Iceland Field Guide
UW Madison Geosciences
Spring 2023

Avenza map with all the stops

May 30th: "Velkomin á Ìslandi"
(Chelsea, Claudia, Andy, Yas)

Summary

#	Stop	Location	Stop duration	Topic
1	Bridge between Continents	63.8683°N, 22.6755°W	1 hour	Tectonics + structure + rift dynamics
2	Reykjanesviti Area	63.81304°N, 22.71474°W	1.5 hours	Volcanic deposits + hot spring
3	Steinahellir Cave (weather permitting)	63.54542°N, 19.72685°W	40 minutes	Cave/archeology/lava deposits
3b*	Skogafoss + Museum (alternative stop)	63.5295°N, 19.51316°W	40 minutes	Cliff + waterfall + Cultural Heritage

Proposed day schedule:
Start: Keflavík International Airport (KEF). Group departure from airport by ~noon.
Stop 1: 22 minute drive from KEF to Hafnir (arrive at ~12:30 PM). ~ 1 hr at site.
Stop 2: 10 minute drive to Reykjanesviti Area (lunch?). Arrive at ~2:45 PM. ~1.5 hrs at site.
Stop 3: 2.5 hrs drive to Steinahellir Cave. Arrive at ~4:15 PM. ~40 mins at site.
Stop 3b*: 2 hr 42 min drive to Skogafoss + Museum. Arrive at ~4:30 PM. ~40 mins at sites.

End: 30 min drive to Vík HI hostel, dinner. (arrive ~5:40 PM).

Stop Information

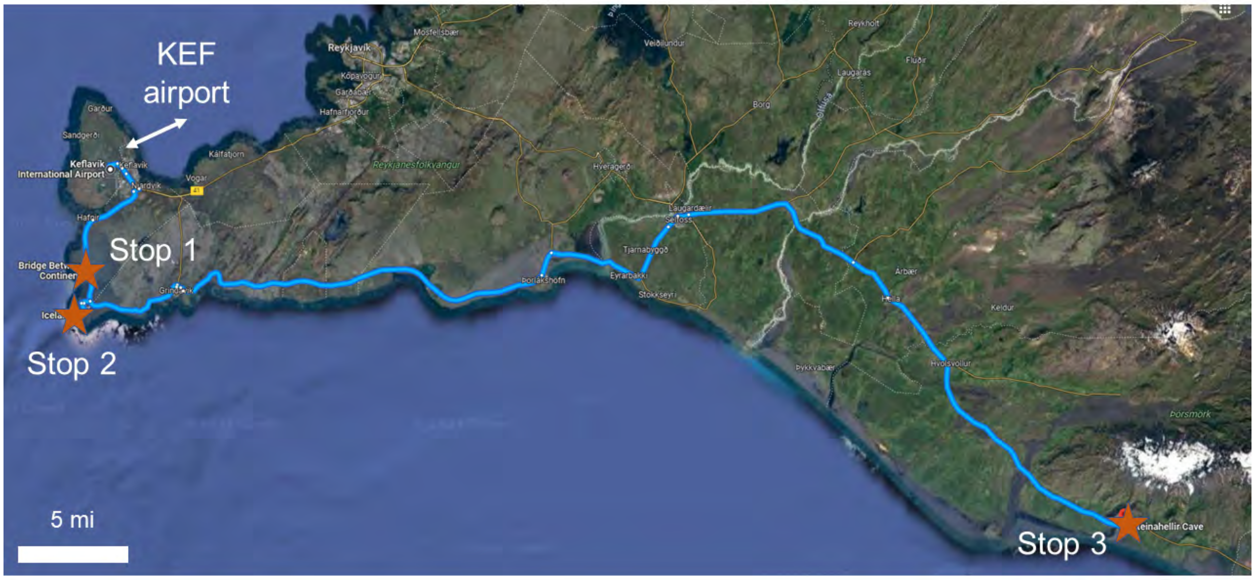

Fig. 1.0: Google Maps image of stops + route for Day 1*. Orange stars represent the stop localities. Stop 1: Bridge between Continents; Stop 2: Reykjanesviti Area; Stop 3: Steinahellir Cave.*

<u>Expression of the Mid-Atlantic Ridge (MAR) in Southwestern Iceland:</u>

Even though rifting is a widespread geodynamical process that leads to separation of a continental plate and the generation of new oceanic crust (Wilson, 1966), Iceland is the only place on Earth where we can directly observe oceanic rifting above sea level. This allows for the study of active rift-controlled fault systems and plate boundary dynamics (Sani et al., 2019). The Reykjanes Ridge (RR) is oriented at an angle of ~60° to the spreading direction and continues onshore on to the Reykjanes Peninsula (RP) in a series of an echelon spreading segments (Karson, 2017) **(Fig. 1.1)**. This part of the MAR is oblique relative to the direction of extension, implying a shear component along the rift zone. These rifting conditions produce very complex sets of normal faults, strike-slip faults, NEtrending elongated volcanic shields, and fissures (Clifton & Einarsson, 2005; Einarsson, 2008; Karson, 2017) **(Fig. 1.3; Fig. 1.5)**. Today we will focus on the geometry and kinematic markers of the Reykjanes Peninsula Oblique Rift (RPOR) propagation and faulting in southwest Iceland by looking into some examples of deformation of older crust and spreading-related structures. The route takes us from the Keflavík International Airport out to the southwestern end of the peninsula where the mid-ocean ridge comes on shore (**Fig. 1.0)**.

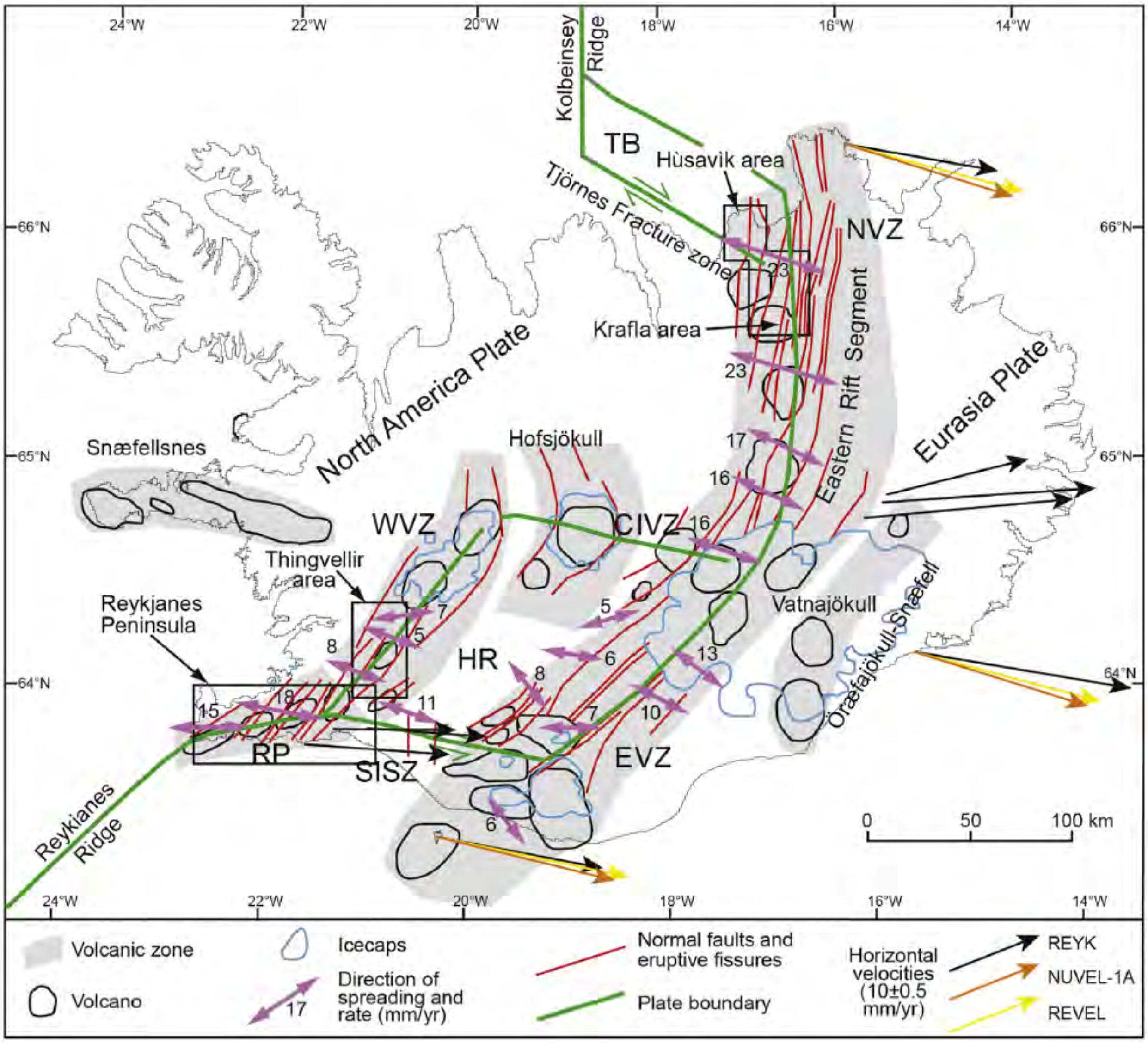

Fig. 1.1: Tectonic overview of the Iceland Plate Boundary. *Main components include: the trends of the oceanic ridges, the major transform zones and the delimited blocks. Major active volcanic zones of Iceland are also indicated: Western Volcanic Zone (WVZ), Reykjanes Peninsula (RP), Northern Volcanic Zone (NVZ), and Eastern Volcanic Zone (EVZ). HR Hreppar block. Snæfellsnes, Öræfajökull-Snæfell, and Central Iceland Volcanic Zone (CIVZ) are the volcanic zones, characterized by no or poor spreading. South Iceland Seismic Zone (SISZ) is also indicated. The green line represents the current spreading axis. Violet double arrows are the current spreading directions with the relative rate. Black, yellow and orange arrows represent the horizontal velocities with respect to the North American Plate, of continuous GPS: REVEL, and NUVEL-1A and MORVEL plate motion models, respectively. Map from (Sani et al., 2019).*

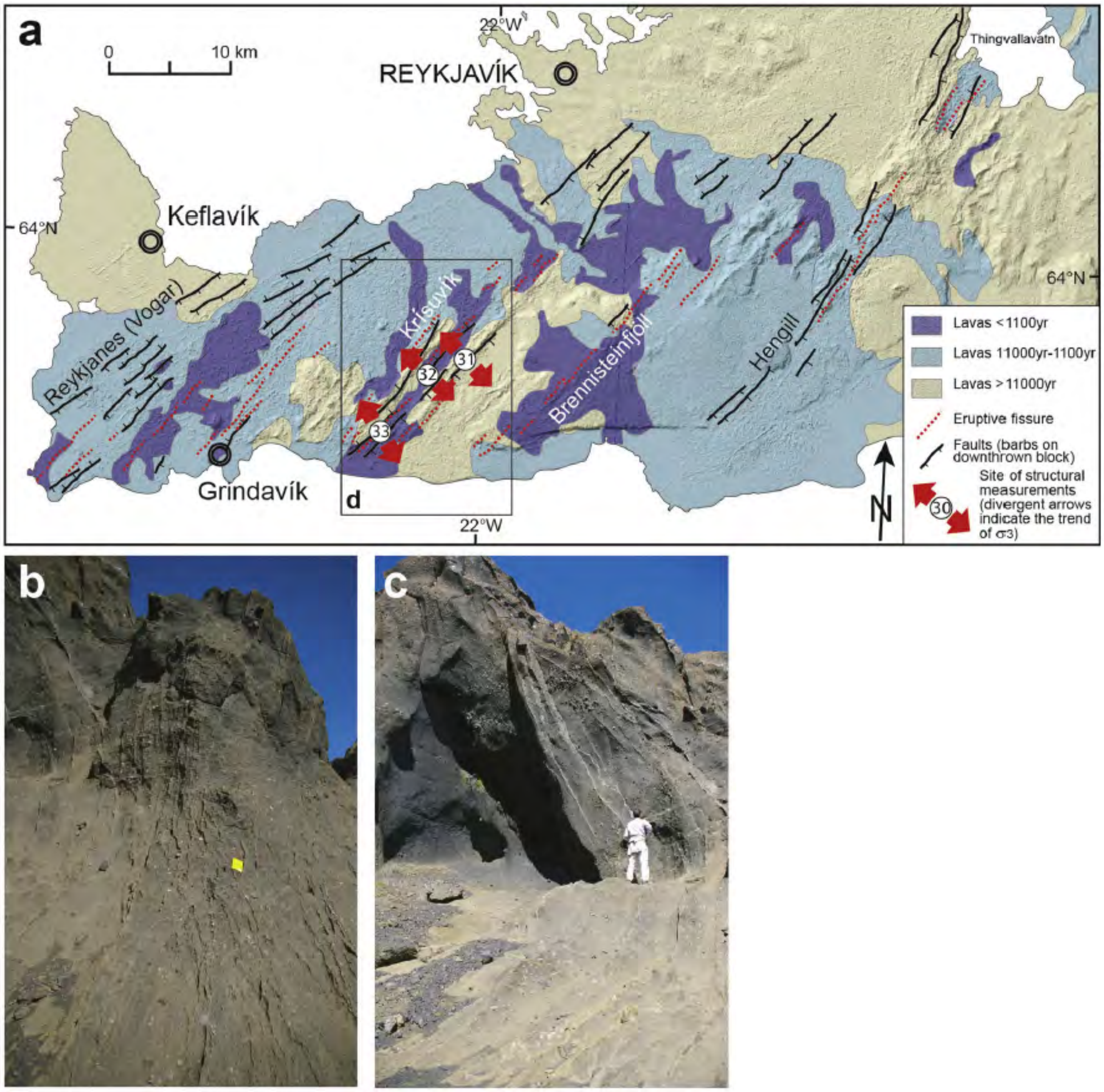

Fig. 1.2: *(a) Geological map of the Reykjanes Peninsula (RP). (b, c) Field examples of normal faults with well-developed vein systems from the Reykjanes area. Figure from (Sani et al., 2019).*

Reykjanes Fissure Swarms: and form a part of a chain of swarms arranged en echelon on the plate boundary of the northern Reykjanes Ridge and the Reykjanes Peninsula **(Fig. 1.3)**. The fissure swarms are arranged approximately perpendicular to the assumed direction of spreading in the region. The volume of the Reykjanes graben (ie- the graben within and NE of the Reykjanes volcanic fissure swarm) which has formed in Holocene time, is approximately 3—4 km^3, assuming the surroundings to be stable. This is only about half of the estimated output of lava on the surface within this swarm. The RP is mostly covered by basaltic lava flows of Holocene (Postglacial) age. The oldest formations outcropping on the western part of the peninsula are vast interglacial basaltic lavas presumably from the last interglacial period. Petrographically, the swarms on the RP range from picrite basalts to saturated tholeiites, intermediate and acid rocks only being found in the easternmost swarm (Hengill) (Björnsson et al., 2020).

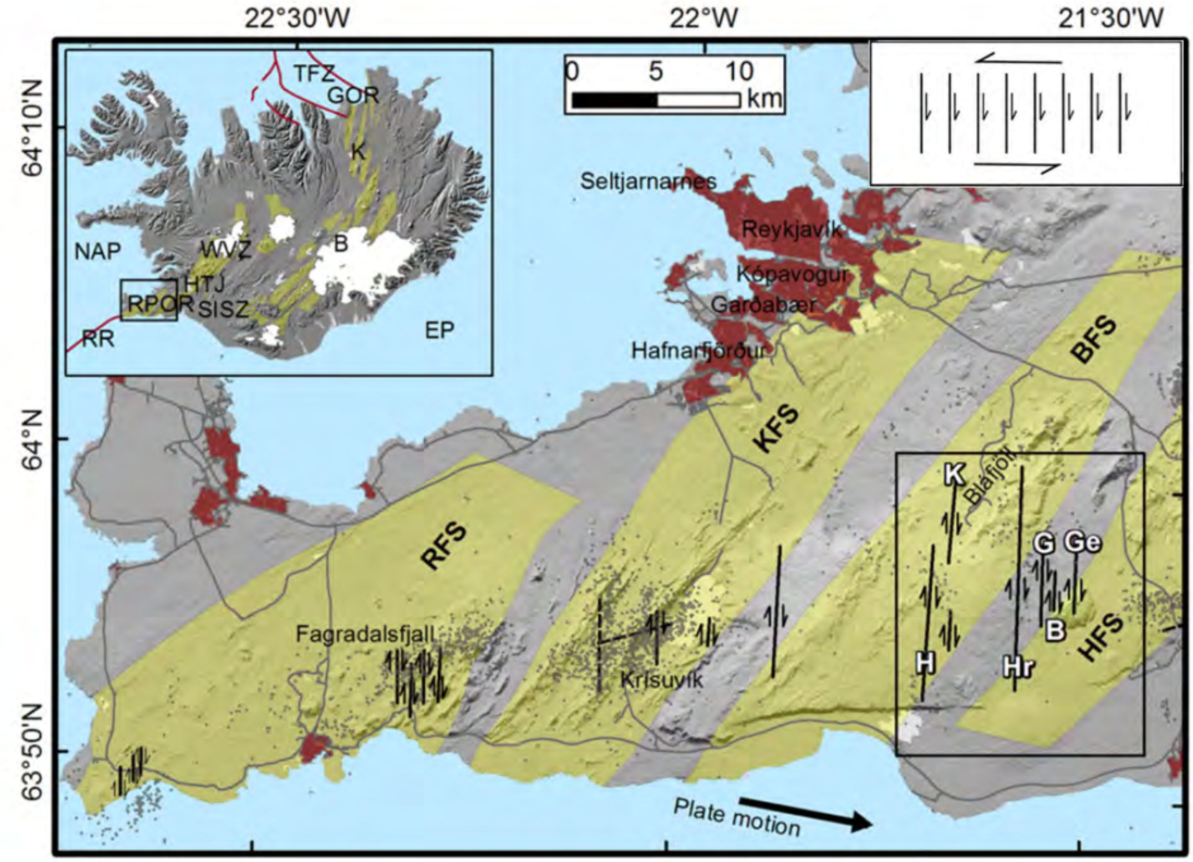

Fig. 1.3: Map of structural features of the Reykjanes Peninsula Oblique Rift, and the active zones of Iceland (inset)*. Fissure swarms are mapped in yellow. Known strike-slip faults mapped at the surface are shown with black lines displaying bookshelf faulting. RFS Reykjanes, KFS Krísuvík, BFS Brennisteinsfjöll, HFS Hengill Fissure Swarm. Map modified from (Einarsson et al., 2018).*

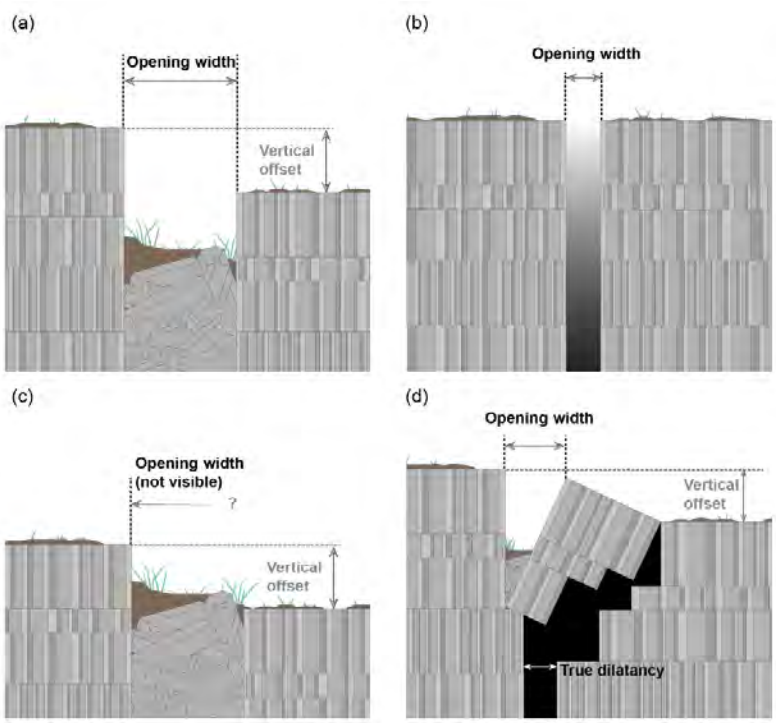

Fig. 1.4: *General block diagrams for dilatant fault fractures in basalts for different off-set and opening scenarios in Icelandic fissures. From (Weismüller et a., 2019).*

Stop 1: Bridge between Continents 63.8683°N, 22.6755°W (1 hour)

Directions: Head north on Komur toward Skammtímastæði for 170 m. Follow Route 41 and Hafnavegur to Nesvegur in Reykjanesbær for 22.8 km. Then turn left (south) to 44 Nesvegur for Hafnir and Reykjanesvirkjun. The view to the south includes several low scarps of north-dipping normal faults cutting through early post-glacial (ca. 14 ka) Þráinsskjaldarhraun lavas. After Hafnir this becomes Route 425, and ~7.7 km south of Hafnir, look for the sign to turn for the parking lot for the "Bridge between Continents" (Brú Milli Heimsjálfa), Stop 1.

Explanatory text (modified from GSA 2019 Field Guide by Jordan et al., 2019):

The "Bridge between Continents" is a ~15 m footbridge over a well-defined ~5-m-deep narrow graben, "open fissure," or "dilatational crack". The fissure trends 050°, and widens to 25 m southwest of the bridge **(Fig. 1.6**). The fissure floor is covered by windblown sand from the sand beach and dunes at Stóra-Sandvík. About 60 m north of the bridge is a prominent south-facing normal fault scarp (**see Fig. 1.4**). The scarp trends 074° here, oblique to the fissure. The precise location of the divergent plate boundary in Reykjanes should not be confused with the Bridge Between Continents. Located near the airport, the tourist attraction consists of a small footbridge spans a narrow sand-filled graben. German for 'grave', it's actually a narrow downdropped block of subsiding crust between a normal fault (a tension fracture between two parallel faults).

Rather than bridging two continents in a literal sense, it's a well-intended misnomer, a surface manifestation of the two massive plates diverging apart in Iceland. In reality, there are many swarms or zones of these faults on Reykjanes and elsewhere in Iceland, depending on where you look. At the Bridge, they're on-strike with the SW-NE trend of the Reykjanes Volcanic Belt, so that any one is good as another for "bridging continents", at least as far as the public is concerned.

The educational point of this site is evident in its name; the idea is that we are at the boundary between the North American and Eurasian plates. The bridge is sometimes used in mass media to demonstrate the plate boundary. While it has educational value in this perspective, it is worth recognizing that the bridge does not literally cross from one plate to the other. We are indeed where the Mid-Atlantic Ridge comes on shore, but the axial rift is 5– 6 km wide here. The fault scarp at this site is the northernmost of several southeast-facing normal fault scarps on the northwest side of the rift zone. Looking southeast one can see several northwest- facing fault scarps that represent the other edge of the rift zone. Based on relationships we describe at that stop, we understand that features like this can form in a matter of hours and are likely to form over dikes propagating at depth. The oblique intersection of the fissure and the fault here has been interpreted to reflect differences in the orientation of the stress field during a magmatic event versus magmatic quiescence (Clifton and Klattenhorn, 2006).

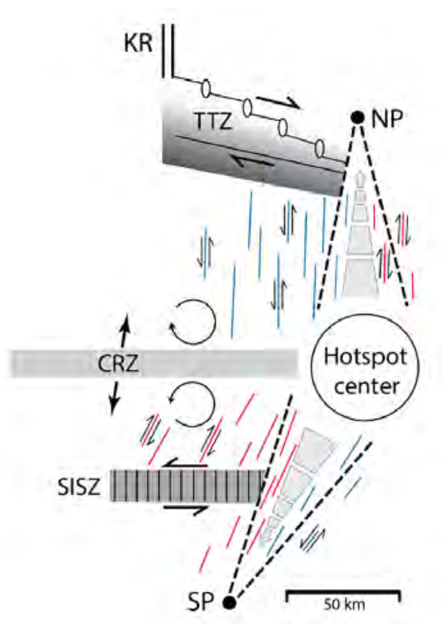

Fig. 1.5: Tectonic sketch of the Iceland Plate Boundary Zone (PBZ). Light gray blocky arrows show flow of middle crust and mantle away from the hotspot toward propagating rift tips to the north (NP) and south (SP). Pseudofaults* (dashed lines) truncate transform fault structures of the South Iceland Seismic Zone (SISZ) and Tjörnes Transform Zone (TTZ). Propagation causes rift-parallel strike-slip faulting (red-dextral; blue-sinistral) that

affects crust over a wide area defining a PBZ >50 km wide. Opposite sense of rotation of crustal blocks to the north and south cause extension across the Central Rift Zone (CRZ). *Diagram from (Karson, 2017).*

**Pseudofaults: Boundary zones between the wedge-shaped areas of crust produced along the propagating rift zone that separate crust formed at the rift from older crust.*

Fig. 1.6. *The northern end of the rift graben (~10 m wide here) at the Bridge between Continents site (Stop 1). Note the oblique intersection with the rift-bounding normal fault in the background. Taken from GSA Field Guide (2019).*

Stop 2: Reykjanesviti Area **63.81304, -22.71474**

Directions: From the ''Bridge between continents'' to Reykjanesviti, it takes 8 km through the Nesvegur/Route 425 to the north.

About the stop:
The Reykjanesviti Area is located at the southwest tip of the peninsula Reykjanes, and, confusingly, the smaller promontory at this location is also called Reykjanes. This stop includes walking to several locations from the parking lot **(Fig. 2.1)**.

Fig. 2.1. *Field sites A-D at Stop 2. Taken from GSA Field Guide.*

According to the GSA Field Guide (2019), the parking area is on younger Stampar lavas from the 1211–1240 Reykjanes Fires eruption event. Next to the east side of the coastal parking area are two hills separated by a small bay, the larger hill on the east called Valahnúkar. Examine the cliff and slopes of the lower west hill. They are composed of pillow lavas. These pillow lavas can be examined on the gentler slopes of the hill, and the sea cliff reached from the west side. Underlying the pillow lavas is palagonite tuff with interbedded breccia. 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 (Björnsson et al., 2020). The small bay between the hills is interpreted as a graben. The pillows, tuff, and breccia here, and in the lighthouse hill Bæjarfell, have been variably interpreted to have formed in a subglacial or submarine environment during the late Weichselian glaciation (GSA Field Guide, 2019). The subglacial interpretation may seem obvious as the Iceland ice cap extended past Reykjanes and global sea level was lower at this time, but the crust was also depressed by the presence of the ice cap, complicating the interpretation. The geological map of the southwest part of the Reykjanes Peninsula can be seen in the Fig. 2.1 covering subaerial and subglacial volcanism areas and coastal deposits over the peninsula.

If the trail to the top of Valahnúkar is not closed, proceed east and southeast on the trail that skirts the base of Valahnúkar. Stop at the wood overlook platform (63.8116°N, 22.7095°W). The younger Stampar lava, which is slabby pāhoehoe at the level of the platform, drops over a short step and becomes an ʻaʻā (*apalhraun* in Icelandic) flow below. This is a common relationship. Two things can cause the transition from pāhoehoe to ʻaʻā: increasing viscosity or increasing strain rate. When a lava flow goes over a steep slope the velocity increases and strain rate increases correspondingly, frequently inducing transition from pāhoehoe to ʻaʻā (GSA Field Guide, 2019).

Also prominent from this viewpoint is the northwest-facing Valbjargagjá fault scarp. This is one of two prominent scarps that mark the southeast side of the rift zone (the other being on the east side of Skálafell). Where these faults cut the older Skálafell lavas, displacements can exceed 15 m (GSA Field Guide, 2019). The Valbjargagjá scarp exposes several compound lavas from

Skálafell. Note that the scarp becomes less prominent to the north where younger Skálafell lavas flowed over it.
If we continue down the stairs and farther east and southeast around Valahnúkar, a prominent boulder beach (63.8104°N, 22.7109°W) connects Valahnúkar to the Valbjargagjá scarp. The sea cliff exposes palagonite intruded by irregular dikes. The ridge of the beach reaches a maximum elevation of 9.8 m, and a boulder field extends ~140 m landward into the younger Stampar lava and tidal lagoon. This is one of many boulder beaches and boulder ridges along the shore of Reykjanes, representing transportation and deposition during powerful storm events (centennial wave heights are estimated at 17–18 m). As mentioned in Etienne and Paris (2010), the cliff-top boulder deposits are highly persistent landforms in coastal landscapes. They constitute sedimentary archives capable of providing essential information on past wave climates and extreme nearshore wave events.
To reach the last site at this stop, ascend the slopes east of the cliff above Kerlingarbás and proceed northwest along a rough road. Leave the road where it turns northward and descend past a small spatter cone. Go around to the northwest side of Kerlingarbás (63.8182°N, 22.7327°W). The pāhoehoe lava seen here underlies scattered remnants of younger Stampar tuff cone deposits, and thus represents an earlier event. These are called the older Stampar (eldri Stampar) lavas because they are also associated with cones in the Stampar cone row, and are estimated to be ~1900 years old. One of the older Stampar cones is the small spatter cone passed on the way to this site. The sea cliff due east exposes a dissected older Stampar cone. The core of the cone includes a lens of lava that ponded in its crater. The eastern flank of the dissected cone is mantled with the two distinct tuff cone deposits, which are in turn overlain by the younger Stampar lava (GSA Field Guide, 2019).

Stop 2a*: Gunnuhver Hot Springs 63.81841, -22.68709

Directions: From the Reykjanesviti area to the Gunnuhver geothermal area it takes 6.3 km of travel by car through the Nesvegur/Route 425.

About the stop:
Gunnuhver is Iceland's largest geothermal mud pool related to a highly active volcano, which continues to the southwest in the Atlantic over the so-called Reykjanes Ridge- Southeast of the island of Eldey, which is situated on this ridge, there was an eruption in 1926. Since 2006, the activity has been limited to small explosions, where clay scrapes are thrown up to 5 m high by rising lava lacquers. Therefore, parts of the area had to be blocked in 2008. Only since 2010 the area is conditionally accessible again. It is, therefore, important to always keep the required distance and under no 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.
The springs' edges are wrapped by lava-rock outcroppings and the large volcano-shaped crater is jutted upwards from an expanse of cracked and fissured red clay (Verney, 2010). According to Newman (2017), Gunnuhver measures 65 feet across and is constantly spewing dense, cloudy steam at a scalding 570˚F. It is unique from Iceland's other hot springs in that it is entirely seawater, due to its proximity to the ocean. The surrounding rocks are impressive as well, colored dazzling oranges and blues from unusual minerals. As mentioned in the Pittsburg Guidebook (2020), mud pools and steam vents are formed where steam generated in a geothermal reservoir emanates, condenses, and mixes with surface water. The accompanied gasses, such as carbon dioxide and hydrogen sulfide, make the water acidic and alter the fresh lavas to clay. Steam released at the surface has increased markedly since 2006 as a consequence of groundwater

exploitation by a nearby geothermal power plant . Evaporites and sulfuric minerals can be seen throughout this hydrothermal area. At depth, metal ores are concentrated, especially copper sulfates.

Fraedrich & Heidari (2019) mention that there is some mythology related to Gunnuhver. Its name is connected to the legend by the Gunna (by Guðrún Önun dardóttir), who, 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. However, Newman (2017) says that Gunna was largely disliked in the community on the Reykjanes peninsula sometime in the 18th century. It was said that she was a witch because there was always something brewing in her pot. Shortly before her death, a judge paid Gunn a visit and ended up in a dispute with her. That same judge attended Gunn's funeral and was discovered dead the next morning, his body bruised and mutilated. The old woman's ghost was to blame, and she didn't stop there. Her spirit terrorized the peninsula, wreaking mayhem. It wasn't until the locals plied a priest with liquor that they found a solution to trap Gudrun. Per the priest's advice, they left a loose end from a ball of twine for the ghost to grab hold of. She did, and the ball rolled into the hot spring, taking the witch's ghost with it and trapping her there forever. The hot spring takes its name from the old woman (Gunnuhver translates to "Gunn's hot spring"). Some say that Gudrun's ghost didn't fall into the boiling pot, but that she's hanging on to the edge for all eternity. The steam is constant and thick enough that it would certainly obscure any ghostly figures in or outside Gunnuhver.

Fig. 2.3. *Geothermal hotspot (left) and mud spot (right) at Grunnuhverand. Taken from Verney (2010).*

Stop 3: Steinahellir Cave 63.54542, -19.72685

<u>Directions:</u> From the Reykjanesviti Area, take Nesvegur/Route 425 to Grindavíkurvegur/Víkurbraut in Grindavík. After 18.6 km, take Route 427, Eyrarbakkavegur/Route 34 and Route 1 to Þjóðvegur in Rangárþing eystra. Steinahellir Cave will be 169 km further.

<u>About the stop:</u>

Steinahellir is a cave 36 km from Hvolsvöllur under Eyjafjall just off the National Road #1 by the Bay of Holtsós. It is about 6 m wide, 4 m high and 15 m deep, and grows higher and wider towards the back. It is located at the foot of the slope above Holtsos. The cave mouth faces south. It is surrounded by grassy slopes that stretch up to the rocky palisades of Mt. Steinafjall. Rock slides occasionally occur from the mountain above.

