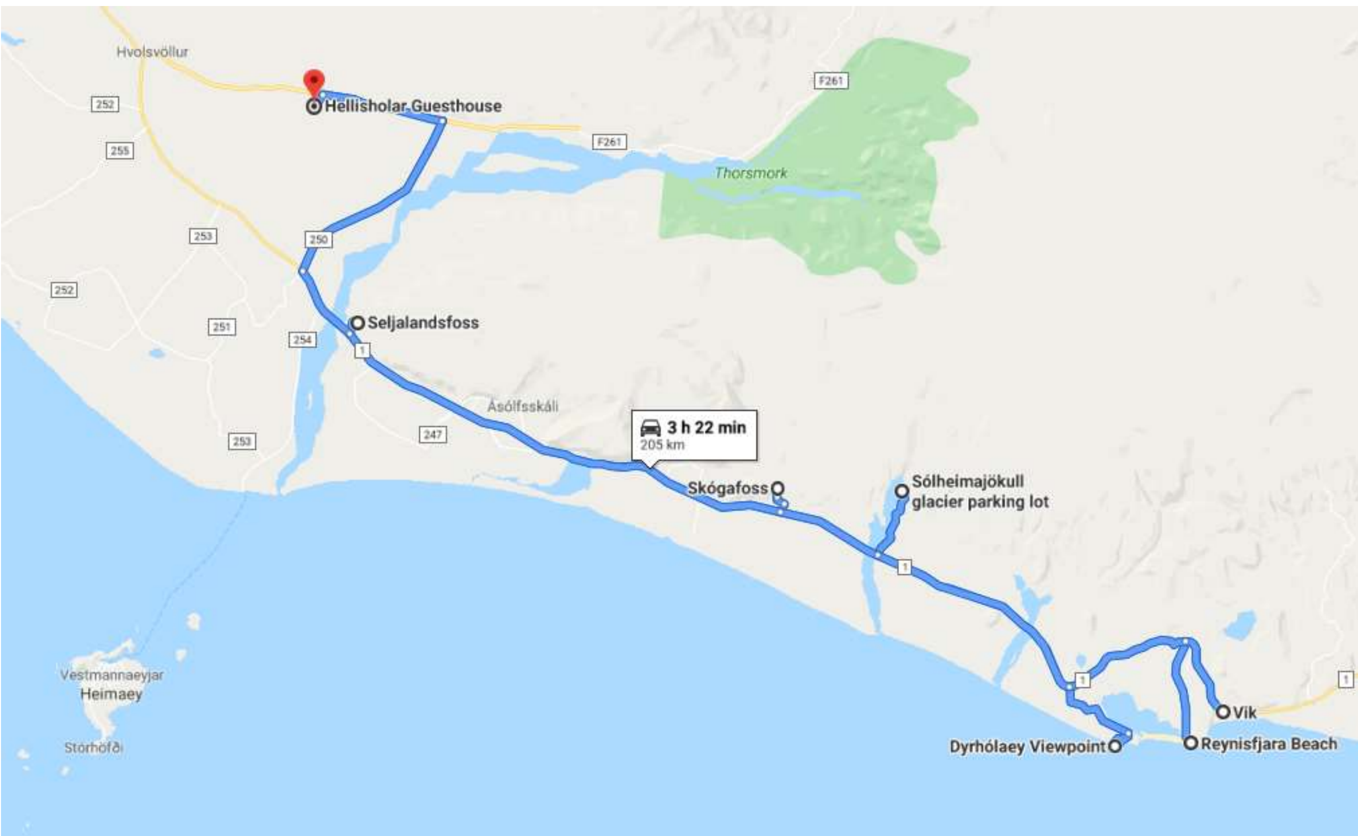


Fig. 6.82 Eldfell—age of lava and thickness of ashes © Wolfgang Fraedrich

Day 5: Wednesday, March 11th, 2020 – Waterfalls, Glaciers and Vik Beaches

7:00AM: Wake-up, breakfast is provided by the hostel.
8:30AM: Depart from the hostel
9:00AM: Arrive at Seljalandsfoss waterfall.
10:30AM: Arrive at Skogafoss waterfall.
11:45AM: Sólheimajökulsvegur Glacier, A pack lunch will be provided by the hostel, we can eat at the glacier
2:30PM: Arrive at Dyrholaey Viewpoint
3:30PM: Arrive at Renisfjara Beach
4:15PM: Arrive at Vik
5:45PM: Arrive back at the hostel
6:30PM: Group meal at the hostel



STOP 5.1 – *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.

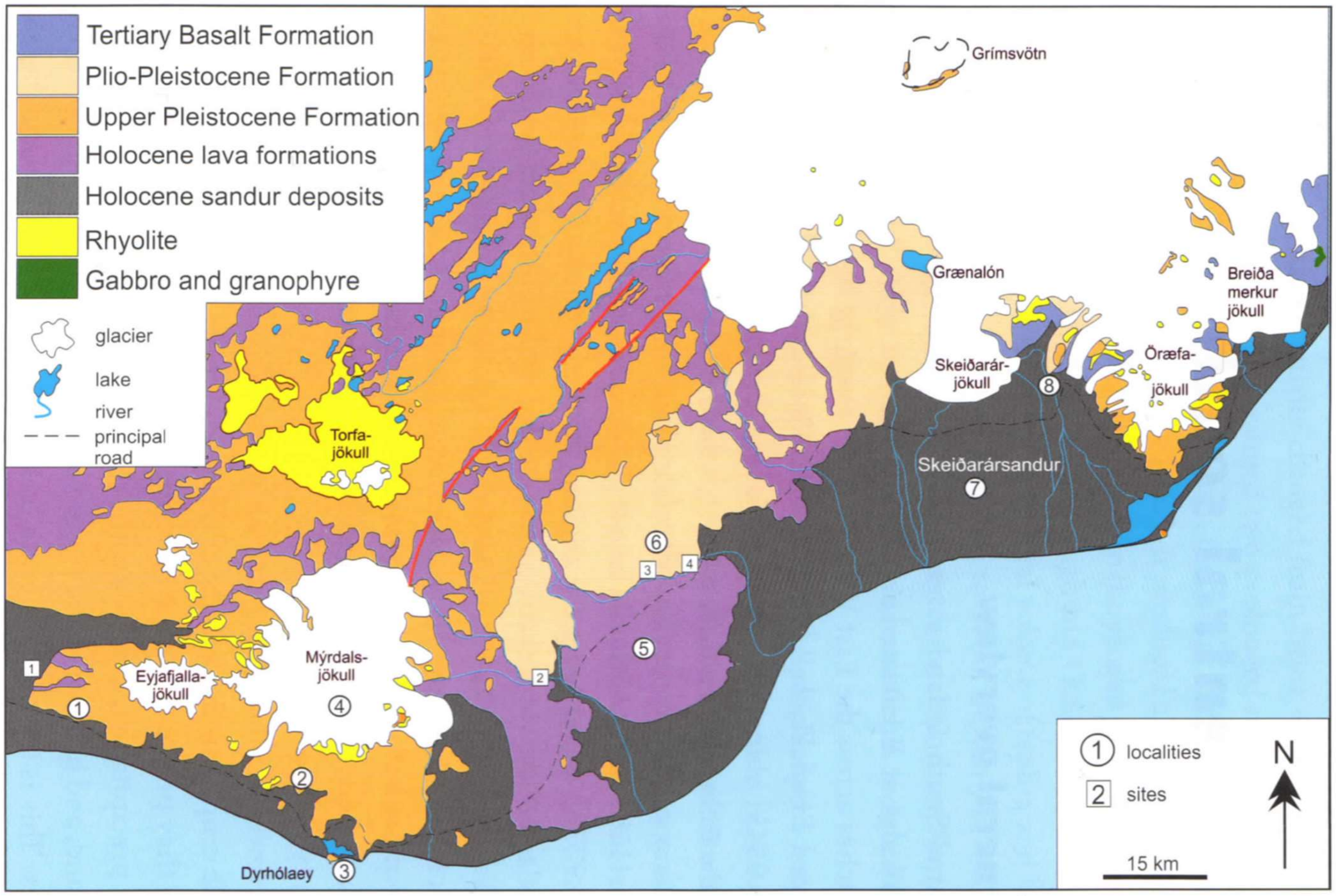


Figure 5.1 The main geological features of Central-South Iceland.

Thordarson, T. and Hoskuldsson, A., 2019, pg. 110

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

We describe the structure of Eyjafjallajökull and its 2010 eruption in a moment, but first we make our **fourth stop (4)** at one of the better-known waterfalls in Iceland, namely **Seljalandsfoss** (Figs. 14.13 and 14.14). To reach this waterfall, we first cross the bridge across the glacial river Markarfljot (**Markarfljót**). The glacial water is mainly derived from the ice caps of Eyjafjallajökull and Myrdalsjökull (**Mýrdalsjökull**), both of which we discuss further today (Fig. 14.12b). 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 metres per second.

A second feature to mention just as you approach the river Markarfljot is the archipelago of **Vestmannaeyjar** (Figs. 14.1 and 14.12b). The main island, **Heimaey**, can usually be seen when you are that close to the coast. You may 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,

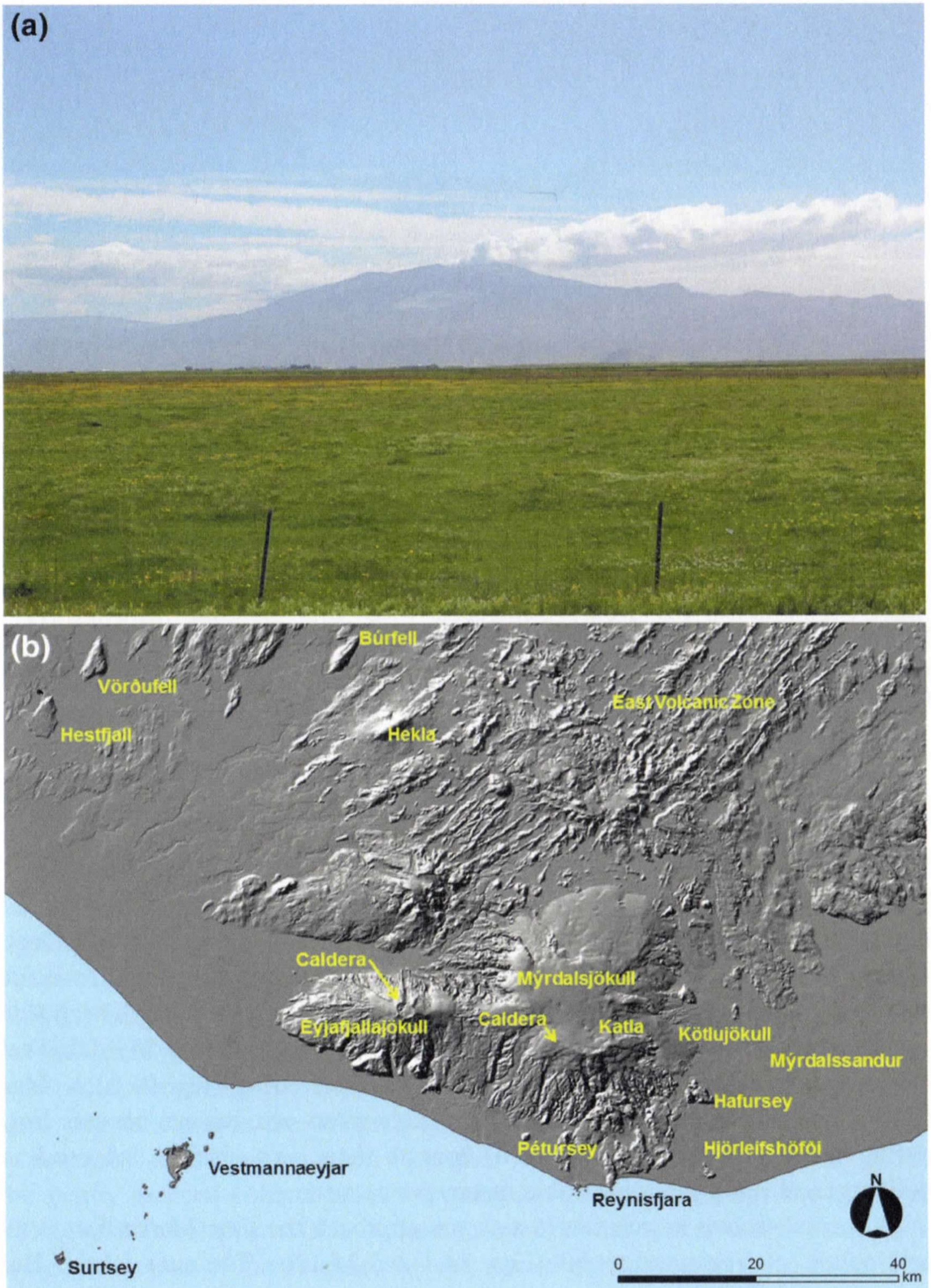


Fig. 14.12 **a** View east, the Eyjafjallajökull Volcano seen from a distance. This photograph is taken soon after the 2010 eruption. The inclined while column is due to heating from the eruptive materials in the caldera. The mist or haze is due to the ash in the air, carried by the wind when the photograph was taken. **b** Location of Eyjafjallajökull, showing its caldera, as well as the names and locations of other main mountains and landscape features discussed in this chapter

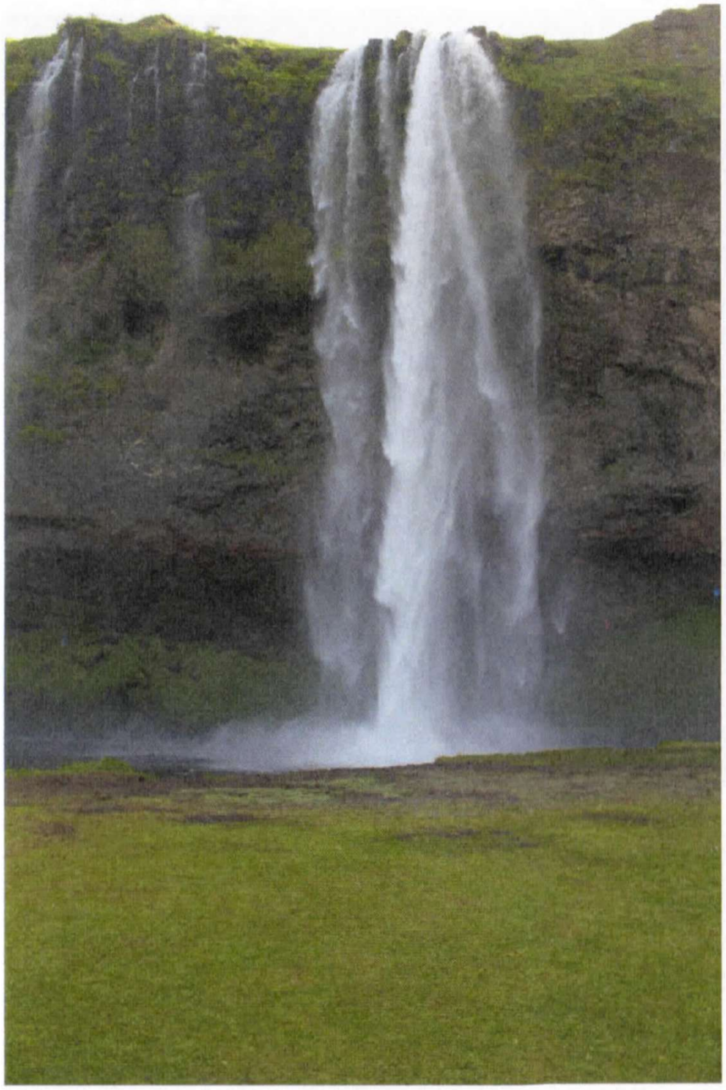


Fig. 14.13 View north, the waterfall Seljalandsfoss. The 60 m high cliff from which the water falls is an old sea cliff, formed by wave erosion when the sea level was much higher some 13 thousand years ago

namely the island of **Surtsey** (Fig. 14.12b), a table mountain formed in the sea (Fig. 6.6, Chaps. 6 and 13) 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 (Chap. 13), 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 than it is today. The same applies to most of the vertical cliffs that constitute the lower part of Eyjafjallajökull, and which we will see in a moment.

Fig. 14.14 Seljalandsfoss is in the river Seljalandsa (Seljalandsá), here seen on the ground in front of the waterfall

The rocks that constitute the cliffs, here as in much of the exposed parts of Eyjafjallajökull, 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 (see Chap. 13 for a discussion on 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 a footpath **behind the waterfall**. Some people walking along that path are seen in Fig. 14.13. The water in the cascade is beautifully clear and clean and constitutes the small river Seljalandsa (**Seljalandsá**) (Fig. 14.14).

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

14.5 Eyjafjallajökull Volcano—Internal Structure and the 2010 Eruptions

From here we drive on along Road 1 to the east along the high cliffs of **Eyjafjallajökull** (Fig. 14.12b). The name means literally ´the ice cap of the island mountains', the islands being Vestmannaeyjar (Figs. 14.1 and 14.12b). 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 relates 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 (Fig. 14.15) to a maximum of about **350 m** (Figs. 14.16 and 14.17). 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 part is the site of an ice cap, Eyjafjallajökull, and also of a small caldera with a diameter of about 3 km (Figs. 14.12c and 14.18).

Fig. 14.15 Vertical cliff, partly an old sea cliff formed where the sea level was much higher some 13 thousand years ago, in the southwestern side of Eyjafjallajökull (the mountain is located in Figs. 14.1 and 14.12b; see also Fig. 14.18). The vertical cliff is about 200 m high and primarily composed of hyaloclastite

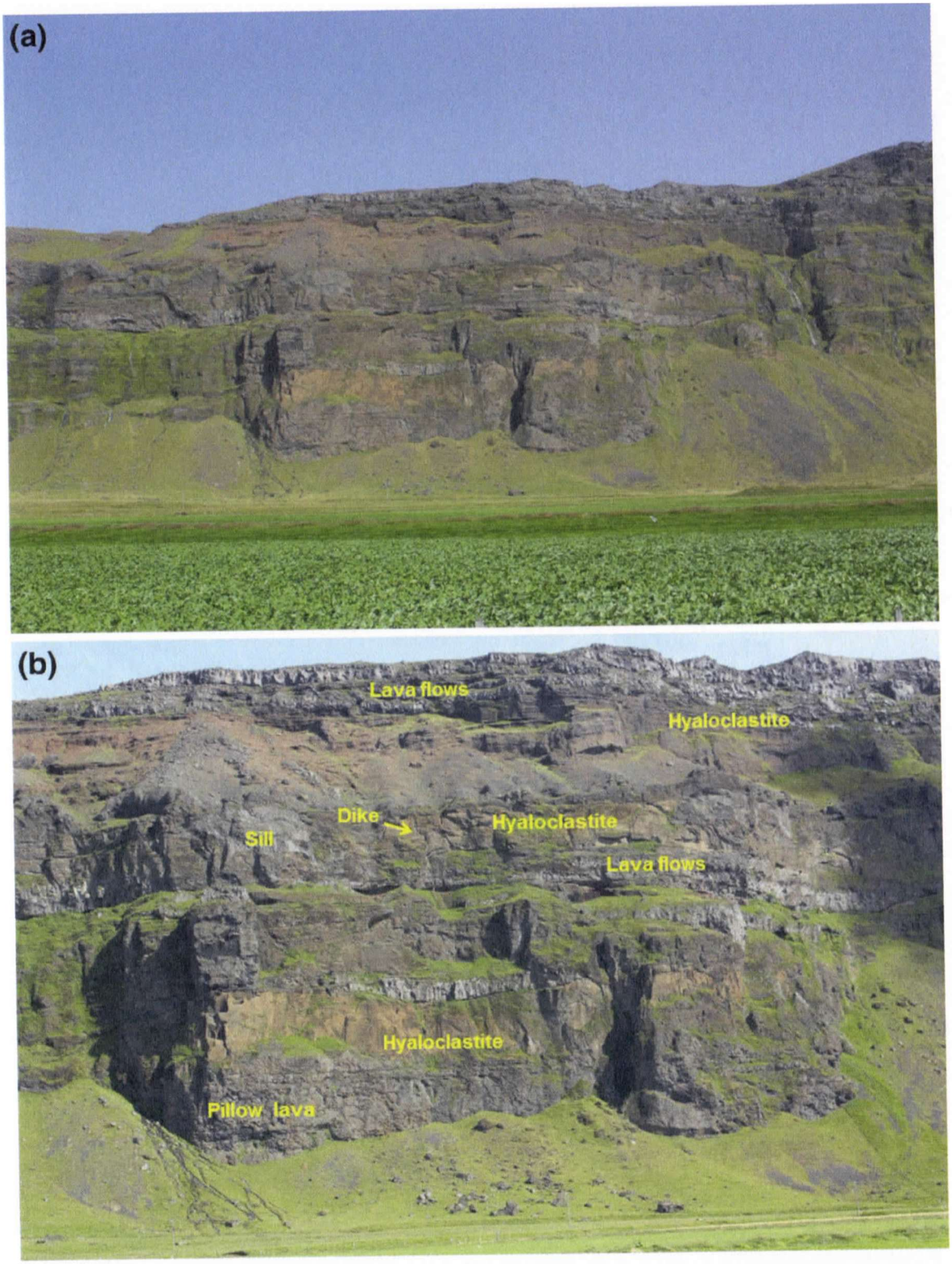


Fig. 14.16 Vertical cliffs showing the internal structure of part of Eyjafjallajökull (located in Figs. 14.1 and 14.12b) as seen from Road 1. **a** he cliff section seen here reaches height of about 350 m and is composed of a variety of rock layers and units. **b** Close-up of a part of the cliff-section 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