It is thought to be a natural cave that was later enlarged by man to make it more habitable. An outstanding feature of the cave are the ferns that grow on the ceiling. In the period 1818-1905 the cave was the regional assembly site for the Eyjafjöll district; at that time it was enclosed by a wooden wall. In 1888 a catastrophic flood damaged the farm buildings at Steinar, and the inhabitants took refuge in the cave. The cave has also served as a sheep shed, a hay barn, and finally a machine shed. In the late 20th century it was cleared and made accessible to visitors (Cultural Heritage Agency of Iceland, 2019).

The cave is believed to be a naturally occurring feature in the palagonite cliff, but was manually deepened and broadened over time (**Fig. 2.4**). Palagonite is the first stable product of volcanic glass alteration and has a heterogeneous chemical composition, generally reflecting the prevailing element mobility of the water-rock system during alteration (Stroncik & Schmincke, 2002). However, according to Warner & Farmer (2010), palagonite has been defined in various ways in the literature, and the compositional and textural meaning of the term is poorly constrained. Mineralogically and texturally, palagonite has been defined differently as (1) an amorphous hydrated gel, (2) composed of poorly crystalline clays (smectites, illite, kaolinite), in close association with amorphous hydrated phases, (3) a yellow-orange hydrated material formed by hydration and devitrification of basaltic glass, and (4) a chemically heterogeneous hydrated mineral assemblage derived by the hydrothermal or weathering alteration of basaltic glass or lavas.

Additionally, there are many stories of supernatural happenings and enchantments connected with Steinahellir cave. In front of the cave is Hellisvatn (Cave Lake), which is said to be inhabited by a kelpie, a malevolent supernatural creature resembling a horse. Ghosts and spirits have been seen in and around the cave for centuries; the most famous is the tale of the 14 sailors who died when their ship stranded at Fjallasandur beach. The following winter the ship was moved over the ice, from Fjallasandur, via Holtsós estuary to Steinahellir. One day Þorgils from Rauðnefsstaðir farm was riding by and exchanged some words with a man he met by the cave. He then looked up and saw 13 'horrible men' standing on the ship. Þorgils realized that this was the dead crew from the wrecked ship and rode away in haste.

One tale warns not to pick the enchanted ferns which grow in the cave as bad luck will befall anyone who does. A farmer from Steinar once picked a fern from the cave and soon afterwards one of his cows, which was grazing in the area, fell down from the top of the cave-mouth and died. Another tale tells of a traveler who picked a fern without knowing about the enchantment, and a few years later he lost his health. Until his death he blamed his misfortune on the accidental picking of the fern in Steinahellir.


Fig. 2.4. *Steinahellir Cave.*

If the weather if bad, we have two alternate stops:

(Alternate) Stop 1: Skógafoss 63.5295, -19.51316

Directions: From the hostel Vik, we follow Route 1 for 34 km until we arrive at Skógafoss. From the parking lot, a walk of 200 m is needed to get to the waterfall.

About the stop:
Skógafoss is a waterfall on the Skóga River at the cliff marking the former coastline in the early post-ice age. It is one of the biggest waterfalls in the country standing 60 m tall and 15 m wide. After the coastline has receded (today, about 5 km away), the former sea cliffs remaine, parallel to the coast for hundreds of kilometers, creating a clear border between the coastal lowlands and the highlands of Iceland (UNH Iceland Field Guide, 2019). According to Share (2019), this cascade is visible from Route 1 and the river below Skógafoss holds a large char and salmon population. Due to the amount of spray the cascade produces, at least one rainbow is present any time the sun emerges from behind the clouds.
On the east side of the waterfall there is a hiking trail that leads up to the Fimmvörðuháls pass, a region between the Eyjafjallajökull and Mýrdalsjökull glaciers (**Fig. 2.5**). A 527-step staircase leads up the slope to the top of the waterfall.
The waterfall was the set of music videos, including Sólstafir (1900s metal band) and was filmed in Marvel's Thor: The Dark World and The Secret Life of Walter Mitty (Gudmansson, 2017).

Fig. 2.5. *Eastern slope of Skógafoss showing the walking path to the viewing area (left) and the view from the top of Skógafoss (right). This viewing area is open to the public year round to summer or winter hikers.*

Its meltwaters are derived from the combined watershed that drains both ice caps Eyjafjallajökull and Mýrdalsjökull. On the other hand, the rock that constitutes the cliff is mainly of hyaloclastite, similar to that found along the cliffs of Eyjafjallajökull and at Seljalandsfoss (Share, 2019). Also, there is a typical layer cake volcanic stratigraphy of the Upper Pleistocene cliff face that alternates between hyaloclastites and lava flows. There are also intrusions of dikes and sills that fed the fury. On close inspection, the walls of the sea cliff are constructed of layered flows of lava, tephra and hyaloclastite breccia that formed when lava contacted ice during the Pleistocene or even marine water and then instantly cooled and shattered. Additionally, this part of Iceland receives much precipitation and is extremely verdant with mosses and vascular plants.

(Option b) Stop 2: Skógar Museum **63.5259, -19.4932**

Directions: From the Skógafoss Waterfall parking, a ride of 1.7 km is needed.

About the stop:
Skógar Museum is a cultural heritage collection founded in 1949 and nowadays hosts more than 18,000 regional folk craft artifacts exhibited in 3 museums and 6 historical buildings. Originally housed in Skógar Regional School, the museum was founded on the initiative of Þórður Tómasson, who curated the museum from its inception until his retirement in 2013, at the age of 92.
It is divided into three parts: (1) the Folk Museum offers a huge variety of artifacts displayed on three floors: fishing, agriculture, textile, and natural history, as well as artifacts dating back to the Viking Age; (2) the Open Air Museum is where visitors can catch the atmosphere of times long gone and experience how Icelanders lived through the centuries in farms made from turf and stone; and (3) the Technical Museum tells the story of technology and transportation and its development in Iceland in the 19th and 20th century. It also houses a souvenir shop and the Skógakaffi cafeteria.

According to an Icelandic legend, the first Viking settler in the area, Þrasi Þórólfsson, buried a treasure in a cave behind the Skógafoss 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 the Skógar museum.

Ticket prices 2023: the entrance fee includes access to all the Museum area and a brochure with detailed information about the Museum.

Adults: 2500 ISK

For group reservations and guided tours, please email booking@skogasafn.is or call +354 487 8845

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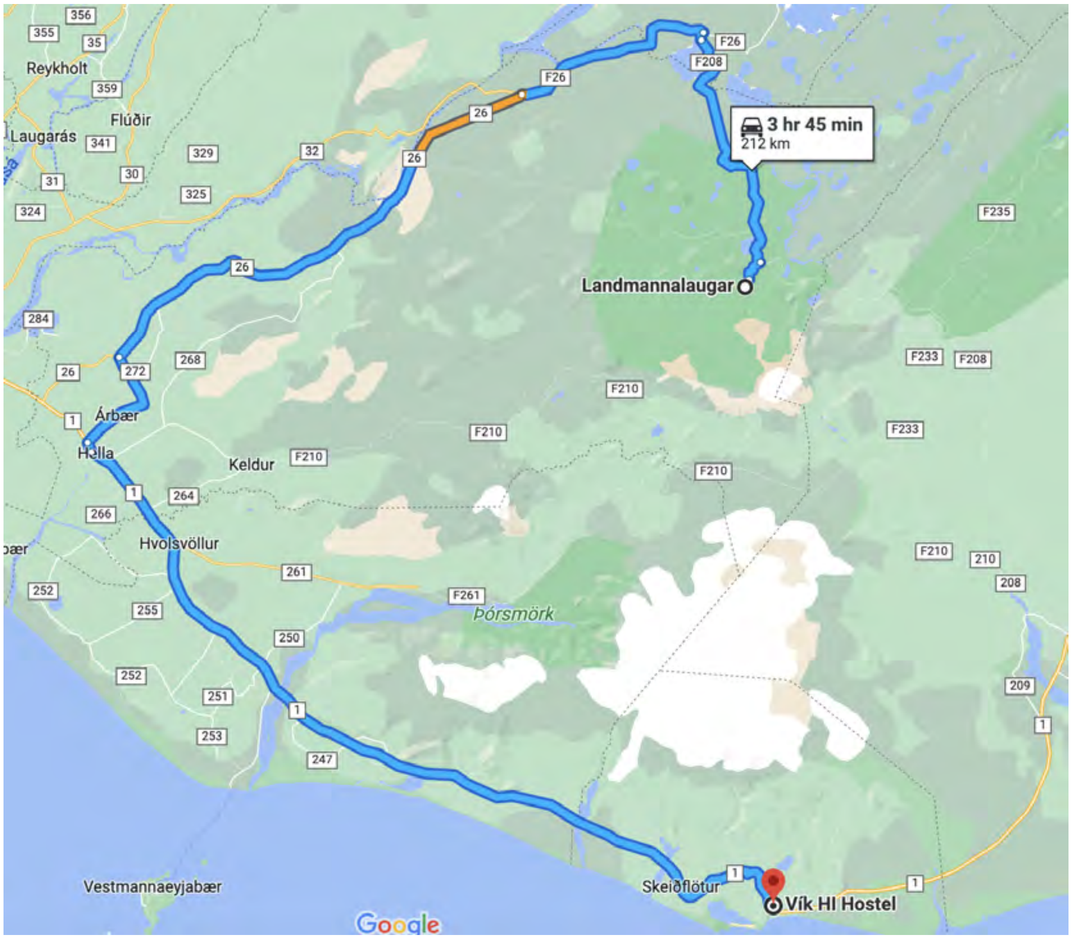
May 31: Landmannalaugar
(Pablo, Emily, Sally)

Summary

Stop	Location	Stop duration	Topic
Highland Center gas station	64.19696, -19.28504	(If needed along F-208 road)	n/a
Landmannalaugar campsite parking	63.99192, -19.05873	~4 hours of hiking	Rhyolite lava flow, hydrothermal alteration, sulphuric vents, central vent volcanoes
Laugahraun rhyolite	63.9908, -19.06096		
Sulphuric vents and geothermal features	63.9847, -19.0891		
View to Bláhnúkur volcano	63.98073, -19.09554		
People's Pool	63.991241, -19.063207	1-2 hours	Hydrothermal

Proposed day schedule:
Start: Vik HI hostel, breakfast. Leave at 8 AM.
3hr 30min drive to Landmannalaugar campsite parking. Arrive ~11:30/12 PM
Stop 1: Laugahraun rhyolite (outbound on Laugahraun Trail) (3-4 hours for Stops 1, 2, 3)
Stop 2: Sulphuric vents + geothermal features
Stop 3: Bláhnúkur volcano, return via the Brennisteinsalda Trail
Stop 4: People's Pool (1-2 hours)
End (5:00 pm): 3hr 30 min drive back to Vik HI hostel,
(*NOTE: long day! dinner en route/in town, or late dinner/leftovers?)

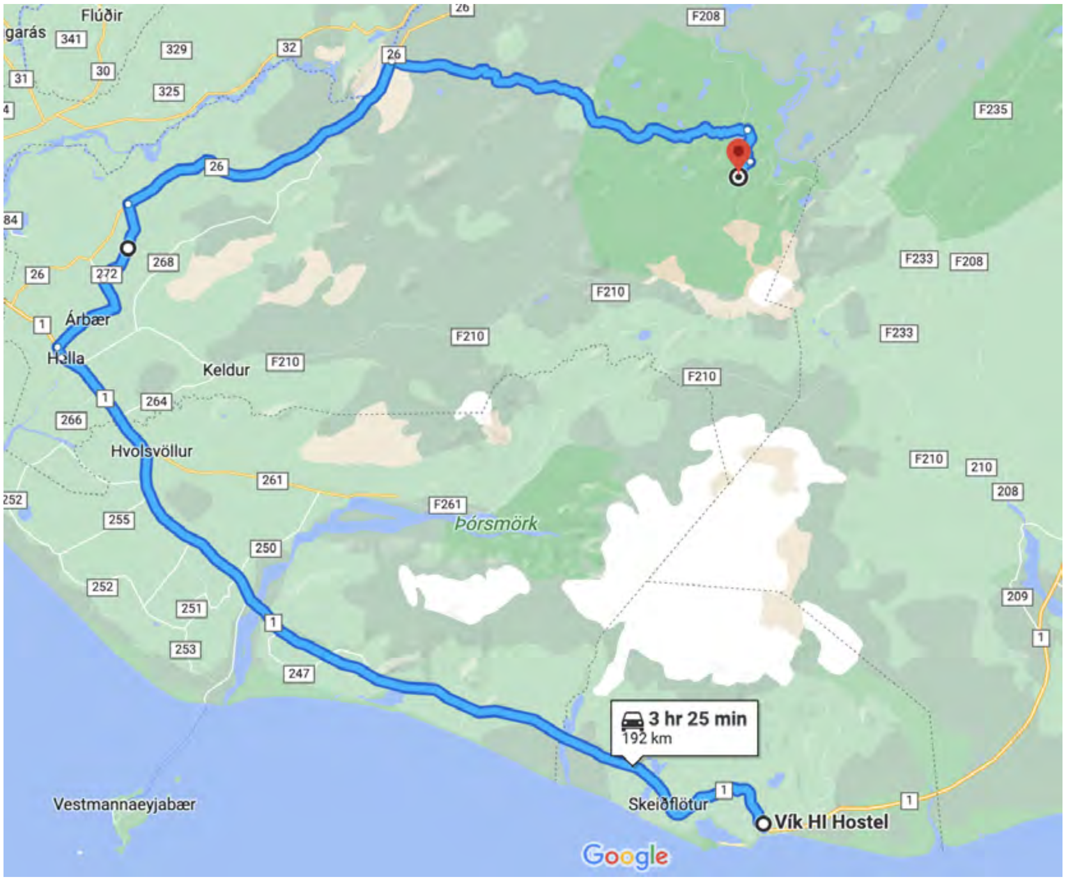
Driving information:
Info for current road conditions (good to check before traveling on F-roads):
https://www.road.is/travel-info/condition-and-opening-of-mountain-roads/



Drive to Landmannalaugar– easiest route from north

General driving directions:

From Vik HI Hostel: take F-26 and F-208 roads in the north.



Drive to Landmannalaugar– second easiest route from the west
If the F225 road is open (see link above): can take F225 to F-26 to the west on the way back.

(Do not take F208 from the south, there are multiple wide river crossings!)

Collection of all driving routes: https://www.google.com/maps/d/u/0/viewer?mid=1mjDcyjlfET_xNBywelesbzBjom6fkHg&ll=64.00690529901642%2C-19.00414579892553&z=10

Stop Information

There are multiple trails to do in Landmannalaugar. This guide includes the **Laugahraun lava field hike** (2.7 mi, 1.5-2hr, easy) and **Mt Brennisteinsalda "Sulphur Wave"** (4 mi, 2-3 hr, medium). *Other hikes: Mt Bláhnúkur ("Blue Peak"): 3.8 mi (2.5-3.5 hr), intermediate; Stutur (park along F208): 30 min, easy.*

Map from: *https://www.earthtrekkers.com/landmannalaugar-best-hikes-for-first-time-visitors/*

Stop 1: Laugahraun rhyolite (Trail starts at 63.9908, -19.06096)

The trail begins around 150 m to the west of the parking lot. We will follow signs for Laugavegur and Hrafntinnusker. After around 10 minutes of hiking, we will cross a lava flow corresponding to an eruption from the Torfajökull Volcanic Complex occurring in 1477 AD (**Fig. 1.1** Laugahraun rhyolite, in the photo). The trail crosses the lava transversely for around 1.3 km. Any of this area looks great to stop and take a look at the flow. Bring your hand lenses!

This flow consists of rhyolite with obsidian blocks. Notably, this lava flow has been used to determine the paleo-ice thickness in one of the edifices of this volcanic complex by measuring the amount of water in the rocks at different elevations (Bláhnúkur; Owen et al., 2012 Bull. Volc.). In a simple subglacial eruptive environment (i.e. assuming that cavity pressure at the eruption site is equal to glaciostatic pressure and that the loading medium is a thick ice sheet of uniform density), the pressure that the ice exerts on material erupting and quenching at the base of the ice sheet will be dependent only on the thickness of the overlying ice (Tuffen et al. 2010). Thus, the dissolved H_2O and CO_2 content of the eruptives, with the application of a suitable solubility model, yields a paleo-ice thickness (**Fig. 1.2**, Owen et al., 2012).

***Figure 1.1**. Laugahraun rhyolite*

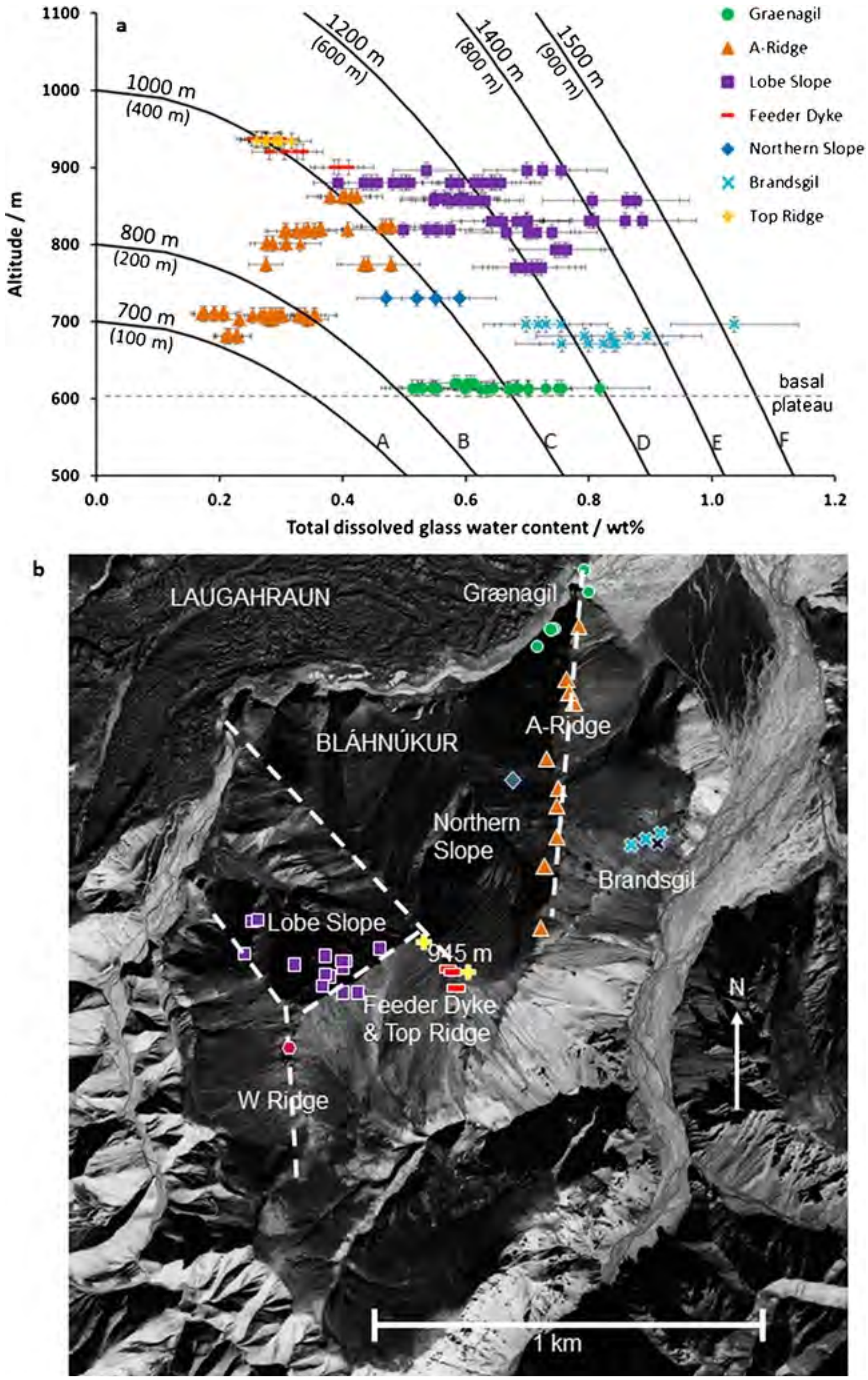


***Figure 1.2**. **a)** Water content plotted as a function of elevation. Y error bars indicate ±10 m, x error bars represent ±10 % **b)** Aerial photograph of Bláhnúkur with sample location. Dashed lines indicate the four eruptive fissures proposed by Tuffen et al. (2001) and summit elevation is indicated. From Owen et al. (2012).*

The geological structure of Torfajökull is shown schematically in **Figure 1.3**. The volcano began as a flank zone volcano constructed within a ~5 million year old crustal block under a stress field with horizontal max compression (NE-SW). A Tertiary central volcano lay buried in the basement crust with acid rocks and a root of intrusive rocks. Heat from the mantle plume caused magma generation. The magma rose to the level of neutral buoyancy the lower (intrusive) and upper (extrusive) crustal boundary causing re-melting of old hydrated crustal material. This occurred during development of the volcano. A profound revolution of eruptive activity occurred in the early Weichselian (beginning 120 ka) when the spreading zone propagated SW across the volcano. The first response was a voluminous eruption of at least 25 km³ of rhyolite on a ring fracture. Partial emptying of the magma chamber was followed by NE-SW fissure eruptions of first transitional basalt from deeper levels of the magma chamber and later mixed volcanics composed of high level lateral intrusions of tholeiite into residual rhyolite magma (small volume compared to past eruptions) underneath the center of the caldera.

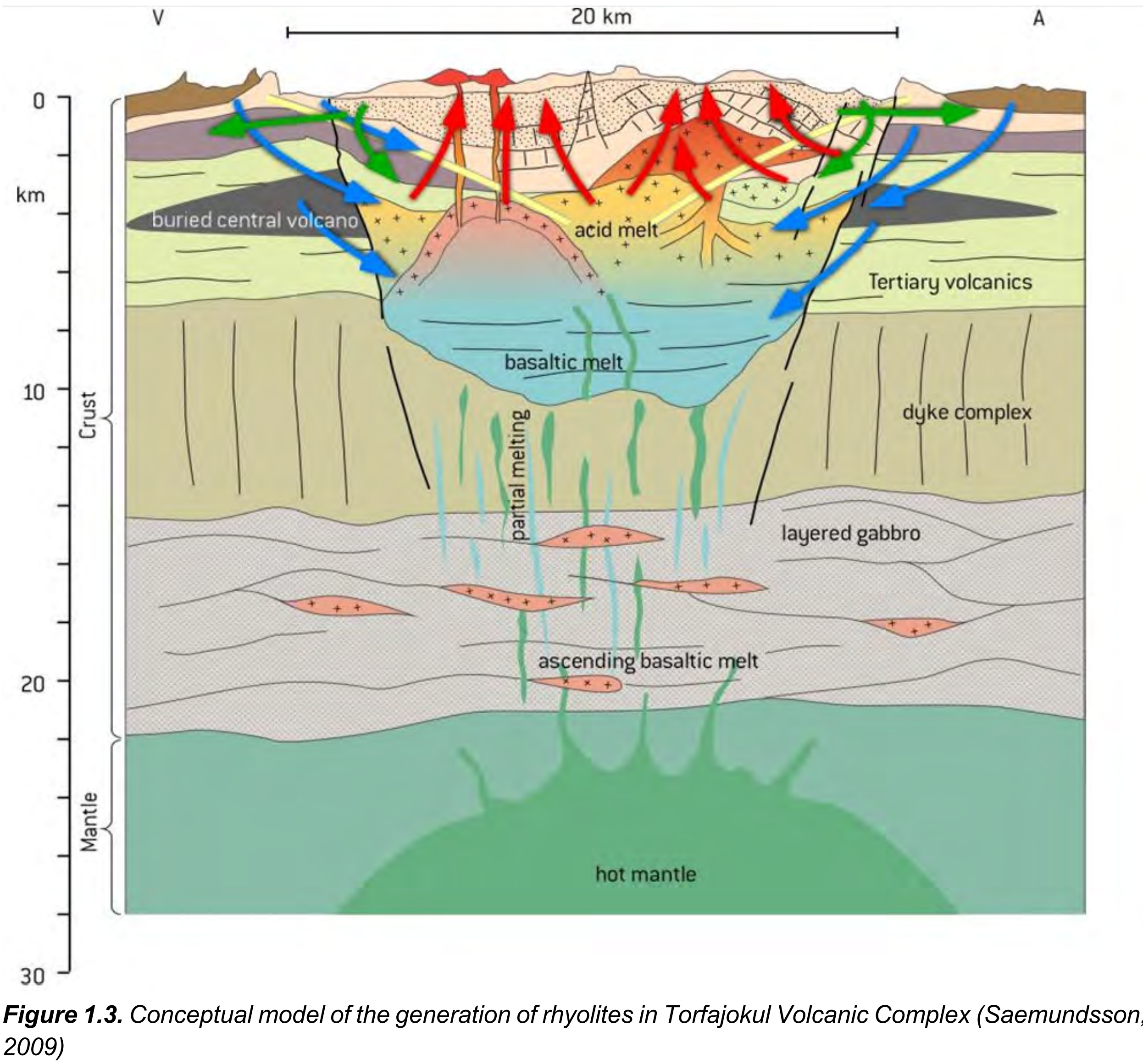


Figure 1.3. *Conceptual model of the generation of rhyolites in Torfajokul Volcanic Complex (Saemundsson, 2009)*

Stop 2: Sulphuric vents and geothermal features (63.9847, -19.0891)

After crossing the lava flow, we will see sulfuric vents and colorful geothermal features. From the top of the climb we can see the lava flow we just passed. These geothermal vents comprise part of the Torfajökull Volcanic Complex. The pink, yellow and red colors of the rocks represent different degrees of hydrothermal alteration and the response of different lithologies (**Fig. 2.1**).

***Figure 2.1**. Sulphuric vents and hydrothermal alteration. Laugahraun rhyolite in the background. From: https://www.earthtrekkers.com/hike-brennisteinsalda-sulphur-wave-landmannalaugar/.*

From the Armannsson 2016 review of "The fluid geochemistry of Icelandic high temperature geothermal areas": The Torfajökull high temperature geothermal area is the largest in Iceland, located within a central volcanic complex. This complex encompasses an 18 × 12 km resurgent caldera with an abundance of rhyolitic rocks (Sæmundsson and Fridleifsson, 2001). Surface thermal manifestations, which include extensive alteration, warm and boiling springs, mudpots, and a large number of fumaroles, cover an area of about 140 km^2. The fumaroles and mudpots appear to be confined to the caldera proper, mostly at altitudes between 850 and 1000 m a.s.l., and virtually all the boiling springs are found there as well.

Stop 3: View to Bláhnúkur volcano (63.98073, -19.09554)

After a good climb, we get to another sign from which we need to turn right to continue to Brennisteinsalda. In this spot we can see Bláhnúkur volcano (**Fig 3.1**), which was the source of the lava flow we crossed (eruption date: 1447 AD). It has been proposed that this edifice erupted under ice and that the lava was constrained in the early eruptive stages by subglacial tunnels (**Fig. 3.2**). On the way back to Landmannalaugar we can observe rhyolite outcrops with different levels of hydrothermal alteration and weathering.

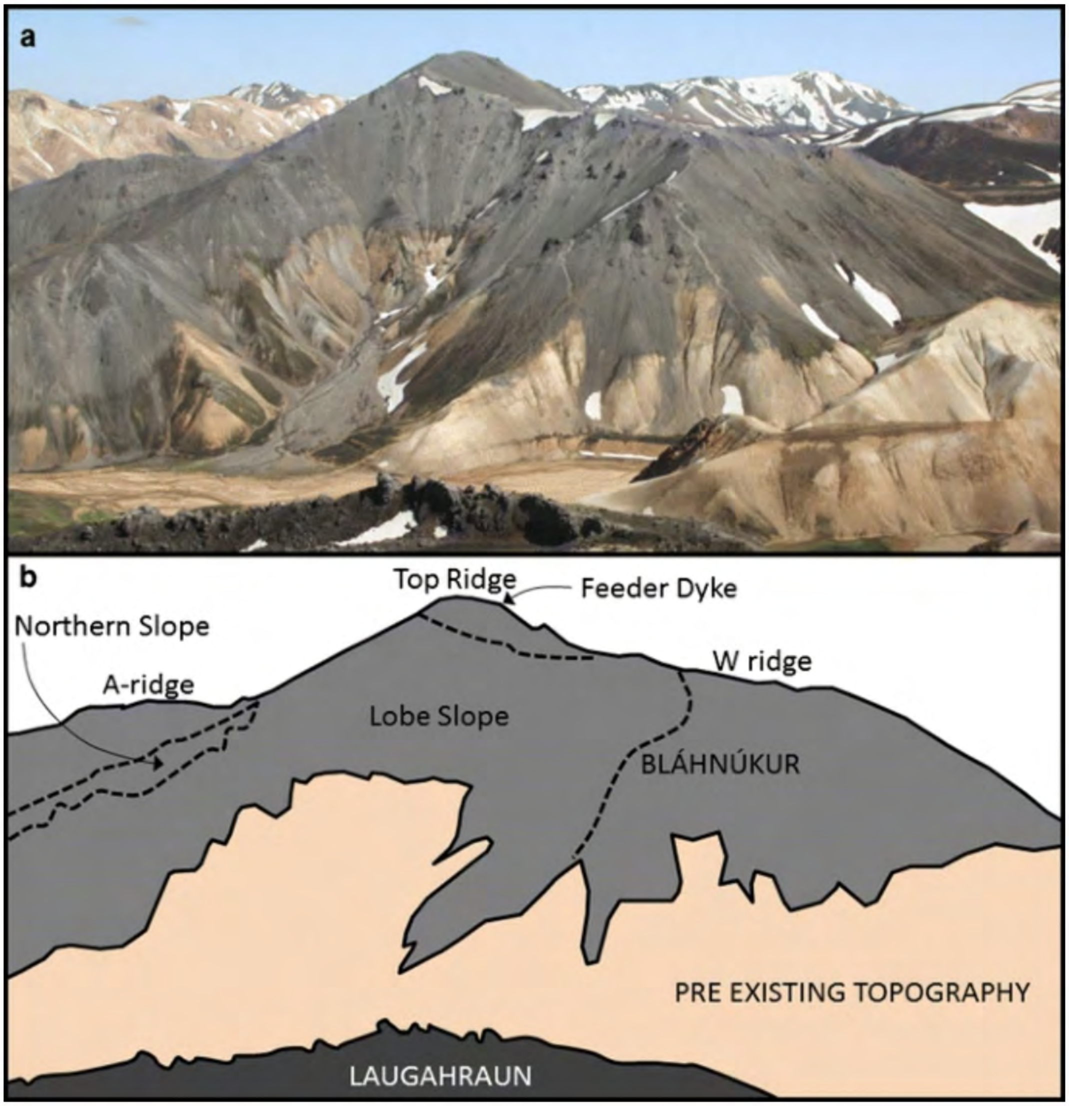


Figure 3.1: From Owen et al. (2012): A. *Bláhnúkur photographed eastward from Brennisteinsalda towards the 'Lobe Slope' where lava lobes protrude from hyaloclastite. Orange material at the edifice base is older rhyolite overlain by gray Bláhnúkur subglacial rhyolite.* ***B.*** *Schematic representation with different colors depicting Bláhnúkur, the pre-existing topography and the 1477 AD lava flow Laugahraun. Dashed lines mark the prominent ridges of Bláhnúkur.*

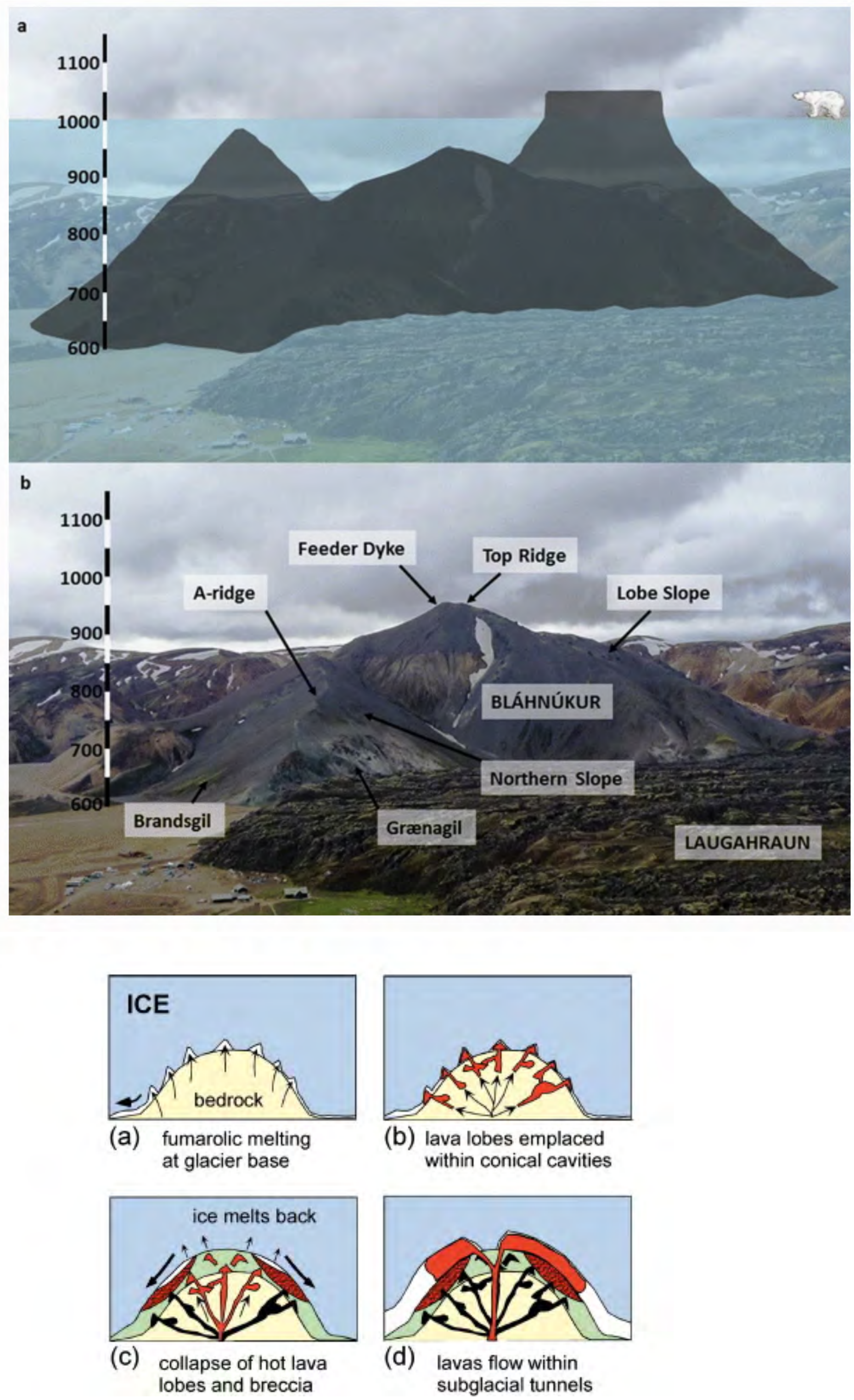


Figure 3.2. *Bláhnúkur.* ***Top:*** *Hypothetical profile of what Bláhnúkur would have looked like immediately after formation with an ice surface of 1,000 m and with the additional thicknesses of hyaloclastite (Owen et al., 2012).* ***Bottom:*** *Model for edifice construction from Tuffen et al. (2001). Note that to explain the widespread distribution of lava lobes, an anastomosing plexus of subsurface conduits has been proposed (McGarvie, 2009).*

Stop 4: People's Pool (63.991241, -19.063207)

Hot spring next to Laugahraun lava field. Temps: 36 C/97 F to 40 C/104 F year round.

From Armannsson 2016 review of "The fluid geochemistry of Icelandic high temperature geothermal areas": The thermal spring water is mostly of the bicarbonate type in the southern part of the Torfajökull field and primarily of the sodium chloride type in the northern part (**Fig. 4.1**). Thus the most mature water closest to the upflow is found in the northern part but outflow water in the southern part. The chalcedony temperatures for springs are rather evenly distributed in the range of 85–182 °C. Their surface temperatures range from 24 to 100 °C. The quartz geothermometer temperature (Fournier and Potter, 1982) for Landmannalaugar is 200 °C which is probably more appropriate as an indication of subsurface temperature. Arnórsson (1985) used mixing models and obtained a temperature of 265 °C for Landmannalaugar. Bjarnason and Ólafsson (2000) came to the conclusion that temperatures up to 350 °C could be expected in the geothermal system. Most of the hot spring waters seem to be close to fluorite saturation. *Although unusual for Iceland, where most rocks are basaltic, this is to be expected in the Torfajökull area, where rhyolite dominates the geology.*

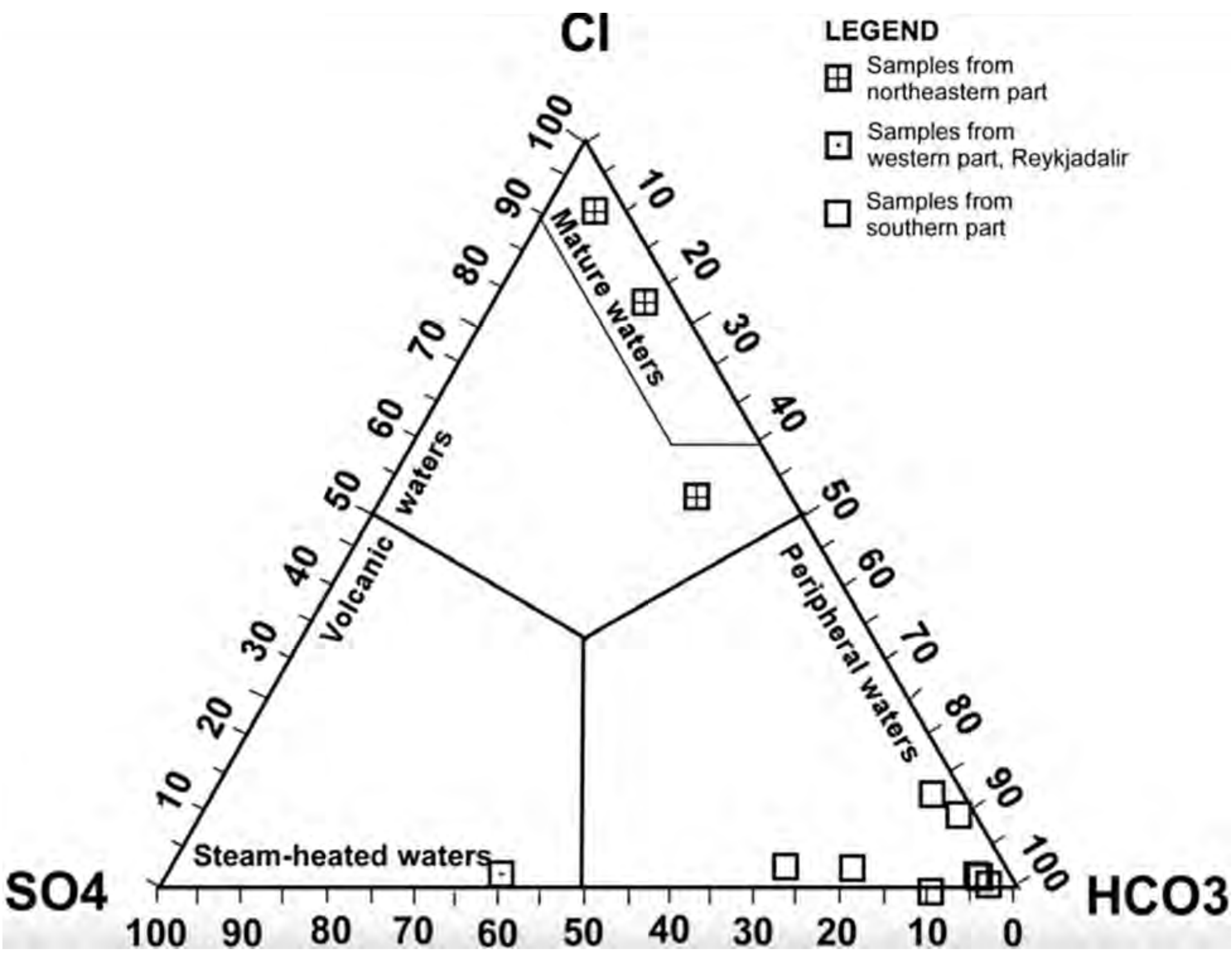


Figure 4.1: *Selected samples from Torfajökull (Armannsson, 2016, modified after Fang and Liping, 2000)*

Figure 4.2: *People's Pool.* *https://www.earthtrekkers.com/landmannalaugar-best-hikes-for-first-time-visitors/*

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June 1st

Stop 1: Reynisfjara Beach

Park here: 63.40438, -19.04519

(Gudmundsson, 2017)

“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,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 therock 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 intrusionsare 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 threeare 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."

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

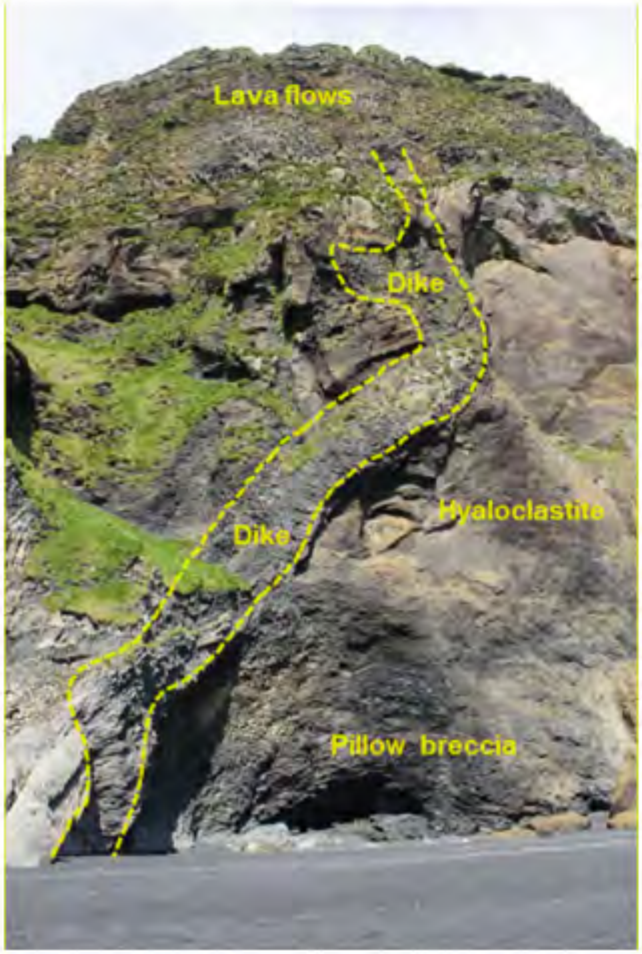


Fig. 14.34 View north of the basaltic feeder-dike to the lava flows on the top of Reynisfjall. The lower part of the dike is steeply inclined, mostly 1–2 m thick, but its uppermost part is much thinner and close to vertical

Stop 2: Dyrhólaey Viewpoint

Park here: 63.40421, -19.12894

(Jovanelly, 2020)

At present, Dryhólaey (63.3996, −19.1269) is a 1.3 km2 tombolo connected to the mainland by two large offshore bars formed from sediment deposited offshore and the surrounding coastline (Photo 28). However, Dryhólaey originated from a violent hydromagmatic eruption during the Surtseyan Episode 1963–1967 (see section 9.7) producing a hyaloclastic tuff cone separate from the mainland [White and Houghton, 2000]. In the later stages of the eruption, the explosions transformed into an effusive pahoehoe event, thus capping the tuff below it while also intersecting the shoreline to create a lava delta [Schmidt and Schmincke, 2000; Thordarson and Höskuldsson, 2007]. It is in the lava delta area that a sea cave later formed by erosion mainly of hyaloclastic deposits. Gadányi [2008] mapped the sea cave to establish that its entranceis 16.4 m wide, 2 m high, and 21.3 m in length. Reynisfjara Beach (63.4053, −19.0764) nearby is known worldwide for its black basalt beaches and its Plio-Pleistocene columnar basalts formed during inter-glacial stages when sea level rose.

(Gudmundsson, 2017)

Dyrholaey is currently the southernmost point of Iceland (for a long time following the 1918 Katla eruption, Kötlutangi, the point of land south of Hjörleif- shöfdi (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.

Stop 3: Mt. Pétursey

Mountain: 63.46751, -19.27189

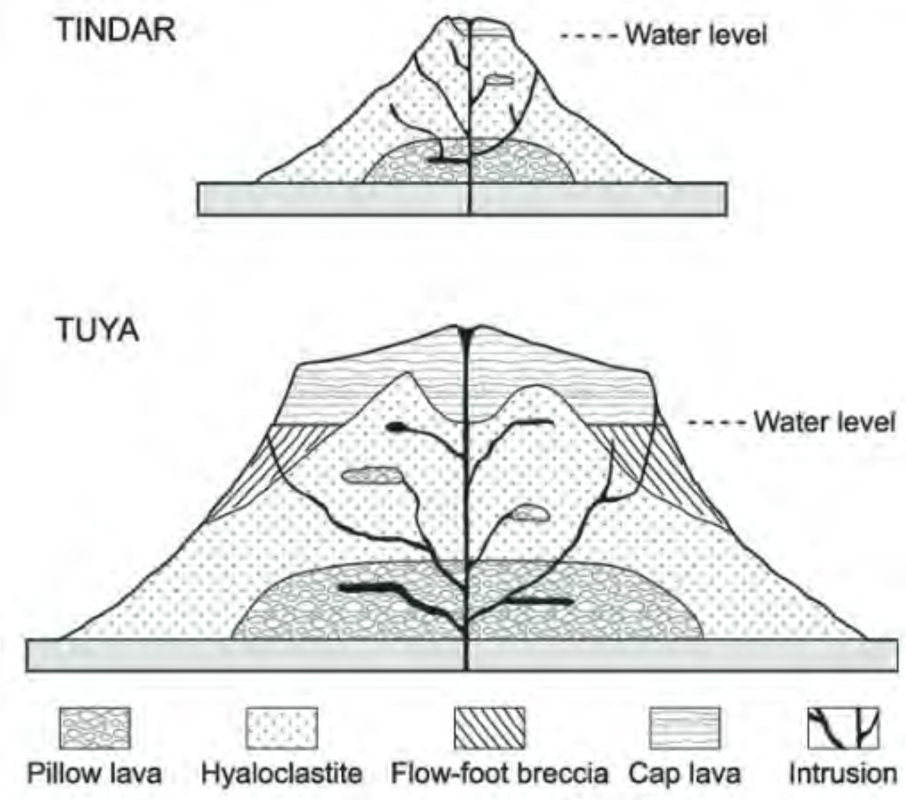
Park here to hike?: 63.467301, -19.287712

- Pétursey Trail

Pull off for viewing from a distance: somewhere along 219

Jakobssen and Gudmossen (2008)

“Interaction o fwater and magma has a major effect on the style of volcanic activity and the morphology of volcanic landforms. At high water pressures effusive activity dominates leading to pillow lava formation, while at lower pressures magma fragmentation and explosive activity are most common(e.g.Wohletz, 1986; Stroncik and Schmincke, 2002; White et al., 2000; Chapman et al.,2000). Eruptions under ice share the same characteristics in terms of style of volcanic activity while ice confinement and changes in water level due to drainage meltwater are among features that distinguish subglacial volcanism from submarine and subaqueous eruptions(e.g.Moore And Calk,1991;Smellie, 2000, 2006; Gudmundssonet al.,2004).”



(Gudmundsson, 2017)

“Strictly, it is a typical small hyaloclastite mountain, most likely formed in an eruption in the sea, a submarine eruption, sometime in the past one or two hundred thousand years. The mountain is not very tall, reaches a maximum height of about 274 m above sea level. The name Petursey means Peter’s Island. The southernmost cliffs of Petursey are now about 3 km from the coast. Like most landform names in Iceland, the name of Petursey is about 1100 years old. It was given to the mountain during the settlement (primarily by Skandinavian, British, and Irish people) some 1100 years ago. Thus 1100 years ago Petursey may have been an island (although this is not certain), whereas today it is 3–4 km inland (the island is just over 1 km in diameter). Petursey therefore could be one indication that the south coast of Iceland at this location has migrated to the south—has extended into the sea—at a rate of about 3 m per year during the past 1100 years.”

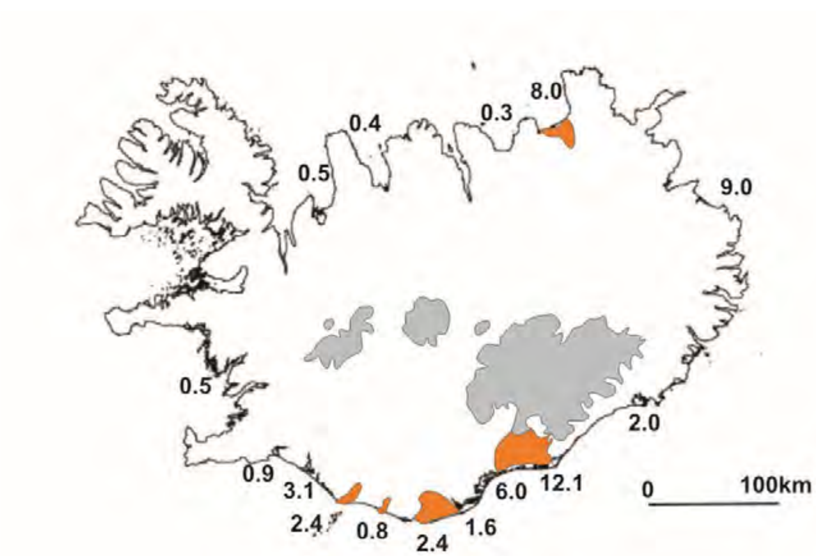
A few years ago the men, who remember an occurrence in Pétursey in Mýrdalur, passed away. There is a big rock in Pétursey, which people believe to be an elf-rock. Thus the farmers prohibited their children to go close to this rock, but one boy, the son of the farmer, didn't obey and used to play close to the rock.

One day the boy disappeared and people went searching for him, especially close to this rock.

Next winter the people were sitting in the cowshed and the farmer thought he saw his son enter the cowshed on two occasions that winter dressed in ragged clothes - and then the boy disappeared again. Next spring they found the skeleton of the boy by the rock.
(Translated into English from Þjóðsögur Jóns Árnasonar - the Collection of Folklore of Jón Árnason).

Stop 4: Nabkah Dunes along the Skogasandur or Sólheimasandur

*****Extra: Solheimasandur Plane Wreck (park here: 63.49091, -19.36342) → we need to go here to get on the sandur to see the dunes)*****



http://www.coastalwiki.org/wiki/Sand_dune_-_Country_Report,_Iceland

As of 2022, this parking lot charges a fee which is 750 ISK for a normal sized car for a day. The walk to the plane is across two miles of flat and fairly featureless desert, and will take you 40 minutes to 1 hour each way, depending on how fast you go and the conditions at the time you visit.

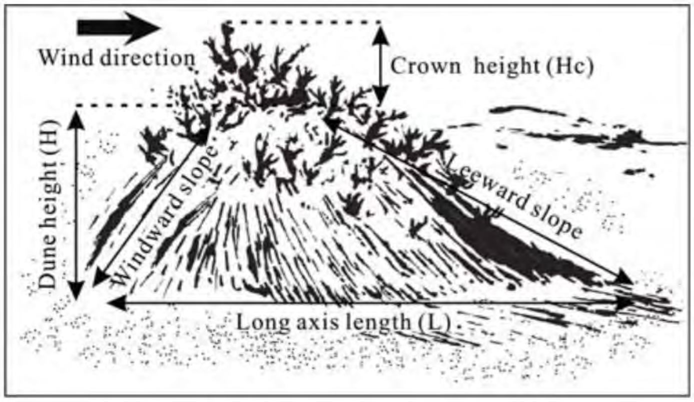


Figure 1 Morphologic characteristics of a nebkha and related parameters described in most studies

Mountey and Russell, 2006

Nebkha dunes are aeolian sand accumulations that are fixed in position (anchored) by the presence of vegetation and are common features in many aeolian settings, including in humid coastal areas. The presence of vegetation acts as an obstacle which disrupts the airflow, causing deceleration and thereby promoting localised aeolian sand accumulation. Even in settings characterised by airflows that are undersaturated with respect to their potential sand carrying capacity, nebkha dunes may still actively grow, as long as the surface of the dune remains colonised by vegetation. Thus, most nebkhas are stabilized by fast growing grasses that can keep pace with rapid rates of sand accumulation.

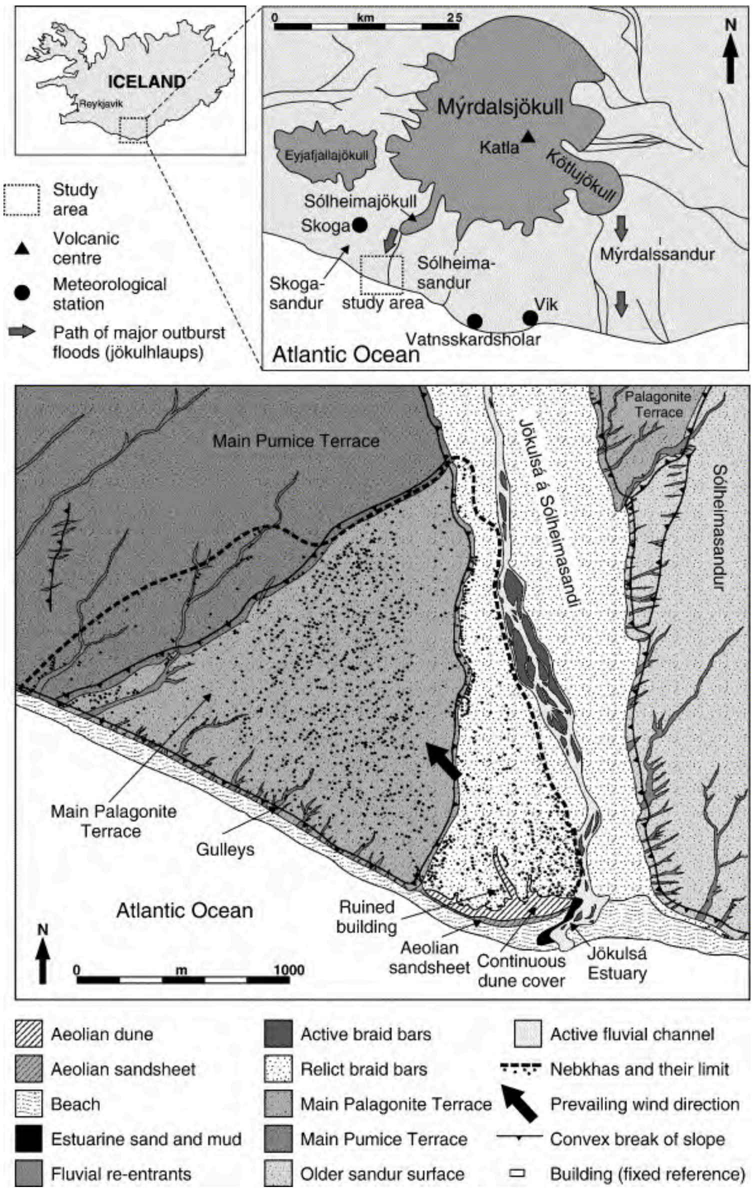


Fig. 1. Location of the Sólheimasandur and the distribution of the main sedimentary and geomorphic zones discussed within the text.

Spatially isolated nebkha dunes dominate the remaining part of the dune field and cover an area of 5 km2, stretching for 2 km inland along the incised river channel and for in excess of 2 km across the low relief, non-incised sandur plain to the northwest (Fig. 1). Most of the nebkhas are colonised by Ammophila which has enabled them to develop steep flanks inclined up to 50° (Fig. 8). Individual dunes attain a maximum height of 2 m and have an elliptical plan-view shape with long axes that are aligned parallel to the prevailing wind direction (towards 280°). Considering the entire population of nebkhas, strong relationships exist between height, long axis length and short axis length (Fig. 9). In some instances, vegetated and apparently stabilized nebkhas have banks of non-vegetated, wind-rippled blown sand up to 1 m thick in their immediate lee. In other cases, nebkhas are oversteepened on their upwind side because of undercutting in their basal part where vegetation is less well developed and the sand is prone to erosion. Internally, the nebkhas, which are composed of moderately- to well-sorted sand (Fig. 5e and f), often lack well-defined stratification, in which case deposits are apparently massive. However, if the dunes are trenched while the sand is wet and the cut face is allowed to dry, then translatent wind-ripple strata (Hunter, 1977) sometimes become evident in the less vegetated lower flanks of the dunes. Thin, parallel laminae (1–3 mm thick), representing the product grainfall are also sometimes evident higher on the dunes where more vegetation is developed. These laminae often thicken around in-situ roots, as has been described for grainfall facies in other coastal aeolian dunes (McCann and Byrne, 1989, Byrne and McCann, 1990, Byrne and McCann, 1993). The characteristic shape of the nebkhas and their tendency to adopt a similar form once they have developed beyond their embryonic state suggests that they attain an equilibrium that reflects an efficient sand-trapping mechanism for the given climatic conditions and for the state of vegetation development. In particular, the effectiveness of Ammophila as an agent to reduce near-surface wind velocity is crucial to the sand trapping and storing that enables nebkha growth (Stockton and Gilette, 1990, Lancaster and Baas, 1998). Furthermore, the ability of vegetation such as Ammophila to stabilize the substrate through growth of a net-like root mat is crucial to the long-term growth and stabilization of the nebkhas (Bressolier and Thomas, 1977, Tengberg and Chen, 1998, Nishimori and Tanaka, 2001).

Fig. 8. Nebkha dune mostly stabilized by *Ammophila*. Prevailing wind direction is from right to left. Note the steep dune slopes inclined at 45–50° and the high ratio of height to basal length. A lower angle-inclined wedge of aeolian sand that is largely free from vegetation has been deposited in the downwind lee (left) side of the bedform. An extensive root mat is evident in the lower part of the bedform and acts as an important sand stabilizing agent. Dune is 2.5 m high.

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June 2: Travel Day/ Skaftafell

(Rachel, Andy, Yas, Mati)

Summary

#	Stop	Location	Stop duration	Type
1	Skeiðará Bridge Monument and Skeiðarársandur viewpoint	**63.984642°, -16.959983°**	30 min	Sandur & monument
2a 2b	Skaftafell Visitor Center (Start point for Waterfalls trail) Skaftafell Visitor Center (Skaftafellsjökull glacier trail + lunch)	**64.014603°, -16.967908°**	3 hours (1 hour at 2a and 2 hours at 2b)	Waterfalls over basaltic columns. Glacier
3	Hangandifoss Waterfall - Múlagljúfur Canyon	**63.993021°; -16.436285°**	2.5 hours	Canyon formation, Waterfalls/ knickzone
4	Vagnsstaðir HI Hostel			Hostel

Proposed day schedule:
8am: Depart from Vik hostel.
10:15am: arrive at stop 1 (Skeiðará Bridge Monument and Skeiðarársandur viewpoint)
10:45am: depart stop 1
11am: Arrive at stop 2 (2a: Skaftafellsjökull Waterfalls trail to see Svartifoss & Magnusarfoss; 2b: Skaftafellsjökull glacier trail + lunch)
2pm: depart stop 2
2:45pm: arrive at stop 3 (Hangandifoss Waterfall - Múlagljúfur Canyon trail)
5:15pm: depart stop 3
6pm: end day at hostel in Hornafirði (Vagnsstaðir HI Hostel, Suðursveit A-Skaftafellssýsla Þjóðvegur, 781 Höfn í Hornafirði, Iceland; https://www.hostel.is/en/hostels/hi-vagnsstadir)

Stop Information

Stop 1: Skeiðará Bridge Monument and Skeiðarársandur viewpoint (63.984642, -16.959983)
Suggested duration: 30 minutes

Directions: From Vik hostel, take Route 1 for 136 km. We will head east acoss Skeiðarársandur, toward Vatnajökull, Skaftafell, and Höfn. There is a parking area on the left (north) where we will stop to get an overview of the Skeiðarársandur.

About the stop:

Skeiðará is a 30 km long glacier river that has its source on the glacier Skeiðarárjökull, one of the southern arms of the Vatnajökull glacier. In spite of its short length, it is especially feared because of the frequent glacier runs that can be fatal. In front of Skaftafell and Skeiðarárjökull, Skeiðará has formed the Skeiðarásandur, a black plain that covers the whole area between the park and the sea (about 40 km long and 5 to 10 km wide). In 1996, the latest of these glacier runs took place as a consequence of an eruption of Grímsvötn volcano. The eruption melted portions of the glacier, created massive floods and destroyed parts of Route 1 (the Ring Road). The 880 meters long bridge was damaged by floating ice boulders the size of houses. At the peak of this glacier run, 45,000 m3/s of water were coming down. No one was harmed. All the remains of the original bridge today are two twisted girders by the side of the new road forming the Skeiðará Bridge Monument (Figure 1).
According to the GSA Field Guide (2019), the Skeiðarársandur (Figure 2 and 3), located at **63.9608°N, 17.1822°W**, is the largest active glacial outwash plain on Earth. It is swept by glacial outburst floods (jökulhlaups) every 1-7 years. As mentioned in the Standford Guidebook (2009), its parent glacier, Skeiðarárjökull is a surge-type piedmont glacial tongue of Iceland's Vatnajökull ice cap. Skeiðarársandur comprises five major channels and innumerable small channels throughout the braided river/fan system. From west to east the major channels are: Núpsvötn, Gígjukvísl, Háöldukvísl, Seluhússkvisl, and Skeiðará. Núpsvötn and Skeiðará directly drain the glacier margin, Gígjukvísl drains meltwater that collects in the proglacial zone (just in front of the glacier front), and Háöldukvísl and Sæluhúsakvísl are the two largest jökulhlaup overflow channels. Terminal moraines indicating the approximate location of the glacier front in 1749 and 1890 are visible on the terraces between these channels (Figure 3).


Figure 1. Skeiðará Bridge Monument.

Figure 2. Sandur viewpoint.

Figure 3. Satellite image of the sandur and glaciers of the area. The dashed lines indicate the 1749 (south) and 1890 end moraines. Taken from GSA Field Guide (2019).

Stop 2: Skaftafell National Park [edited from Bice et al. 2006; Umhverfisstofnun, 2009b; 2009c; Nanuls, 2007, adapted from 2009 Stanford field guide] - Visitor center: 64.014603°, -16.967908°

The landscape of Skaftafell has been shaped by glacial action and water erosion. The valley glaciers Skeiðarárjökull, Morsárjökull and Skaftafellsjökull are prominent features of this landscape, and the rivers Skeiðará, Morsá and Skaftafellsá emerge from them. Skaftafellsjöllis the range of mountains between the piedmont glacier Skeiðarárjökull in the east and theVatnajökull ice-sheet in the north. The range's mountains include Miðfellstindur (1430 m),Þumall (1279 m) and Blátindur (1177 m). The park is divided into three different areas:Skaftafell and sandur, Lakagígar, and the Vatnajökull ice sheet itself. Vatnajökull is the largest glacier in Europe and covers approximately 8% of Iceland. About 2/3 of the glacier is inside the park boundaries.The Skaftafell climate is sometimes much warmer than in

Figure 4. Location of the Visitor Center, Stop 2a, Stop 2b and Stop 2b (alternative).

neighboring districts because it is sheltered by Öræfajökull. Vegetation in Skaftafell is quite varied; approximately 250 species of higher plants can be found in Skaftafell, and over 30 species of birds nest here. The Mountain slopes are covered with birch, interspersed with rowan trees in some places.Vegetation has been rapidly gaining ground since grazing was prohibited in the park, andspecies hardly ever seen on pasture land are common here. The only wild mammals are fox and field mice.Skaftafell was one of the original farms occupying a fertile plain that was rich with the tephra from Öræfajökull. The farm passed from the hands of private farmers to a large manor during the Middle Ages, then to the church. The farm remained in church hands through Iceland becoming part of Norway in 1271 and then part of Denmark in 1397. In 1536 church landswere seized by the Danish king as part of the Reformation, so Skaftafell became a royal estate. The

farm at this time was located at a spot called Gömlutún (‘Old Hay Field’), at the foot of the hills just to the west of the present campsite, where its ruins can still be seen today. Between the years 1830 and 1850 the tephra and glacial outwash of Skeiðarársandurencroached on the farmland, covering the fields in sand. The farm was forced to relocate 100m higher up the mountainside where it remained until 1964 when the Icelandic government acquired the land and designated the area as a national park. Cultural remains in the park include the old farm Sel and the home power station below Magnúsarfoss waterfall. (Skaftafell National Park, 2009; Nanuls, 2007)
The Skaftafell central volcano was active between 2-3 Ma. At least 16 glacial and interglacial intervals have been identified in the Skaftafell and Hafrafell volcanic strata during the last 5Ma (Helgason and Duncan, 2001). The strata is made up of subaerially erupted tholeiitic lava flows and basaltic andesites and subglacially formed volcanic ridges made up of pillow breccias and hyaloclastites. Magnetostratigraphic mapping and K-Ar radiometric dating indicates that the frequency and intensity of glaciations increased significantly at ca. 2.6 Maand particularly since 0.8 Ma, as most of the strata from 100 m a.s.l. to the peak ofÖræfajökull, at 2119 m a.s.l. has been formed during the Bruhnes magnetic epoch. These climatic changes correlate with increases in global ice volume, ice-rafted debris, and development from local to regional glacial conditions in the North Atlantic. tic. (B. Brandsdottir).

Stop 2a: Svartifoss and Magnusarfoss waterfalls (64.027334°, -16.974659°)


Figure 5. Svartifoss.

Waterfall over basalt columns, what more could you ask for?

Go to the Skaftafell turnoff (800 m west), and proceed down the road to the Skaftafell Visitor Centre for Vatnajökull National Park. Hike as out-and-back to the waterfall Svartifoss (spectacular columns). (Source: GSA Field Guide, 2019).