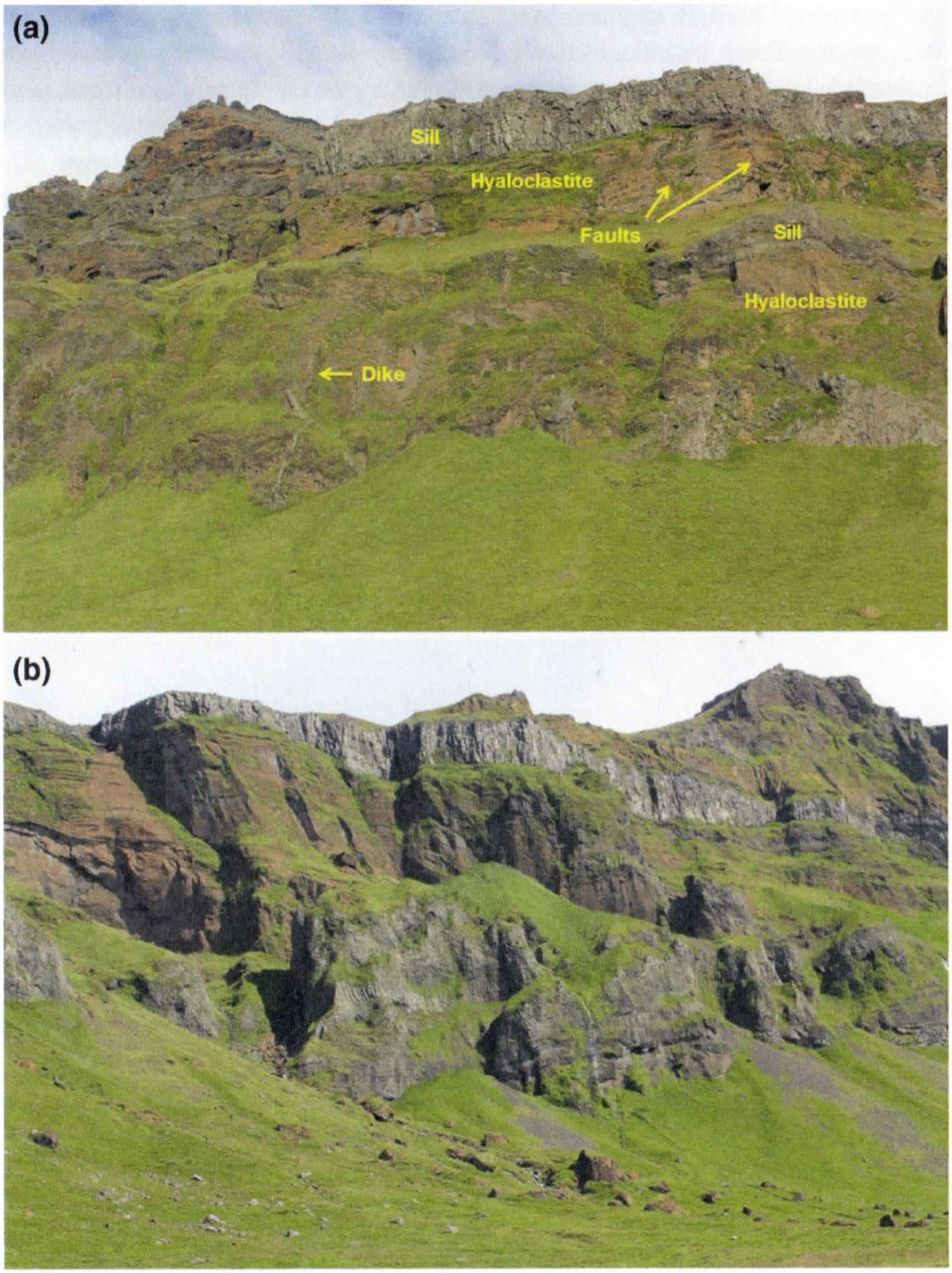


Fig. 14.17 More details on the internal structure of Eyjafjallajökull (located in Figs. 14.1 and 14.12b) as seen from Road 1. **a** The internal structure of Eyjafjallajökull, as seen here, is characterised by thick layers of hyaloclastite, together with lava flows (seen in Fig. 14.16). In addition, 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

Figures 14.15, 14.16 and 14.17 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 (Figs. 14.1 and 14.12b). 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 **Grimsvötn (Grímsvötn)**. Grimsvötn is located in the Vatnajökull ice sheet (located in Fig. 2.2), and thus

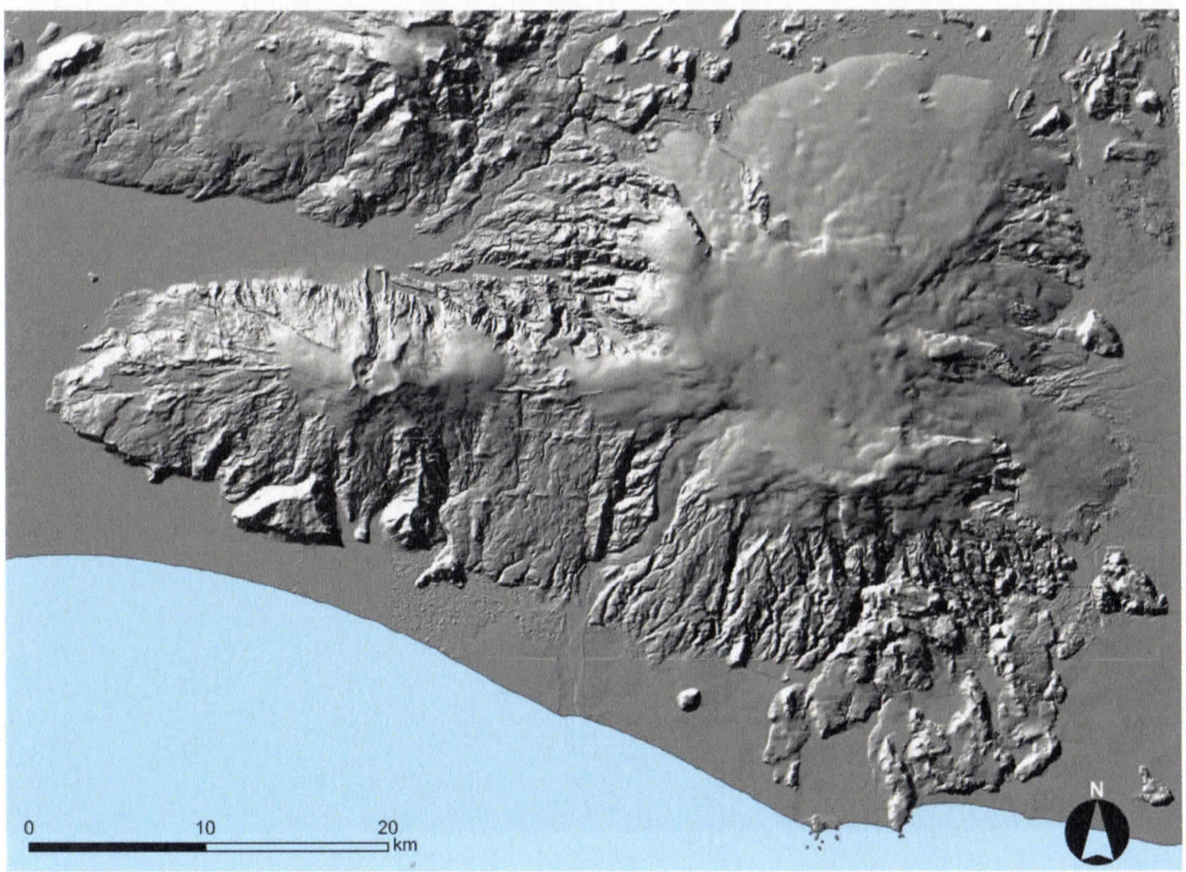


Fig. 14.18 Digital elevation map of Eyjafjallajökull and Myrdalsjökull (Mýrdalsjökull) showing the shapes of the volcanoes and their calderas. The names and structures are identified in Figs. 14.1 and, in particular, in Fig. 14.12b

outside this excursion, but is the most active volcano in Iceland in terms of frequency of eruptions. During the past 1100 years Grimsvötn has eruptive about 70 times, or 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 20 March 2010 in the pass between the glaciers Eyjafjallajökull and Myrdalsjökull (Figs. 14.1, 14.12b and 14.18). This fissure eruption, producing low-viscosity primitive basalt, came to an end 12 April. 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 (Chap. 11) 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 very small (total volume 0.02 km^2) 'gentle' outpouring of aa lava (Fig. 14.11)—the kind of eruption that some refer nowadays to as a 'touristic eruption'.

The first eruption faded away and finally came to an end on 12 April. Then a **second eruption** began 14 April 2010, but this time beneath the ice cap in the summit **caldera** (Figs. 14.12b and 14.18). 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 22 May 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 eruption was thus about 0.2 km^3. This is thus a typical **small eruption** from 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 (Figs. 2.1 and 3.1) with a total area of about 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 the aeroplanes, hence the closure of the airspaces.

There were three fissures associated with the 2010 eruption, all of them several hundred metres long (maximum length 6–700 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 (Figs. 14.12b and 14.18), and the northeast trend which is the general trend of the East Volcanic Zone (Fig. 14.12b).

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 in the volcano from the year 2000 until 2009, when earthquakes and deformation began again. The rate of deformation and earthquakes increased much from early March 2010 until the eruption began on 20 March.

All these main earthquake and deformation episodes in Eyjafjallajökull have been interpreted as being related to **dike injections** from great depths (some 20 km) that became deflected into **sills** (Figs. 14.16, 14.17 and 14.19) 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 that 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 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 unusual about these dike-sill intrusive events in the past 17 years? Certainly not. The cliffs sections show **exactly the same structures**,

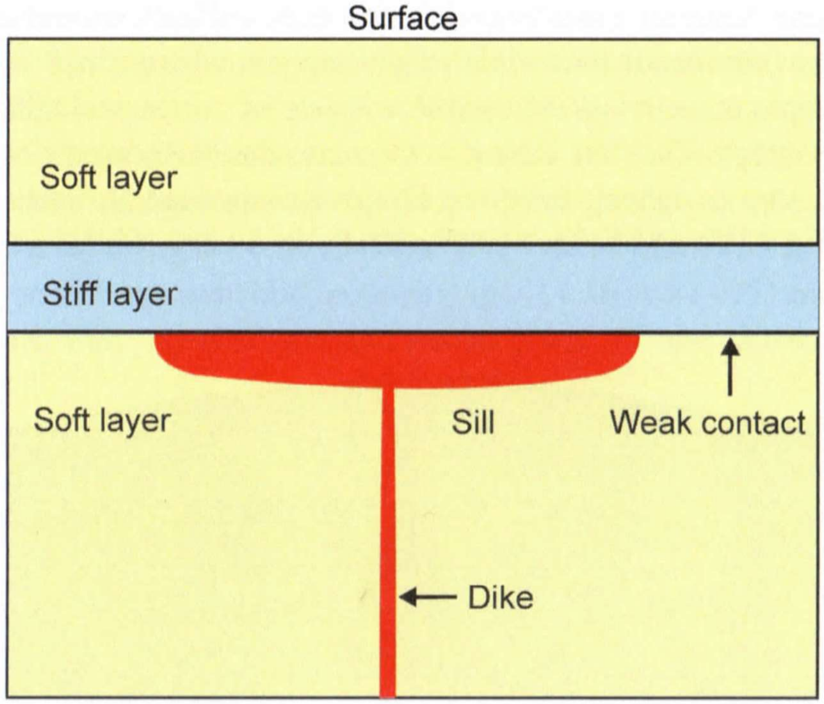


Fig. 14.19 Dikes are commonly deflected into sills at contacts between mechanically dissimilar rock layers. Here the dike was transformed into a sill at the contact between a stiff layer (for example, a basaltic lava flow or an earlier sill) above and a softer (more compliant) layer below (for example, hyaloclastite or tuff). Many of the sills in Eyjafjallajökull are formed at such contacts. Alternatively, if the driving magmatic pressure (overpressure, see Chap. 11) 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 (Fig. 13.35)

even at shallow depths, namely dikes and sills. In particular, Figs. 14.16 and 14.17 show many sills and dikes. As is common, the dikes tend to be much thinner than the sills (Fig. 14.19). 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 seen at depths of 1–1.6 km below the top of the volcano in the cliff sections in Figs. 14.16 and 14.17; namely injected dikes failing to reach the surface—becoming arrested—and many changing into sills (Fig. 14.19).

Why is dike arrest and dike deflection into sills so common in Eyjafjallajökull (and stratovolcanoes in general). Answer: because Eyjfjallajökull 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 aeroplanes, 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** (Fig. 11.3) and behave mechanically in a very similar way to artificial

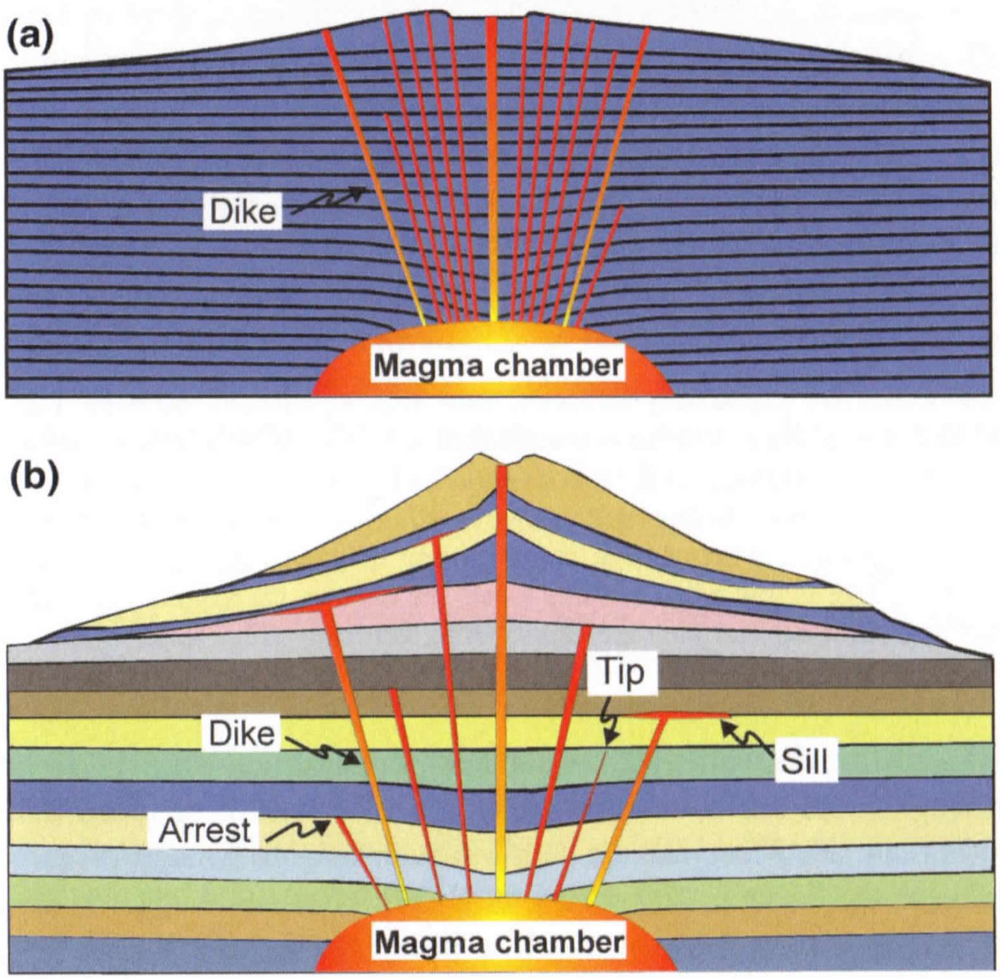


Fig. 14.20 Basaltic edifices are composed of rock layers all of which have very similar mechanical properties (basaltic lava flows) whereas stratovolcanoes (central volcanoes, composite volcanoes) are composed of rock layers with widely different mechanical properties (including lava flows of various compositions, layers of pyroclastics (e.g. hyaloclastites) and sediments, and intrusions). 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 Fuji in Japan

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 encourage 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 tip stops propagating—or the dike become deflected into a sill along the contact (Figs. 14.19 and 14.20). This latter is what we see as common in the present cliff sections (Figs. 14.16 and 14.17) 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** (Fig. 14.20). 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 (Chaps. 2, 5, 6 and 13) than in areas composed of widely different rocks types, such as hyaloclastite mountains and stratovolcanoes.

STOP 5.2 – *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.

14.6 Skogarfoss (Skógarfoss) 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 (Skógá)**, which is roughly at the boundary between Eyjafjallajökull and the next volcano to the east, namely **Katla**. The river Skoga (Fig. 14.21a), however, not only marks the boundary between these two large and active volcanoes, but also hosts the famous and beautiful waterfall **Skogarfoss (Skógarfoss)**, seen in Fig. 14.21b. It is worthwhile to drive the road to Skógarfoss to have a closer look at this exceptionally well-formed waterfall. Like Seljalandsfoss (Fig. 14.13) 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 (Fig. 14.21b). The rock that constitutes the cliff is mainly of hyaloclastite, similar to that found along the cliffs of Eyjafjallajökull and at Seljalandsfoss. There is a path to the top of the waterfall.

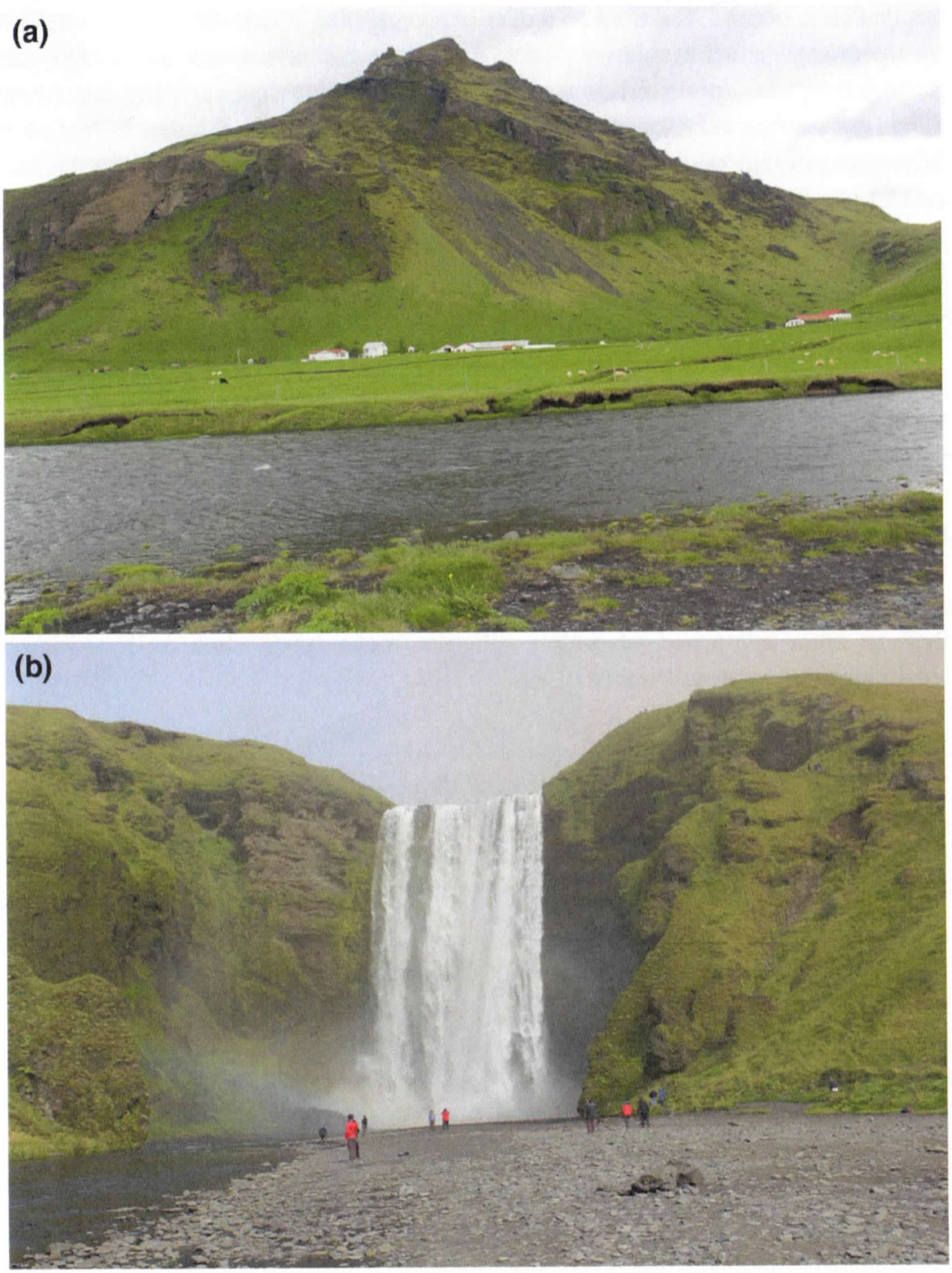


Fig. 14.21 River Skoga (Skógá) and its waterfall Skogarfoss (Skógarfoss). **a** View west, Skoga is roughly at the boundary between the volcanoes Eyjafjallajökull in the west and Myrdalsjökull/Katla in the east. **b** The waterfall Skogarfoss, 60 m high, is one of the best-known landmarks in Iceland

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.

Locality 5.2 Hofsá River – myth and the truth about the formation of Skógasandur and Sólheimasandur

The Book of Settlement tells the story of a dispute between Þrasi at *Skógar* [63.5279, −19.4995] and Loðmundur at *Sólheimar* [63.4946, −19.3281], two farms on either side of Jökulsá at *Sólheimasandur* [63.4735, −19.3761]. According to the folktale, one morning Þrasi saw a great flood approaching from the mountains and used sorcery to force it into a more easterly path towards Sólheimar. Loðmundur, 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. Loðmundur knew Þrasi's game, so he used his own powers to redirect the floodwaters westwards in the direction of Skógar. Þrasi responded and Loðmundur repeated his act. This apparently went on for a while until they agreed on a floodpath midway between the farms, where the *River Jökulsá* [63.4984, −19.3989] on Sólheimasandur now runs directly to the sea. Also, according to one version of the tale, these floods formed the sandur plain of Sólheimasandur.