Stop 2b: Skaftafellsjökull Glacier Trail (64.033017°, -16.931583°)

Directions: Hike to Skaftafellsjökull glacier overlook. Return to the trail junction previously encountered just before Svartifoss. Take the trail to the left (east)towards Sjónarnípa or Nípa (trail signs do not necessarily correspond to names on the map, but are usually some variation on the name you're looking for). Hike up over the east side of the point of land on which Svartifoss is located. Towards the end the trail runs over rocks and is hard to see but the colored stakes can be followed relatively easily to see where the trail goes. The trail goes right out onto a promontory overlooking Skaftafellsjökull.The Sjónarnípa viewpoint provides one of the most spectacular views in Iceland. Look for nunataks (from Inuit nunataq): exposed, rocky bits of a ridge or peak within an ice field or glacier, often named and used as navigation aids. Also observed the proglacial lake at the glacier front, medial moraines, and crevasses. To the right, the sandur spreads out below you. Note the difference between theSkaftafellsandur (below Skaftafellsjökull), which has not been eroded by a recent catastrophic jökulhlaupand is green and vegetation versus the black sediments of Skeiðarársandur (to the west), devoid of vegetation since the 1996 catastrophic jökulhlaup.To return to the visitor center, go back up the trail only the distance of a few of the colored stakes. A trail (different from the one you arrived on) branches off to the left (south), heading down the face of the hill.The head of this trail is a little difficult to find among the rocky ground, on which trails are not obvious, but just keep to the left along the top of the cliff/hill, and you'll find it a short distance from the overlook.This trail traverses the face of the hill and angles directly down towards the visitor center. On the way, you walk through what is considered a "forest" in Iceland – some of the trees are taller than you! The Trees (as in most of Iceland) are almost all native Northern Birch (Betula pubescens).

Fig. 6. a) Path to Sjónarnípa; b) Northern Birch forest; c) View from Sjónarnípaof Skaftafellsjökull.

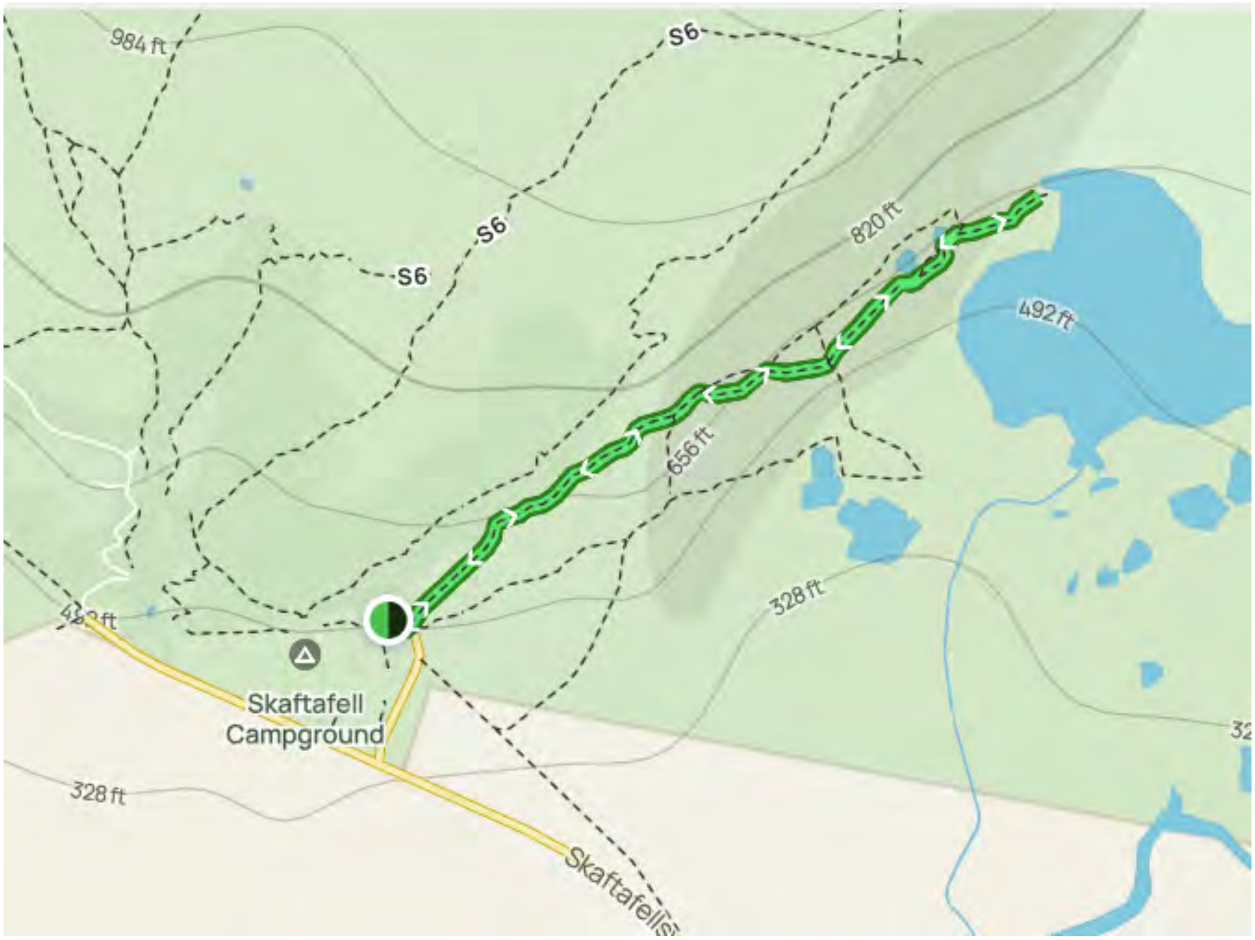

Fig. 7. Skaftafellsjökull Glacier Trail map.

Alternative hike towards Skaftafellsjökull glacier along Little Ice Age Timeline (64.022912°, -16.942855°)

This walk to/from the glacier front includes interpretive signs showing former glacial extent and subsequent retreat. The trail departs on the east side of the visitor center. Englacial debris bands may be visible on the glacier. The hike remains on the flat valley floor and so is a possibility for anyone unable to make the climb up to Svartifoss.

Fig. 8: Skaftafellsjökull Glacier.

Stop 3: Hangandifoss Waterfall - Múlagljúfur Canyon (N 63.993021°; W 16.436285°)
Directions:
Take Route 1 to (N 63.9886667°; W 16.3971589°) where you'll find a gravel road turn-off. Take this gravel road until you reach the parking lot at (N 63.993021°; W 16.436285°). Trail markers above the glacier river retaining wall should be visible from the parking lot. There are 2 shallow creek crossings on this hike, a view of a small waterfall called Múlafoss, and finally a view of Hangandifoss.
Hiking boots highly recommended for this hike

Fig. 9: Múlagljúfur Canyon cut by Múlaá River.

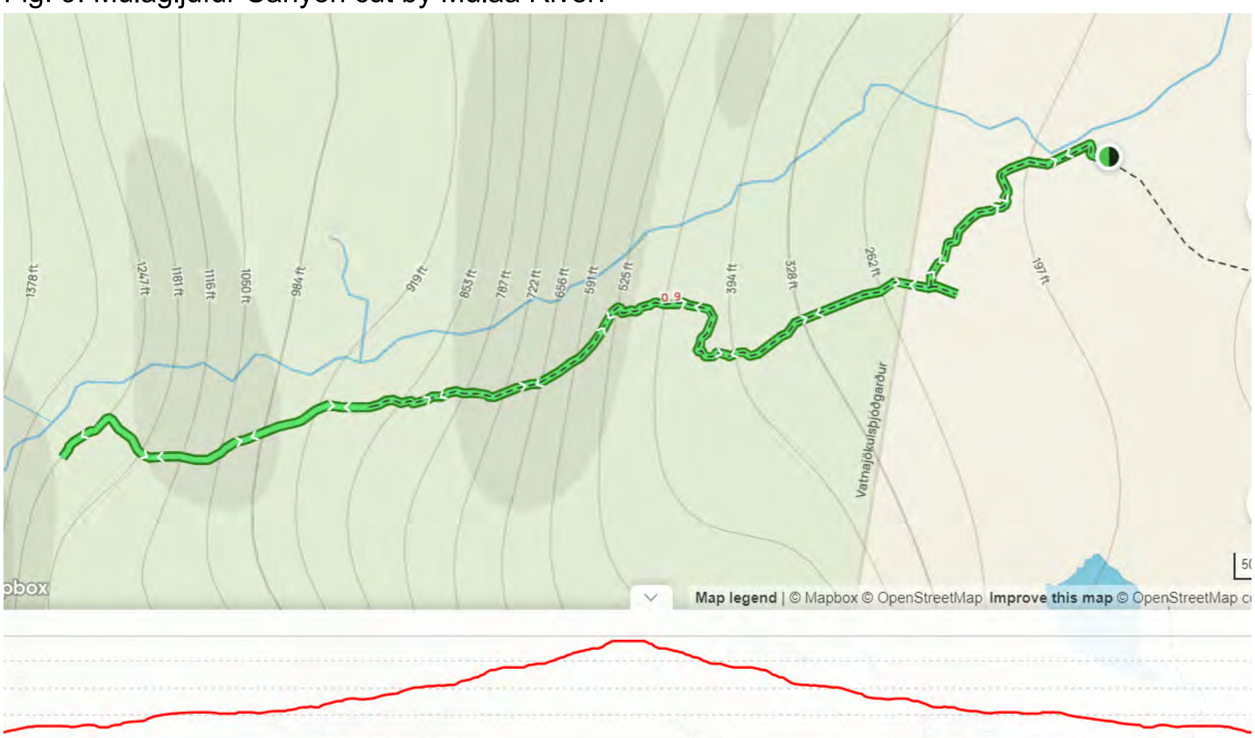

Fig. 10: Trail map starting and ending at parking lot and traveling along Múlagljúfur Canyon to see Múlafoss, Hangandifoss and canyon outlook. (courtesy of alltrails)

About the stop:

Múlagljúfur Canyon is a canyon modernly cut by the River Múlaá (also referred to as Múlakvísl; translated to Mule River) in the Öræfi Region of southeast Iceland. The flow from the River Múlaá is dominantly supported by glacial meltwater from Öræfajökull glacier via small outlet glaciers south of Hrútárjökull (referred to as Kvískerjajöklar by Guðmundsson & Björnsson 2020; fig. 11). The quantity of this meltwater is in part due to heat and activity associated with the Öræfajökull volcano, an ice covered stratovolcano consisting of a 4-5 km diameter caldera. In the narrows of the canyon, there are deposits of unconsolidated cover, outwash gravel, moraines, etc., and towards the mouth of the canyon, there are deposits of both subaerial and subglacial basic and intermediate volcanic rocks related to eruptions of Öræfajökull (fig. 12). Most activity of Öræfajökull has occurred during glacial times, as evidenced by hyaloclastites (volcanoclastic accumulation or breccia consisting of glass fragments formed by quench fragmentation of lava flow surfaces during submarine or subglacial extrusion). During the Little Ice Age, Mulagljufur Canyon and the flow of the River Múlaá was dammed by Hrútárjökull, forming an ice-dammed lake in the canyon at least twice (Guðmundsson & Björnsson 2020).

Öræfajökull had two historic eruptions in 1362 and 1727, of which the former has been more thoroughly studied. Pyroclastic flows and falls from the 1362 eruption were deposited and subsequently reworked in Múlagljúfur Canyon and stratigraphic sections and isopachs of the flows and falls related to the 1362 eruption are described in figures 13 and 14 respectively (Sharma et al. 2008). Total fall deposit volume associated with the 1362 eruption is ~2.3 km^3 (Sharma et al. 2008).

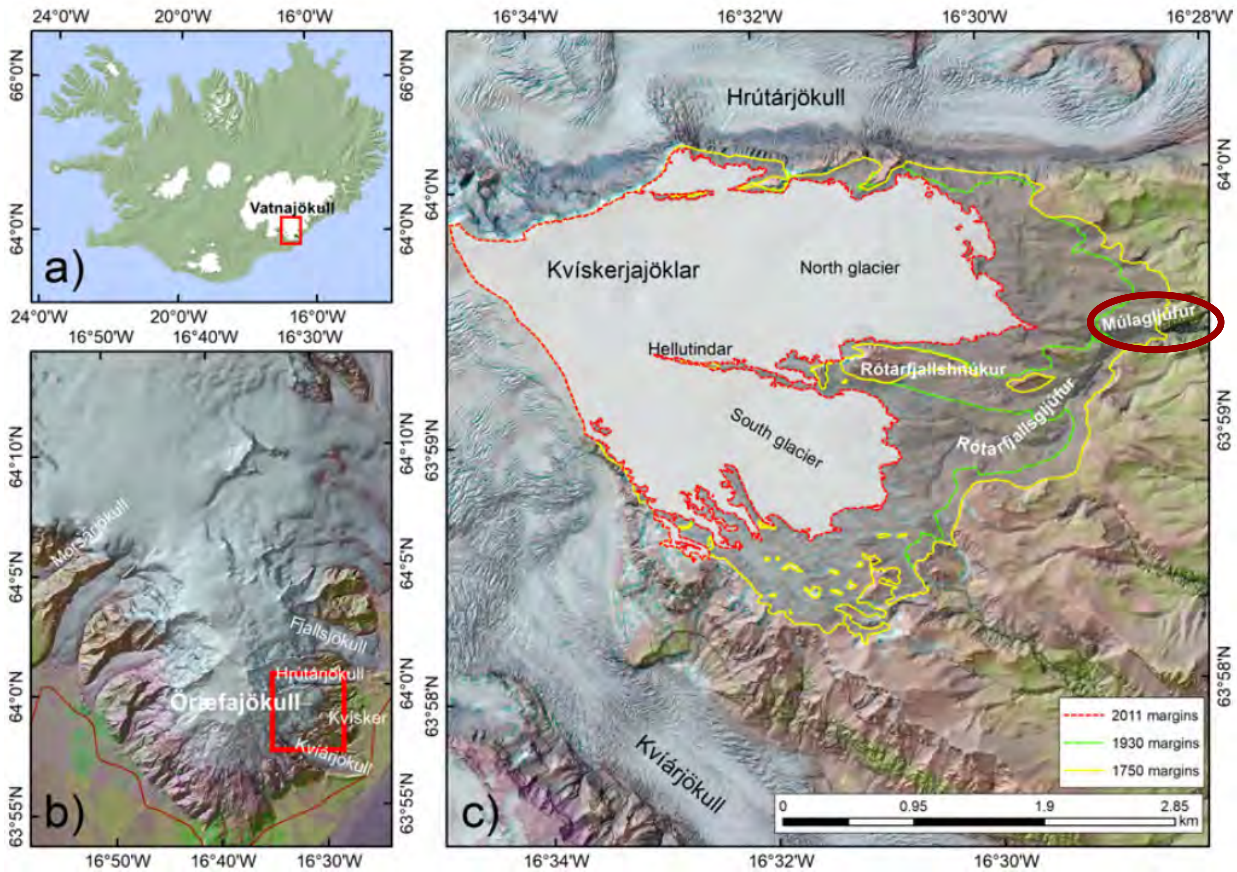

Fig. 11: a) Iceland and the location of Vatnajökull and Öræfajökul. b) Öræfajökull with outlet glaciers. c) The South and North Kvískerjajöklar glaciers (white area), the ice margins at LIA max (yellow line), in 1930 (green broken line) and 2011 (red broken line). Map based on data from the National Land Survey of Iceland, the Icelandic Meteorological Office and the Institute of Earth Sciences, University of Iceland. Figure from Guðmundsson & Björnsson (2020).

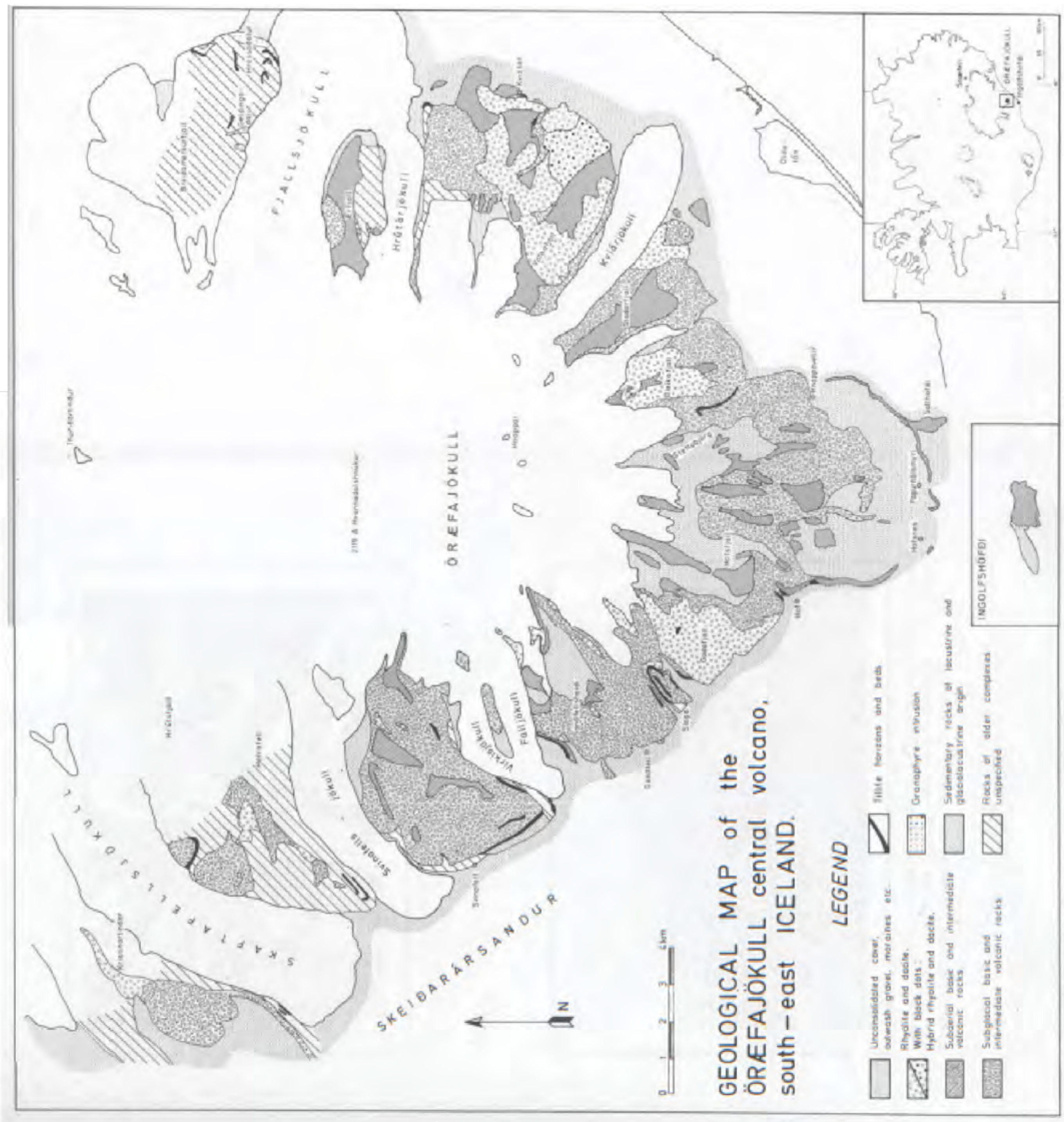

Fig. 12: Geology of the Öræfi region in southeast Iceland (Prestvik, 1979)

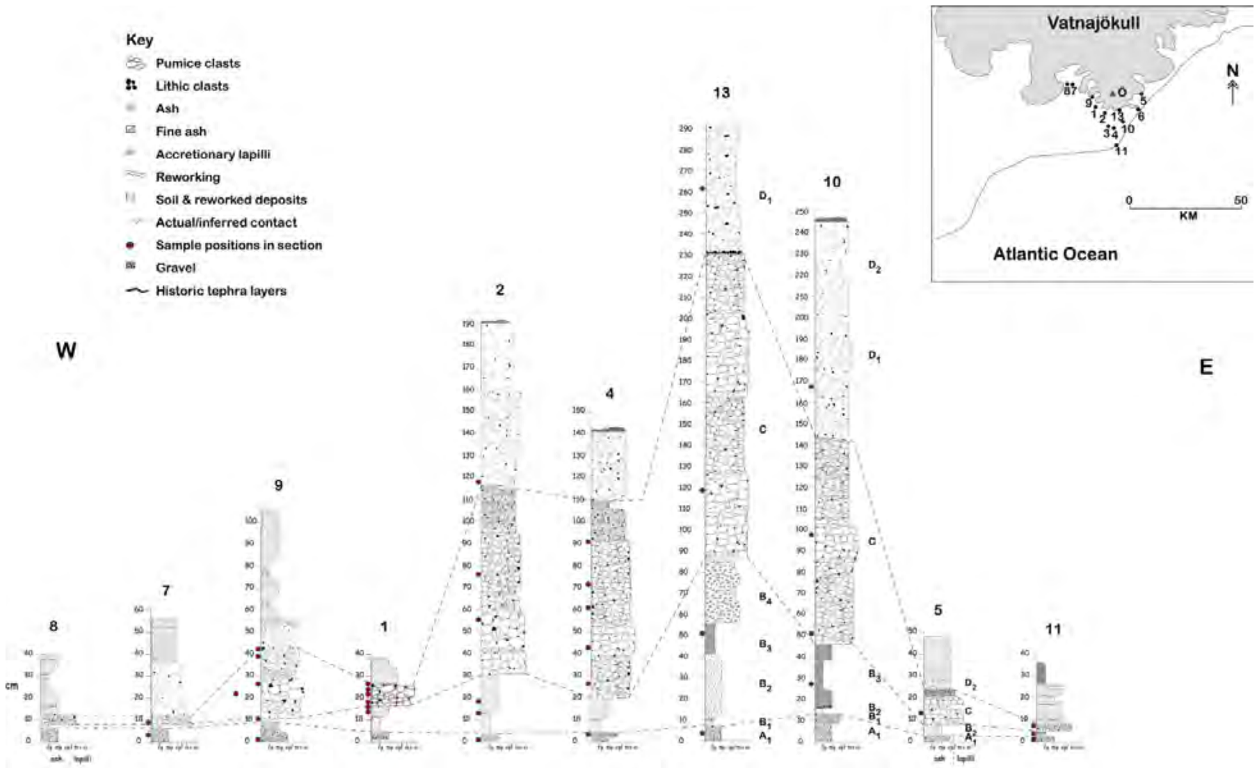

Fig. 13: sections through Öræfajökull 1362 (Ö1362) deposits (soil below not shown). Sections are all from proximal locations on south flank of the volcano. Index map shows approximate location of each section (black circles with location number); red triangle (labeled Ö) marks volcano summit, grey shaded area marks Vatnajökull ice cap. Thickness of stratigraphic sections given in cm. (Sharma et al. 2008)

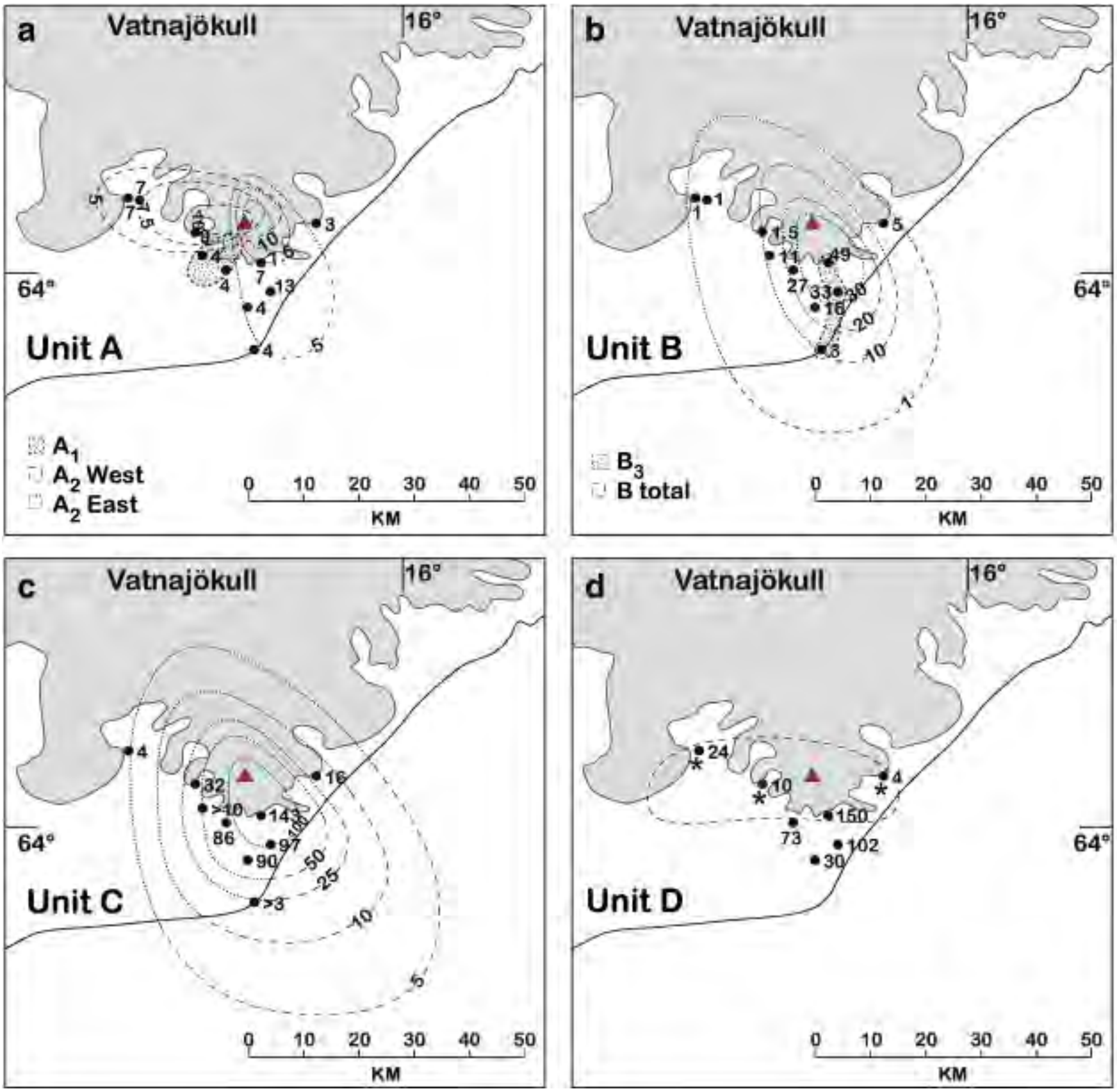

Fig. 14: Thickness distribution maps for Öræfajökull 1362 proximal fall and flow units (isopach and individual location data in cm). Only locations where primary unit thickness was preserved are shown. Locations where possible pyroclastic flow bed is largely reworked are marked with an asterisk. Shaded grey area on all maps represents the Vatnajökull ice cap. (Sharma et al. 2008)

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Iceland field guide (June 3, 2023): Breiðamerkurjökull and Kvíárjökull

Summary

Stop	Location	Time
Proglacial hydrology and glaciofluvial deposits in Breiðamerkursandur	64.125612, -16.192940	1 hour
Glacier, kames and kettles, streamlined features	64.2158, -20.8836	1 hour
Fellsfjara (Diamond Beach)	64.0438263, -16.1803975	1 hour
Little Ice Age terminal moraine	64.0438263, -16.1803975	30-45 min
Jökulsárlón	64.047262, -16.178323	30-45 min
Eskers and recessional moraine	64.046047, -16.315292	1-2 hours
Kvíárjökull moraines	63.9390, -16.4390	1 hour

Stop Itinerary:

- Leave Vagnsstaðir HI Hostel at 8:00am.
- Arrive at Stop 1 and 2 gravel road parking area by 8:45am.
- **Stop 1 Proglacial Hydrology**: 8:45-9:15am.
- **Stop 2 Glacier, Kames and Kettles, Streamlined Features**: 9:15-11:00am.
- Drive back down gravel road to Diamond Beach, arrive by 11:45am.
- Eat lunch and explore **Stop 3 Diamond Beach**: 11:45am-12:45pm.
- **Stop 4 Little Ice Age moraine hike**: 12:45-1:30pm.
- **Stop 5 Jökulsárlón**: 1:30-2:15pm.
- Drive to Stop 6 parking area, arrive by 2:30pm.
- **Stop 6 Esker hike**: 2:30-4:00pm.
- Drive to Kvíárjökull, arrive by 4:20pm.
- **Stop 7 Kvíárjökull**: 4:20 – 5:30pm.
    - Optional, could do this stop after dinner or on June 5 when we drive by it on our way to Laugarvatn.
- Drive back to Vagnsstaðir HI Hostel, arrive by 6:00pm.

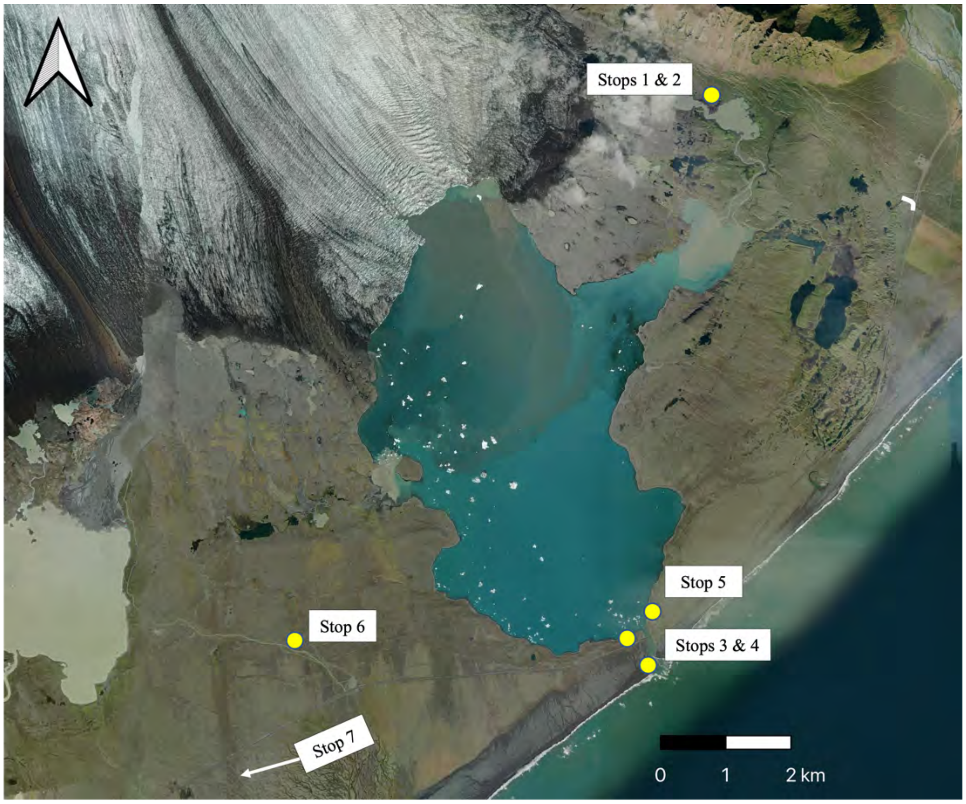


Figure 1: Overview map of Breiðamerkurjökull stops.

Figure 2: 5 m contour map of Breiðamerkurjökull (Guðmundsson and Evans, 2022).