For a long time it was thought that the floods mentioned in the tale of Þrasi and Loðmundur had formed the whole outwash plain of *Skógasandur* [63.5039, −19.4831] and Sólheimasandur, 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 Skógasandur are prehistoric (Fig. 5.7) and were formed by a jökulhlaup 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 Sólheimajökull outlet glacier. However, younger flood deposits of lesser volume that formed during Settlement age cover part of Sólheimasandur. We also know from tephrochronological studies that the early settlers soon became acutely aware of the awesome

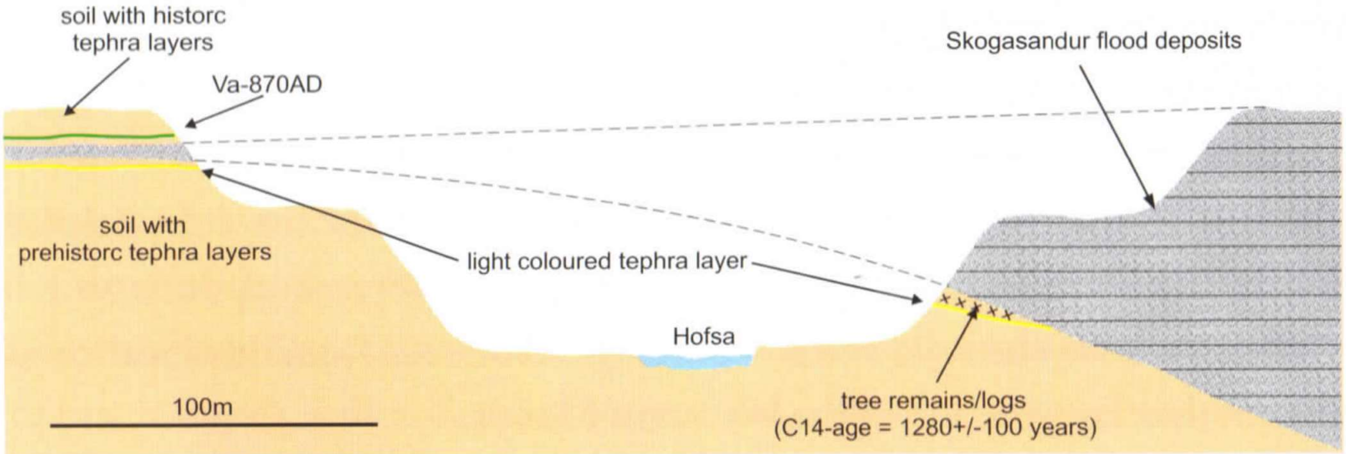


Figure 5.7 Schematic cross section of the Hofsá River [63.5237, −19.4552] channel where it dissects the main Skógasandur flood deposits. On the east bank of the river the tephra-rich flood deposits are several metres thick and overlay a soil containing many prehistoric tephra layers and a distinct horizon 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 Skógasandur floods occurred well before the first settlers arrived in Iceland.

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 Eldgjá–Katla Fires. One of these eruptions is likely to have been responsible for the historical jökulhlaups onto Sólheimasandur, which supposedly kindled the dispute between Þrasi and Loðmundur.

STOP 5.3 – *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.

Stop 4.4. Sólheimajökull
63.5264°N, 19.3673°W

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

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 (Fig. 56). For a period of years this trail provided the principal access for glacier walks on Sólheimajökull. The trail heads northeast up a small valley and is ~1.5 km in length leading to an overlook of Sólheimajökull a bit above its terminus. The mountain ridge that separates this valley from the main glacial valley of Sólheimajökull is called Jökulhaus. 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 63.5299°N, 19.3490°W. This point marks the position of a lobe of Sólheimajökull that flowed on the east side of Jökulhaus during its maximum recent advance at ca. 1904 when the glacier was thick enough to cover the northern end of Jökulhaus (see 1904 map, Fig. 56). The glacier extended farther down valley and covered much of Jökulhaus at ca. 1860 (Friis, 2011).

Figure 57. A small kame hill at the end of the trail at Stop 4.4.

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 Sólheimajökull. 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 (Fig. 57).

Sólheimajökull is widely known for its rapid retreat, which was featured, via time-lapse photography, by James Balog of the 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 (Figs. 56 and 58). 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 jökulhlaups may have reflected small subglacial eruptions). Katla volcano is discussed in the next stop description (Stop 4.5).

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 (63.5303°N, 19.3708°W). 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 Hvölsöllur School. Due to the rapid retreat of Sólheimajökull at this time, the length of the hike and character of the terminus change from year to year. Guide services provide glacier walks from the main parking area.

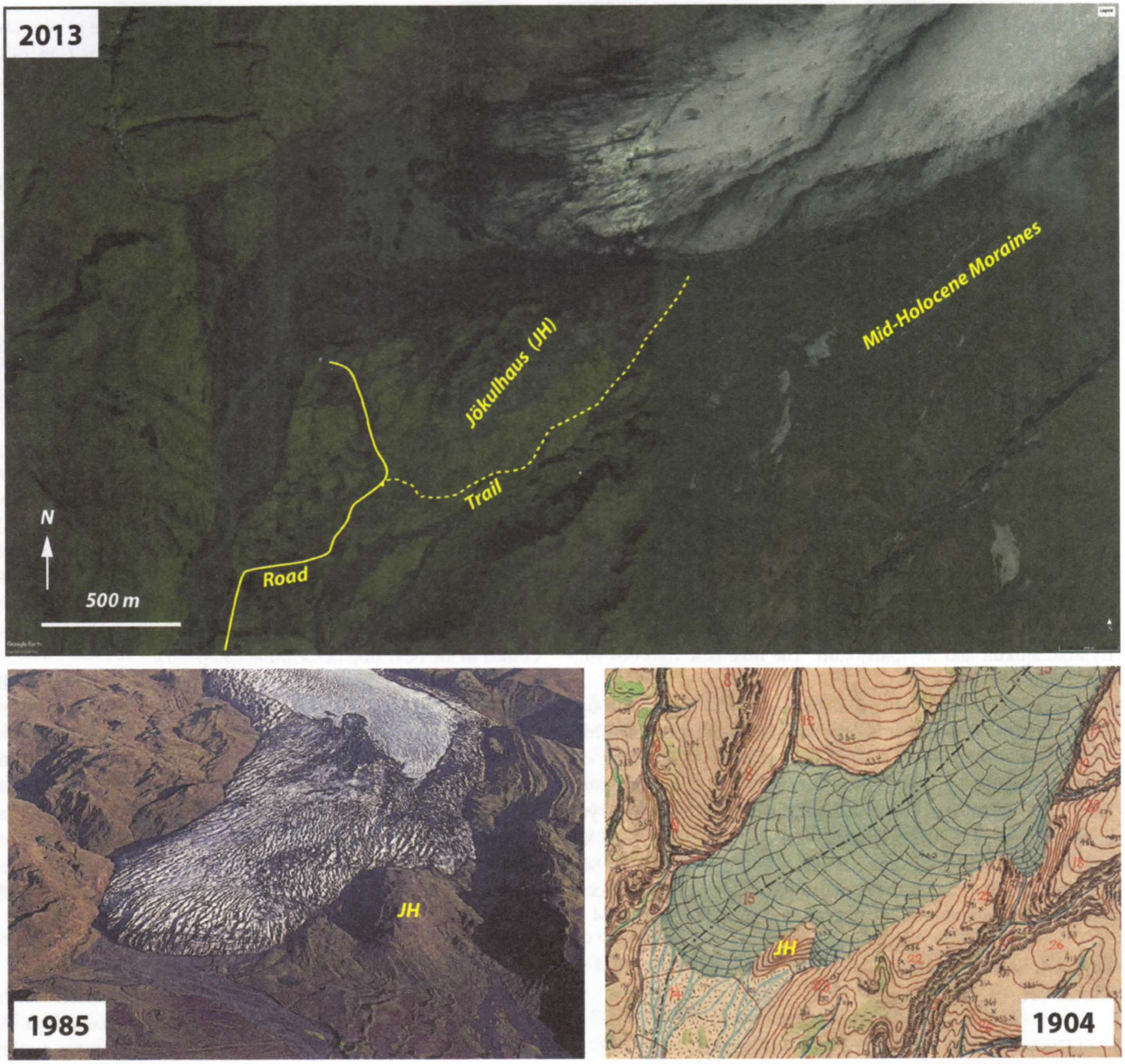


Figure 56. Maps and photos of the area of the terminus of Sólheimajökull, and outlet glacier of Mýrdalsjökull: 2013 satellite image (Google, DigitalGlobe); 1985 photo from Sigurðsson and Williams (2008); and 1904 from map No.69 NV, Danish General Staff, 1905 (scale 1:50 000, surveyed in 1904). Note the difference in both the position of the terminus and the amount of ice on the northeast side of the hill Jökulhaus (JH).

STOP 5.4 – *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.

Locality 5.3 Dyrhólaey and the islands in the sand: volcanoes telling the tale of a different past

Some of the unusual features of the region around Mýrdalur are the mountains *Pétursey* [63.4673, −19.2711], *Dyrhólaey* [63.4075, −19.1137] and *Hjörleifshöfði* [63.4166, −18.7551], which stand as isolated crags in a sea of sand and generally a good distance inland from 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.

Dyrhólaey (Portland) is the southernmost point of Iceland (63°23′N) and is a heavily eroded submarine volcano of the Surtseyan type (Fig. 5.8). The main part of Dyrhólaey is built of well-bedded tuff formed by hydromagmatic explosions, and it represents the remains of a larger tuff cone. On the eastern flank of Dyrhólaey, 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 Dyrhólaey sequence is typical for Surtseyan eruptions and, if visibility allows, the type-volcano Surtsey can be seen from this location as the southernmost island of the Westman Islands.

Other, perhaps a little more obscure, evidence of submarine volcanic activity is found above Mýrdalur in the móberg 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

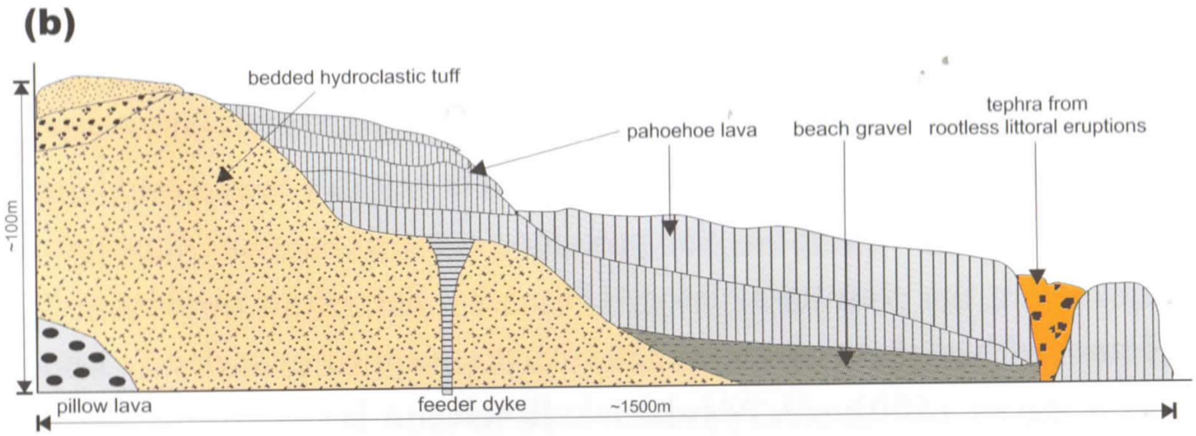


Figure 5.8 (**a**) Aerial view of Dyrhólaey; (**b**) Simplified cross section showing the structure of the Dyrhólaey tuff cone (~100 m deep, ~1500 m wide).

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 *Serripes* layers at Tjörnes in North Iceland (see p. 175).

Similar shell-bearing blocks are found sporadically in the móberg tuffs extending from Pétursey in the west to *Höfðabrekka* [63.4267, −18.8982] in the east, indicating that the volcanic formations of Mýrdalur 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 1963–4, which contain fossils of only modern day species. Thus, some 2–3 million years ago the sea inundated the Mýrdalur area, and it is likely that the now-majestic volcanoes of Mýrdalsjökull and Eyjafjallajökull began their life some 600,000–700,000 years ago in a similar fashion to the Westman Islands, as a cluster of small volcanic islands in the middle of the sea.

STOP 5.5 – *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.

14.12 The Beach of Reynisfjara

We now drive back to the west along 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 (Dyrhólaey)** in the west (Fig. 14.29). Some of you might like to visit that locality as well. This is easy along

Fig. 14.29 View west, Dyrholaey (Dyrhólaey) 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

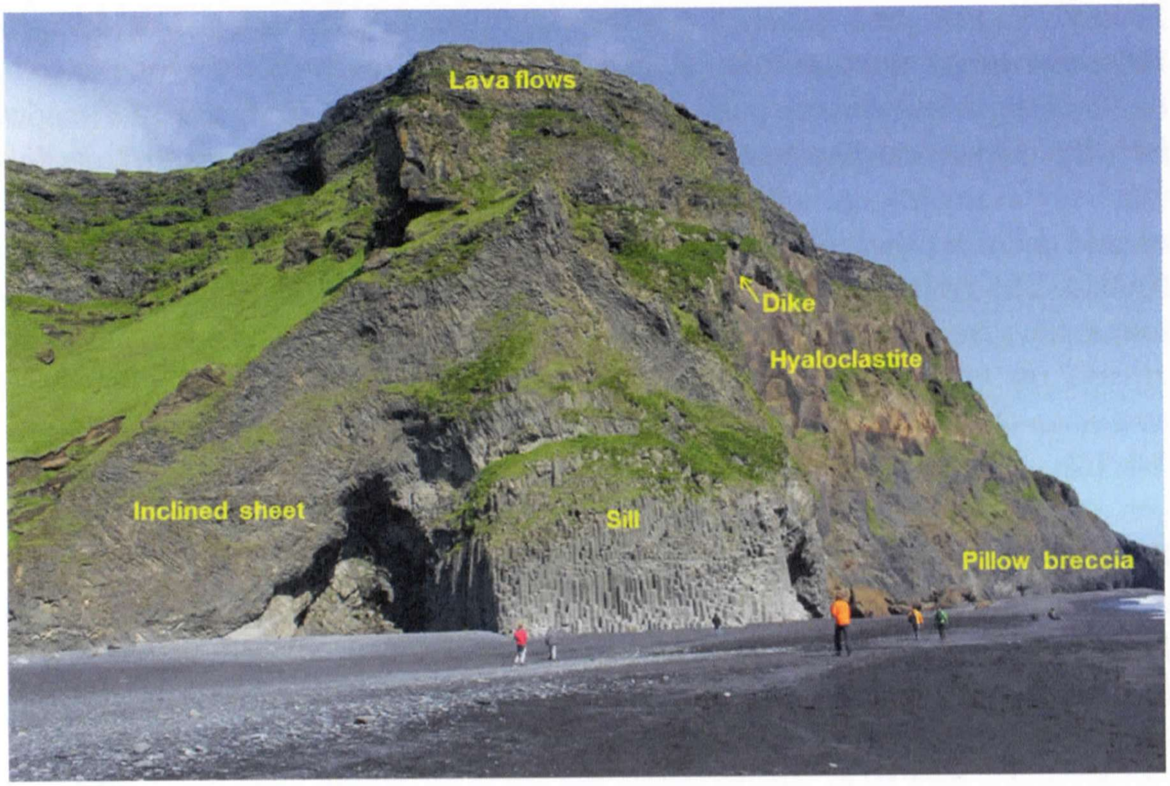


Fig. 14.30 View east, the southernmost part of the hyaloclastite mountain Reynisfjall and the Reynisfjara beach. The mountain is 5 km long and reaches a maximum height of 340 m above sea level. However, at the coast here the height is about 150 m. On the top is a cap of lava flows supplied with magma 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 Figs. 14.31 and 14.32 and of the feeder-dike in Fig. 14.34. The people also provide a scale

Road 218. Dyrholaey is currently the southernmost point of Iceland (for a long time following the 1918 Katla eruption, Kötlutangi, the point of land south of Hjörleifshöfdi (ninth stop) 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, Hjörleifshöfdi, 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** (Fig. 14.30). We saw its eastern slopes from a distance at the eighth stop

(Fig. 4.25), and here we take a much closer look at its western slopes. Reynisfjall is a typical hyaloclastite mountain, just like Petursey, Hjörleifshöfdi, 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 (Fig. 14.30) the height is about 150 m above sea level. Reynisfjall is of similar age to the mountains mentioned above, and most likely formed in several eruptions, partly in the sea and perhaps partly beneath ice caps, during the past 200 thousand years.

Reynisfjall is composed 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 (Fig. 14.30). 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 1200–1300 °C. 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 larger volume than liquid water).

The fractures are called **columnar** or **cooling** joints, and we have seen them many times before in sills (Fig. 4.9), lava flows (Figs. 5.5 and 5.6), and dikes (Figs. 11.6 and 11.10), 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 800 °C and continue to develop as the rock cools further. Heat transport or '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 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 (Figs. 11.6 and 11.10) and vertical in horizontal sills (Figs. 4.9 and 14.17) and lava flows (Figs. 5.5 and 5.6).

In Fig. 14.30 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,

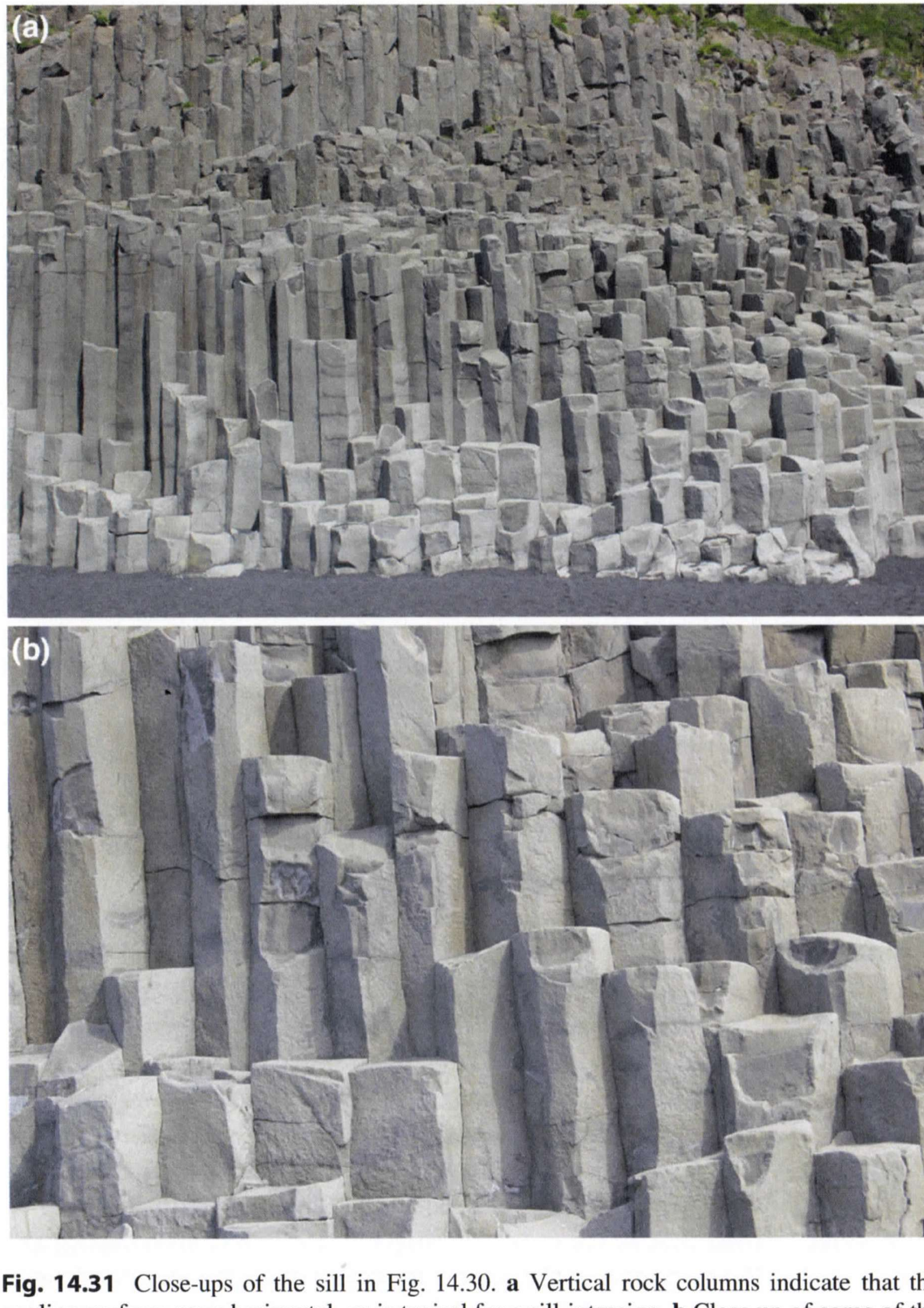


Fig. 14.31 Close-ups of the sill in Fig. 14.30. **a** Vertical rock columns indicate that the cooling surfaces were horizontal, as is typical for a sill intrusion. **b** Close-up of some of the columns seen in **a**. All the rock columns are generated through the development of cooling joints, columnar joints, as the magma cools down following emplacement as a sill

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.