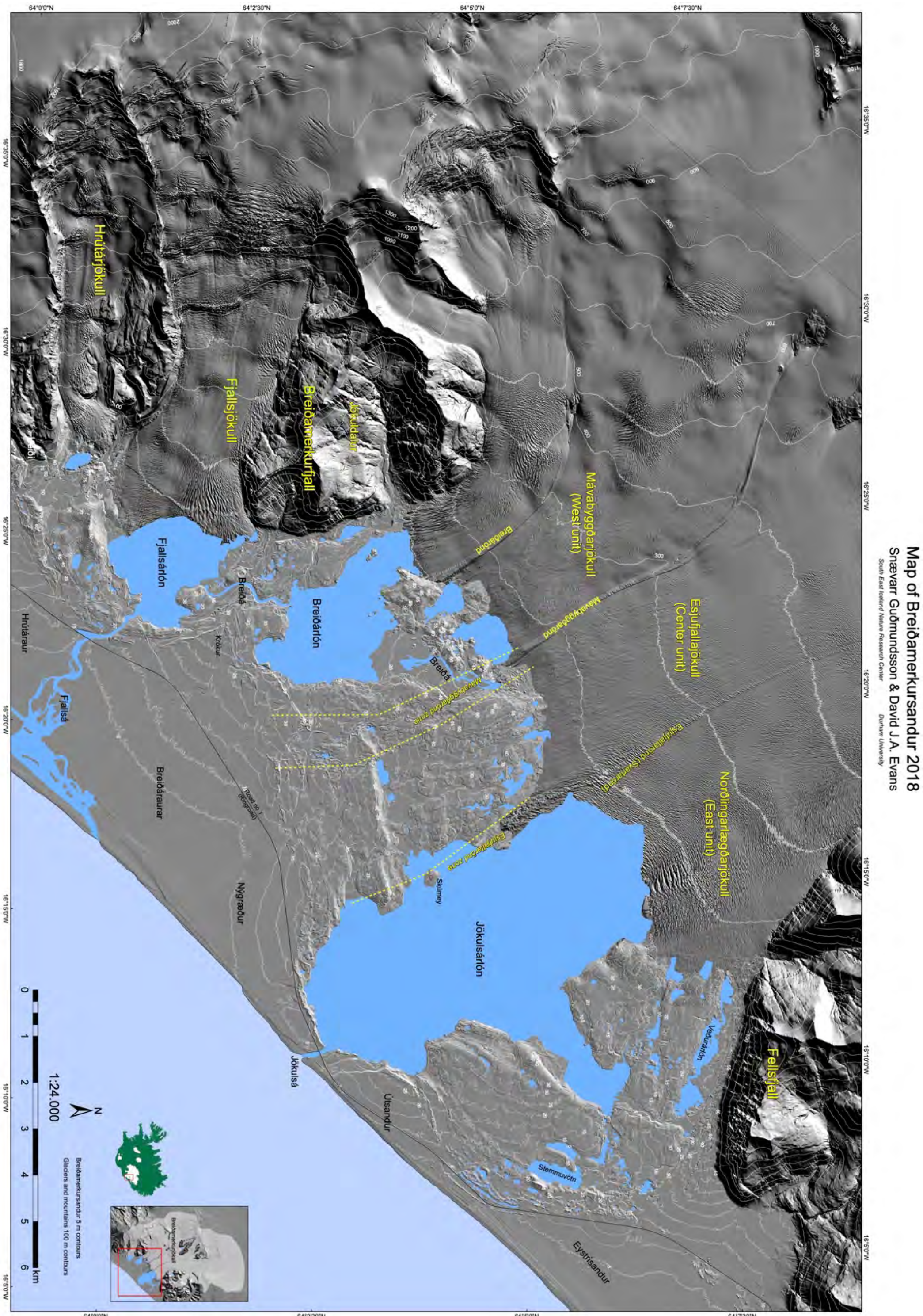
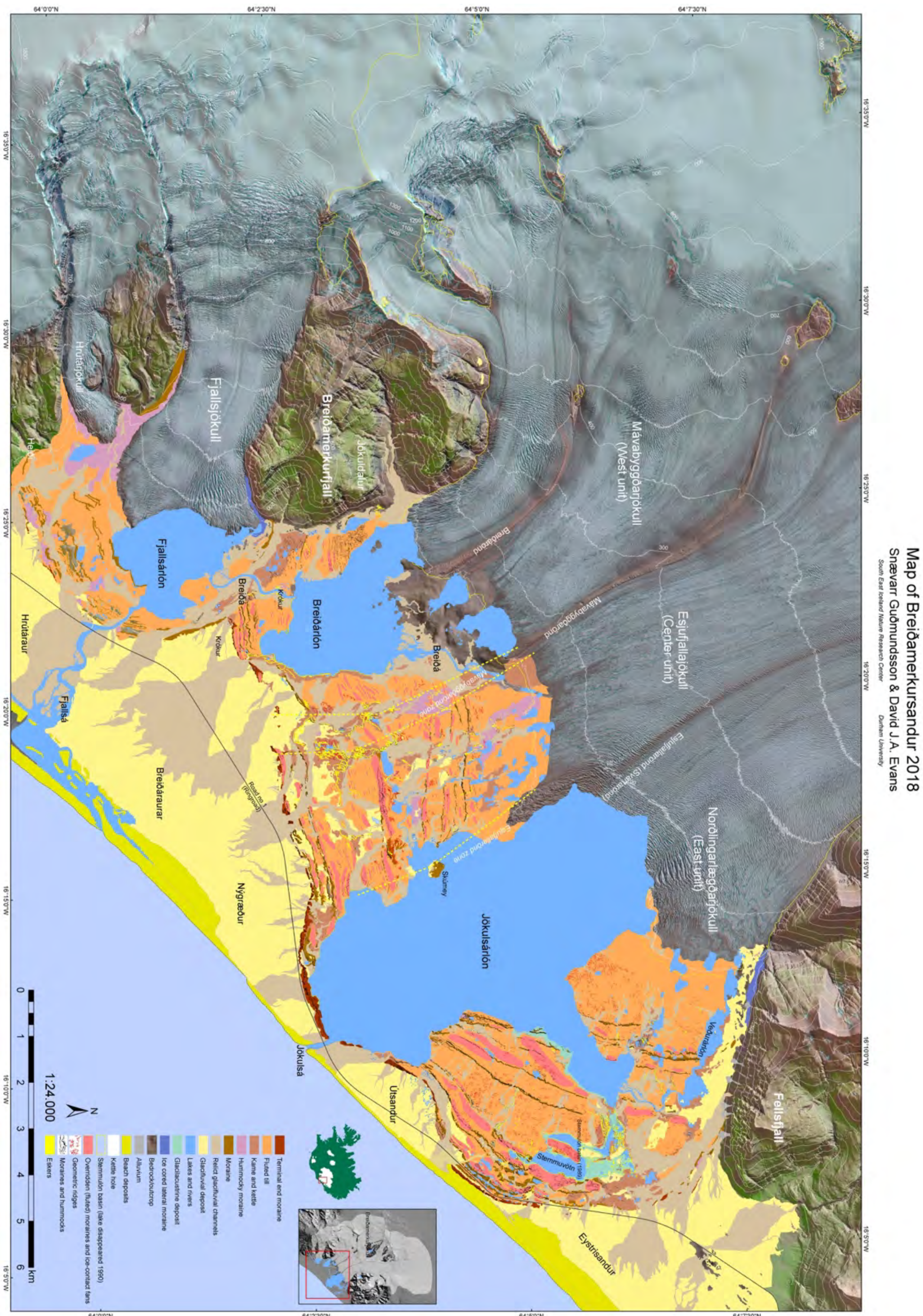


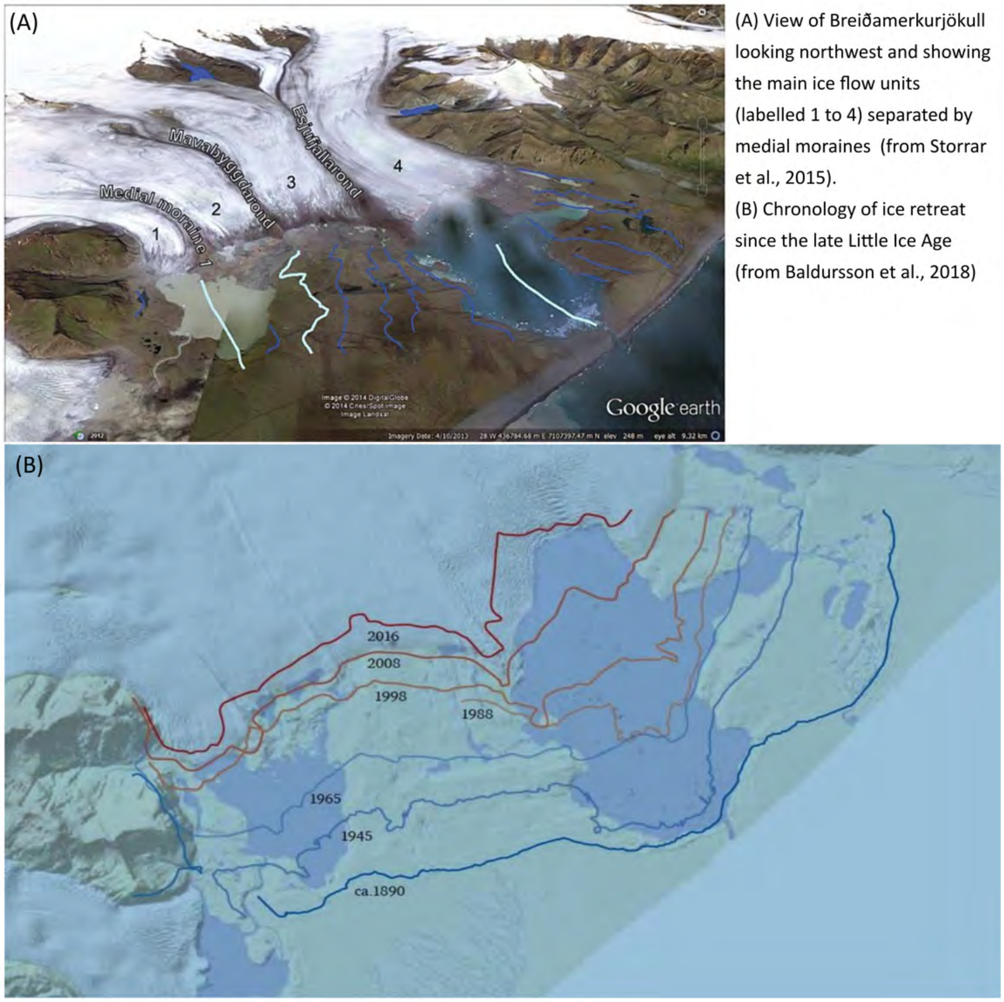
Figure 3: Glacial geologic map of Breiðamerkurjökull (Guðmundsson and Evans, 2022)



Introduction

Breiðamerkurjökull is the second largest outlet glacier (ice drainage area of ~900 km^2) of Vatnajökull Ice Cap, and it flows down from the uplands of Oræfi volcano in the west and Veðurárdalsfjöll in the east. During the late Little Ice Age (ca. 1890 CE), Breiðamerkurjökull extended almost to the coastline but has since retreated ~10 km, with small readvances occurring during winter of most years. The recently exposed area in front of the glacier is Breiðamerkursandur, an outwash plain containing proglacial lakes and streams. Because of its easy accessibility from the ring road and the variety of glacial landforms, Breiðamerkursandur is one of the most well-studied glacial geologic environments on Earth and has been used as the basis for a landsystem model for temperate receding glaciers (Evans and Twigg, 2002). Because of Breiðamerkurjökull's wide terminus (~13.5 km), its sedimentary deposits are not strongly influenced by mountain topography, making it one of the best modern analogues for what the southern land-terminating lobes of the paleo-ice sheets looked like, such as the Laurentide Ice Sheet lobes of Wisconsin. Breiðamerkurjökull has fairly low englacial and supraglacial debris content, leading to limited deposition of sediment on top of subglacial landforms during glacial retreat (and hence, landform preservation). Glacial geologists have mapped and characterized landforms in Breiðamerkursandur since 1903, providing a unique series of "snapshots" of the evolving glacial geomorphology (Evans and Twigg, 2002).

There are three main depositional types present in Breiðamerkursandur: (a) extensive moraines (dump, push, and squeeze types) that often record annual recession of the glacier front; (b) glaciofluvial deposits and landforms such as eskers and ice-contact fans; (c) subglacial landforms such as flutes and drumlins. Our stops today will take us on a tour of these different glacial geologic features and we will discuss how glaciers erode, transport, and deposit sediment. Additionally, we will visit Fellsfjara (Diamond Beach) and Jökulsárlón (Glacier Lagoon). Time permitting, we will also visit nearby Kvíárjökull, which has the largest latero-terminal moraine complex in Iceland and a series of recessional moraines.



(A) View of Breiðamerkurjökull looking northwest and showing the main ice flow units (labelled 1 to 4) separated by medial moraines (from Storrar et al., 2015).
(B) Chronology of ice retreat since the late Little Ice Age (from Baldursson et al., 2018)

Figure 4: (A) Aerial view of Breiðamerkurjökull, (B) historical terminus positions of Breiðamerkurjökull.

Stops

Stop 1: Proglacial hydrology and glaciofluvial deposits in Breiðamerkursandur

Coordinates (park at): **64.125612, -16.192940**

Here we will stop at the parking area prior to crossing the makeshift bridge across the proglacial river near the terminus of Breiðamerkurjökull. The drive along the gravel road leading up to the parking area passes through Breiðamerkursandur (outwash plain), including traveling through many glaciofluvial deposits, relict glaciofluvial channels, and skirting by recessional moraines (Fig. 5).

Proglacial water discharge in Iceland varies on multiple timescales. During the summer, discharge is greater because the glacier surface in the ablation area melts and contributes to runoff. Glacial runoff also exhibits substantial daily variations with maxima occurring during the late afternoon because of warmer temperatures and sunlight, and minima occurring during the night. In Iceland, jökulhlaups also contribute to short-lived peaks in discharge. Examples of melt seasons hydrographs (using stream height as a proxy for discharge) are provided for Jökulsá á Breiðamerkursandi (the short river connecting the glacier lagoon with the ocean) and Skálm (a river draining part of southeastern Mýrdalsjökull).

Sandur is an Icelandic term that originally meant sandy ground. They are outwash plains that form along the margins of ice bodies and are created by deposition from networks of subglacial and proglacial streams. Breiðamerkursandur is formed by glaciofluvial deposition and consists of outwash reworked by braided streams and containing landforms such as eskers, kames, and kettles (which we will focus on during later stops). Proglacial discharge generally decreases with distance from the glacier, leading to size sorting with boulders and cobbles present closer to the ice margin and finer particles such as silt being deposited more distally. Over time, braided channels and intervening bars migrate and produce broad outwash plains. Moraines force channels to converge and flow through breaches in the moraine, or run parallel to moraines for some distance. Many Icelandic sandurs are periodically flooded by jökulhlaups, leading to distinct lithofacies that includes deposits of hyper-concentrated flows, erosional contacts, and post-surge fluid flows.

Within the sandur, we will also observe ice-contact fans. These are wedges of sediment formed at the ice margin from a combination of glacial and glacifluvial sediments. They can be identified by their observed asymmetry with a steep side "up-ice" where this wedge of material was once in contact with the ice (Benn and Evans, 2010).

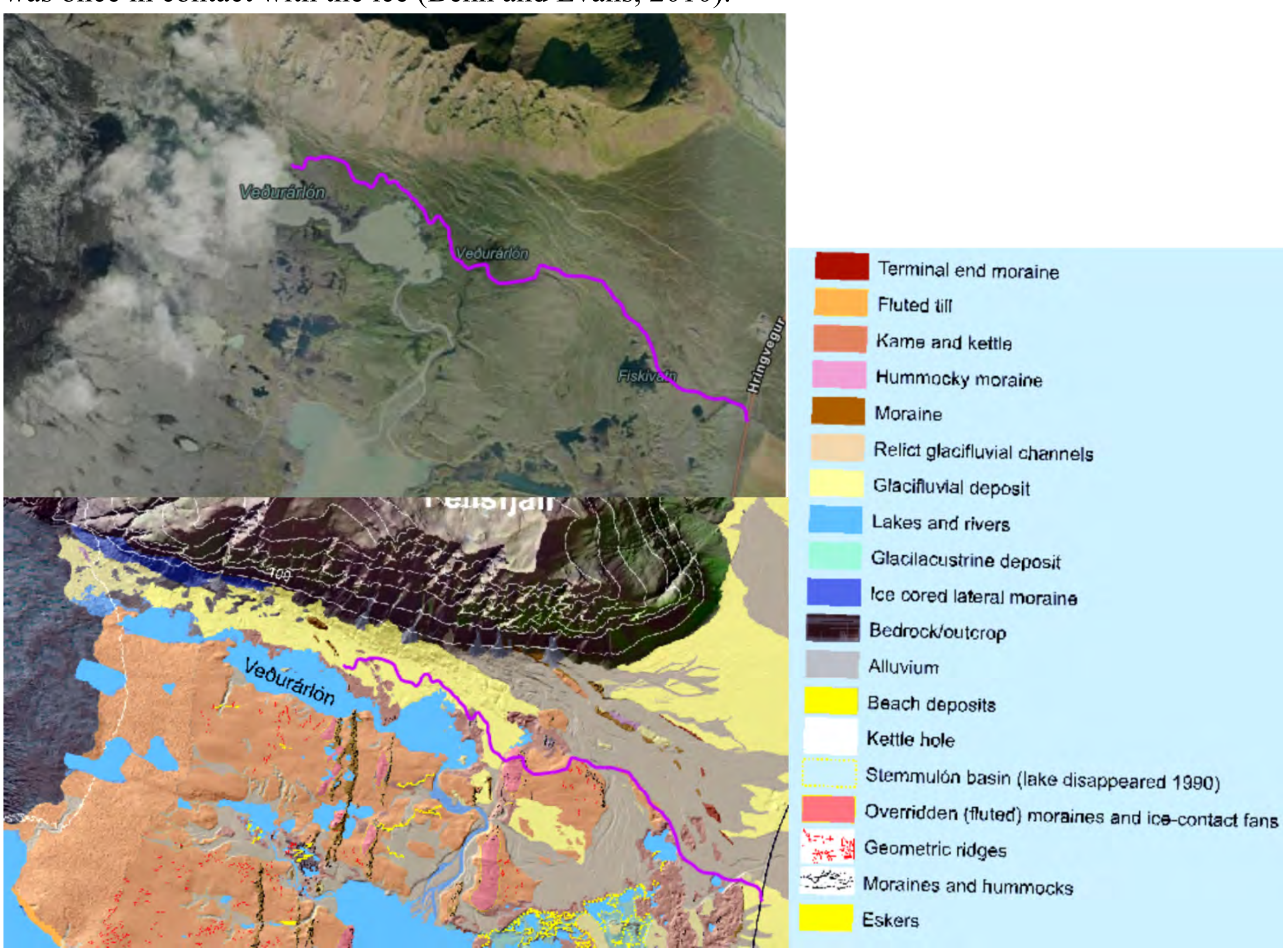


Figure 5: Path of gravel road (part of the way) in satellite view and viewed with the glacial geologic map of Guðmundsson and Evans (2022). The road continues much closer to the glacier terminus.

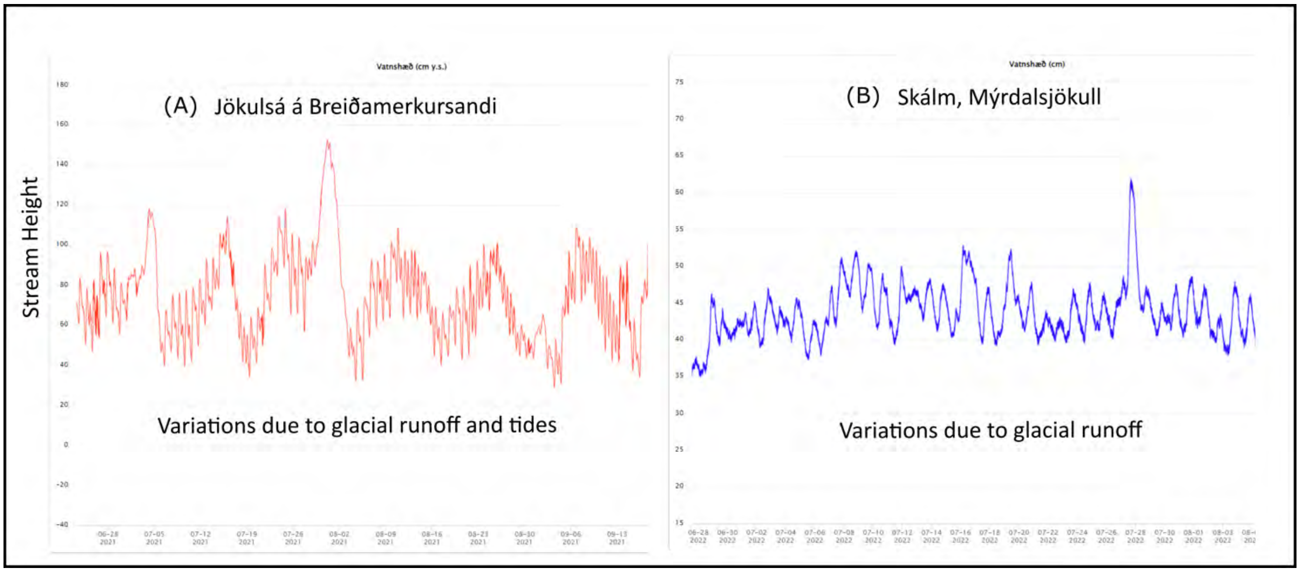


Figure 6: Measurements of proglacial stream stage (proxy for discharge) for two streams (Iceland Meteorological Office).

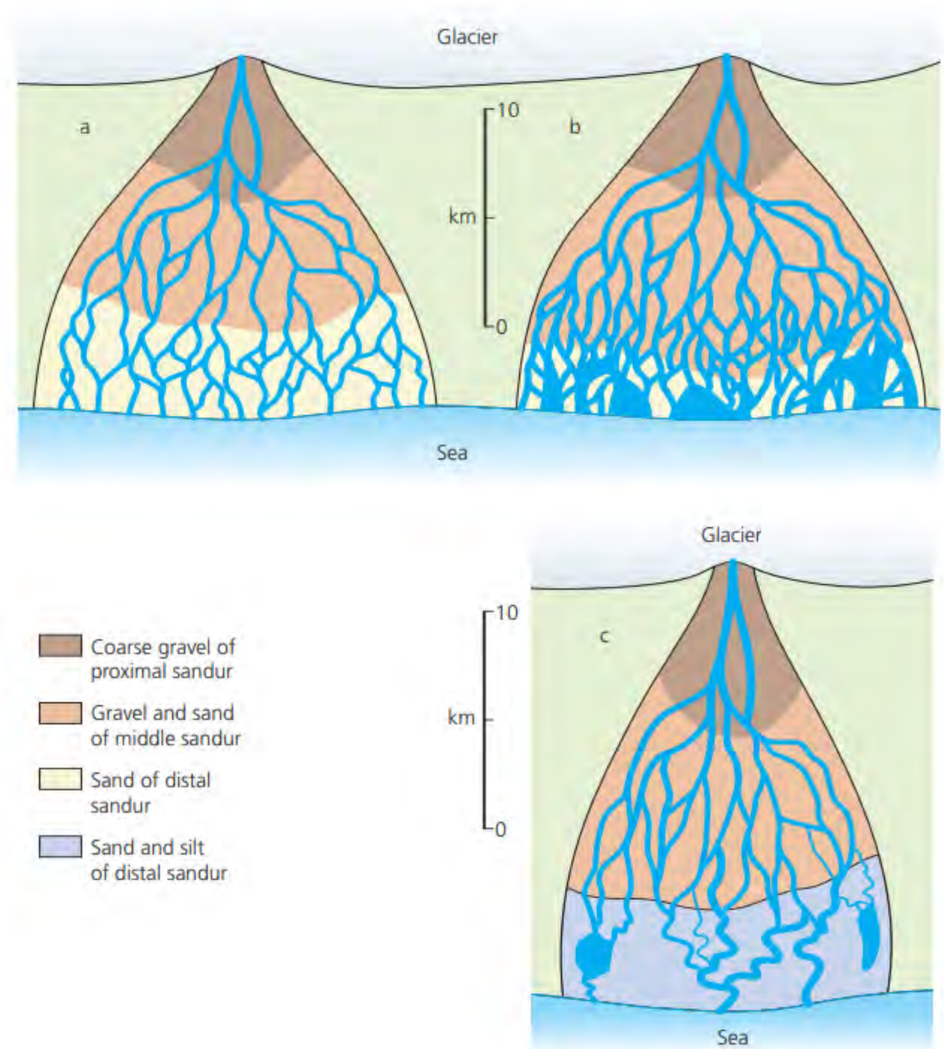


Figure 7: Sandur development and example of size sorting in sandurs (Benn and Evans, 2010).

Stop 2: Glacier front, kames and kettles, streamlined features
Coordinates (park at): 64.125612, -16.192940 (same as stop 1)

Drumlins

Subglacial deposits that are aligned with the glacial flow. They are formed by accumulation and erosion. At Breiðamerkurjökull, we can see stream-lined features covered with gravel that have been called drumlins.

Kames

Kames are mounds formed by the deposition of glacial sediments in depressions on the surface of the ice sheets. They are composed of a mixture of boulders, gravel, sand and clay and are mostly found in groups.

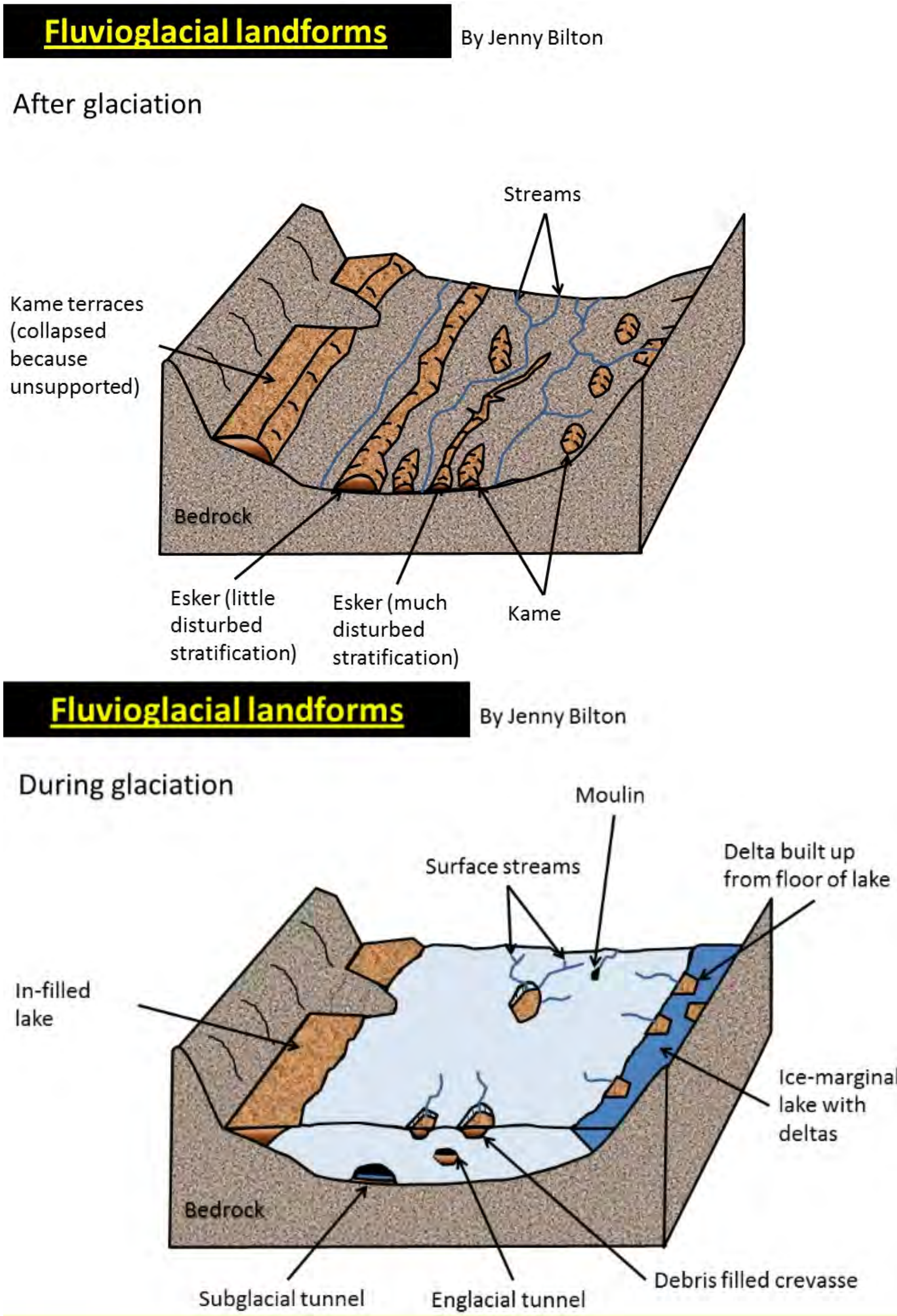


Figure 8: Schematic of common glacialfluvial landforms (Jenny Bilton).

On the other hand, kettles are round depressions formed by the melting of large blocks of ice that were left behind after the ice sheet retreated.

Kettle Formation

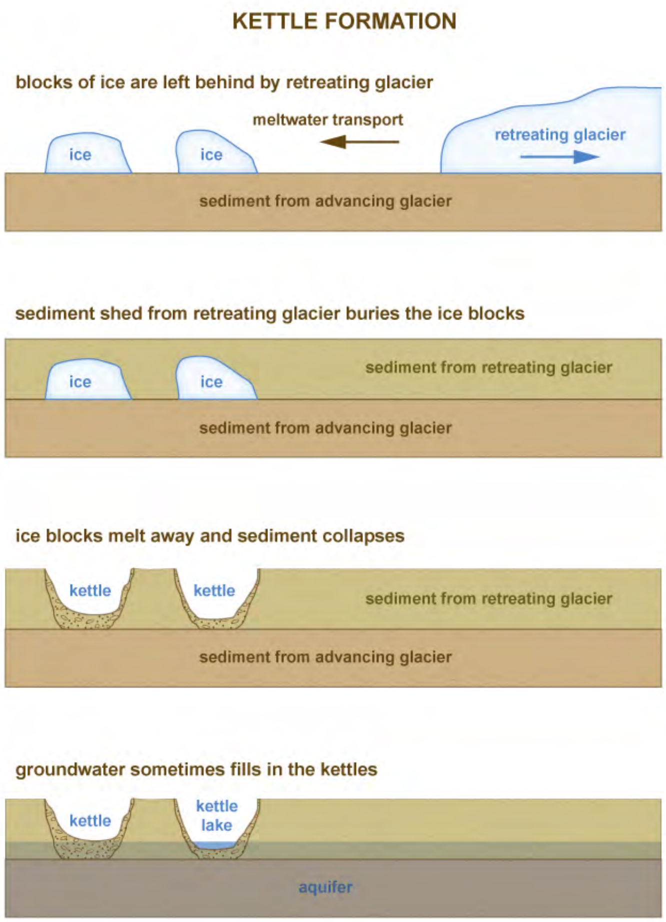


Figure 9: Schematic of kettle and kame formation (Wisconsin Geological and Natural History Survey).

Stop 3: Fellsfjara (Diamond Beach)

Coordinates (park at): 64.0438263, -16.1803975 (Eystri-Fellsfjara parking lot)

Fellsfjara (Diamond Beach) is composed of black volcanic sand and contains "diamonds" (melting icebergs) that have been carried from Jökulsárlón through the river Jökulsá á Breiðamerkursandi and now lay on the beach. Because Jökulsárlón acts as a sediment trap for glaciofluvial deposition, relatively little sediment is supplied through Jökulsá and deposited on the spits flanking it. Absent deposition, rapid coastal erosion from littoral currents breaks down the spits (which are composed of weak sandur material), which eventually will connect Jökulsárlón with the sea and form a fjord. Following the establishment of Jökulsárlón, the shoreline eroded ~750 m over ~100 years (Jóhannesson and Sigurðarson, 2005). If this rate continues, Jökulsárlón would connect to the sea in ~75 years. However, starting in 2003, the government of Iceland has stabilized the river banks and shoreline using armored stone to slow down coastal erosion and prevent costly road maintenance. Continued melt of the Vatnajökull ice cap will lead to higher land uplift rates, which will also slow down coastal erosion.

There is not much geology to see here, please enjoy the volcanic beach. Keep a lookout for melting icebergs, puffins, and seals.

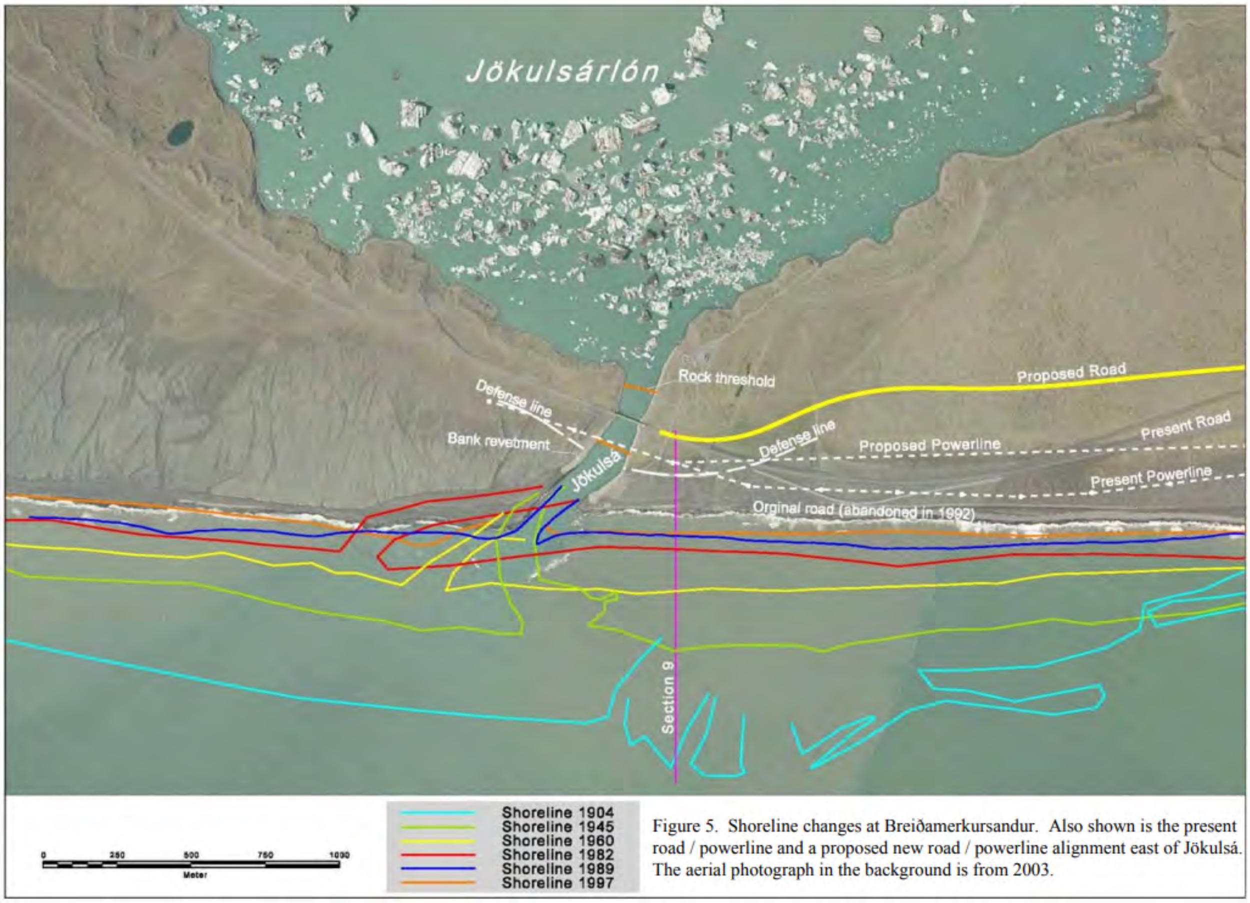


Figure 5. Shoreline changes at Breiðamerkursandur. Also shown is the present road / powerline and a proposed new road / powerline alignment east of Jökulsá. The aerial photograph in the background is from 2003.