If we now take a closer look at this lower part (Fig. 14.31) 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 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 the poor conduction of heat through rocks ensures that the cooling of the magma, that is, of the intrusion, will be slow. Given that the

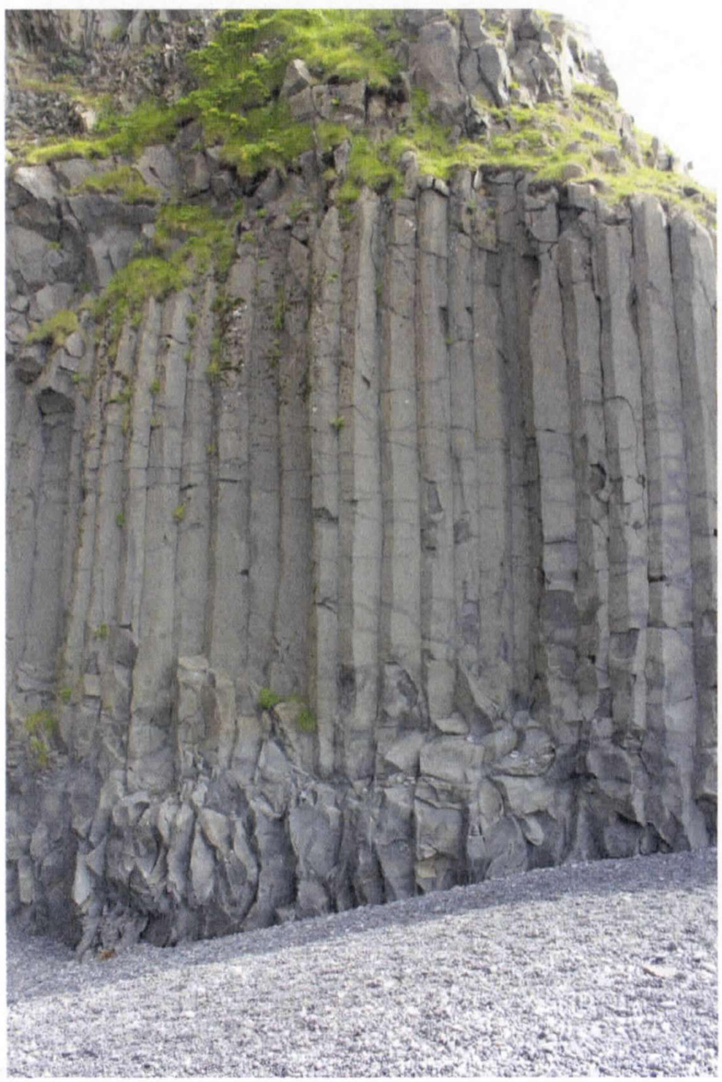


Fig. 14.32 View southeast, some of the rock columns in the sill seen in Figs. 14.30 and 14.31 are very tall. The height of these columns is about 10 m

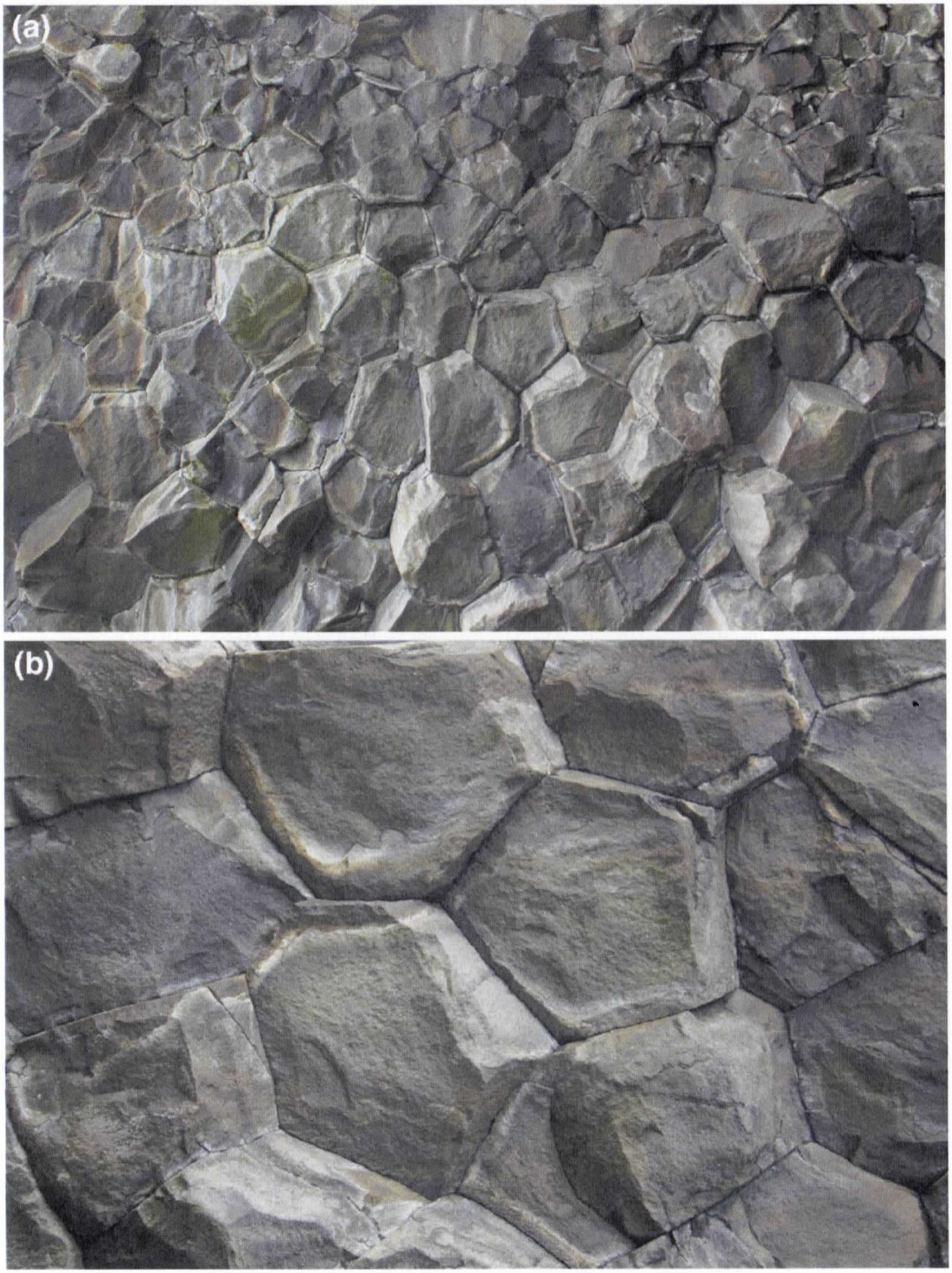


Fig. 14.33 Cross-sectional shapes of the rock columns as seen in the ceiling of the cave of Halsanefshellir (Hálsanefshelli). While the columns have a variety of shapes most are 5-sided (pentagons) or 6-sided (hexagons). **a** General view of the ceiling. **b** Close-up of some of the columns

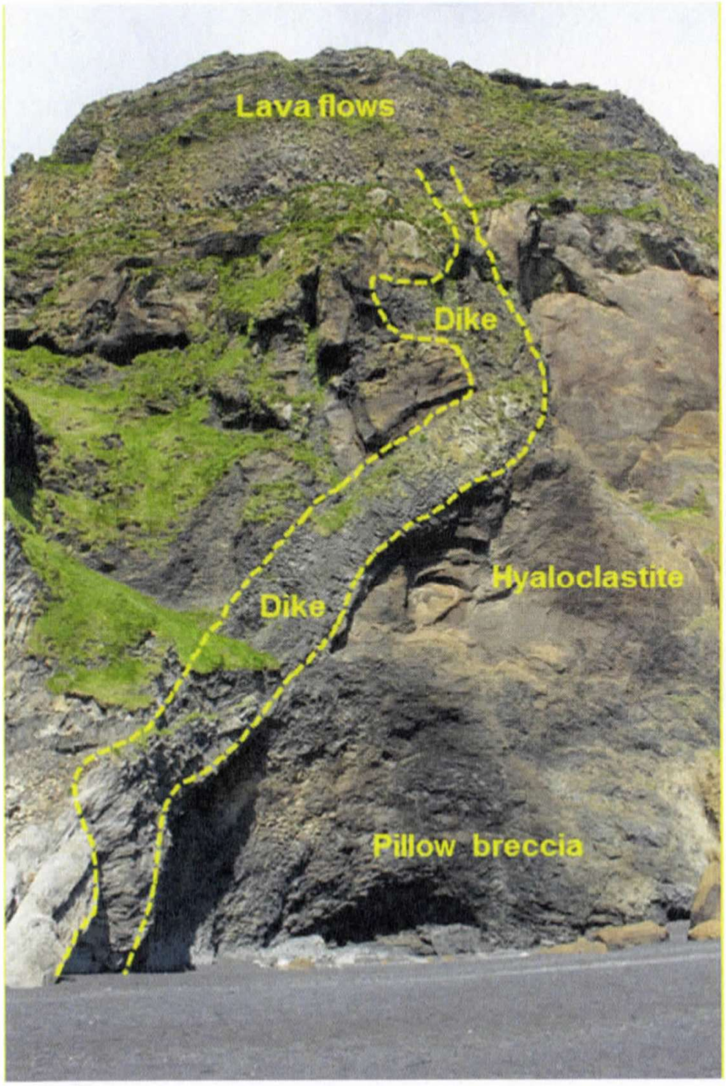


Fig. 14.34 View north of the basaltic feeder-dike to the lava flows on the top of Reynisfjall. The lower part of the dike is steeply inclined, mostly 1–2 m thick, but its uppermost part is much thinner and close to vertical

rock columns in this part are very well shaped, the cooling must have been slow, so that this is an intrusion. And from the vertical orientation of the columns we infer that the intrusion itself was horizontal, and thus a **sill**. Some of the columns at Reynisfjara are as tall as 10 m (Fig. 14.32). Similar columns are found in many sills in Iceland (Figs. 4.9 and 14.17), although rarely as well-developed and finely shaped as here

To get a better three-dimensional view of the columns, we can enter the cave **Halsanefshellir (Hálsanefshellir)** which is just around the corner (Fig. 14.33). 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 properties and thickness, as well as in those of the 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 of Reynisfjall (Fig. 14.34). 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 the eighth stop (Fig. 14.25). But because we are much closer to them here, and view them from a different angle, they are really worth a closer look. In Fig. 14.35 we view them from a greater distance, and all the three

Fig. 14.35 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

Fig. 14.36 View southeast, close-up of two of the sea-rock pillars that constitute Reynisdrangar. All are made of basaltic rocks

are seen, although the third one (whose two peaks are seen) is somewhat hidden behind the one closest to us. In Fig. 14.36, however, the third one is completely hidden from view, so only two of them are seen. Reynisdrangar are a famous landmark in Iceland, and an appropriate one for the last formal geological stop in this excursion.

From here, we drive back to Road 1 and then to the west to our final stop in this excursion, Reykjavik.

STOP 5.6 – *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

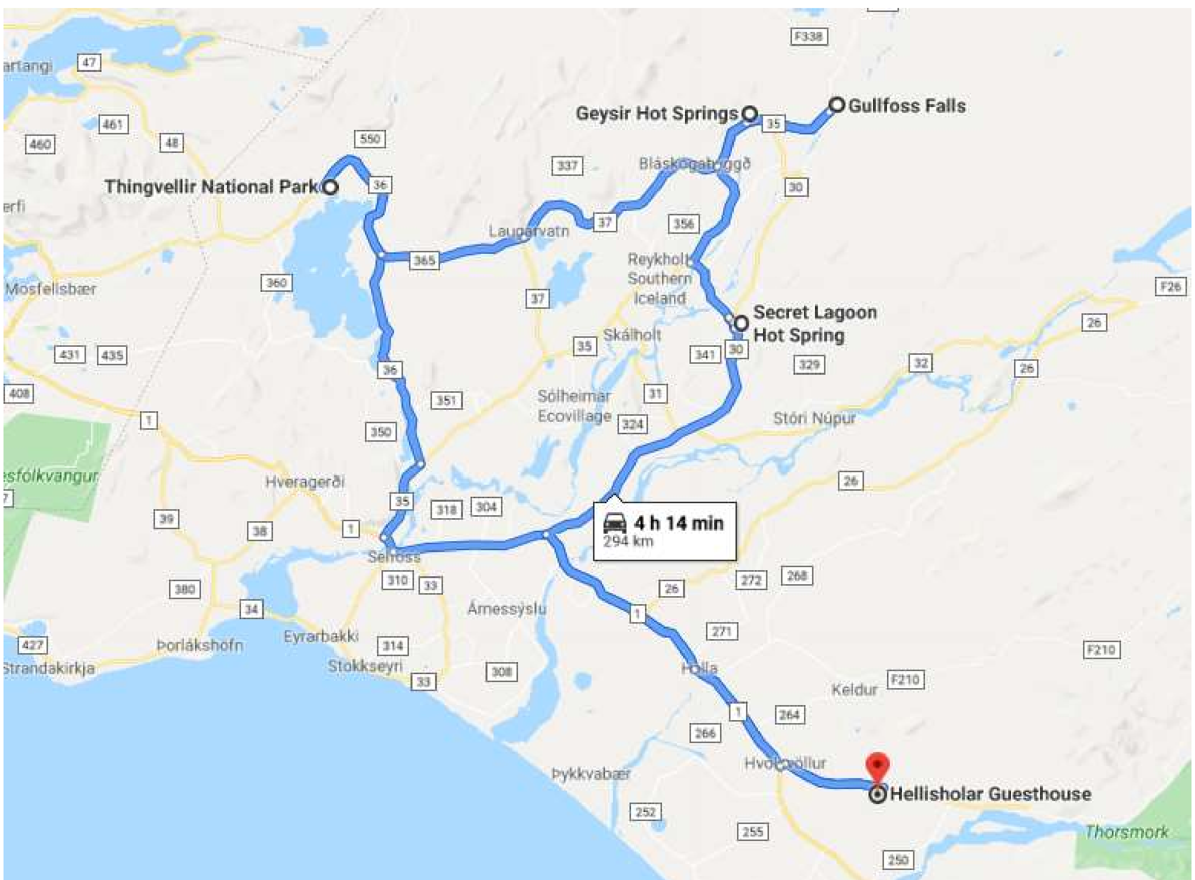
Vík lies directly beneath the Mýrdalsjökull glacier, which itself is on top of the Katla volcano. Katla has not erupted since 1918, and this longer than typical repose period has led to speculation that an eruption may occur soon. An eruption of Katla could melt enough ice to trigger an enormous flash 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.

Day 6: Thursday, March 12th, 2020 – Þingvellir, Geysir, Gulfoss

7:00AM: Wake-up, breakfast at the hostel
8:00AM: Depart for Þingvellir National Park
9:30AM: Arrived at Þingvellir National Park
10:00AM: Walk to the Law Rock and through the rift valley.
11:30AM: Depart for Geysir
12:30PM: Arrive at Geysir, have lunch (the hostel will be providing packed lunches, but there is also a café there).
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 Hellisholar Guesthouse
6:00PM: Arrive at hostel
6:30PM: Group dinner at the hostel



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 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 (Fig. 5.1; see also Fig. 4.1). I therefore include many aerial photographs in this chapter.

Thingvellir constitutes a graben that forms a part of the West Volcanic Zone (Fig. 2.2). More specifically, the Thingvellir Graben is located in the northern part of the Hengill Volcanic System (Figs. 2.3 and 5.2). Although the area is geologically a wonderland, and all the sites are spectacular, it is worth mentioning 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**.

5.1 Almannagja (Almannagjá)

The **fourth stop (4)** on the Circle is normally at the entrance to the largest fracture of the Thingvellir area, **Almannagja (Almannagjá)**, 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 in Fig. 5.3 (cf. Fig. 6.1). For comparison, Figs. 5.1 and 5.2 show a larger part of Almannagja from the air. More detailed aspects of this part of

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A. Gudmundsson, *The Glorious Geology of Iceland's Golden Circle*, GeoGuide, DOI 10.1007/978-3-319-55152-4_5

Fig. 5.1 Aerial photograph showing the location of the four main sites visited at Thingvellir. The numbering refers to the stops indicated in Fig. 4.1. 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 Lögberg, the site for parliamentary meetings when Iceland's parliament was located at Thingvellir, but also geologically an interesting place. The seventh (7) stop has two sites. The first is the 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 river Öxara (Öxará) flows to the southwest along part of Almannagja, from the waterfall Öxararfoss (Öxarárfoss)

Almannagja are in Figs. 5.4, 5.5, 5.6, 5.7 and 5.8. In particular, Fig. 5.8 indicates some of the main geological structures associated with Almannagja. The main geological points regarding Almannagja may be summarised as follows (with references to Figs. 5.1, 5.2, 5.3, 5.4, 5.5, 5.6, 5.7 and 5.8):

- The fracture is formed through two main processes: opening and subsidence (vertical displacement). The maximum opening is just over 60 m; the maximum subsidence or vertical displacement is about 40 m (Fig. 5.9). Both processes relate to the plate-tectonic forces that tear the crust apart (discussed further in Sect. 5.3).

- The opening of 60 m by this single fracture gives a spreading rate (Fig. 4.5; Chap. 4) 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 thousand 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.

Fig. 5.2 The fractures of Thingvellir, including Almannagja, are a 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 Fig. 5.1, and the hotel (with a red roof close to the fourth stop) in Fig. 5.1 is no longer seen in Fig. 5.2 (it burned down in 2009). Stops 4, 5 and 6 in Fig. 5.1 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 thousand years. The last major subsidence was during earthquakes 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 Lögberg (the sixth stop in Fig. 5.1)

Fig. 5.3 Photograph of Almannagja from the fourth stop in Fig. 5.1. View northeast, the surface of the eastern (right) fault wall is inclined by about 11° to the east, whereas the surface of the western (right) wall is horizontal (see Figs. 5.8 and 5.9 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 (see also Fig. 6.4 for Armannsfell and Fig. 6.6 for Skjaldbreidur)

- The elevation difference between the top of the western wall to the lowest ground of the eastern wall, is about 40 m (Fig. 5.9). 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 or spreading in the Thingvellir area.
- 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 (Figs. 4.14 and 5.9). 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 centre of the Thingvelllir 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 (Sect. 5.3). 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 (Fig. 5.8; cf. Sect. 5.3). 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 (Figs. 5.2, 5.4 and 5.8).

Fig. 5.4 The 'entrance' to Almannagja. This part can be seen on the aerial photographs (Figs. 5.2 and 5.8) 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 Figs. 5.11, 5.12 and 5.15

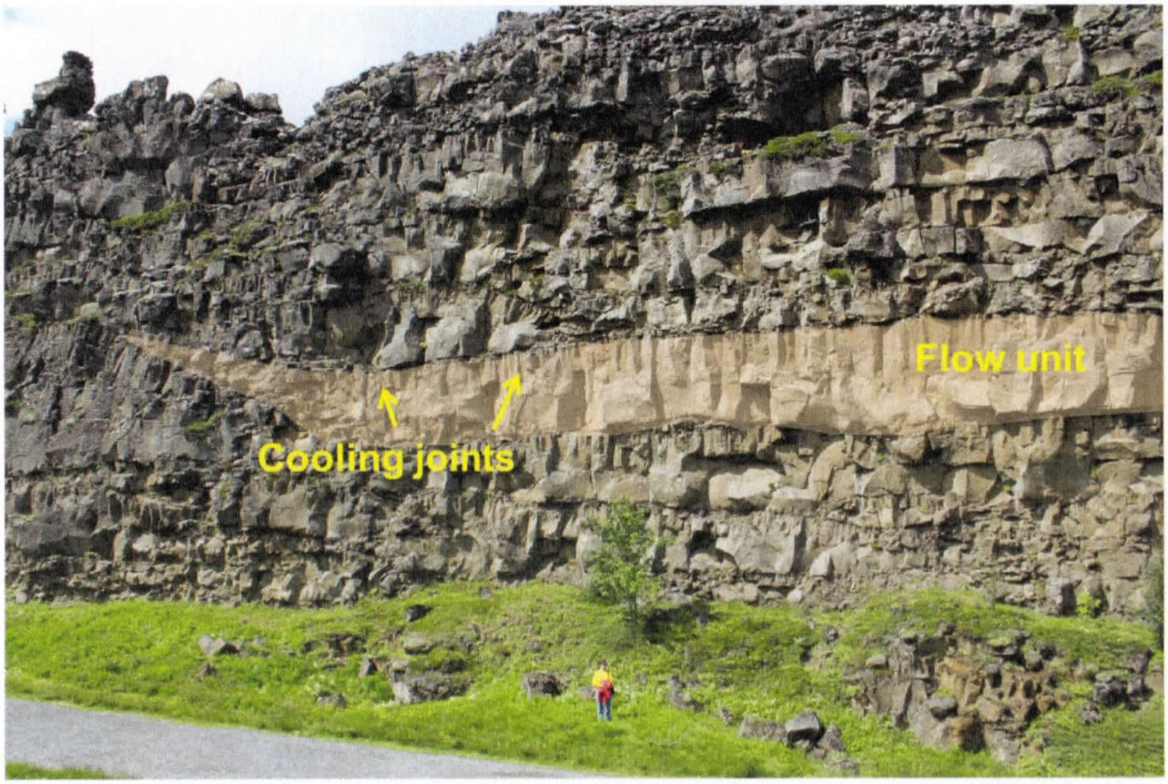

Fig. 5.5 The lava flow that constitutes the walls of Almannagja is a pahoehoe lava flow. Such flows are basaltic and composed of numerous flow units, commonly with vertical cooling or columnar joints, and can reach thicknesses of several hundred metres, as does the present lava flow. For a vertical section through a thick pahoehoe lava flow, much older than the Thingvellir flow, see Figs. 11.19, 11.20 and 11.21

Walking down the path along Almannagja, we should make the **fifth stop (5)** so as to take a look at the fracture walls (Figs. 5.5 and 5.6). 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 metres. In the walls we see only the uppermost twenty metres or so (the maximum height of the western wall is about 28 m). The lava flow is about 10 thousand 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** (Figs. 5.5 and 5.6). There may be many tens, sometimes hundreds, of flow units in a single thick pahoehoe flow (in Chap. 11 we see a vertical section thorough a thick pahoehoe lava flow). As mentioned in Chap. 2, pahoehoe lavas are made of magma that is very hot (around 1300 °C). When erupted, the magma forms a flowing lava with a temperature of about 1200 °C 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 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 **lava tube**. When the tubes drain at the end of the eruption, they form **caves**, some of which may reach many kilometres in length.