1. mynd. Jökulsá á Breiðamerkursandi og brúin yfir hana. – *The glacial river Jökulsá á Breiðamerkursandi and the bridge. Ljósm./Photo: Náttúrustofa Suðausturlands/Snævarr Guðmundsson, 13. júní 2018.*

Figure 10. a) Shoreline changes at Jökulsá (Jóhannesson and Sigurðarson, 2005), b) Puffins, c) Aerial view of bridge crossing Jökulsá.

Stop 4: Little Ice Age terminal moraine hike

Coordinates (park at): 64.0438263, -16.1803975 (Eystri-Fellsfjara parking lot)

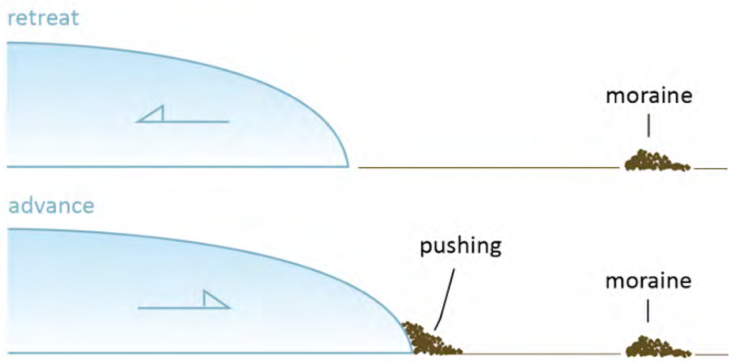
Coordinates (walk to): 64.0452412, -16.1836767 (two paths lead up to the crest, this is the one slightly closer to our vans)

The Little Ice Age terminal moraines

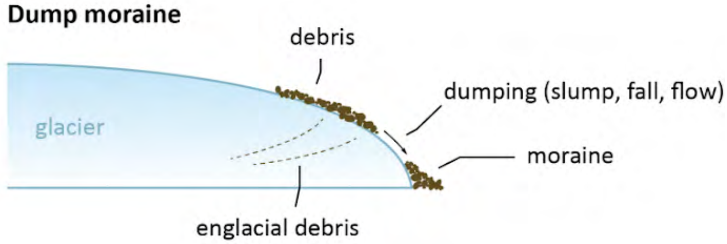
At Iceland's settlement during the Medieval Warm Period (A.D. 874), Vatnajökull is considered to have been divided into 2-3 main shields with much smaller outlet glaciers than today. At that time the Breiðamerkurjökull glacier snout lay at least 15 km behind the 1894 moraine. Two settlement farms are known to have existed on Breiðamerkursandur until around 1700. Their ruins were engulfed by the advancing glacier before 1720. In 1732 the Breiðamerkurjökull glacier snout lay about 9 km from the shore whereas in 1869 only 200 m separated the snout from the shore. (MIT/Woods Hole Field Guide 2006). The deposits north of Road 1, just before the bridge at Jökulsárlón, are part of the Little Ice Age terminal moraine that marks this furthest extent of the Breiðamerkurjökull ice streams since the settlements.

Terminal moraines are long ridges that form along the snout of a glacier, and mark the greatest extent of that glacier on the landscape. Because they form at the ice margin, preserved moraines are used to reconstruct the past positions of the glacier margin. They are generally formed from dumping of englacial and supraglacial material while the ice front is relatively stable, and during retreat also incorporate ablation moraines that are often ice-cored. A "fresh" moraine is often very unconsolidated, little to no vegetation, often ice-cored, and have sharper "crests". As the moraine settles this crest widens, the sediments condense, and entrained ice melts out and can create a hummocky surface. At the terminal moraines, we can observe what an "older" moraine looks like and compare to the fresh deposits we may see proximal to the terminus.

Push moraine



Dump moraine



Ablation moraine

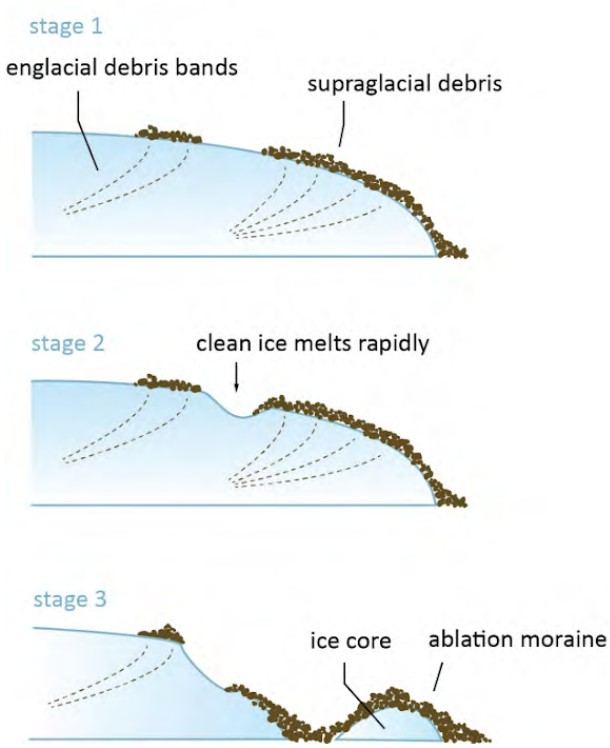


Figure 11. Summary of the three main moraine-forming processes. Push moraines (top) form during periods of ice-front stillstand or advance that bulldoze proglacial sediments. Dump moraines (middle) consist of rock and sediment that fall, flow and slump from the ice margin by gravity. Ablation moraines (bottom) form due to the varying rates of ice melt across the snout. Where debris cover is sparse (i.e., where the ice is 'clean') melting is relatively rapid and the glacier surface lowers quickly. Where surface debris cover is thick, the ice is insulated from melting and ice-cored moraines can exist. Created by J. Bendle. Source: www.antarcticglaciers.org

Stop 5: Jökulsárlón (Glacier Lagoon)

Coordinates (park at): 64.047262, -16.178323 (this lagoon parking lot has toilets)

Jökulsárlón is the proglacial lagoon formed by the retreat of Breiðamerkurjökull from its Little Ice Age moraines. The lagoon is currently 23 km^2 in area and up to 248 m deep. Breiðamerkurjökull contacts Jökulsárlón for 4.5 km along its terminus, producing an active iceberg calving margin that enhances glacial retreat. Because the post-Little Ice Age retreat of Breiðamerkurjökull and the growth of Jökulsárlón are both well-constrained over time, glaciologists have used this locality to evaluate the proposed mechanisms that control iceberg calving rates (Nick et al., 2007) and how proglacial lakes increase ice flow velocities (Baurley et al., 2020).

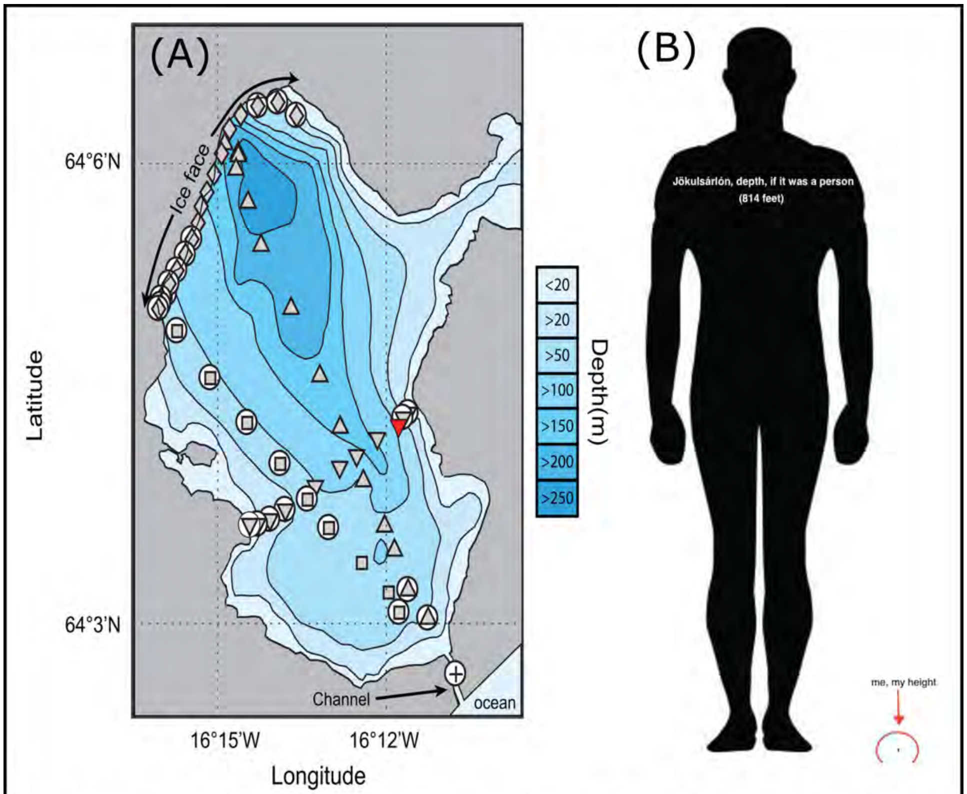
Why is Jökulsárlón so deep? Glacial erosion.

Jökulsárlón is an example of an overdeepening, which is a deep topographic basin formed within a glacial valley. Overdeepenings are commonly observed in deglaciated landscapes and underneath present glaciers and ice sheets. Overdeepenings require elevated glacial erosion to form the topographic depression. What could cause enhanced localized erosion? One hypothesis put forth by Hooke (1991) is that initial small bumps in bedrock topography kickstart a positive feedback process that produces overdeepenings. As ice flows over a bumpy obstacle, the drag on the upstream side of the bump causes the glacier flow to slow down (compressional longitudinal stress). Then, on the downstream side of the bump, the glacier flow speeds up (extensional longitudinal stress). This gradient in stress and flow velocity leads to tensile fracture (crevasses) at the surface. Crevasses allow for meltwater to flow more easily to the bed, which does two things relevant for glacial erosion:

(1) It enhances the erosional process of quarrying, which is when glaciers pluck off blocks of rock from the bed. Quarrying is greatest next to water-filled cavities with fluctuating water pressure (such as those experiencing time-varying water input from crevasses).
(2) Subglacial water can form channels that transports eroded material (sediment, quarried rocks) farther downglacier. This is important because otherwise, eroded material would build up in place as a layer of till and shield the underlying bedrock from subsequent erosion.

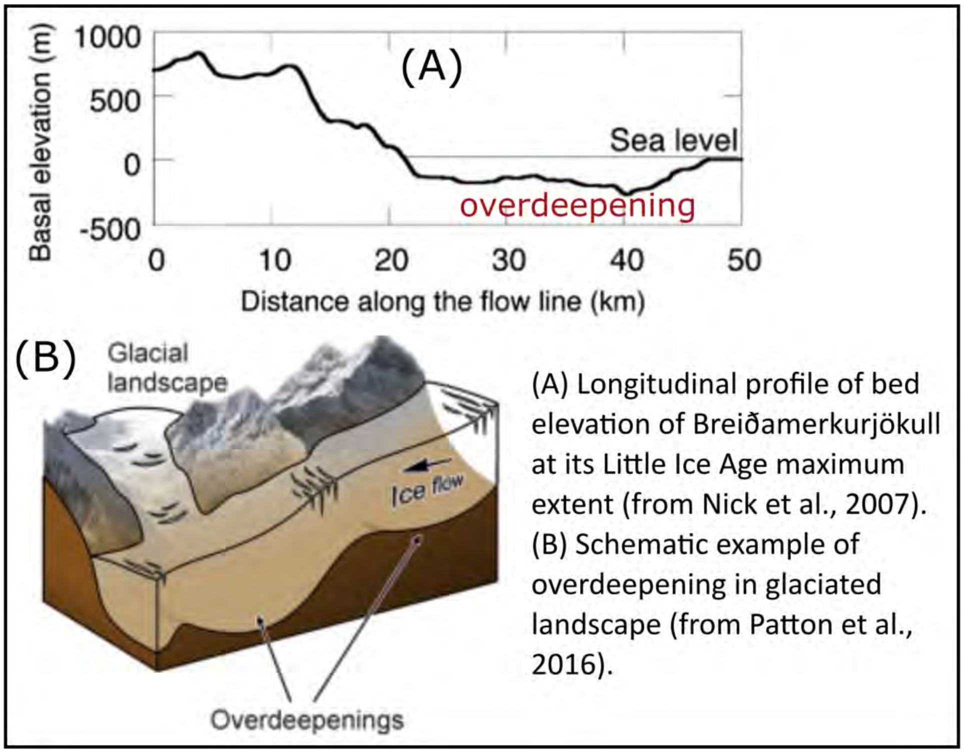
This hypothesis explains how locally enhanced erosion can form overdeepenings. Other hypotheses that may explain some overdeepenings include the "focusing" of ice flow when multiple glacier tributaries combine, and lithological variations along a glacier's flow path in which overdeepenings form in areas of weaker bedrock.

Prior to the late Little Ice Age, Breiðamerkurjökull was retracted several kilometers from its maximum extent, and an earlier sandur titled Breiðamork formed in the same area currently occupied by Breiðamerkursandur. Historical records do not refer to any large lakes on Breiðamork, implying that the overdeepening that Jökulsárlón occupies was filled with sandur sediments prior to the late Little Ice Age. When Breiðamerkurjökull advanced ~9 km between 1730 and 1890, it excavated hundreds of meters of sediment that previously filled the overdeepening (Bjornsson, 1996).



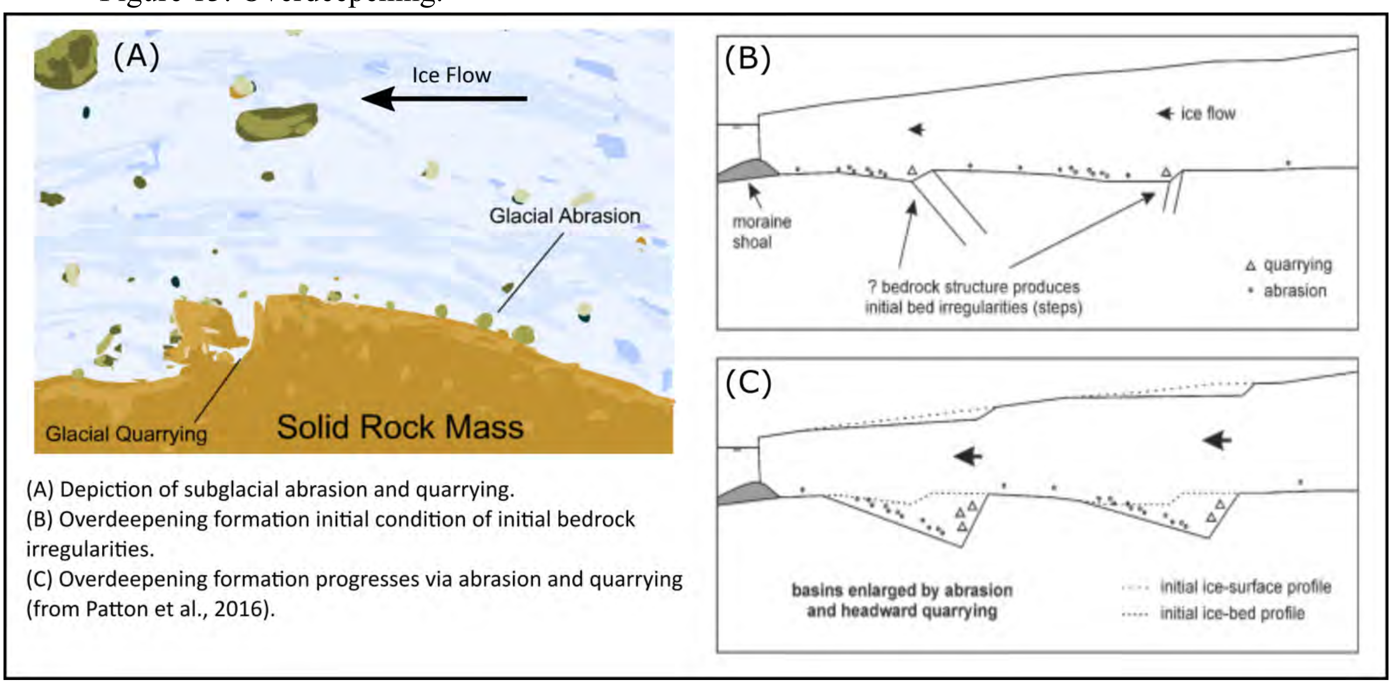
(A) Depth of Jökulsárlón in 2012 (Brandon et al., 2017). (B) Schematic depiction of Jökulsárlón max depth (~248 m) compared to Lizzi Runge's height (1.59 m). 155 Lizzi Runge's could drown in 1 Jökulsárlón. Photo courtesty of Runge (2023).

Figure 12: Jökulsárlón.



(A) Longitudinal profile of bed elevation of Breiðamerkurjökull at its Little Ice Age maximum extent (from Nick et al., 2007). (B) Schematic example of overdeepening in glaciated landscape (from Patton et al., 2016).

Figure 13: Overdeepening.



(A) Depiction of subglacial abrasion and quarrying.
(B) Overdeepening formation initial condition of initial bedrock irregularities.
(C) Overdeepening formation progresses via abrasion and quarrying (from Patton et al., 2016).

Figure 14: Glacial erosion and overdeepening formation.

Stop 6: Eskers and Recessional Moraines

Coordinates (pull off for recessional moraines): 64.0444266, -16.2852980,
Coordinates (park at for esker stops): 64.046047, -16.315292

Coordinates (walk to esker stop 1): 64.053994, -16.319243
Coordinates (walk to esker stop 2): 64.052771, -16.306026
Coordinates (walk to kame/kettle topography): 64.049451, -16.310488

Push moraines form at the snout of active glaciers. Rock and sediment debris at the ice margin is molded into ridges by the bulldozing of material (ice pushing) by an advancing glacier (Benn and Evans, 2010; Boulton, 1986). Due to the nature of their formation, push moraines tend to take on the shape of the ice margin during the time at which they formed (see image below). They are often found at the margin of active temperate glaciers (such as those found in southern Norway and Iceland) that experience brief periods of ice-front stability or advance despite a general pattern of recession. In some cases, a series of annual push moraines may form, where low-relief ridges are formed during winter advances of the glacier snout, leaving behind a detailed record of glacier extent over time (Sharp, 1984; Chandler et al., 2016).

Eskers are long, narrow and sinuous ridges of gravel and sand formed by glaciofluvial deposition within channels. The water that flows through channels within the ice can move and transport sediment uphill and downhill because the water follows the direction of the moving ice. This fact plays a fundamental role in the esker formation because it creates two different types of eskers: sharp crested eskers and broad-crested eskers (Figure 15). The former is very narrow with a pointy surface, well sorted, and is formed when the water flows downhill on flat or descending slopes, while the latter is wider with a round surface, well sorted with stratified layers of sediment, and is formed when the water flows uphill in ascending slopes.

Here we will walk to multiple eskers in Breiðamerkursandur that have been mapped in detail by Storrar et al. (2015), in what they term Major Esker System (MES) 1 and 2 (Figure 2 & 3). This area has the greatest density of eskers in the sandur.

Our first stop takes us to "Esker F" which was exposed as a result of glacial recession between 1945 and 1955. This esker was initially broad-crested with flat-topped cross section (width up to 70 m), but has since decreased in width to 20 to 30 m with a more triangular cross section. This esker is the widest within the MES 1 study area.

Our second stop point corresponds to a distributary esker complex ("J") of MES 2 and was exposed between 1955 and 1965. The largest esker in the system is 110 m long and up to 70m wide.

As we walk back to the parking area, we will traverse kame and kettle topography.

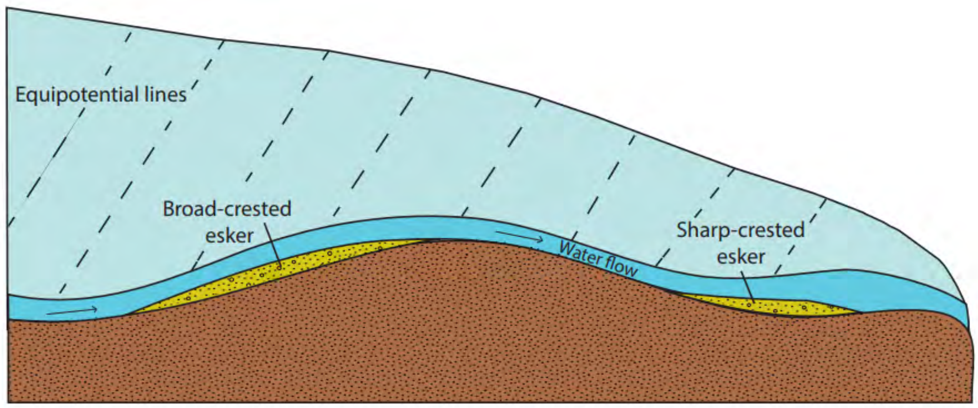


Figure 15. Broad-crested esker and sharp-crested eskers position along the subglacial channel.

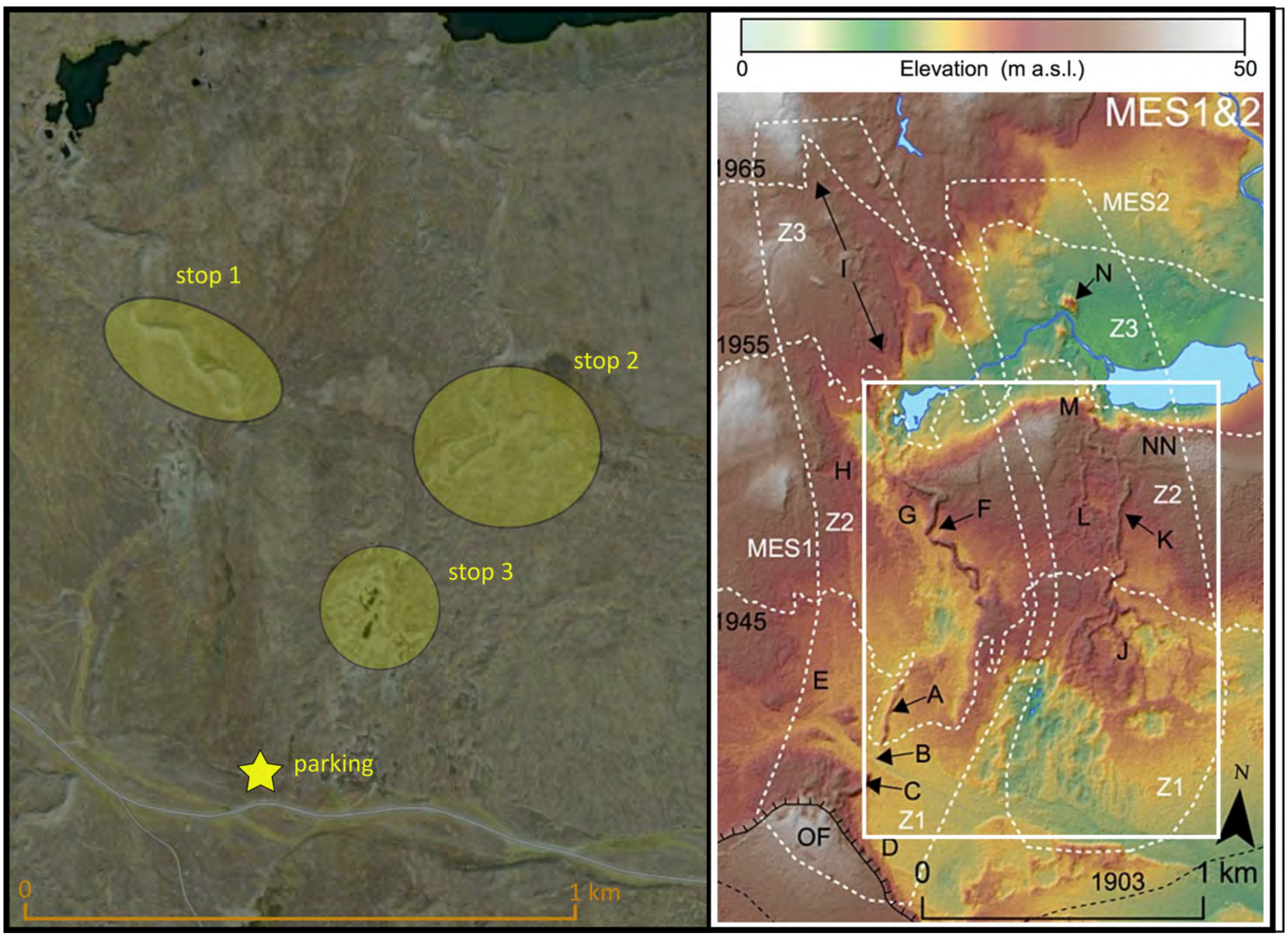


Figure 16. Location of the stops to see eskers and kame/kettle features. The map of Storrar et al. (2015) is shown on the right, with the white box corresponding to the satellite image on the left.

Stop 7: Kvíárjökull lateral moraine
Coordinates (park at): 63.9390°N, 16.4390°W
From Jordan et al., 2019

The parking area is just within the largest latero-terminal moraine complex in Iceland, marking the maximum late Holocene extent of the glacier Kvíárjökull (e.g., Spedding and Evans, 2002). The latero-terminal moraine system is defined by a set of high ridges, Kvíármýrarkambur on the south and Kambsmýrarkambur on the north, rising to a height of >100 m above the surrounding coastal plains (Fig. 70). The moraine system reaches to within 1.5 km of the current shoreline. The proximal slopes of the moraines are considerably steeper than the distal slopes. The latero-terminal moraine complex is breached by outwash streams at the eastern end (parking lot area) and northeast, and where the southern moraine meets the mountain front and a small lobe of the glacier cut through the moraine. Kvíárjökull is an outlet glacier of Öræfajökull, the small ice cap covering a stratovolcano of the same name introduced in the On Route section between Stops 5.5 and 5.6. Ice flowing off of the north side of the Öræfajökull massif merges with Vatnajökull. On all other sides, the Öræfajökull ice cap feeds outlet glaciers like Kvíárjökull. Because it extends beyond the mountain front, the lower portion of Kvíárjökull is classified as a piedmont lobe, though lateral spread is confined by the large latero-terminal moraines (Bennett et al., 2010). In front of the terminus are a proglacial lake and an outwash plain with scattered kettle lakes.

The high latero-terminal moraines are interpreted to have initially formed during Neoglacial cooling ~3200 years ago and have been progressively built by repeated occupations (e.g., Spedding and Evans, 2002). During Little Ice Age (ca. 1550–1900) advance Kvíárjökull again reached the extent marked by the latero-terminal moraine complex, as documented in the Danish maps from 1903 and 1904. Surveyed points on the glacier in these maps show that it would have been possible to see over the moraines from parts of the piedmont lobe, which is certainly not true today. The lateroterminal moraine system is breached at several points, including its end where the river Kvíá flows from the proglacial lake to the sea. A notable breach occurs at Kambsskarð where the southern moraine ridge meets the mountain front. A lobe of ice has spilled through this breach in the past and a beautiful set of accreted lateral moraine ridges on the mountain front (Iturrizaga, 2008) marks previous glacial occupations of this breach (Fig. 71).

The area immediately west of the parking lot consists of hummocky recessional end moraine deposits. Well-defined low (<3 m) inset lateral push moraines formed during retreat from the Figure 71. The view up Kvíárjökull (Stop 5.7) from the hummocky recessional end moraine complex in front of its proglacial lake. Figure 73. The breach in the Kvíármýrarkambur latero-terminal moraine where it reaches the mountain front at Kambsskarð. Note the well-developed lateral moraines. Figure 72. Small but well-defined push moraines on the proximal slope of Kvíármýrarkambur above Kvíárjökull (Stop 5.7). Little Ice Age maximum (Bennett et al., 2010) diagonal up the proximal side of the southern moraine ridge (Fig. 72). Though generally retreating since the end of the Little Ice Age, Kvíárjökull underwent periodic advances during the 1980s and 1990s (Bennett and Evans, 2012) and more recently advanced ~200 m along its northern terminus in the winter of 2013–2014 producing a push moraine (Phillips et al., 2017). Time permitting, one gains a better perspective hiking up on to Kvíármýrarkambur (the southern moraine ridge), and the longer walk along the ridge to the Kambsskarð breach (Fig. 73), encountering spillover channels along the way, is well worthwhile (~3 km each way).

The explanation for the large latero-terminal moraines of Kvíárjökull is that it carries an unusually high sediment load. Kvíárjökull is characterized as debris-charged (e.g., Spedding and Evans, 2002; Bennett et al., 2010). One of the most important sources of this debris is rockfall (Spedding and Evans, 2002). The glacial valley through which Kvíárjökull flows is unusual in Iceland for its steep continuous valley walls carved into thick rhyolite lavas (Fig. 71)

Figure 17. On-land view of the lateral moraine of Kvíárjökull glacier.