When looking very closely at the flow units—which is perhaps best to do as you enter Almannagja where the walls are still low and little danger of rock falls (Fig. 5.4)—you see a lot of cavities in them. Most of the cavities are either circular or somewhat elliptical in shape, and with a common diameter between half and one centimetre. 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

Fig. 5.6 Close-up of some of the flow units and cooling or columnar joints seen in Fig. 5.5. 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 in the topmost flow unit. Vertical columnar joints are typical for horizontal flow units and lava flows in general, but are normally much better developed (more beautiful) in intrusions (see Figs. 11.6, 11.8 and 11.10 for horizontal columnar joints in a dike, and Figs. 14.30, 14.32 and 14.33 for vertical columnar joints in a sill)

Fig. 5.7 The surface of the eastern wall (left) of Almannagja is tilted by about 11° to the east. The tilting is most likely because of friction along the fault at depth (illustrated in Fig. 5.9). The tilting of the eastern wall is along the greater part of Almannagja (Figs. 5.1 and 5.8)

indication of the viscosity of the lava—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 1050 °C. These are **aa** lava flows and easily ten times more viscous than the lava flow seen in the walls of Almannagja. (I provide more discussion on vesicles in basaltic rocks, with close-up photographs, in Chap. 13.)

The **sixth stop (6)** is at the site of Lögberg, which was the main site for the parliament meetings while the parliament still met at Thingvellir (Figs. 5.1, 5.2 and 5.8). 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 speakers voice. One thing that is particularly clear at this site is that the surface of the eastern wall of Almannagja is inclined or tilted down to the east by about 11°. This is clearly seen on the ground (Fig. 5.7) and also from the air (Fig. 5.8). We could also see the sloping eastern wall from the first stop (Fig. 5.3) but perhaps less clearly. By contrast, the surface of the western wall is perfectly horizontal (Figs. 5.2 and 5.8).

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 (Fig. 5.9). Almannagja and other fractures in the volcanic zones of Iceland are open or gaping only to shallow depths. At depths of several tens of metres 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 (Fig. 5.9). At the contact between the walls, however, there is so much friction that

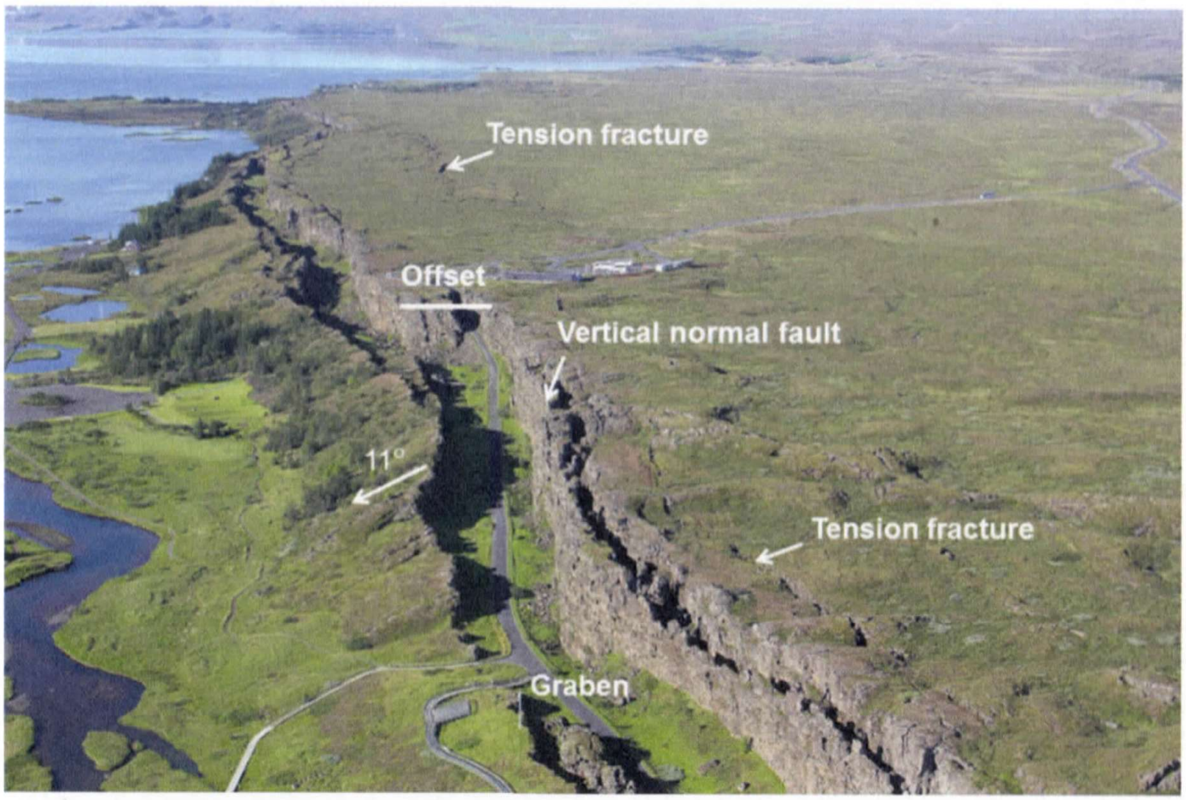

Fig. 5.8 Aerial photograph showing some of the main structures associated with Almannagja. Around Almannagja itself there are many smaller structures. These include small tension fractures (discussed in detail in connection with Figs. 5.11, 5.12 and 5.15) and the inclined eastern fault wall (its surface is inclined by 11° 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 or 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 Fig. 5.9

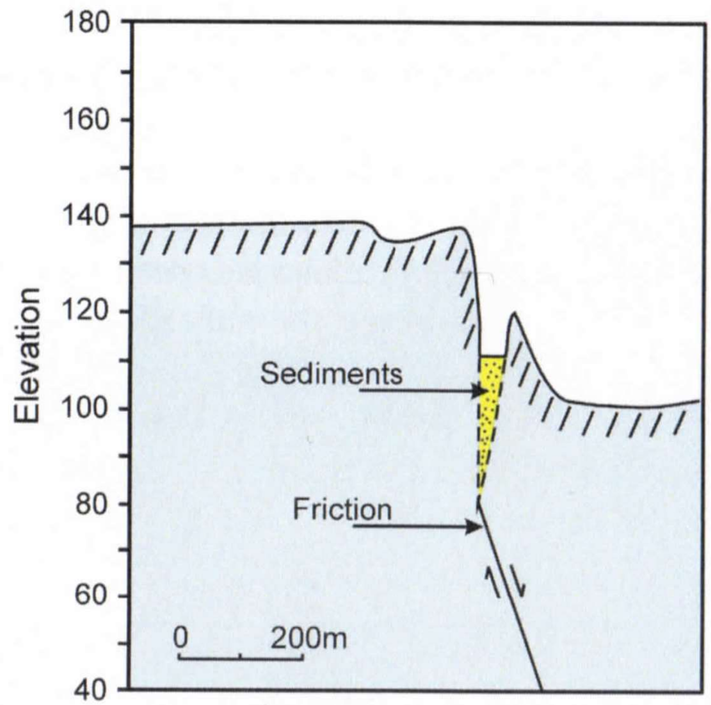

Fig. 5.9 Vertical section through Almannagja (roughly the central part seen in Fig. 5.2). The surface of the western (left) fault wall is at close to 140 m above sea level, whereas the lowest surface on the eastern (right) wall is at about 100 m above sea level. The maximum vertical displacement ('subsidence') 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 or sloping of the eastern fault wall. The vertical scale is exaggerated about 8-times relative to the horizontal scale

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 Fig. 5.10. Here we see a stone which is 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 or spreading at the rate of close to a centimetre per year, no earthquakes of these sizes have occurred on Almannagja for many decades.

5.2 Peningagja and Flosagja (Peningagjá and Flosagjá)

We now move on to the **seventh stop (7)**. This stop is split in two parts, as explained below, and indicated in Figs. 4.1 and 5.1. It is easy to walk to this stop along the path from stop (6). Part of the path is seen in Figs. 5.1 and 5.2. 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 (Peningagjá)**. 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 part of a larger fissure whose name is **Nikulasargja** (**Nikulásargjá**) which, in turn, is a part or segment of a larger fissure whose name is

Fig. 5.10 View west, the uppermost part of the western fault wall of Almannagja at stop 6 (Fig. 5.1). 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 Almannagja for many decades and probably not since 1789

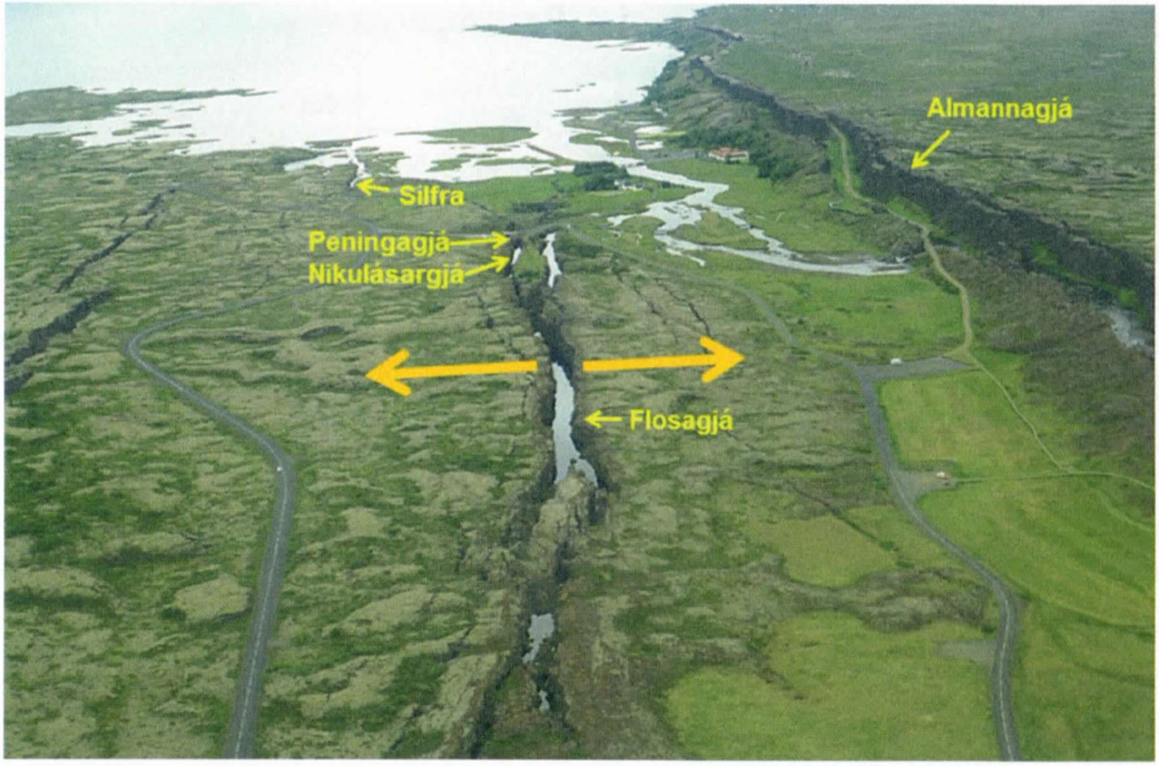

Fig. 5.11 Aerial view of the tension fractures Peningagja (Peningagjá), Nikulasargja (Nikulásargjá), Flosagja (Flosagjá), and Silfra, as well as the normal fault Almanngja (Almannagjá). View southwest, the plate-tectonic forces, indicated schematically by orange arrows at Flosagja, tear the crust apart, rupture it, and form tension fractures and normal faults. Close to the road, at the east (left) margin of the photographs are normal faults

Flosagja (Flosagjá). The latter, Flosagja, is the original name of the entire fissure, and Peningagja and Nikulararargja are just among its southernmost segments or parts (Fig. 5.11).

Peningagja and Nikulasargja are very impressive structures (Fig. 5.12). But in some ways the main fracture, Flosagja, is the most spectacular of them all (Fig. 5.13). Peningagja/Nikulasargja and Flosagja here count as the **seventh stop (7)** in two parts. Flosagja (Fig. 5.13) can be reached through walking from Peningagja/Nikularsargja. Alternatively, if you drive into the Thingvellir Graben along Road 36 and then take Road 52 to the south to the parking place close to the waterfall **Öxararfoss (Öxarárfoss)**, seen in Fig. 5.3, and walk from there to the fracture. In Sect. 5.3 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 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 Langjökull 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** (Figs. 5.1, 5.11 and 5.14). 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 Langjökull and the surrounding highlands, it takes 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 (Fig. 5.14) and is at the same elevation as the water level in the fractures (Figs. 5.11, 5.12 and 5.13). 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 water in the fractures close to the lake are at the same elevation (Figs. 5.1 and 5.11), named the **water table**. The lake itself exists because the valley or graben it occupies reaches below the water table—a common

Fig. 5.12 Peningagja, the water-filled fissure with numerous coins at its bottom, is a part of a tension fracture named Nikulasargja, most of which is seen here

Fig. 5.13 Peningagja and Nikulasargja (Fig. 5.11) are a 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 or 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 Fig. 5.11

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 (Fig. 5.14).

The fractures (Figs. 5.11 and 5.12) were not in any way formed by the pressure of the water. All the fractures are formed directly by plate-tectonic forces or stresses (Fig. 5.11) 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 fractures the water temperature is mostly 3–4 °C (Figs. 5.12 and 5.13). 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 (Fig. 5.14), 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 1 °C, but 9–10 °C in July and August. The average temperature of the 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 5 °C. In the present century, that is, after the year 2000, however, the temperature has so far been above 5 °C. This is, at least partly, related to the general warming in Iceland (and elsewhere) which has been most noticeable in the past two decades or so. Ice does form on the whole lake during the winter but

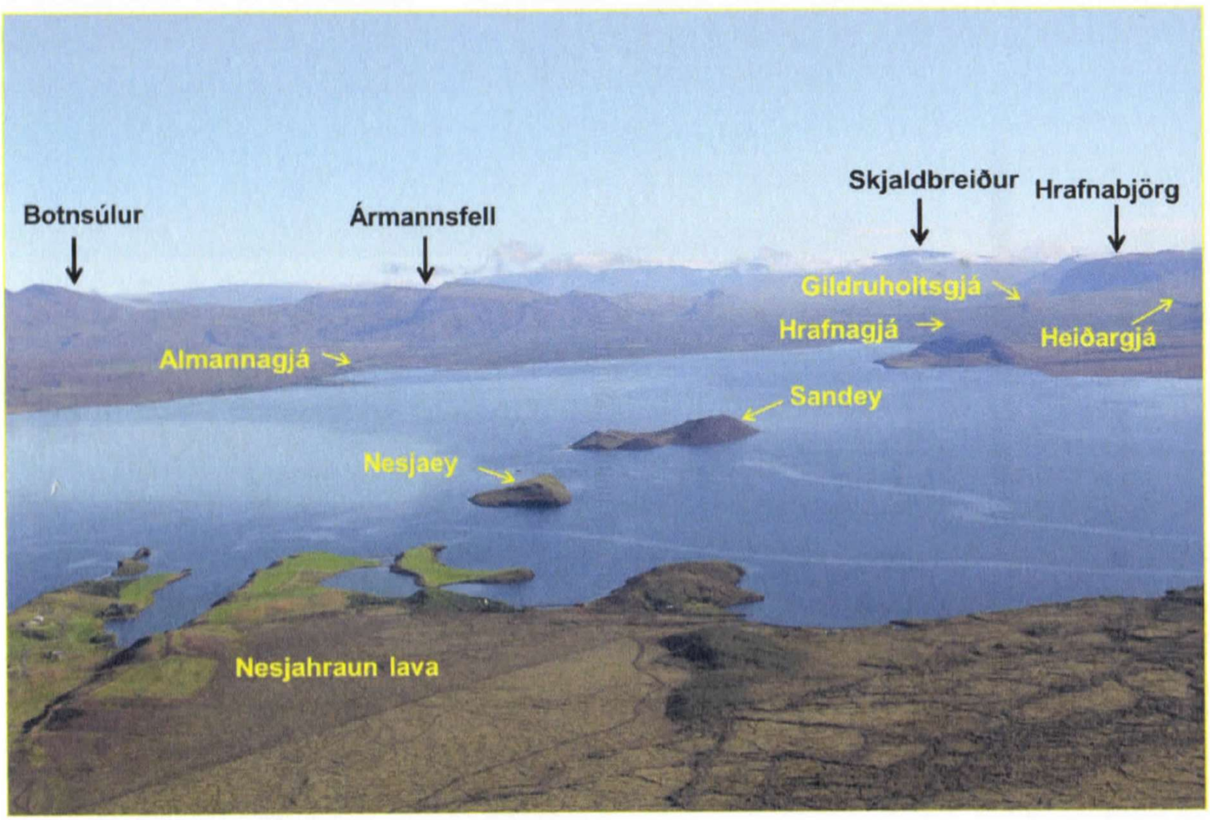

Fig. 5.14 The greater part of Lake Thingvallavatn. This aerial photograph shows the lake from the southwest. Most of the water in the lake originates in groundwater springs. The surface elevation of the lake is about 100 m above sea level, whereas its deepest part reaches a depth of 114 m, so that it extends below sea level. Lake Thingvallavatn, with an area of 84 km^2, is the largest natural lake in Iceland. For discussion of the mountains north of the lake (Armannsfell, Skjaldbreidur, and Hrafnabjörg) see Chap. 6 and for Botnsulur see Chap. 4. The largest faults at Thingvellir are indicated (Almannagja, Hrafnagja, Gildruholtsgja, and Heidargja) and discussed in Chaps. 5 and 6. The lava flow Nesjahraun 2-thousand year-old lava flow Nesjahraun on the south shore of the lake and the island Sandey formed about 2-thousand years ago and are discussed in Chap. 12

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.

5.3 How Do the Fractures Form?

Coming back to water-filled fractures (Figs. 5.11 and 5.12), 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 (Fig. 4.5). 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 (Fig. 2.2), in particular Thingvellir itself, the spreading is continuous, but its effects as regards fracture formation within 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, an 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 (Figs. 5.11, 5.12 and 5.13) raise or concentrate the plate-tectonic stress at their lateral ends or 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 (Fig. 5.11). As rifting events continue, small offset fractures propagate and link up into larger fractures (Figs. 5.15 and 5.16).

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 (Figs. 5.11, 5.12 and 5.13). By contrast, the eastern wall of Almannagja has subsided by as much as 40 m relative to the western wall (Figs. 5.1, 5.2, 5.7, 5.8 and 5.9). In geological terms, Almannagja is a **fault**, and more specifically a **normal fault**, whereas Flosagja (and Nikulasargja and

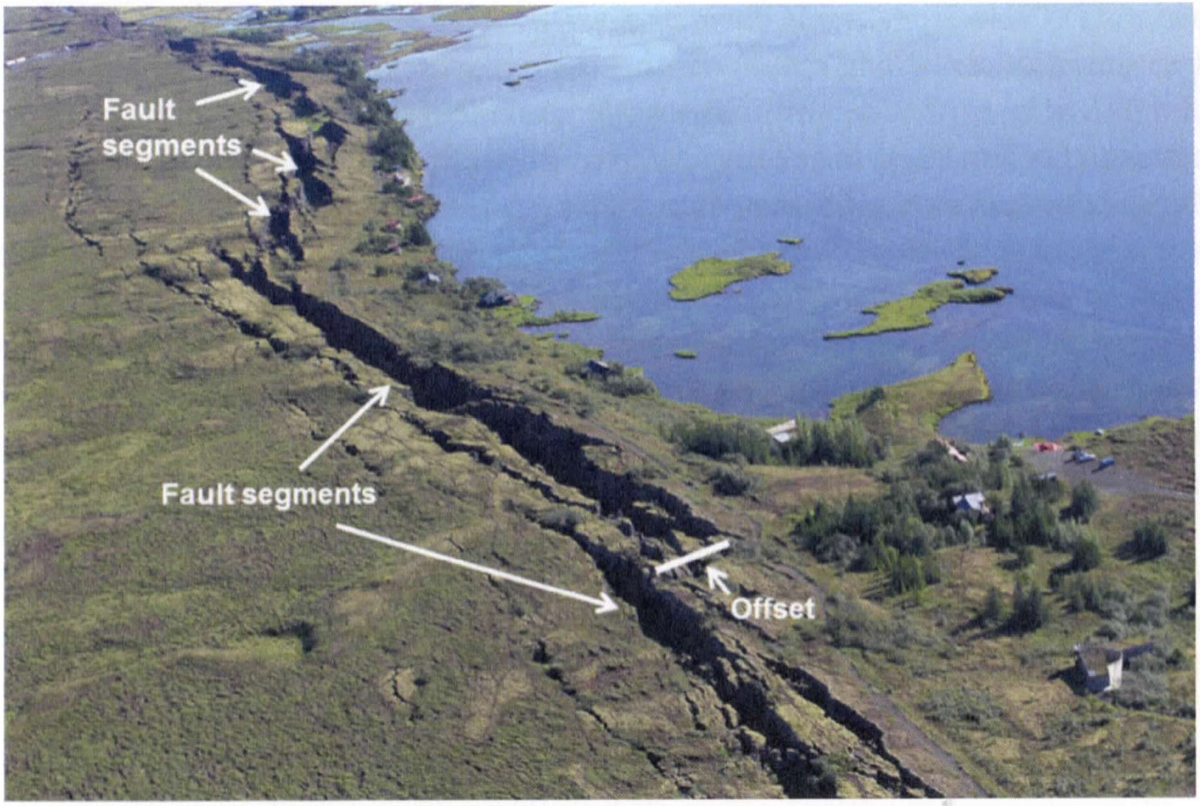

Fig. 5.15 The southwestern part of Almannagja is highly segmented, that is, divided into many smaller fractures. This is partly because the old fault beneath the surface lava flow and which controls where the surface fractures occur is no longer perpendicular to the main plate-tectonic force (as shown in Fig. 5.14). 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

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 (Fig. 5.11). There is thus no fracture-parallel movement during tension-fracture formation, and therefore no friction between the fracture walls (Fig. 5.9). 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 metre)—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 millimetre thick. At the bottom of a 2-m deep swimming pool the pressure due to the water is about 20 thousand pascal. At the bottom of Lake Thingvallavatn, at 114 m, the pressure due to the water is about 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 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 (Fig. 5.5). 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 or extend the object—here the rocks at the

Fig. 5.16 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

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 (Chap. 4), at depths of one to three kilometres, the vertical stress is between about 24 million and 80 million pascal. The magnitude of the vertical stress in the roofs of shallow chambers is thus 8–27 times larger than the tensile stress needed to rupture the crust and form tension fractures at Thingvellir.

5.4 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 (Figs. 5.11 and 5.13). 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 (Fig. 5.11). Silfra is very popular for diving.

The second question is to what depths in the crust do the tension fractures reach? Here I mean the 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, 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 very little seismic activity. One crude indication of the 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 or 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 and 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 (Figs. 5.8, 5.15 and 5.16). 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, Ármannsfell, Chap. 6), as well as to the southwest along Lake Thingvallavatn and towards the Hengill Volcano (Chap. 12). 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 kilometres 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 (Fig. 2.2), 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 (Fig. 5.17).

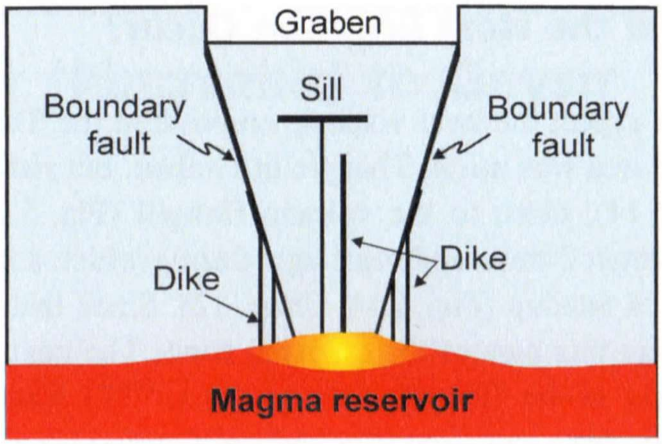

Fig. 5.17 Grabens are common in volcanic rift zones, such as in Iceland. Grabens can often act, temporarily at least, as barriers to dike propagation to the surface, and thus to fissure eruptions. Graben acts as a barrier to vertical dikes when the boundary faults deflect or stop or arrest the dikes 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

If so, why does the magma then not come up along the faults? The reason is their inclination and the unfavourable stresses generated temporarily in the graben following earthquake slip (Fig. 5.17). In a volcanic rift zone such as Thingvellir, the magma almost always travels to the surface through vertical magma-filled fractures, that is, **dikes** (Chap. 11). 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 (Figs. 5.5, 5.6 and 5.10) 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 (Hrafnagja is discussed in Chap. 6), 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 (Figs. 4.14 and 5.17), so that 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 or stop altogether (Fig. 5.17). In either case the dike is unable to reach the surface to erupt.

5.5 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 (Fig. 5.14), close to the volcano Hengill (Fig. 5.2; Chap. 12). This eruption occurred about 2 thousand years ago, during which a lava flow formed as well as the island of Sandey (Fig. 5.14; Chap. 12). 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 (Chap. 12) than in the Thingvellir Graben. This follows from pure statistics. As we discussed in Chap. 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 thousand year old (from Skjaldbreidur, Chap. 6), 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 that 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 Grimsvötn (Grímsvötn), Hekla, and Eyjafjallajökull (Chap. 14). In fact, an eruption in the Thingvellir area, when it occurs, is not unlikely to be of the order of several cubic kilometres.

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 (the Great Geysir) may be the most famous geyser in the world, and is our **tenth stop (10)** in Fig. 4.1. The Geysir area is also located in Fig. 2.2. Geysir is the nameshake of all erupting (gushing) hot springs: they are referred to as **geysers**. 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 geysir 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 it erupting (Fig. 7.1). 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 (Figs. 7.1, 7.2, 7.3 and 7.4). 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 earthquakes in South Iceland in the year 2000, Geysir became reactivated and for some days reportedly erupted to heights of about 120 m (Sect. 7.2).

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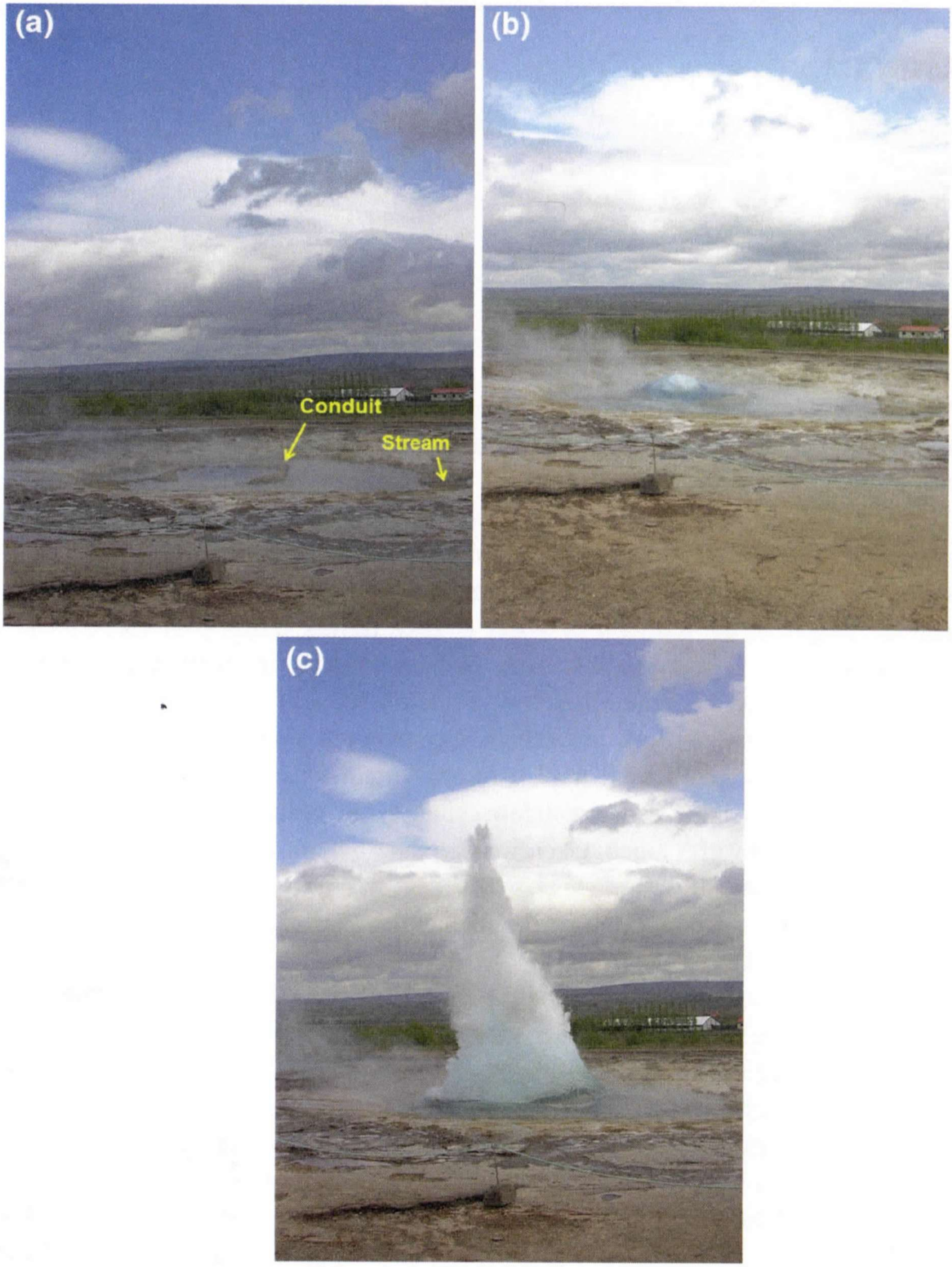

Fig. 7.1 **a**, **b**, **c** Three stages in the eruption of the geyser Strokkur. **a** The main conduit or pipe (indicated) is being filled with water. **b** Swelling of the water surface, so as to form a half-sphere on the top of the conduit, indicating the beginning of the eruption. **c** The eruption itself

7.1 Mechanism of Eruption

This brings us to 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 middle of the 19th century.

Eruptions in a geyser are driven by boiling of the geothermal water in the geyser pipe or conduit (Fig. 7.5). The water is everywhere above 100 °C 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 the water boils (**boiling temperature**) and changes into steam also increases with depth. The boiling temperature is thus well above 100 °C

Fig. 7.2 Some eruptions in Strokkur fail to reach their peak and remain very small. Here is an example of one such 'failed' eruption

Fig. 7.3 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

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 120 °C, which is still not enough to cause boiling. Overheating of the geothermal water is needed in order to reach the 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.

In detail the process is then as follows. When the boiling begins in the conduit or pipe at a certain depth (Fig. 7.5), 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.

Fig. 7.4 Large eruption in Strokkur

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 (Fig. 7.1a, 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 (Fig. 7.1b) triggers further boiling in the upper part of the pipe, resulting in an eruption (Fig. 7.1c).

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 or gushes of water into the air in a rapid succession (Figs. 7.3 and 7.4). 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 (Fig. 7.1). Much of the water that makes the fountain falls back into the pipe (Fig. 7.6), or flows back into it form the surrounding bowl, but some leaks away along the tiny stream (Figs. 7.1b and 7.3).

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 (Fig. 7.2) and their size distribution presumably follows a power law (Chap. 6). 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

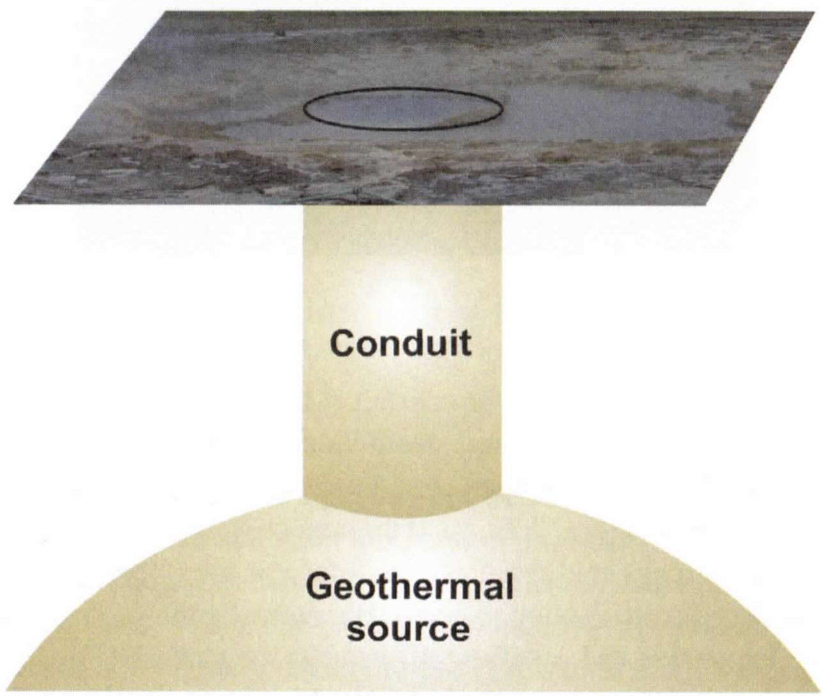

Fig. 7.5 Very schematic illustration of the conduit, the pipe, of a geyser. The pipe is normally a crude cylinder, into which hot water flows. Here we use the rim of the conduit of Strokkur as a model (Fig. 7.1a). The geothermal source is shown in a generalised way. Water can flow into the pipe from 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

a while. Another factor is the rate of inflow of water into the pipe (Fig. 7.5), which is variable, and also the water temperature. Generally, geothermal fields, such as the Geysir area (the formal name is **Haukadalur**, the Haukar Valley), are continuously changing. For example, the inflow of water into the pipe depends on the openings or apertures of the fractures through which the water flows. The apertures gradually change because of mineralisation, 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 of 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?

Fig. 7.6 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 amount of water flows from the geyser, mostly along a human-made stream (Figs. 7.1a and 7.3)

7.2 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 metres of the solid rock (bedrock) is referred to as groundwater, the water which we see in the open fissures and the lake at Thingvellir (Chap. 5). Some water, however, goes deeper, and in areas of volcanic activity, or 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 fractures (joints), cavities from expanding gas (vesicles), as we saw in the lava in the walls of Almannagja (Figs. 5.5 and 5.6, Chap. 5) and in the pillow lavas (Figs. 6.14–6.18, Chap. 6). 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 (Figs. 7.1a and 7.5), 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 (Fig. 7.5), 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 (Sect. 7.1). 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 from the Great Geysir) is about 1.5 litre per second. A **single fracture** some tens of centimetres long and with an opening or aperture of about one millimetre 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 a 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.

7.3 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 much earlier, but these are the oldest written accounts (annals) describing its activity. Even if it was active earlier, it may 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 earthquakes in South Iceland 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 the pipe (to make it easier for the water surface to rupture) where made to keep its eruptions going. However, Geysir had been essentially dormant for decades prior to the 2000 earthquakes in South Iceland (Chap. 14) 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.

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 metres deep, was drilled into the bottom of its conduit in 1963. Since then Strokkur has been erupting on average once every 5–10 minutes.

7.4 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 25 °C for every kilometre. 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 40 °C. In areas with great volcanic activity, such as Iceland, the temperature in the volcanic zones is commonly at or above 200 °C at the depth of one kilometre. In fact, that is the definition of a **high-temperature geothermal field** in Iceland: the water temperature is above 200 °C at the depth of 1000 m. By contrast, if the temperature at the depth of 1000 m is below 150 °C, the geothermal field is referred to as a **low-temperature geothermal field**. While there are over 250 low temperature areas 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 Earth as a whole, the heat source is mainly **radioactive decay** of elements, accumulated when the Earth formed. Heat is generated in the crust through 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, one 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 in Stardalur in Esja in Chap. 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 (Chap. 12).

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 thousand years, so that it is not regarded as volcanically active. Rather, it is located at the **margin** of the active volcanic zone (Fig. 2.2). 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 thousand years. It is well known that most magma-filled fractures, dikes (Chap. 11), 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 kilometres in such fractures (Figs. 4.5 and 5.17), and then migrate to the surface, where it forms hot springs and erupting 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 emphasising again the fracture network that allows the flow of geothermal water through 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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The drive from Geysir to the waterfall Gullfoss along Road 35 is short. The waterfall, which constitutes the **eleventh stop (11)**, is located in Fig. 4.1. 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 **Langjökul**l (the Long Ice Sheet). However, to really enjoy the glaciers or 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 (Fig. 8.1).

8.1 Why Has Gullfoss Two Oblique Steps?

Gullfoss (The Golden Waterfall) is in the glacier river **Hvita (Hvítá, 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 (Fig. 8.1). These steps make an (acute) angle of about 60°—and thus a larger (obtuse) angle of about 120° (Fig. 8.2). More specifically, the upper waterfall or step has a direction (trend, strike, azimuth) of about 75° (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 15°. Then main river channel to the southwest of Gullfoss has a general trend or azimuth of about 40°. All these fracture directions are indicated schematically in Fig. 8.2.

The same main directions are seen at other locations southwest along the main river channel, that is, the main channel itself trends about 40° (always referring to azimuth, that is, east of north) and is dissected by fractures with the two other trends, the one at about 15° and the other at about 75°. 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 of earthquake fractures and are easy to explain.

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Fig. 8.1 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 (Fig. 8.2)

Fractures with the trend of about 40°, that is, trending northeast-southwest, characterise all the volcanic systems in the southern half of Iceland, as well as the West and East Volcanic Zones (Fig. 2.2). As we already know from the Reykjanes Peninsula and Thingvellir (Chaps. 2, 5 and 6) 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 Fig. 8.2). Thus, the main canyon presumably developed along a normal fault zone, containing also tension fractures, which may originally have been partly similar to Almannagja (Figs. 5.1, 5.2 and 5.8).

The other two directions, 15° (marked by C in Fig. 8.2) and 75° (marked by A in Fig. 8.2) 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** (Chaps. 9 and 14). Everywhere in South Iceland there are faults with these two directions: one is north-northeast (about 15° at Gullfoss but somewhat variable), and the other one is east-northeast (about 75° 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; Figs. 4.14 and 5.9), the movements of the walls of the faults that characterise South Iceland Seismic Zone are primarily horizontal. Such 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 example being in **Vördufell**, which we will discuss at the twelfth stop later today (Chap. 9).

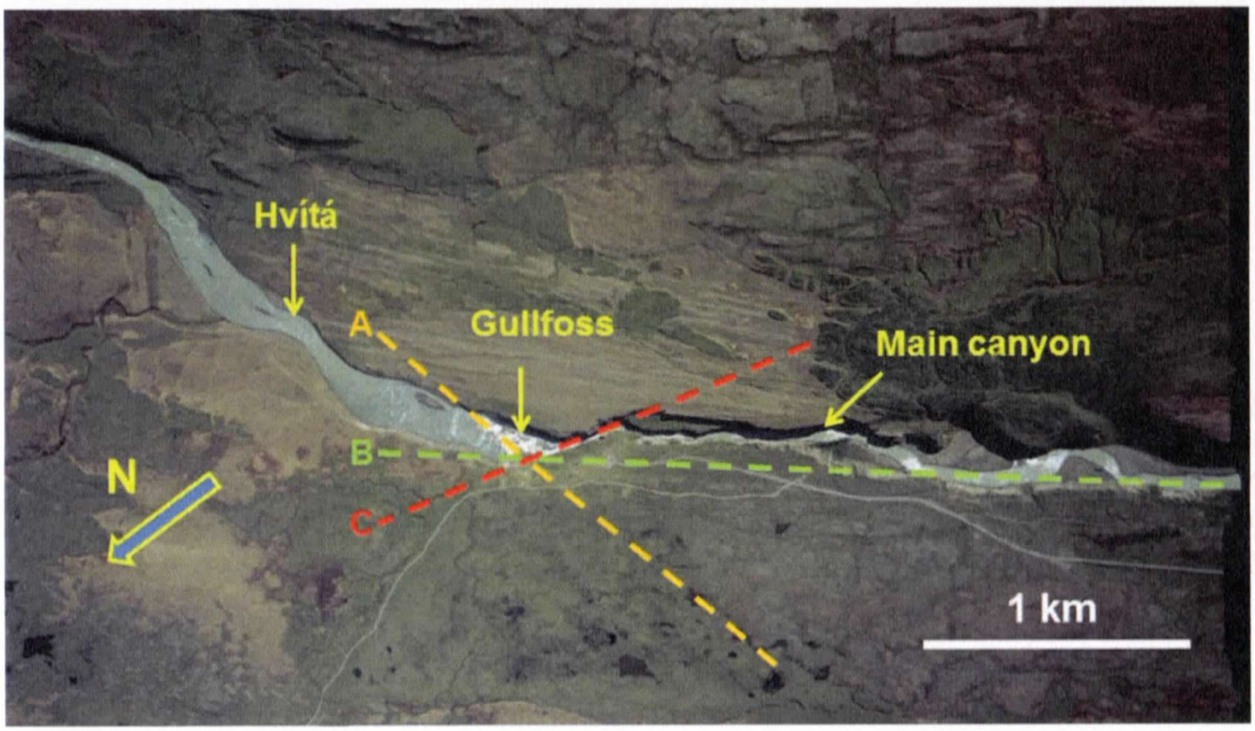


Fig. 8.2 Aerial view of the canyon of the river Hvita (Hvítá), namely Hvitargljufur (Hvítárgljúfur), and Gullfoss. The main steps that constitute Gullfoss have very different orientations, and are also different in orientation from the trend of the main canyon itself. All the three orientations are related 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 (Chap. 5), and trends about 40°. 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 case 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