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June 4: Hvannagil Rhyolites + Dikes, Hvalnes Gabbros + Zeolites
(Noah, Pablo, Claudia, Emily)

Summary

Stop	Location	Stop duration	Topic
Hvannagil Hike	64.6610°N, 14.3064°W	3-4 hours	Rhyolites + Dikes
Hvalnes Beach + Roadside	64.4022°N, 14.5399°W	2 hours	Gabbro + Zeolites
Múlaþing, Iceland Outcrops	64.6208°N, 14.4127°W	1 hour	Zeolites primarily
Optional: SE Coast Overlook	*64.2840°N, 15.0354°W*	*30 minutes*	*Pretty Overview*

Proposed day schedule:

Start: Vagnsstadir hostel, breakfast. Leave at 9 AM

Stop 1: 1 hr drive to Hvannagil (arrive ~ 10 AM), Rhyolites, Dikes, ~5 mi loop, ~3 hours
Stop 2: 30 min drive to Hvalnes Beach (arrive ~ 2 PM), Gabbro, Zeolites, ~2 hours
Stop 3: 30 min drive to the good zeolite outcrops at Múlaþing, Iceland ~ 1 Hour (Potentially contained within the two hours listed above)
Stop 3: Optional, en route on way back to hostel: SE Coast Overlook (30 minutes)

End: 1-1h30 drive back to Vagnsstadir hostel, dinner. (arrive ~6:30 PM)

Stop Information

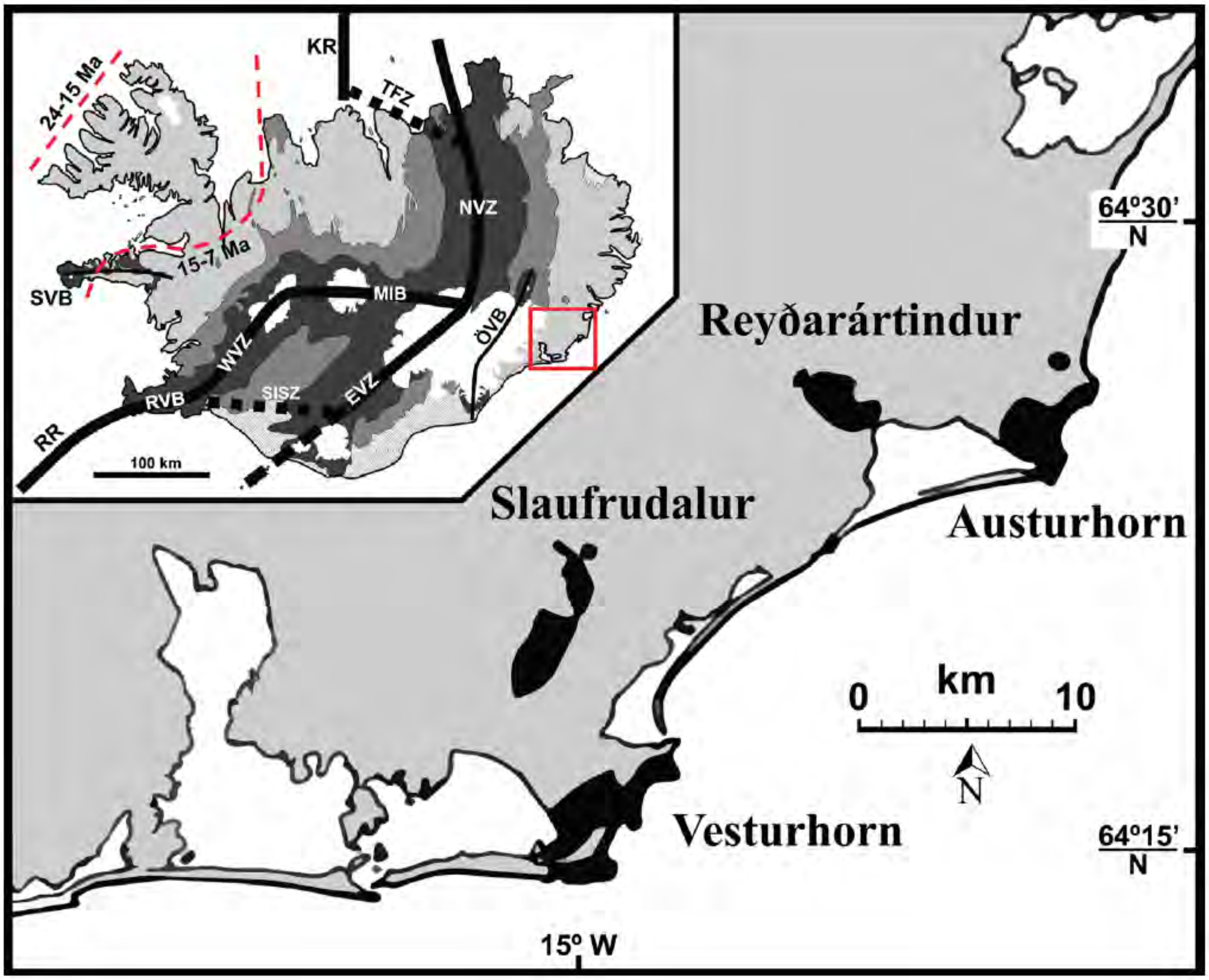
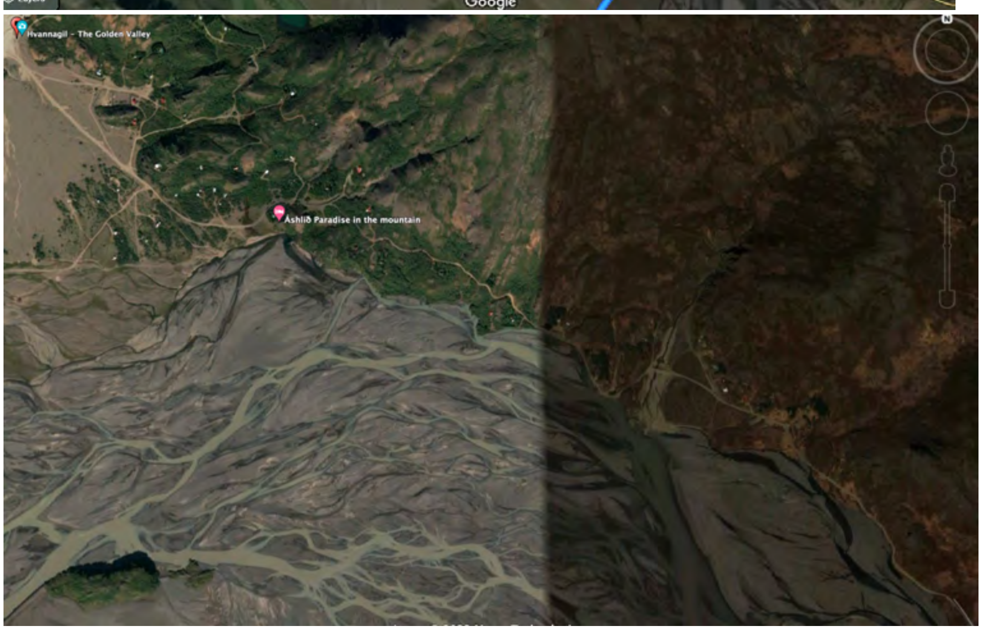


Fig. 1.0. *Regional map of southeast Iceland outlining the four major composite silicic intrusions exposed in the area (black shaded areas). Inset box is an overview map of Iceland and its major tectonovolcanic zones: Northern (NVZ), Eastern (EVZ), and Western Volcanic Zones (WVZ), Snæfellsness Volcanic Belt (SVB), Reykjanes Ridge (RR), Reykjanes Volcanic Belt (RVB), South Iceland Seismic Zone (SISZ), Öræfi Volcanic Belt (ÖVB), Tjornes Fracture Zone (TFZ), Kolbeinsey Ridge (KR), and the Mid-Iceland Belt (MIB). The red dashed lines represent extinct rifts. The red box indicates the location of the intrusions. The shades of gray indicate age divisions: light gray = Neogene (17–3.3 Ma); medium gray = Plio–Pleistocene (3.3–0.7 Ma); dark gray = upper Pleistocene to present (0.7–0 Ma); white = ice caps or water. Map from Padilla et al. (2016).*

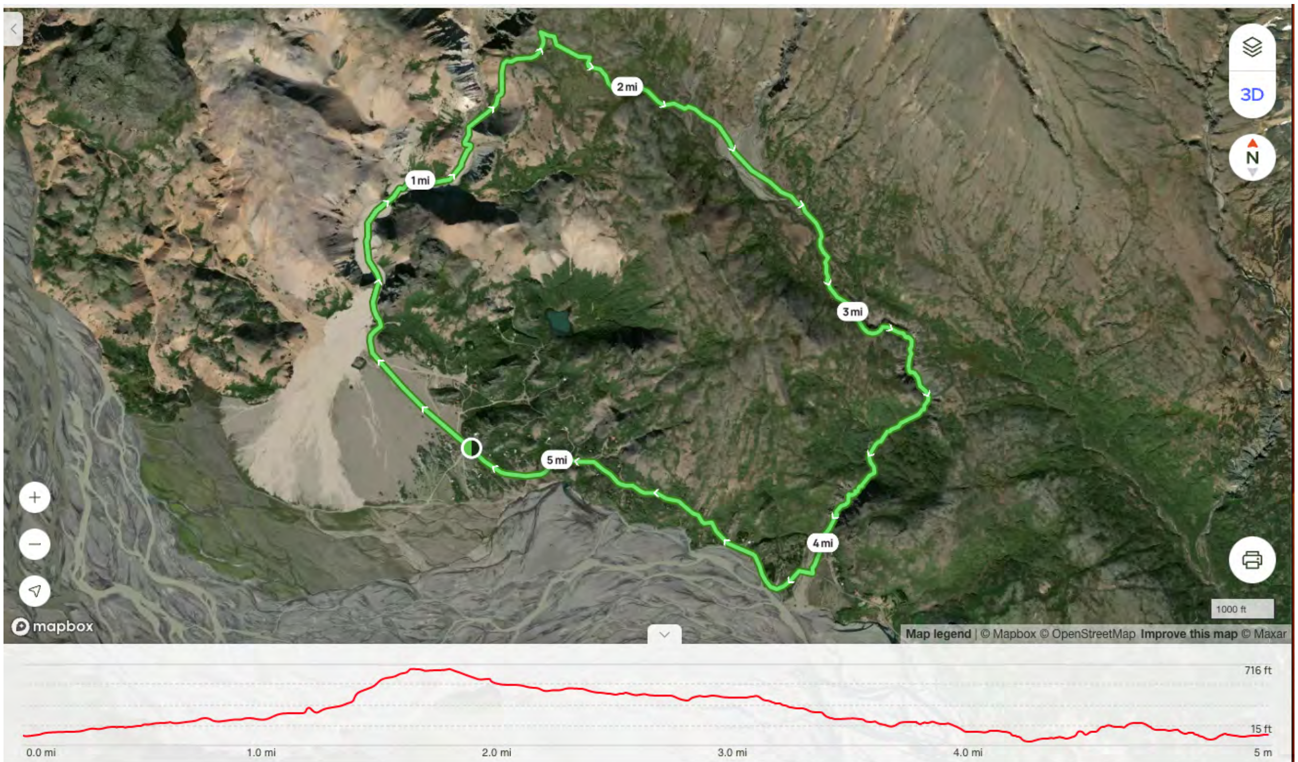
Stop 1: Hvannagil "Golden Valley" Rhyolites 64.6610°N, 14.3064°W (3-4 hours)

Directions: **From a visitor in 2022:** We took the road right after the bridge, Grænahlíð, which goes past a ton of small holiday homes. There had clearly been a lot of work done on it recently, and was very doable, though a single track and you must be ready to back up etc. After parking, we walked into the valley to the right, and honestly it was one of the most beautiful places we hiked. This avoids the F road issue. But definitely needs a 4X4. There was no river crossing on the drive. But hiking into this valley we had to cross many small streams, very doable though.



From a visitor in September 2022: The dirt road begins just N of the bridge over the river and it leads upstream past numerous holiday homes to the entrance to the canyon. A hiking trail gives access to the canyon and you can walk several hundred meters upstream into its wildest section, where the path then climbs steeply out of the gorge. You may get to the start of the Hvannagil hike trail by any car in summer. The road leading to Hvannagil valley is semi-paved and narrow but **without any river crossings**. There's no designated car park, but you can safely park your car at the huge pebbles area located here. This is a good starting point for the hikes in the area.

From AllTrails: 5.3 mi hike, average 2h25 minutes to complete, 810m elevation gain.



Older Central Volcanoes (from Jordan et al., 2019): As the volcanic plateau of the Tertiary Basalt Formation formed, central volcanoes grew in places with concentrated eruptive vents that allowed repeated eruptions. The majority of central volcanoes older than Holocene have been variably eroded by repeated glaciation, but remnants of their eruptive products and underlying magmatic systems remain accessible. In addition to providing a glimpse into the petrogenesis of silicic and basaltic magmas throughout the majority of Iceland's history, these older central volcanoes also provide a template by which to understand Neovolcanic systems. The oldest central volcanic systems are exposed at the western (e.g., Hrafnsfjörður ca. 14 Ma; Banik, 2015) and easternmost (e.g., Breiðuvík ca. 13 Ma; Carley et al., 2017) edges of Iceland and generally young toward the Neovolcanic zone, in accordance with Iceland's crustal evolution. In southeastern Iceland, central volcanic systems experienced such extensive erosion that only the intrusive complexes associated with the volcanic systems remain (e.g., Austurhorn, Furman et al., 1992a; Padilla et al., 2016). These exposed intrusive complexes provide glimpses into the processes operating several kilometers deep in the crust (**Fig. 1.1**)

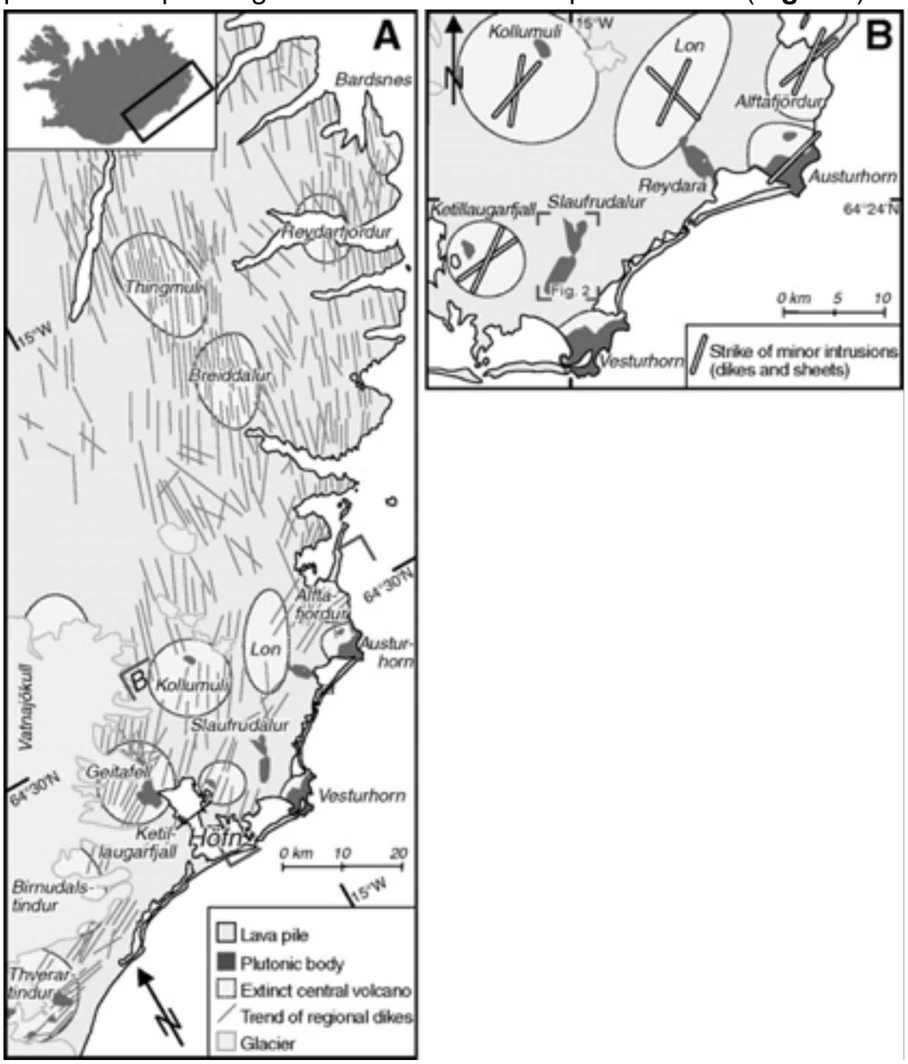
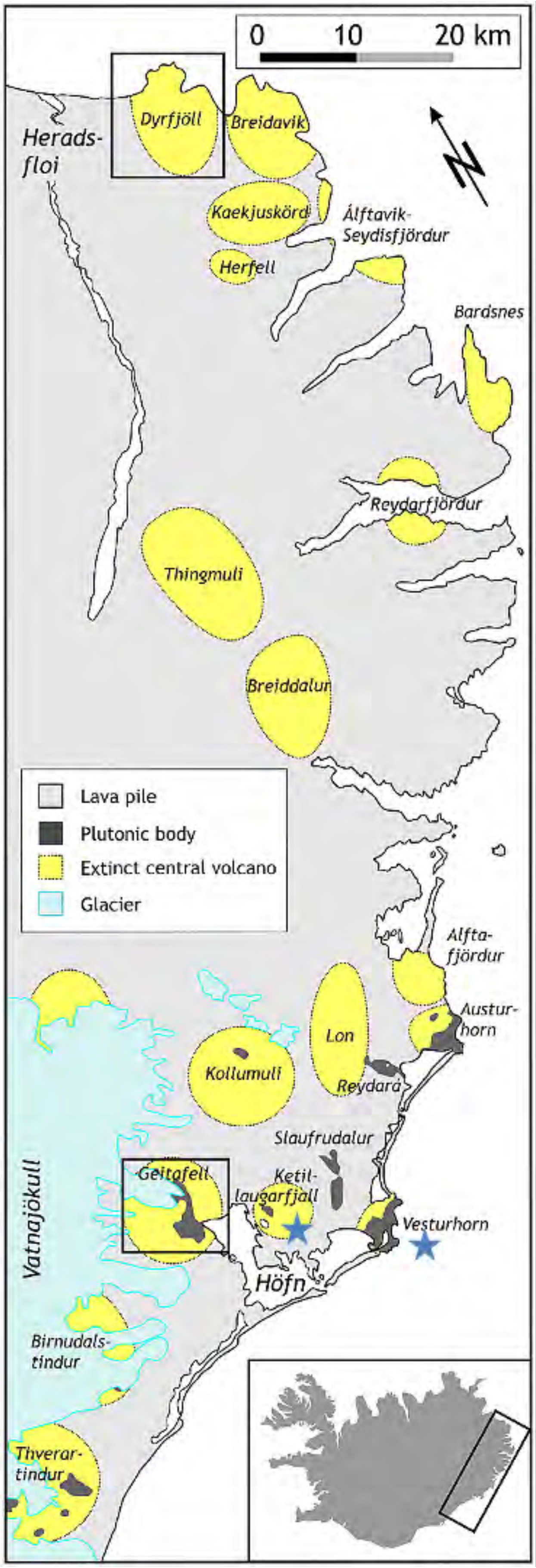


Figure 1.1: *(A) Schematic tectonic map of southeast Iceland, modified after Walker (1974) (location shown in inset map). Trends of regional dikes, according to Walker (1974), are representative values for every tenth dike. (B) Detailed tectonic map of the greater Lónsöraefi area (location marked in A).*



0
10
20 km
Dyrfjöll
Breidavik
Herads-
floi
Kaekjuskörd
Álftavik-
Seydisfjördur
Herfell
Bardsnes
Reydarfjördur
Thingmuli
Breiddalur
Lava pile
Plutonic body
Extinct central volcano
Glacier
Alfta-
fjördur
Austur-
horn
Lon
Kollumuli
Reydará
Slaufrudalur
Geitafell
Ketil-
laugarfjall
Vesturhorn
Vatnajökull
Höfn
Birnudals-
tindur
Thverar-
tindur

<u>Extinct volcanic systems (**Figure 1.2**) are often characterized by:</u>

(1) the occurrence of acid rocks that are restricted in Iceland to volcanic centers

(2) inclined sheet swarms

(3) plutons composed of gabbro and/or granophyre

(4) disturbances of the regional metamorphic zones and local occurrence of alteration zones from volcanic high-temperature geothermal systems

(5) deviations from the regional dip of the surrounding country rock as a consequence of uplift and/or subsidence of the center of the volcano and

(6) associated swarms of vertical dikes that represent the feeders of fissure eruptions

(Burchardt et al., 2011; 2021)

Figure 1.2: *Schematic map of eastern Iceland that illustrates the distribution of extinct central volcanoes embedded in the Tertiary lava pile. The depth of glacial erosion decreases northward so that the volcanoes in the south are exposed at deeper levels, including plutons that represent parts of their magma chambers. (Burchardt et al., 2011)* **Blue stars = our stops!**

Dyrfjöll and Njarðvík (12-13 Ma) to the north, and Geitafell (4-5 Ma), nearby Hofn, are possible fossil analogues of the Torfajökull Volcano in Southern Iceland that contains the largest volume of exposed silicic rocks in Iceland.

Origin of silicic and intermediate magmas (from Jordan et al., 2019): Despite its position at the junction of a mid-ocean ridge and an oceanic hotspot (traditionally basaltic settings), Iceland is home to a surprising abundance of silicic igneous rocks. In a survey of Icelandic rocks from the late Pleistocene and Holocene, ~14% of rocks are estimated to be intermediate and 11% silicic, with the remaining 75% basaltic (Jakobsson et al., 2008). The Icelandic crust as a whole is thought to consist of ~10% silicic rocks. This makes Iceland a global anomaly as home to the greatest known concentration of silicic rocks in the modern ocean (e.g., Walker, 1966; Gunnarsson et al., 1998). <u>Explanations for silicic abundance (end members) :</u>

(1) **Extreme fractional crystallization of mafic magma:** According to Bowen's reaction series, however, fractional crystallization is unlikely to produce large volumes of silicic rocks, as only ~5–10 parts rhyolite can be distilled from 100 parts basalt. In our field area in Borgarfjörður Eystri, in the late 1980s Gústafsson recognized that silicic rocks represent

20–25 percent of the total rock mass exposed and, hence, fractional crystallization alone might not to be the sole process responsible for rhyolite petrogenesis here.

(2) **Assimilation or partial melting of hydrothermally altered basalt:** Crustal melting may also have made a contribution and is thought to occur when voluminous accumulations of basalts in mature rift zones undergo relatively rapid burial during crustal accretion. During this burial the basaltic lavas experience hydrothermal alteration and an associated metamorphism that can reach up to amphibolite facies. In the vicinity of additional heat sources, e.g. a basaltic intrusion, partial melting will set in locally However, this hypothesis is also, in a sense, problematic. It cannot explain the discrete (i.e. non-continuous) occurrence of rhyolites along the rift zone, as burial and basaltic activity are likely to be ongoing processes along the entire rift.

(3) **Tectonic underpinning:** One explanation for the relative abundance of silicic magma is that a sliver of ancient crust might be tectonically pinned beneath Iceland. If present, this pinned crust might influence some of the island's unusual characteristics, as discussed in the Tectonic Features of Iceland section (e.g., overly thickened crust, abundance of felsic material, heterogeneous isotope compositions: Foulger et al., 2005b; Martin et al., 2011; Torsvik et al., 2015).

Regional context for dikes: In the Eastfjords, closely spaced dikes cut through the thick deposits of westward dipping Tertiary lavas that compose the bedrock of the area. The hundreds of dikes in this region tend to be 3–6 m in width, sub-vertical, striking NNE. These fissure eruptions are thought to be accommodated by NNE-SSW extension and subsequent graben faults (Burchardt et al., 2021). The number of dikes declines in frequency from the base to the surface of the Tertiary lava pile. Dikes, like lava flows, will lose heat to their cooler surroundings. The rocks contract perpendicularly to the direction of cooling, and form thermal contraction joints parallel to the direction of dominant heat loss (**Fig. 1.3**). For example, some dikes lose heat horizontally to the surrounding bedrock, and so do not always have vertically oriented columns (**Fig. 1.3, 1.4**).

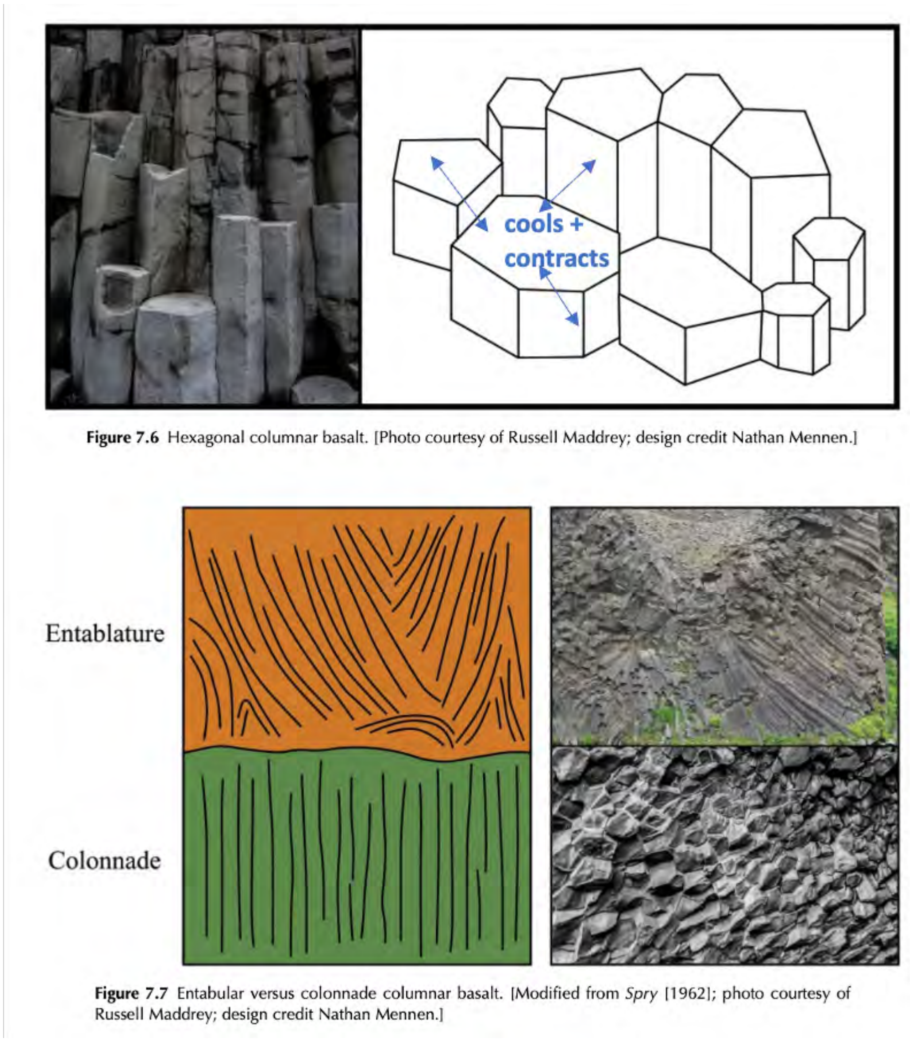


Figure 1.3*: Schematics + photos of cooling/contracting, in different orientations. (Jordan et al., 2019)*

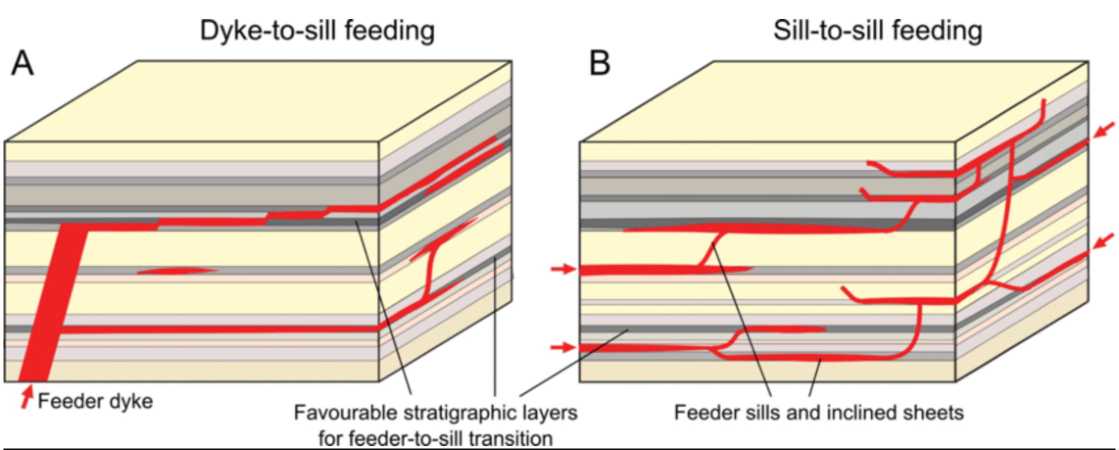


Figure 1.4*:* ***A.*** *Schematic drawing of a dike feeding sills.* ***B.*** *Schematic drawing of sills feeding sills via inclined sheets, modified from Airoldi et al. (2016). Note that in both cases, feeder-to-sill transitions occur abruptly at favorable stratigraphic levels*

Figure 1.5: *Basaltic dikes cross-cutting altered rhyolite hills in Hvannagil Canyon*

Stop 2: Austurhorn/Hvalnes Beach Gabbro + Zeolites (64.4022°N, 14.5399°W) (1.5 hours)

Directions: Drive to the lighthouse, park, and then examine outcrops exposed along the cliffs and shore. From the lighthouse, you will have a beautiful view of Hvalnesfjall (the gabbroic peaks rising to the north; **Fig 2.1**), the lagoon Lón, protected by an extensive baymouth bar, and the Vesturhorn intrusive peak on the western horizon (**Fig 2.2**).

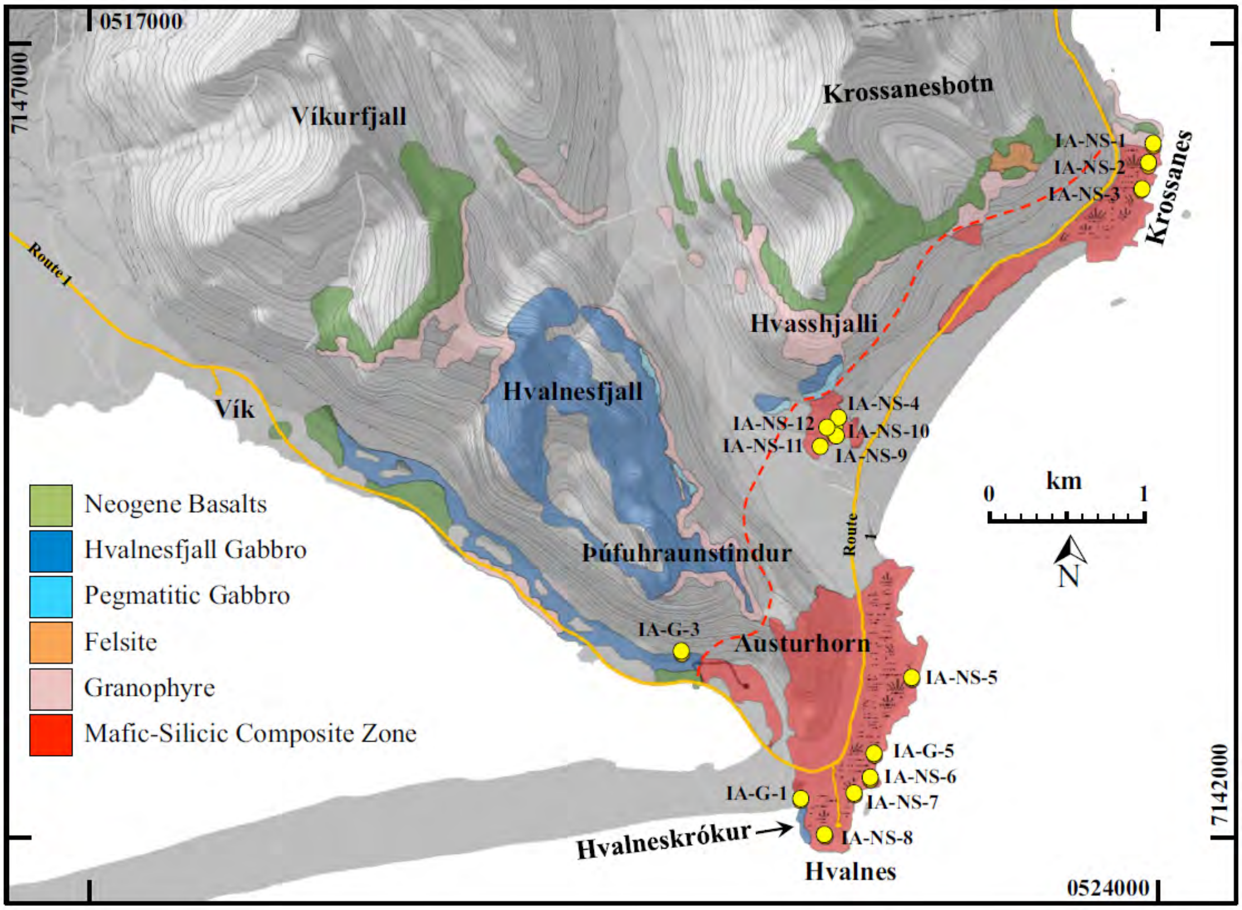


Fig 2.1: Map: *Geologic map of Austurhorn from Padilla et al. (2016). Yellow dots and labels indicate sampling locations from the original publication. The implied structural top of the mafic-felsic composite zone is indicated with a dashed red line.*

Fig 2.2: Panorama: *View looking west from the Hvalnes Peninsula at Austurhorn, across the Lón baymouth bar to Vesturhorn (Jordan et al., 2019)*

Explanatory text (modified from GSA 2019 Field Guide by Jordan et al., 2019):

Former magma conduits—dikes and sills—are relatively common features that you will see as you travel around the periphery of Iceland. **Former magma reservoirs—plutons and intrusions—are far rarer, largely due to Iceland's shallow level of erosion (no more than a few km). At this stop, you will explore one of the few—and one of the largest—exposures of intrusive silicic rock in Iceland.** Approximately 6.5 Ma, along the SE coast of Iceland, mafic and felsic magmas were intruded into lavas and tuffs erupted from now-extinct Miocene central volcanoes (Álftafjörður and Lón; Walker, 1964; Blake, 1966, 1970; Ross and Mussett, 1976). These magmas, which we now refer to as the Austurhorn Intrusive Complex (AIC), were emplaced at ~2 km depth (Blake, 1966; Walker, 1960, 1964) and now occupy a footprint of ~15 km^2 as delineated by a 1-km-wide contact metamorphism aureole (Walker, 1964; Blake, 1966, 1970; Ross and Mussett, 1976). These depths and dimensions match expectations for active magma bodies beneath modern central volcanoes (e.g., Furman et al., 1992b). This suggests that Austurhorn can provide rare insight into modern subvolcanic magmatism at Icelandic central volcanoes. The compositional complexity observed at Austurhorn helps to explain the origin of mafic-felsic features observed in young eruptive deposits.

The intrusive rocks at Austurhorn include gabbro (mafic), granophyre (felsic), and intermediate rocks. The intermediate rocks at Austurhorn are the result of complex mixing, mingling, and remelting of mafic and felsic magmatic endmembers (Walker, 1966; Furman et al., 1992a, 1992b; Padilla et al., 2016) **(Fig. 2.3)**. The construction of Austurhorn was a dynamic process which involved multiple pulses of magma interacting with previously emplaced melts and mushes and rock. Zircon ages suggest that the construction of Austurhorn likely spanned ~320 k.y., beginning ca. 6.67 Ma and continuing until ca. 6.35 Ma (Padilla et al., 2016). The compositional end members (i.e., the most mafic and the most felsic) are somewhat older than the intermediate rocks exposed in the intrusive complex (Padilla et al., 2016). The "horn" at Austurhorn (East Horn) is a ridge in the middle of the intrusive complex that contains the peaks Hvalnesfjall and Þúfuhraunstindur (**Fig 2.1**). The majority of the gabbro at Austurhorn is confined to these peaks, and is mostly surrounded by granophyre (Padilla et al., 2016). The intermediate mixed, mingled, and melted portions of Austurhorn account for ~30–40% of the intrusive complex, exposed in a somewhat-continuous zone that extends from the base of Þúfuhraunstindur, south to the peninsula Hvalnes, and north to the point Krossanes (**Fig 2.1**).

This zone, bounded by granophyre and country rock, is referred to as the "net-veined complex" (e.g., Blake, 1966; Mattson et al., 1986; Furman et al., 1992a, Weidendorfer et al., 2014) and the "mafic silicic composite zone" or MSCZ (Padilla et al., 2016).