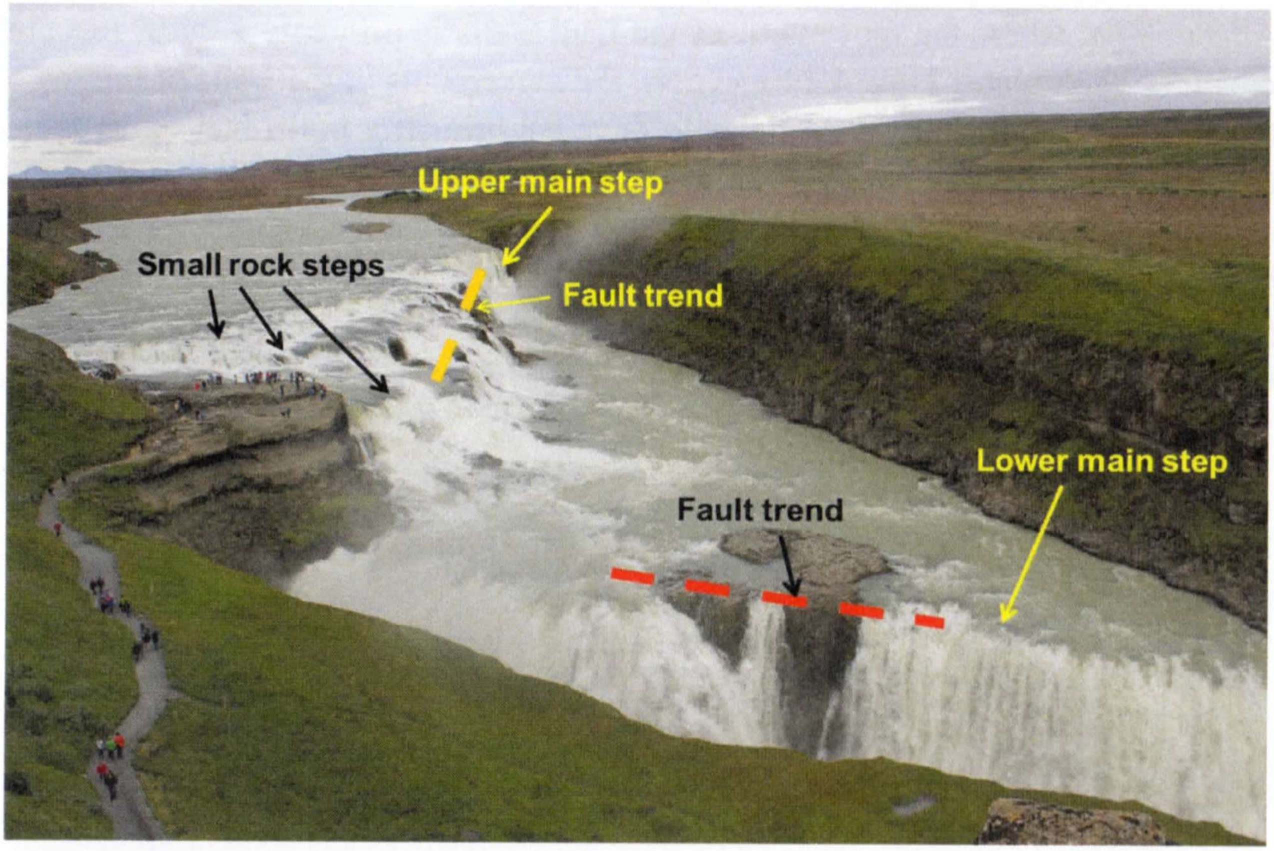


Fig. 8.3 Details of Gullfoss. View east, the main upper step is composed of several smaller rock steps (forming a series of cascades). By contrast, the lower main step is a single one. The upper step is about 11 m in total, whereas the lower step is about 21 m. Also indicated, crudely, are the two fault trends that contribute to the formation of the oblique steps (Fig. 8.2)

So the earthquake fractures offer zones of weakness in the rocks that the water of the river Hvitá can easily erode, forming a major gorge or canyon (Figs. 8.2, 8.3, 8.4 and 8.5). The main canyon (Fig. 8.2) follows the more fractured and thus more easily eroded normal fault zone. It is named for the river as Hvitargljufur (**Hvítárgljúfur**, 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 (Fig. 8.2), 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 Fig. 8.2) that make for fractured rocks and easy erosion.

Fig. 8.4 The part of the canyon that is parallel with the strike-slip fault, indicated by red broken line in Figs. 8.2 and 8.3. View south, at its south end, this canyon joins the main canyon at an acute angle of about 35°

8.2 How Did the Canyon Evolve?

How easily the river **erodes** the rocks and expands the canyon depends on the properties of the rock layers themselves (Figs. 8.1, 8.3 and 8.6). 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 (Figs. 8.4 and 8.5). 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 (Chaps. 3 and 4).

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 layer thickness: thin layers with numerous vertical fractures are generally more easily eroded by flowing water than thick layers.

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 Fig. 8.6) 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

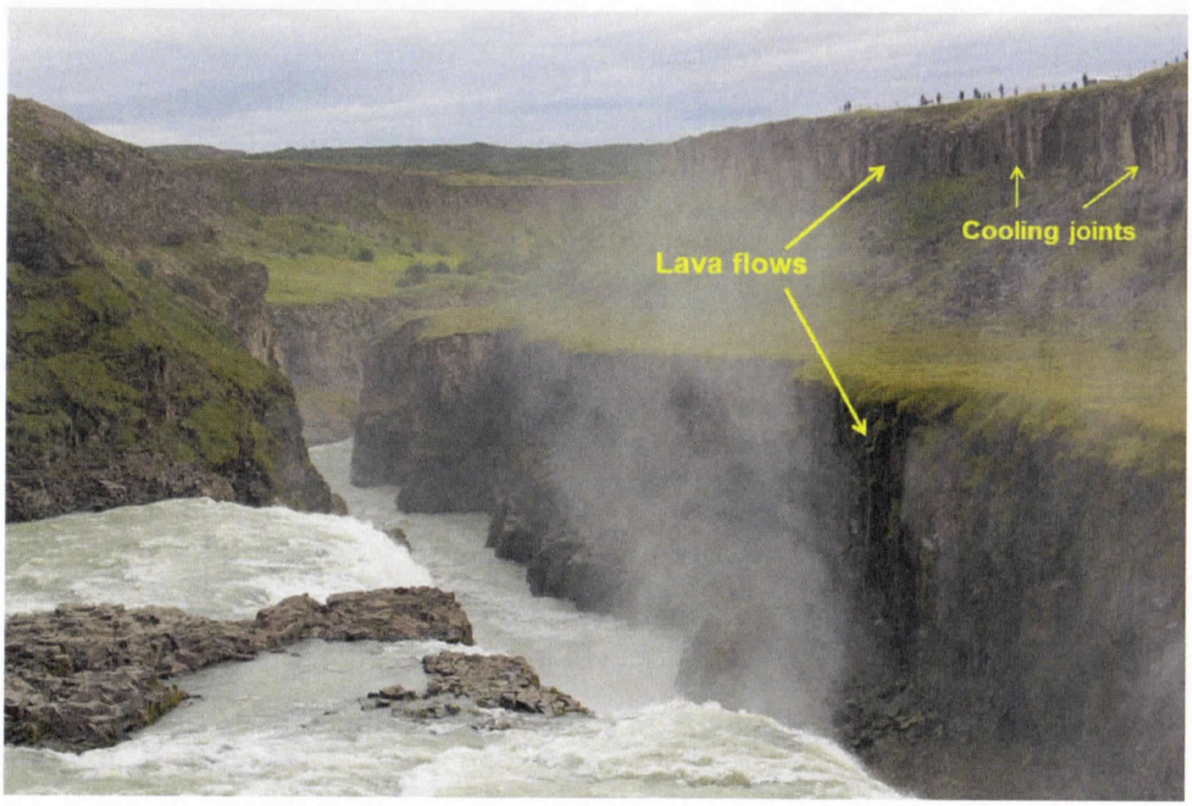


Fig. 8.5 The same part of the canyon as in Fig. 8.4 but from a different perspective. The canyon is primarily composed of basaltic lava flows, indicated, with numerous vertical columnar joints. These are aa lava flows, and thus formed of a single unit, in contrast with the pahoehoe lava flows seen in the walls of Almannagja, which are composed of many thin flow units (Figs. 5.5 and 5.6). The columnar joints are very well developed in these lava flows and made them comparatively easy to erode by the river

Fig. 8.6 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 (Fig. 8.5), that make the rocks more easily eroded, or '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 that characterise the upper step (Fig. 8.3)

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 to five **small rock steps, cascades** (Figs. 8.1 and 8.3), each of which corresponds to one of the layers in Fig. 8.6.

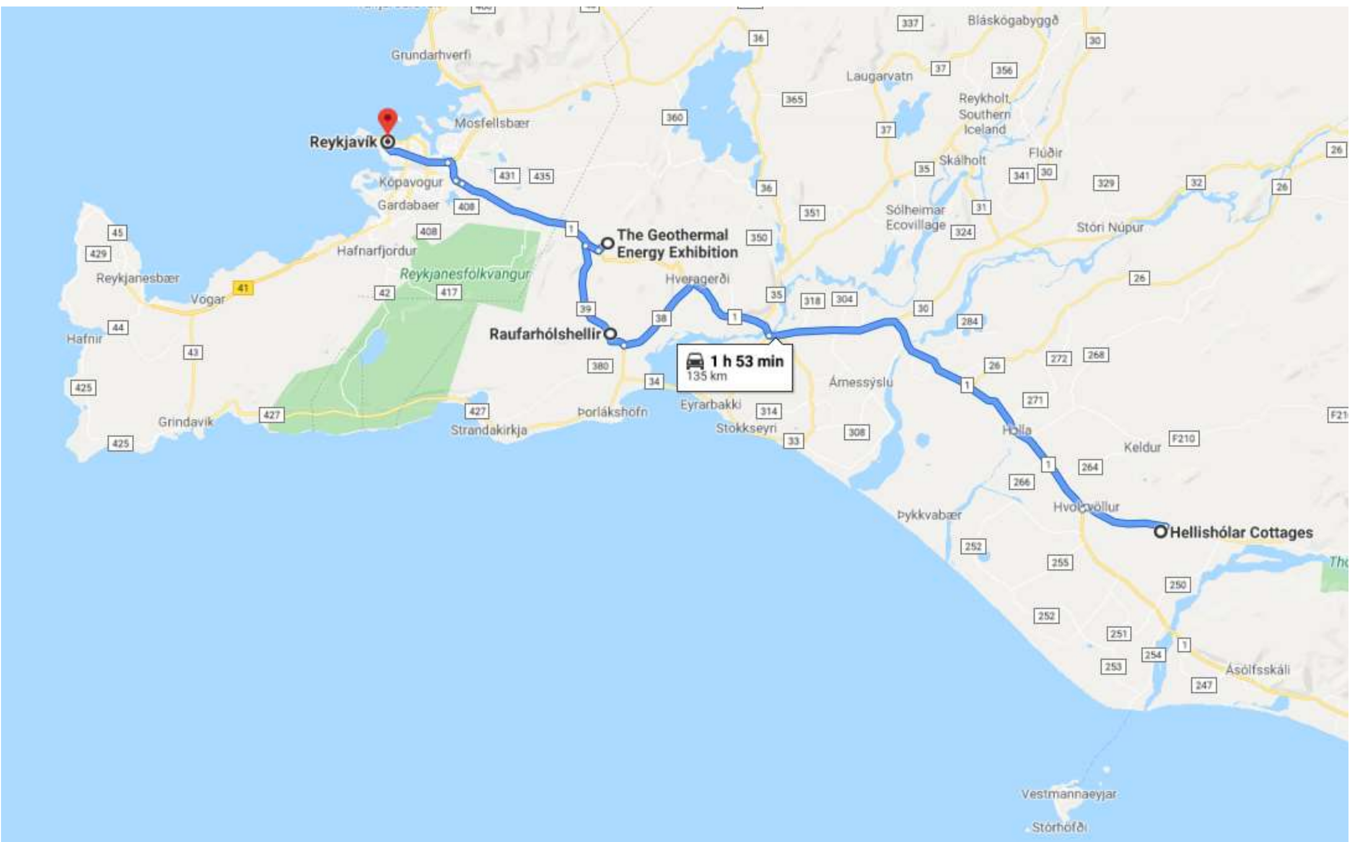
Gradually, however, the layers become eroded and the canyons become longer. The main canyon, Hvitargljufur (Figs. 8.4 and 8.5) and all the structural features associated with Gullfoss itself as seen today must be formed since the ice caps of the last ice period disappeared. This follows because glaciers 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 (Figs. 8.4 and 8.5)—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.

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 13th, 2020 – Hellisheiði Power Plant, Raurfarholshellir Lava Tube, and back to Reykjavik

6:00AM: Wake-up, have breakfast, pack our things, and load the vans.
7:30AM: Depart for Raurfarholshellir Lava Tube
9:00AM: Take a tour of the Raurfarholshellir Lava Tube (http://thelavatunnel.is/) THIS REQUIRES STURDY BOOTS
10:30AM: Take a tour of the Hellisheiði Power Plant geothermal museum and a "behind-the-scenes" tour of the power plant
12:00PM: Finished tour. Have lunch.
1:30PM: Returned to the van and head into Reykjavik. We will be staying in the same accommodations (Igdlo Guesthouse, Gunnarsbraut 46, 105 Reykjavík).



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 – *Back to Reykjavik*

Day 8: Saturday, March 14th, 2020 – 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 15th, 2020 – Reykjavik and return home

8:00: Wake-up and have breakfast (provided by the hostel)
9:00: Load the vehicles
10:00: Hang out in Reykjavik

We have to be checked out of the hostel by 11AM

2:00PM: Return the rental vehicles
3:00PM: Arrive at the airport
4:30PM: Boarding Icelandair Flight 645
7:25PM: Arrive in Dulles, Washington DC

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

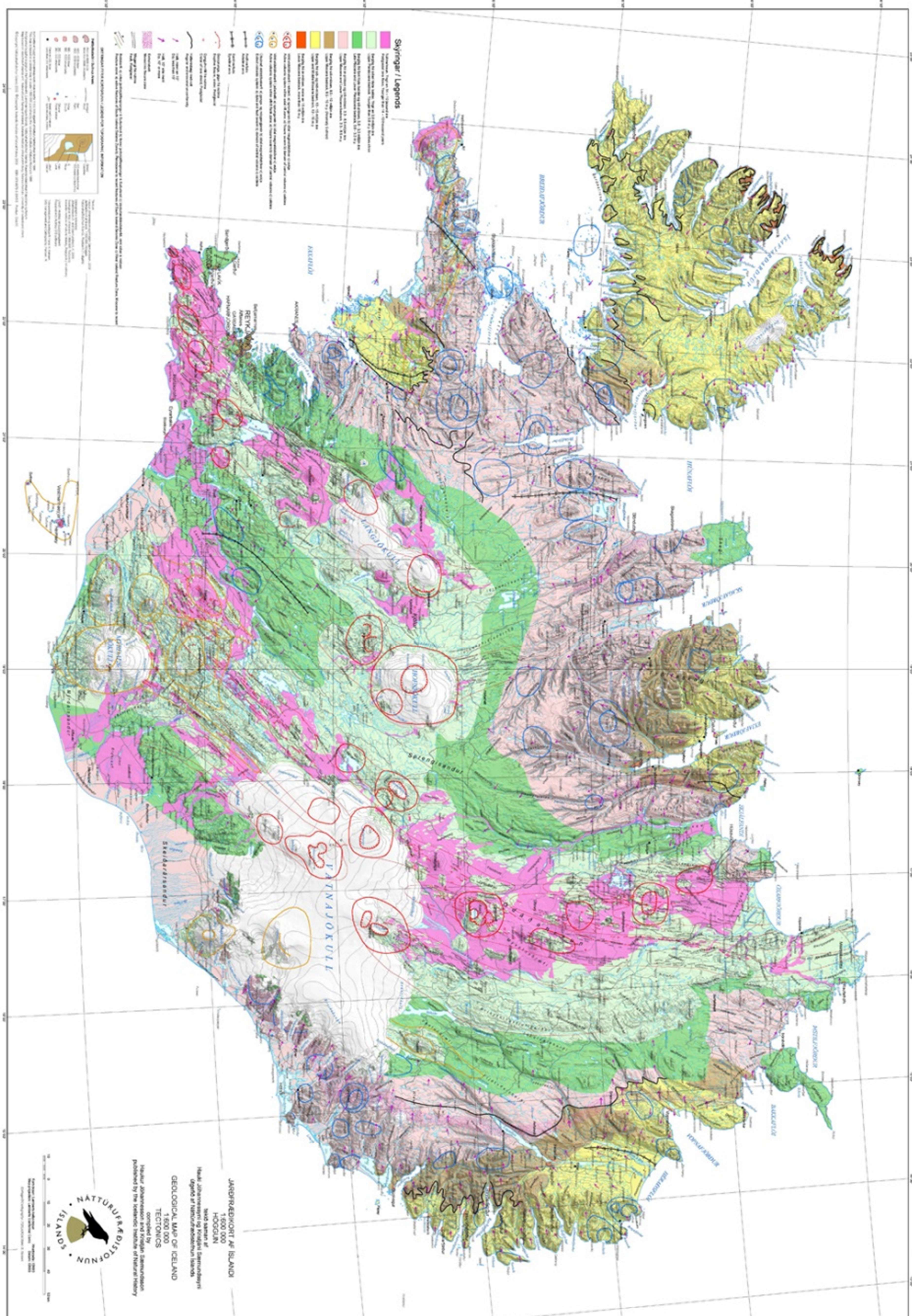
Reykjavik is one of the greenest cities in the world. Space heating is provided completely by geothermal energy. Some buses in Reykjavik use public hydrogen fueling stations (The Ecological City Transport System, ECTOS, project, Figure 2).

Places to visit

- ***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 28 Euro for adults, 7 Euro for teens.

GEOLOGIC MAP OF ICELAND



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 (SiO_2).
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.
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 (SiO_2) 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.

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.

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.

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.

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.

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.

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.

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.

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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BUDGET INFORMATION

(as of 03/01/20)

Funds Collected from Trip Attendees:

- 15 students at $1100
- 2 UPJ Profs at $1300
- 1 unaffiliated traveler (Jess) at $1800
- Total funds collected from Trip attendees = $20,900

Total Funds:

- $8,800 Allocated from Student Activities via Student Government
- Total funds = $29,700

1.	Airfare – Iceland Air		$ 11,118.06
2.	Transport - Guðmundur Jónasson Travel (GJ Travel)		$ 6,295.00
3.	Lodging		
	a.	Reykjavik – 3 nights at Igdlo Guesthouse	$ 2,100.95
	b.	Heimay – 1 night at Aska Hostel	$ 916.37
	c.	Hellisholar – 3 nights at Hellisholar Guesthouse	$ 5,070.33
4.	Miscellaneous		
	a.	Guidebook (to be paid to the UPJ print shop)	$ 270.00

Payments to be made during the trip

1.	Eldheimar Museum	$ 261.73
2.	Lava Centre	$ 170.32
3.	Thingvellir Visitor Center	$ 123.18
4.	Secret Lagoon Hot Springs	$ 352.20
5.	Hellshiedi Power Plant	$ 272.89
6.	Raurfarholshellir Lava Tube	$ 513.00
7.	Group Meals	$ 2,235.97

BOOKING RECEIPTS

ICELANDAIR

10/17/2019

Dear Ryan Kerrigan,

GROUP NAME:
Pitt Johnstown Geology Club

I am pleased to advise you that air space for the above referenced group has been confirmed based on the following Group Contract.

For future concerns related to this group please contact Icelandair's Group Desk at:
Telephone: 1-800-757-7242 option 3.

Itinerary/Dates and Record Locator(s): UADKHP

```
RP/BWIFI0103/BWIFI0103          AA/SU  17OCT19/1436Z   UADKHP
BWIFI0103/3009GA/17OCT19
0. 24PITT JOHNSTOWN GEOLOGY CLUB  NM: 0
  1  FI 644 G 07MAR 6 IADKEF HK24        1940 0630+1 *1A/E*
  2  FI 645 G 15MAR 7 KEFIAD HK24        1650 1925   *1A/E*
```

Net Fare: $395.00 **per person, plus taxes and fuel surcharge**

Airport taxes: $82.67, **Q fuel surcharge** $140.00 -- currently $222.67 per person.

Total cost = $617.67 **per person**

Note: Taxes may change from the originally quoted amount due to currency fluctuations. Final tax and fee amounts will be reflected on the final invoice. Add-on fares are subject to change by the airline and cannot be guaranteed until ticketing.

Children/Infant Fares: CHD under 12 years of age pay 75% adult rate; INF pay 10%

Optional upgrade charge based on availability:
From Economy Class to Saga Class: $1,000 one-way or $2,000 round-trip.

Icelandair information:
Go to http://www.icelandair.us/information/ for information on Travel Classes, On Board Service and Baggage.

Deposit: A $100 per person deposit is due on **December 14, 2019.** Form of payment accepted: one check or one credit card. If not received, reservations are subject to automatic canc

Final Payment/Ticketing: Full and Final Payment is due no later than **January 25, 2020.**
Form of payment accepted: one credit card.
Icelandair's Group Desk will issue the tickets as e-tickets.
No passive bookings are permitted.
Icelandair requires seven (7) bank days for checks to clear before tickets can be issued!
Reservations are subject to cancellation if final payment is not received.

Name Lists: Please email names list **using the provided form** to Icelandair's Group Desk groupsusa@icelandair.is ATTN: Genosky Andujar

A) Preliminary names are due: **December 14, 2019.**
   a. 100% of group names are due at this time. Names can be changed until ticketing.
   b. Any unnamed seats will be cancelled at this time.
   c. Group seats will be assigned at this time. ***No specific seat requests are permitted.*** All requests for seating will be done at airport check-in and are on a first come first serve basis.
   d. ***For seat changes, any and all requests must be done at the airport, on the date of departure.***

B) Final names are due: **January 25, 2020**.
   a. These names must match the passenger's passport. Incorrect names will be assessed a name change fee.

Advance Passenger Information System (APIS):

Icelandair is required to adhere to the Advance Passenger Information System (APIS), which requires the collection of specific information from every passenger traveling on all flights to/from the United States. This information is required for the purposes of ensuring aviation safety and security.

The following is a list of information required:

1. Gender
2. Nationality
3. Country of residence
4. Date of birth

Deviation Policy: Icelandair allows a maximum of 15% in deviations for this group. A $150 per person fee shall be assessed for any change in travel dates. No changes to routings are permitted after ticketing.