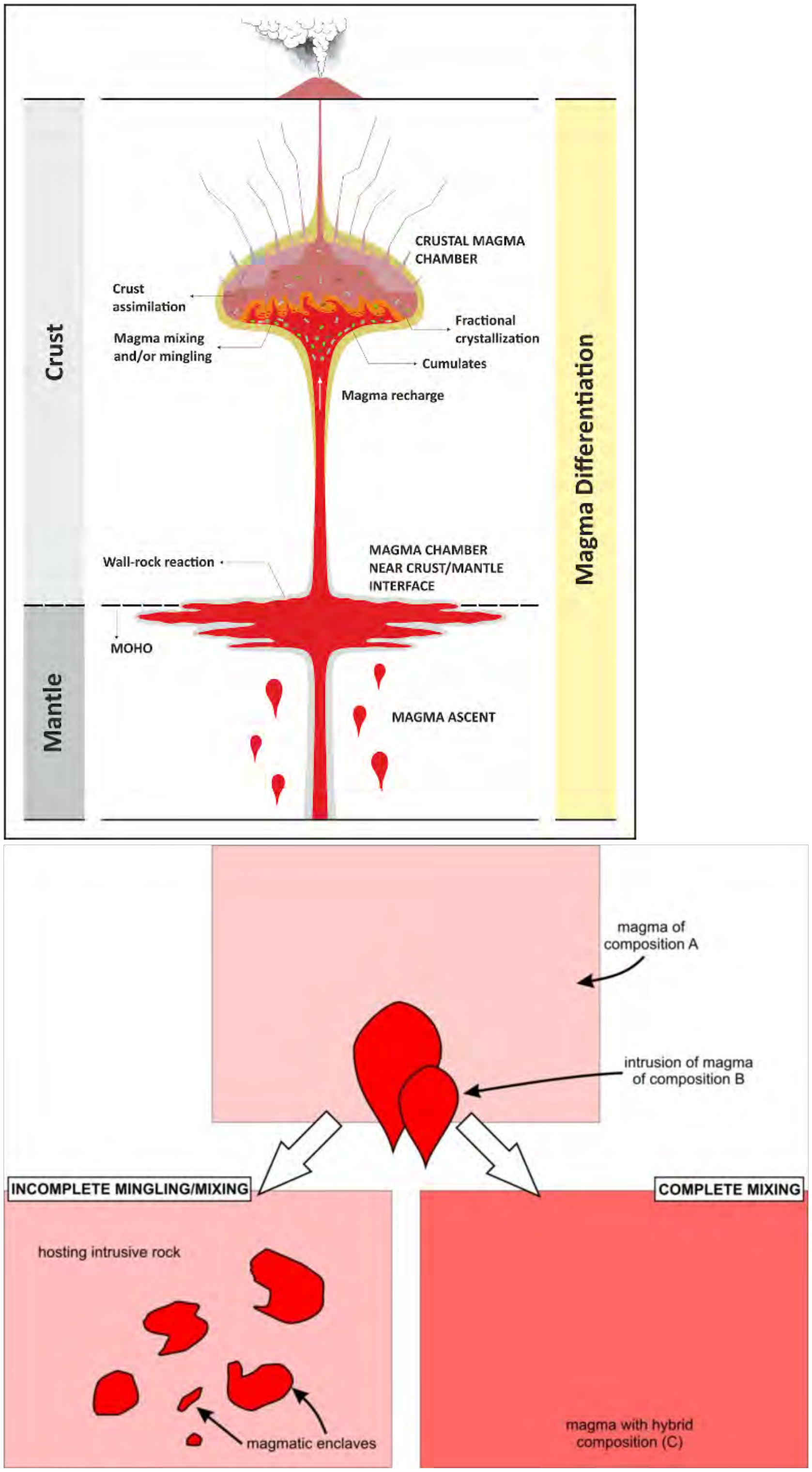


***Fig. 2.3. Top**: Schematic model for magma differentiation (Gündüz and Asan, 2022). **Bottom**: Example of incomplete magma mixing and mingling, and complete hybridization with respect to the parent magmas. From: https://geologyistheway.com/igneous/magma-mingling-and-mixing/.*

For evidence of molten interaction between mafic and felsic magmas, look for pillow-like mafic enclaves with crenulate, cuspate, and/or chilled (glassy) margins (**Fig 2.4A)**. These indicate magma mingling, with differences in temperature and viscosity inhibiting compositional exchange between the two end-member magmas. In your quest for evidence of molten interaction between mafic and felsic magmas, you may also observe diffuse boundaries with a visible gradation from mafic to intermediate to felsic composition (**Fig 2.4B**). These features can be interpreted as magma mingling between mafic and felsic endmembers, or disruption and dispersion of crystal mushes. In addition to evidence of molten-molten interaction, you will discover evidence of mobile magma that interacted with chilled rocks during construction of the pluton. As you consider molten-solid interactions, look for angular clasts of mafic rock (seemingly shattered or brecciated enclaves) suspended in felsic matrixes (**Fig. 2.4C**).

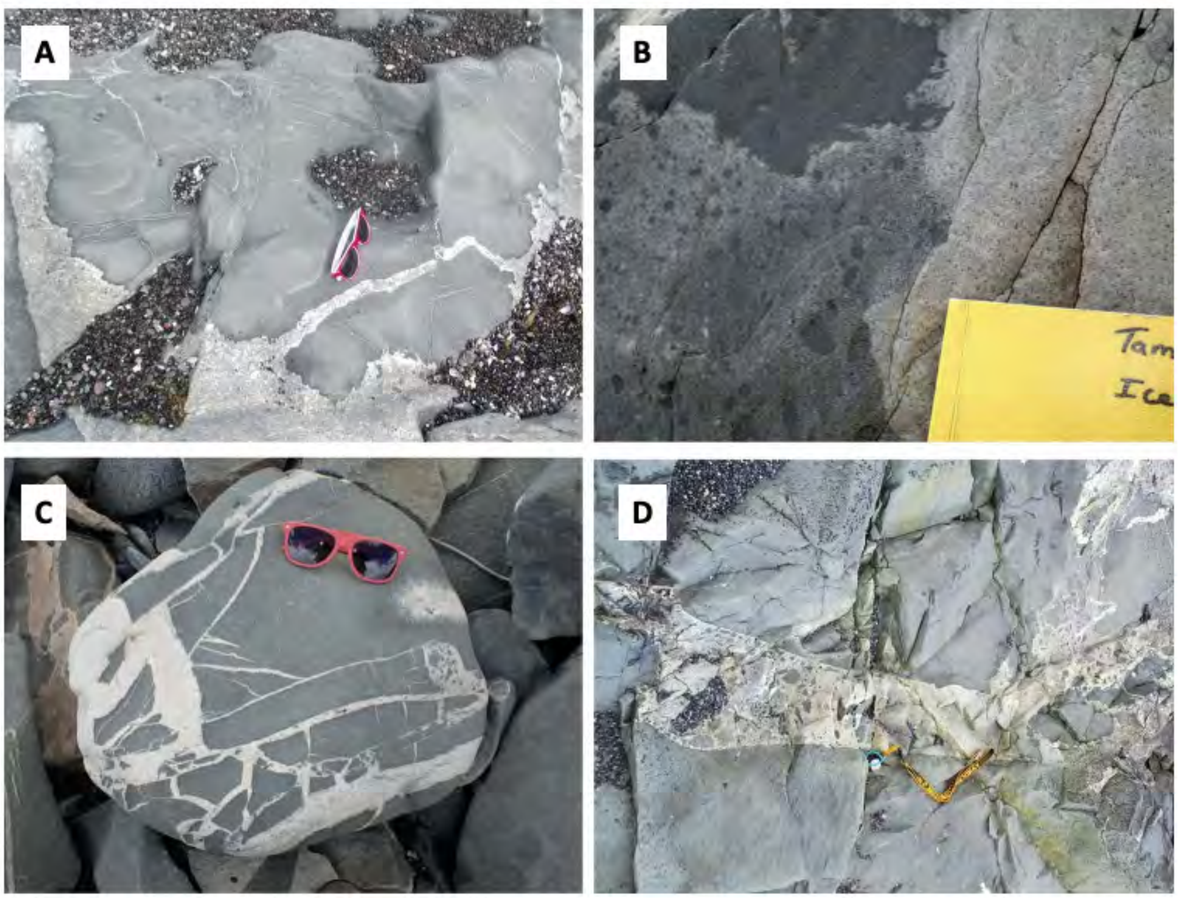


Fig. 2.4: Mixing + Mingling: *Diversity of magma mixing and mingling in the Austurhorn Intrusive Complex (AIC). (A) Mafic pillows with crenulate margins; (B) intermediate compositions from mixing at diffuse boundaries; (C) brecciated mafic blocks in a felsic matrix; (D) an example of a felsic tabular body, containing brecciated blocks, cross-cutting mafic rocks. (Jordan et al., 2019).*

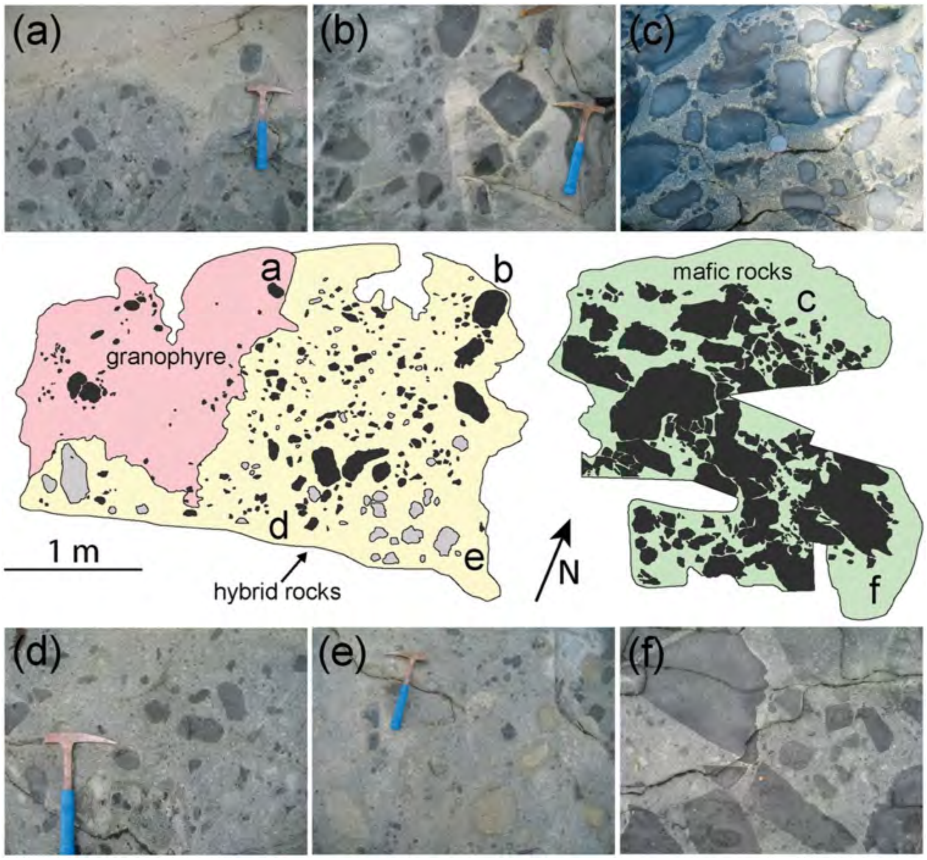


Figure 2.5 *(Weidendorfer et al., 2014) Photographs of outcrops at Hvalnes beach. The digitized sketch illustrates the contact zone between the granophyre and the hybrid and that between the hybrid and the mafic rocks. Letters within the sketch indicate the locations of the photographs. The right-hand side of the sketch is dominated by mafic pillows and rounded to angular mafic fragments contained within a hybrid matrix. The mafic sheet from which the pillows originate is located ~3 m to the NE. Black objects represent mafic enclaves and grey objects are felsic enclaves. (a) Contact zone between the felsic endmember (granophyre) and hybrid rocks. At the position of the hammer, a sharp contact zone separates two hybrid generations. In this zone the felsic endmember appears affected by hybridization. (b) Cross-cutting relationships between hybrid generations. (c) Mafic pillows form at the tip of the mafic sheet that intrudes into the granophyre host. Pillows at Hvalnes beach are characterized by only weakly developed chilled margins and a yellowish halo. (d) Mafic enclaves close to the contact between the hybrid and granophyre rocks. (e) Felsic, coarse-grained enclaves are commonly well rounded compared with angular mafic fragments. (f) High variability of mafic enclave geometries indicates complex mixing and mingling dynamics.*

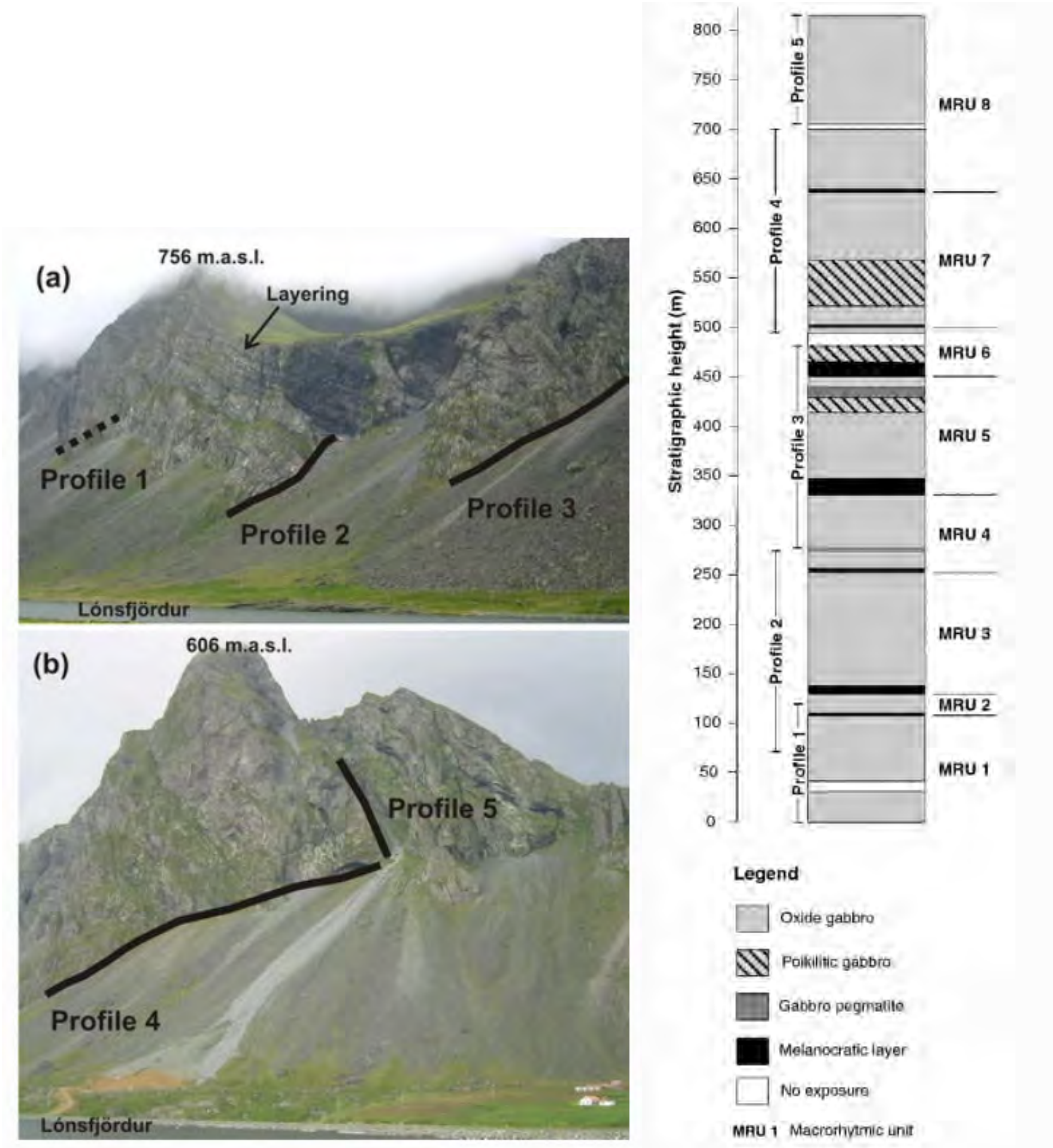


Figure 2.6: *Macrorhythmic units (Thorarinsson and Tenger, 2009): dark/melanocratic = clinopyroxene, olivine; light/leucocratic = plagioclase rich. These melanocratic layers are interpreted as the crystalline products following primitive magma replenishment and mixing with residual magma. Steady decreases in Mg# in clinopyroxene up-section in some macrorhythmic units, coupled with decreases in whole-rock Mg# and Cr2O3 in magnetite, indicate that periods of normal fractionation in some cases followed recharge. Forward fractionation modeling of these compositions indicates that individual macrorhythmic units crystallized from relatively thin (200–300 m) melt lenses, which implies similarity with the Grímsvötn magma chamber and 'mushy' mid-ocean ridge magma chambers*

Optional: Austurhorn Roadside (64.4238°N, 14.5371°W)

Directions: This stop is related to Hvalnes Beach. If weather, tides, and time permit, cross the road, walk along the coastline and reconvene at the roadside outcrop (~1.5 mi, easy terrain)***.***

Relevant Mineralogy Vocabulary (Stanford 2009 field guide)

Actinolite: A bright-green or grayish-green monoclinic mineral of the amphibole group: Ca2(Mg,Fe)5(OH) 2[Si8O22]. It occurs in fibrous, radiated, columnar, or asbestos forms in metamorphic rocks (such as schists) and in altered igneous rocks (**Fig. 2.7B**).

Epidote: A yellowish-green, pistachio-green, or blackish-green mineral: Ca2Al2(Fe3+,Al)(SiO4)(Si2O7)O(OH). Minerals in the epidote group are common, known to be found in many types of metamorphic rocks, hydrothermal rocks (rocks that have been modified by the interaction of hot fluids) and certain kinds of igneous rocks, where it represents alteration products of ferromagnesian minerals. It commonly occurs associated with plagioclase and chlorite as formless grains or veins, or as monoclinic single-crystals in low-grade metamorphic rocks (**Fig. 2.7A**).

Zeolites: Microporous, hydrous aluminosilicates, similar to the feldspars. They easily lose and regain their water of hydration (and associated cations) and they fuse and swell when heated. Differences in zeolite mineralogy can be used to diagnose differences in temperature, pressure, and chemistry during rock formation (**Fig. 2.7C**).

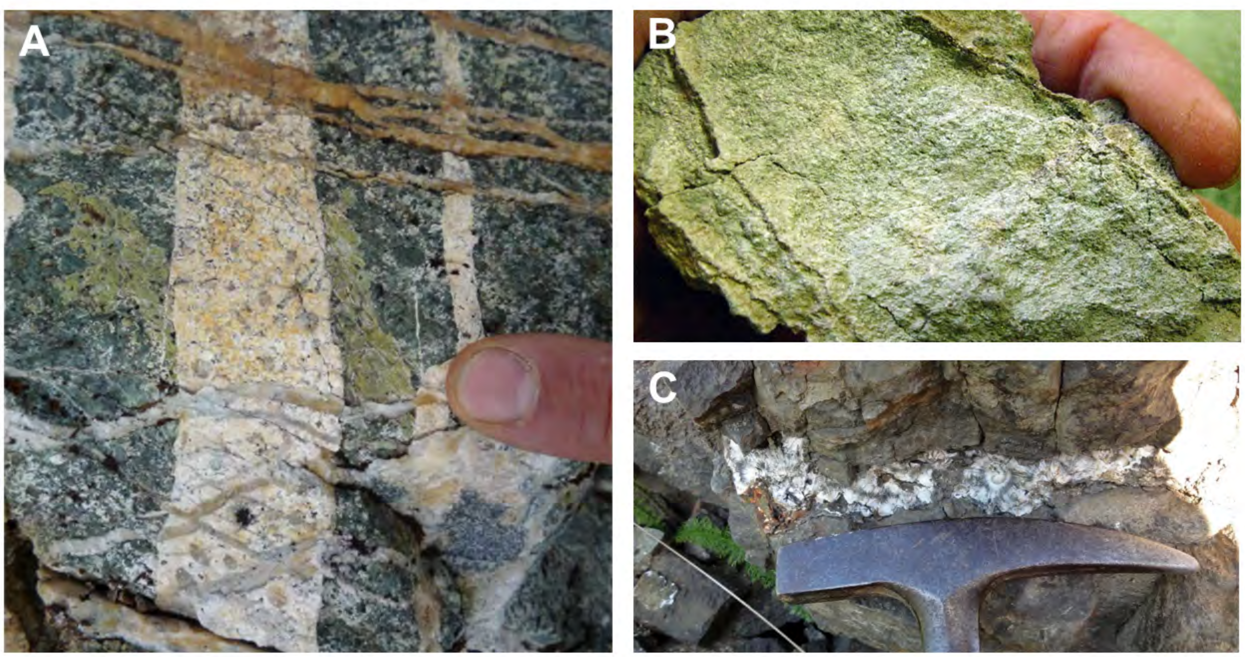


Fig. 2.7: *(A) Epidote in altered gabbro. Gabbro is observed to be cross-cut by leucosome veins. Image from Mihalynuk et al. (2011). (B) Tremolite and Actinolite skarn. Image from https://highway8a.blogspot.com/2011/10/tremolite-actinolite-skarn.html. (C) Zeolite vein and amygdules. Hammer for scale. Image from https://blogs.agu.org/georneys/2012/10/28/geology-word-of-the-week-z-is-for-zeolite/.*

Epidote-amphibolite facies: The facies (set of metamorphic mineral assemblages) in which mafic rocks are represented by hornblende + albite + epidote. It is transitional between the greenschist facies and the amphibolites-facies, and represents the low-temperature end of amphibolite facies regional metamorphism. Epidote-group minerals are common and widespread in regional- and contact-metamorphic rocks, both as primary and secondary (alteration) minerals. Epidote is found in mafic schists and gneisses together with the minerals hornblende, albite, and chloritoid; it is also found in hornfels along with diopside, actinolite, grossularite, and albite.

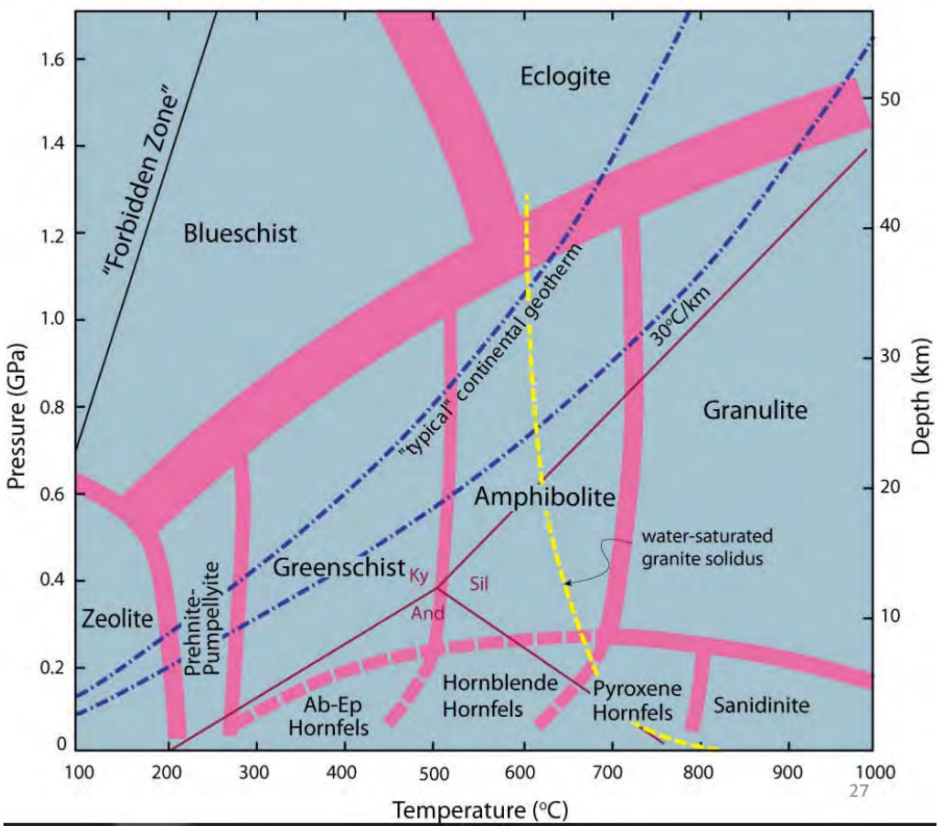


Fig. 2.8: *Temperature-pressure diagram showing the major types of metamorphic facies series proposed by Miyashiro (1973) and Miyashiro (1994). Included are the facies boundaries. Each series is representative of a different type of tectonic environment. The high P/T series is characteristic of subduction zones, medium P/T of continental regional metamorphism, and low P/T of high-heat-flow orogens, rift areas, and contact metamorphism.*

Aphyric: Said of the texture of a fine-grained or aphanitic igneous rock that lacks phenocrysts; also a rock exhibiting such a texture.

Granophyre: subvolcanic intrusive rock that crystallizes at shallow depths. Compositions are similar to those of granites, containing quartz and alkali feldspar in characteristic angular intergrowths. A common occurrence of granophyre is within layered igneous intrusions dominated by rocks with compositions like that of gabbro. Source: https://www.alexstrekeisen.it/english/pluto/granophyre.php.

Stop 3: Near Múlaþing, Iceland (Best Zeolites) (64.6208°N, 14.4127°W) (1.5 hours)

Following Hvalnes Beach, we will drive 30 minutes to the north. We will arrive around the Múlaþing, Iceland area to find some of the best zeolite outcrops we can access throughout the entirety of the portion of Iceland that we are visiting. We should definitely be able to find some Stilbite, Heulandite, Epistilbite, and my personal favorite zeolite group: Scolecite! The catch is that we need to find our way to the beach once we reach this general area which shouldn't require more than a little bit of searching.

Zeolites are a group of minerals belonging to the aluminosilicate family. They are commonly found in volcanic ash deposits and sedimentary rocks. Zeolites are formed through a process known as secondary mineralization, where volcanic activity or hydrothermal alteration of existing minerals leads to the formation of zeolite crystals.
Zeolites are defined and described as such:

1. **Mineral Classification and Composition:**
    - Zeolites belong to the tectosilicate mineral class, specifically the zeolite group, which includes various zeolite minerals with similar crystal structures and properties.
    - The basic composition of zeolites consists of a framework of aluminum, silicon, and oxygen tetrahedra, with additional cations (such as sodium, potassium, calcium, or magnesium) and water molecules occupying the cavities and channels within the structure.

2. **Crystal Structure and Pore System:**
    - Zeolites exhibit a framework structure characterized by an arrangement of interconnected tetrahedra, forming channels and cavities.
    - The framework structure of zeolites consists of various building units, such as sodalite cages, double-six rings, and intersecting channels.
    - The arrangement of these building units gives rise to the unique pore system of zeolites, which allows for the adsorption, exchange, and separation of molecules.

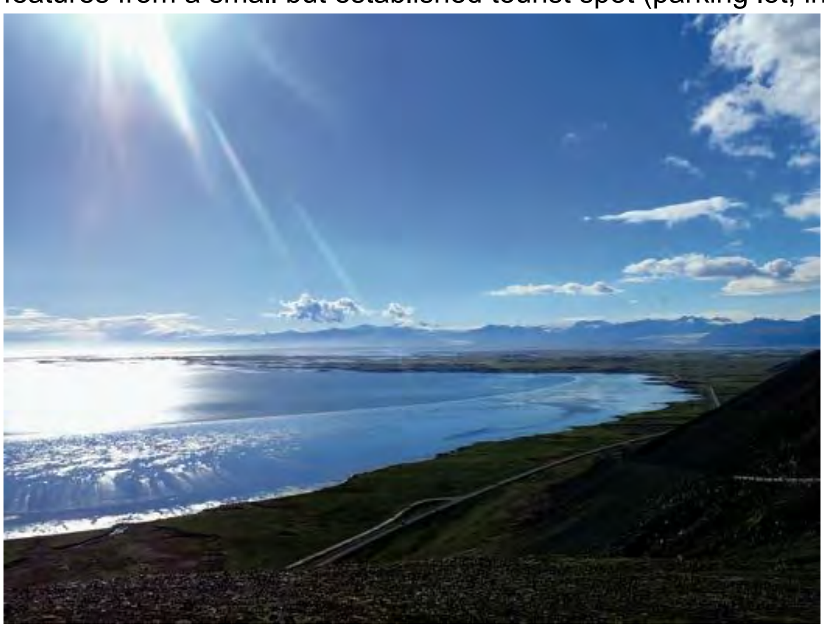
3. **Occurrence and Formation:**
    - Zeolites are found in various geological environments, including volcanic deposits, sedimentary rocks, and hydrothermal veins.
    - The primary source of zeolites is volcanic ash deposits, where alteration processes involving hot fluids and volcanic gasses lead to the formation of zeolite minerals.
    - Zeolites can also form in sedimentary rocks through diagenetic processes, where pore waters rich in silica and alumina interact with pre-existing minerals.

4. **Zeolite Species and Varieties:**

- There are numerous zeolite species identified, each with its own unique crystal structure, composition, and properties.
- Some commonly recognized zeolite species include clinoptilolite, mordenite, chabazite, heulandite, and natrolite, among others.
- Varieties of zeolites are distinguished based on their physical properties, colors, and occurrences in specific locations.

3 Stilbite specimens collected from the exact area we are visiting!

Optional (en route): Southeastern Coast Overlook (64.2840°N, 15.0354°W) (15-30 minutes)
Directions: If the weather is fair and the views are clear, be prepared to make a sharp turn off from Route 1 (turning right/east) ~200 m before entering the tunnel. You will ascend a steep road, reaching the crest of the mountain after driving ~1 km. Before the construction of the tunnel, this road served as the main passageway between S and E Iceland. The through-road is now closed to the public, but (on a clear day!) you can enjoy sweeping views of the S coast and its glacial features from a small but established tourist spot (parking lot, informative signs, etc.).



To quote Icelandic naturalist Stefan Stefansson, “He who has not looked out across East Skaftafellssýsla from Almannaskar. on a fine summer’s day has not seen Iceland.” A touristic sign (removed or vandalized in 2019, but perhaps replaced) identifies major features in the landscape, including Öræfajökull (Iceland's highest peak) as well as dozens of other peaks, ridges, outlet glaciers, and glacial valleys emerging from Vatnajökull You will get a perspective of the Höfn area including several low islands scattered across the lagoon. The touristic sign at the viewpoint also provides information about the establishment of Höfn as a population center in southeastern Iceland, summarizing a history of productive agriculture and fishing coupled with the challenges of isolation in a dangerous and dynamic landscape.

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June 5

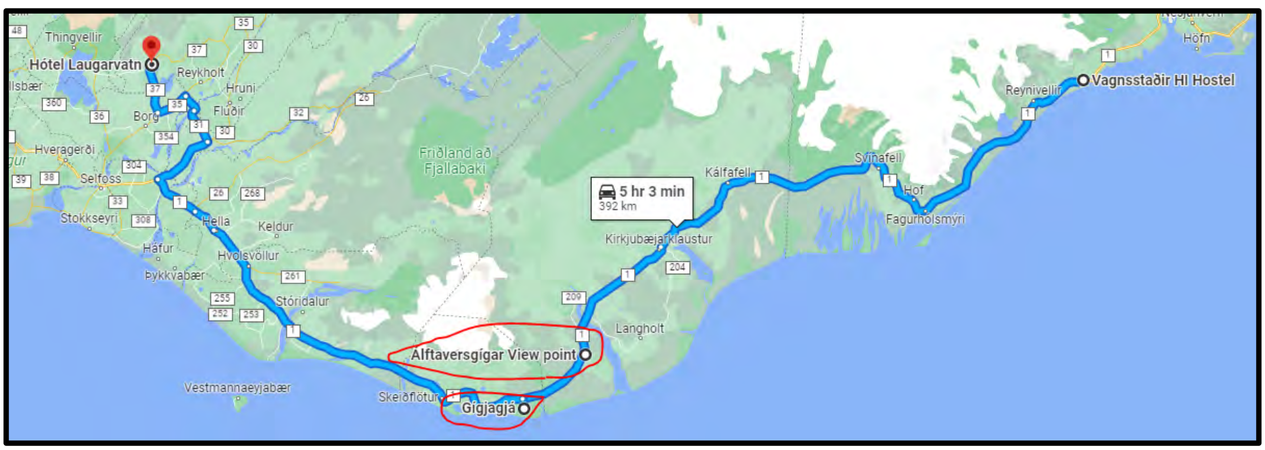
(Catherine, Natasha, Lizzi)

Summary

Stop	Location	Stop duration	Type
Álftaversgígar View Point	63°32'35.33"N 18°26'23.23"W	30 minutes	Igneous structures
Gígjagjá (Hjörleifshöfði & Yoda Cave)	63.4167°N, 18.7643°W	1 hour	Caves
Hotel Laugarvatn	64.2180989799842, -20.733260720389463	End of day	Hotel

Purpose: Today is largely focused on traveling between Vagnsstadir hostel and Laugarvatn, which will be at least a 5 hour drive without stops.

Start: Vagnsstadir Hostel, check out, depart by 9:30am



Stop 1: 2 hr 17 minute drive to **Álftaversgígar View point** (creepy cones) – *arrive at 12:00 PM*

Parking: 63°32'35.33"N 18°26'23.23"W – *drive 1 km off main road onto gravel road to access view point; no official parking; gravel round-about*

Geologic Information:

Pseudocraters (rootless cones) are cone shaped structures caused by the interaction of hot lava and surface water. Trapped water can cause explosions that leave formations similar to phreatic eruptions. Tephra and debris build up producing the 'creepy cones' similar to other volcanic features. The first documented sighting of a rootless cone formation was in March 2010, at Eyjafjallajökull.

Stop 2: 21 minute drive to **Gígjagjá (Hjörleifshöfði & Yoda Cave)**

Parking: 63.4167°N, 18.7643°W – Hjörleifshöfði

Logistics: Eat lunch upon arrival.

Geologic Information:
Iceland Field Guide (Jordan et al., 2019)

Hjörleifshöfði seems like an island in