Reissue Fee: For any revision after ticketing, the cost will be $200 per person plus any additional fares and/or taxes.

Cancellations and Reductions:

A) From **November 16, 2019** to **December 14, 2019** there will be a penalty of $200 charged for entire group cancellation for groups of 29 or less. For those groups with 30 seats or more, entire group cancellation penalty, will be $500.00.

B) From **December 14, 2019** to **January 25, 2020** 100% utilization is required. $100 penalty per person applies for all unused seats.

C) From **January 25, 2020** to 48 hours prior to departure 50% per person is non-refundable.
D) Within 48 hours or less prior to departure date all payments received are non-refundable.

Name Changes/Corrections: A $150 per person fee will be charged for name replacements and $75 for name corrections after ticketing. Name changes are not permitted within 48 hours of the departure date.

The above conditions apply unless otherwise agree upon in writing.

Thank you for booking this group with Icelandair. **Please email signed contract to** groupsusa@icelandair.is ATTN: Genosky Andujar

GJ TRAVEL

GJ Travel Iceland / Ferðaskrifstofa Guðmundar Jónassonar, Vesturvör 34, 200 Kópavogur
tel: (+354) 511 1515 / Fax: (+354) 511 1511 www.gjtravel.is – lara@gjtravel.is

4. Offer for University of Pittsburgh_ Valid for March 2020

COACH AND DRIVER

All prices are net for coach and driver in USD:

16/19-seater: 5.755,-
27/29-seater: 6.340,-

Included:

- Transfer Keflavík airport – Reykjavík via Reykjanes Peninsula, without guide (6 hrs.)
  - Incl. KEF airport parking fee
- Coach and driver for 5 days as per program outside of Reykjavík, Day 2-6
  - Maximum 900km in total
  - Maximum 9 hours per day between 08:00-19:00
  - Lunch and Dinner for the driver outside of Reykjavík
  - Ferry to/from Heimaey for coach and driver
- Parking fee at Þingvellir & Seljalandsfoss
- Transfer Reykjavík - Keflavík airport, without guide
- All GJ Travel busses include:
  - free WIFI
  - simple non-slip snow & ice grippers spikes for shoes during winter departures

This offer is based on you providing accommodation for the driver for the nights outside of Reykjavík. Accommodation must be in a Single room incl. breakfast, same standard as for the group.

HOTEL ACCOMMODATION

All prices are net per room in USD:

Double Room: 1.195,-
Single Room: 930,-

Included:

- Accommodation for 7 nights (11% VAT) incl. breakfast
  - 3 nights in Reykjavík, 4 nights outside of Reykjavík

This offer is based on the following hotels:

- Skuggi by KEA Hotels
- HÍ Hostel Vestmannaeyjar *(DBL & SGL rooms with private facilities)*
- Hótel Hvolsvöllur

Please note that these areas are very popular and very heavily booked for 2020.
I have not checked availability nor booked any rooms. Changes in the hotels will affect the prices.

Keep in mind that due to narrow streets in Reykjavík City Center many hotels do not have enough space for a coach to stop outside. Walking distance for passengers can be up to 10 minutes, depending on location. GJ Travel

GJ Travel Iceland / Ferðaskrifstofa Guðmundar Jónassonar, Vesturvör 34, 200 Kópavogur
tel: (+354) 511 1515 / Fax: (+354) 511 1511 www.gjtravel.is – lara@gjtravel.is

*will use a shuttle to transfer the luggage that passengers need to pick up outside their hotel **without** any extra charge.*

Herjólfur ferry

Price per child (12-15 years old): 15,- USD

Price per adult: 30,- USD

Included:

- Herjólfur ferry to/from Vestmannaeyjar **Weather depending*

**Herjólfur ferry is weather depending. Offer is based on ferry departing from Landeyjarhöfn, additional charges apply if ferry departs from Þórslákshöfn due to weather conditions.*

DINNER SUPPLEMENT

All prices are net per person in USD: 195,-

Included:

- 4x 3-course dinner menu including coffee/tea
  - 1x in Reykjavík, 3x at hotel in Hvolsvöllur

Not included:

- Drinks during included dinner
- Other not mentioned meals or refreshments
- Other not mentioned tours, activities or extras
- Guide during the departure transfer
- Extra fee due to early breakfast or grab & go
- Other unexpected costs for nature sights

Program:

08.03.20: Arrival – Keflavík airport – Reykjanes Peninsula – Reykjavík

09.03.20: Reykjavík – LAVA Centre – Landeyjarhöfn – Vestmannaeyjar/ Heimaey

10.03.20: Eldheimar museum – Heimaey – Landeyjarhöfn – Hvolsvöllur

11.03.20: Seljalandsfoss – Skógafoss – Sólheimajökull glacier walk – Reynisfjara – Vík - Dyrhólaey

12.03.20: Þingvellir – Geysir – Gullfoss – Flúðir – Secret lagoon

13.03.20: Hveragerði – Hellisheiðarvirkjun – Raufarhólshellir – Short Reykjavík City tour – Hotel

14.03.20: Free for leisure – Explore the Northernmost capital on your own

15.03.20: Departure – Reykjavík – KEF airport

Note: In rare cases, a change of itinerary might be necessary during programs in Iceland, should snow, road and weather conditions do not allow to follow the scheduled itinerary, and certain outdoor activities/day tours might be cancelled. In this case no refund will be given, but GJ-Travel will try to find reasonable alternatives where and whenever possible.

General terms and conditions

Payment:

GJ Travel requires full payment 8 weeks before the arrival of the group (the invoice being sent out after the final name list is received).

Deposits:

GJ Travel might require a non-refundable deposit for certain coach types, for high season dates or last-minute bookings.

Changing fee:

GJ Travel reserves the right to charge a changing fee of 500, - ISK per person for changes made within 2 weeks prior to arrival. This applies for changes made in the program, activities, guide or menus.

Name list:

We need to receive the first name list for the hotels no later than 8 weeks prior to arrival. Cancellations within the 12 weeks mark will result in cancellation fees per our cancellation policy below. The reminder of booked rooms will be kept under No name according to availability of the hotel. No later than 6 weeks before arrival of the group we have to receive the final name list and all unused rooms (should there be any) have to be released or paid in full.

General cancellation policy:

Cancellations are only valid if reconfirmed in writing by GJ Travel. GJ Travel does not have to ask for rooming list first (or if group will be operated) in order for cancellation fees not to be charged. It is the responsibility of the tour operator to send cancellation in time.
10% cancellation fee for cancellation 12 to 9 weeks prior to arrival
50% cancellation fee for cancellation 8 to 5 weeks prior to arrival
Full charge for cancellation 4 weeks to 0 days prior to arrival as well as for no-shows.

Individual cancellation policy within groups:

Cancellations are only valid if reconfirmed in writing by GJ Travel. It is the responsibility of the tour operator to send cancellation in time.
50% cancellation fee for cancellation 4 to 2 weeks prior to arrival.
90% cancellation fee for cancellation 2 weeks to 1 day prior to arrival
Full charge for cancellation 0 day prior to arrival as well as for no-shows.

Payment for coach hire only:

Non-refundable deposits for certain coach types, for high season dates or last-minute bookings.
Full payment 4 weeks before the arrival of the group.

Cancellation policy for coach hire only:

Cancellations are only valid if reconfirmed in writing by GJ Travel.
50 % cancellation fee for cancellation 4 weeks to 2 weeks prior to arrival.
Full charge for cancellation within 2 weeks prior to arrival or no-shows.

Cancellation policy for Greenland:

72 hours after booking and up to 8 weeks before departure: Changes (of ANY kind) will cost 10% of the tour package price. Cancellation will cost 20% of tour package price. To finalise a booking and issue the flight ticket, a deposit of DKK 7000 (EUR 1000) per person is required within 72 hours of booking confirmation.
If the reservation is cancelled within 8 weeks of departure, there will be a charge of 40% of the tour package price.
If the reservation is cancelled within 6 weeks of departure, there will be a charge of 60% of the tour package price.
If the reservation is cancelled within 4 weeks before departure, there will be a charge of 80 % of the tour package price.
If the reservation is cancelled within 2 weeks before departure, there will be a charge of 100% of the tour package price.
If the reservation is cancelled on the day of departure or in case of no-show, there will be a charge of 100% of the tour package price (no refund at all).
Depending on availability flight supplements up to EUR 500/DKK 3700 per person might apply
Other cancellation policies may apply when packages include flights in Iceland, Faroe Islands or Greenland.

Please note:

GJ Travel will arrange coaches according to final routing, group sizes, availability and based on minimum seat requests (if applicable). Traveling in the highlands of Iceland requires special highland vehicles. Therefore, a change of vehicles might be necessary depending on the program and availability. In case of shortage of GJ Travel coaches, we will arrange coaches and drivers from 3rd party with similar standard and safety rules as GJ Travel.
Please bear in mind that our drivers are by law not allowed to drive more than 9 hours per day. Working hours should take place between 08.00 and 19.00h unless mentioned otherwise in the offer. Daily rest period for driver shall be at least 11 hours, with an exception of going down to 9 hours maximum twice a week. If the program includes any evening excursions or night transfer the departure time for the following day will be adjusted to minimum required resting time. **Please note that our drivers do not act as guides.**

GJ Travel Iceland / Ferðaskrifstofa Guðmundar Jónassonar, Vesturvör 34, 200 Kópavogur
tel: (+354) 511 1515 / Fax: (+354) 511 1511 www.gjtravel.is – lara@gjtravel.is

Our offer is based on the enclosed itinerary and is fully legal.
General terms and conditions apply unless otherwise agreed upon in writing.

All prices include 11% VAT and are subject to change. We reserve the right to update prices due to exchange rate fluctuations, changed VAT regulations or new enforced entrance and parking fees for nature sights.

This offer is made 08.10.2019 by Lára Ösp Oliversdóttir and valid 08.12.2019
Updated 14.10.2019 by Lára Ösp Oliversdóttir
Updated 21.10.2019 by Lára Ösp Oliversdóttir
Updated 02.01.2019 by Kristín Anna Guðnadóttir

We hope you like our offer.
Please do not hesitate to contact us anytime if you have questions, remarks or wish to book.

We look forward to hearing from you soon again.

Lára Ösp Oliversdóttir
Söludeild/ Sales Department
Guðmundur Jónasson Travel
Vesturvör 34
200 Kópavogur
Tel: +354-511-1515

Agreed and accepted by:

On behalf of GJ Travel Iceland	Date	On behalf of UNIVERSITY OF PITTSBURGH	Date

Kerrigan, Ryan

From: Igdlo Guesthouse - Car Rental - Travel <booking@igdlo.com>
Sent: Saturday, December 7, 2019 4:09 AM
To: Kerrigan, Ryan
Subject: Re: Accommodations March 2020

Good morning Ryan,

Sorry for that, I thought we had sent the details about the deposit. We just ask for 50% deposit at least 2 weeks prior to your arrival date, so February 23rd.

Best regards,
Bailey

From: Kerrigan, Ryan <kerrigan@pitt.edu>
Sent: 06 December 2019 17:38
To: Igdlo Guesthouse - Car Rental - Travel
Subject: RE: Accommodations March 2020

Hello,
I just want to confirm our reservation and find out if a deposit is needed. Our group, Pitt-Johnstown Geology Club, has reservations for six rooms (1 double, 1 single, 3 family, and 2 twin) of the evenings of March 8th, 13th, and 14th.
Ryan

Ryan Kerrigan, Ph.D., P.G.
Assistant Professor
Energy & Earth Resources
University of Pittsburgh at Johnstown
Johnstown, PA 15904
(814) 269-2942

From: Igdlo Guesthouse - Car Rental - Travel <booking@igdlo.com>
Sent: Saturday, November 16, 2019 5:51 AM
To: Kerrigan, Ryan <kerrigan@pitt.edu>
Subject: Re: Accommodations March 2020

Good morning Ryan,

Thanks for giving us the final count for your group. I've gone ahead and adjusted the rooms so what we have is 1 double for you and your wife, 1 single for the other professor, 2 family rooms (4 beds each) for the girls, and 1 family room and 2 twins for the boys. :-) I will have my boss confirm for you when he arrives back in the office Monday on the change in price and details on the deposit, but I assume the price will remain at 35 euro per person per night so a total of 1890 euro for the 3 nights.

Aska Hostel

Kt: 610616-1190
Bárustígur 11

900 Vestmannaeyjar

Kerrigan Ryan

Vestmannaeyjar,

Invoice

Invoice Number:

Description	Quantity	Price	Net	Vat %	Vat	Total
Accommodation for 1 night, March 9 2020 for 15 Students	15	5,500.00	82,500.00	0%	0.00	82,500.00
2 Single rooms for teachers	2	8,000.00	16,000.00	0%	0.00	16,000.00
Double room	1	11,500.00	11,500.00	0%	0.00	11,500.00
Grand Total						**110,000.00**

We thank you very much for choosing Aska Hostel. We hope you enjoyed your stay with us.

Best regards,

Aska Hostel

Kerrigan, Ryan

From: Hellisholar ehf <hellisholar@hellisholar.is>
Sent: Thursday, December 19, 2019 6:24 AM
To: Kerrigan, Ryan
Subject: RE: March 2020 Accommodations
Attachments: CONCERNING TRANSFER BY SWIFT.doc

This is how to make bankpayment

Note.
We onley have bankaccont in Iceland

Best regards / Með kveðju
Hellishólar ehf
Hellishólum
861-Hvolsvöllur
Sími : 00354 4878360
Iceland
email : hellisholar@hellisholar.is
homepages : http://hellisholar.is/
homepages : http://hoteleyjafjallajokull.is/

From: Kerrigan, Ryan <kerrigan@pitt.edu>
Sent: miðvikudagur, 18. desember 2019 19:29
To: Hellisholar ehf <hellisholar@hellisholar.is>
Subject: RE: March 2020 Accommodations

Hey Joanna,
I am trying to get some of the logistics for my Iceland trip taken care of and I would like to send you payment for our group's accommodations at Hellisholar Guesthouse for March 10th, 11th, and 12th. We had agreed upon $80 euro per person per night for lodging, breakfast, packed lunch, and dinner. For 19 people for 3 nights that would be 4,560 euro. What would be the best way to submit payment? Also, it would be someone from my university (University of Pittsburgh at Johnstown) that will contact you for payment, likely a guy named John Ziats.
Thanks!
Ryan

From: Hellisholar ehf <hellisholar@hellisholar.is>
Sent: Wednesday, November 20, 2019 1:10 PM
To: Kerrigan, Ryan <kerrigan@pitt.edu>
Subject: RE: March 2020 Accommodations

HI
We will send you a invoice 1mont before arrival and you need to pay befor arrival og on arrival

Best regards / Með kveðju
Hellishólar ehf
Hellishólum

Kerrigan, Ryan

From:	Kristín Jóhannsdóttir <kristin@vestmannaeyjar.is>
Sent:	Sunday, October 13, 2019 11:05 AM
To:	Kerrigan, Ryan
Subject:	RE: Educational Group: March 9, 2020

Hi and many thanks for your email.

It will be our pleasure to welcome your group on the 9th of March.

I can offer you a special price of isk 1.700.- each person

Best regards

Kristín

Kristín Jóhannsdóttir
Director Eldheimar
Tel: +354 488-2702
Mob: +354 846-6497
kristin@vestmannaeyjar.is
www.eldheimar.is

From: Kerrigan, Ryan [mailto:kerrigan@pitt.edu]
Sent: Friday, October 11, 2019 5:38 PM
To: Kristín Jóhannsdóttir <kristin@vestmannaeyjar.is>
Subject: Educational Group: March 9, 2020

Hello,
I will be leading a group of university students and professor on a geology trip to Iceland and Vestmannaeyjar in March. We were hoping to visit your museum on March 9th, 2020. I was wondering if you have any special rates for educational groups. There will be 24 of us.
Thank you
Ryan

Ryan Kerrigan, Ph.D., P.G.
Assistant Professor
Energy & Earth Resources
University of Pittsburgh at Johnstown
Johnstown, PA 15904
(814) 269-2942
https://rjkerrigan.com/

Kerrigan, Ryan

From:	schoolgroups LAVA <schoolgroups@lavacentre.is>
Sent:	Thursday, December 19, 2019 5:08 AM
To:	Kerrigan, Ryan
Subject:	Re: University Group March 11, 2020

Hi.

It costs 1400 ISK for each student. Teachers and team leaders get free.

Best Regards
Leó

On Wed, Dec 18, 2019 at 8:16 PM Kerrigan, Ryan <kerrigan@pitt.edu> wrote:

> Hello,
>
> I am interested in receiving a quote for a group of 19 people (university students and professors) for entrance into the Lava Centre on Wednesday, March 11, 2020. Could you provide the rates for our group? Let me know if there is any other information you need.
> Thanks
>
> Ryan

Lava Centre
Austurvegur 14
860 Hvolsvelli
Sími: 4155200
Kt.: 4211151170

Reikn. prentaður: 05.02.2020 09:37:27
Reikningur nr: 120029060
Sölumaður: Hulda
Kassi nr.: 12
Tilvísun: 9. March

***** Staðgreitt *****

Fl:	Lýsing:	Verð:
U0	Schoolgroups: Exhibition and 15,000 * 1.400kr	21.000kr
Samtals:		**21.000kr**
Mastercard		21.000kr
U0	VSK: 0,00% af 21.000kr	0kr

Thank you for your visit!

Þessi reikningur á uppruna sinn í rafrænu bókhaldskerfi skv. reglugerð nr. 505/2013.

Kerrigan, Ryan

From: Secret Lagoon <info@secretlagoon.is>
Sent: Thursday, December 19, 2019 2:15 PM
To: Kerrigan, Ryan
Subject: Re: New submission from Group reservation

Hello,
Thank you for explanation. We can make for you reservation on 12th of March and offer a 20% discount for admission. It means 2400 isk.

Is it possible that you visit us at 14:30 or 15:00 ?

Please notice that this reservation isn´t prepaid and group will be charged at the reception.

Best regards,
Með bestu kveðju,

Adam Blaszczak

Secret Lagoon
Gamla Laugin

tel: (+354) 853 3033
email: info@secretlagoon.is

On Thu, Dec 19, 2019 at 5:06 PM Kerrigan, Ryan <kerrigan@pitt.edu> wrote:

> Hello,
>
> Thank you for the response. The students range in age from 18 to 23, there would be 15 students and 3 professors. We would likely be at the hot spring for 1 hr. Based on our itinerary, the afternoon would work out best for us, if you were able to allow it. We could do a different day, if you have other groups booked for the 12th of March.
>
> Much appreciated,
>
> Ryan

Kerrigan, Ryan

From:	Jóna Sigurlína Pálmadóttir <Jona.Sigurlina.Palmadottir@on.is> on behalf of ON jarðhitasýning <syning@on.is>
Sent:	Thursday, December 19, 2019 6:47 AM
To:	Kerrigan, Ryan
Subject:	RE: University Group March 13, 2020

Dear Kerrigan,

The price per students 2020 is 1.250.-kr. per students. Teachers, guides, drivers or other staff members following the group get a free access. It's possible to pay this before or upon arrival. We can do a prepayment through credit card.

We are open here every day from 09:00-17:00, and we book tours on the half/whole hour over the day (like 09:00, 09:30, 10:00 etc.). So far the 13th of March is very much open so you can choose the time that will suit your group the best to have a guided tour.

Our regular tours are around 20-30 min where we go over all the basics of geothermal energy. We end our tours on some short videos (around 10 min). After that we offer our guests to walk around the exhibition as they like or check out our souvenir store or café at the entrance. With the regular tour groups usually spend here around an hour.

However we also offer a longer and more detailed private tours. In those tours, Private tours, we go into more details so the tour takes around 40 min up to and hour. This will costs for students 1.250.-kr. per person plus 9.900.-kr. for a private guide.

We also offer a VIP tour which includes a longer a more detailed private tour, refreshments, welcoming drinks and a unique Icelandic gift. This will costs 9.900.-kr. per person.

With a private tour or a VIP tour groups usually spend here around an hour and a half.

I Hope this information helps but welcome to contact us should you need any further information

Kær kveðja / Best Regards,

Jóna Sigurlína Pálmadóttir
Starfsmaður jarðhitasýningar / Geothermal Exhibition Employee
Sími / Tel: +354 591 2700 · Farsími / Mobile: +354 617 2884
Netfang / E-mail: Jona.Sigurlina.Palmadottir@on.is

Kerrigan, Ryan

From: no-reply@korta.is
Sent: Friday, February 7, 2020 8:27 AM
To: Kerrigan, Ryan
Subject: Receipt from THE LAVA TUNNEL - Order 163567201

Webpay THE LAVA TUNNEL

Your order has been received

Products

Payment for: LAVAT-T13471015 15 students @3850. Total is 57750 Isk.

Total amount : 57.750 ISK

Seller

THE LAVA TUNNEL
Klettagarðar 12
104 Reykjavík
ISL
https://nam05.safelinks.protection.outlook.com/?url=http%3A%2F%2Fthelavatunnel.is%2Fbooking-success%2F&data=02%7C01%7Ckerrigan%40pitt.edu%7C96f29b48d52d4a81626a08d7abd16826%7C9ef9f489e0a04eeb87cc3a526112fd0d%7C1%7C1%7C637166788214905810&sdata=Yc0zxVm6aZqXRRo8RRxVd3jKbh6sMAH2Vj2c4Pagtoo%3D&reserved=0
hk@thelavatunnel.is
Reg.id. 7005161210
Tel. 7601000

Buyer

Ryan Kerrigan
University of Pittsburgh at Jo
141 Krebs Hall
15904 Johnstown
United States
Tel. 8142692942
Fax kerrigan@pitt.edu
email kerrigan@pitt.edu

Payment received

Amount 57.750 ISK
Reference 163567201
Time 07-02-2020 13:25:52 GMT

PREVIOUS SPRING BREAK GROUPS

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: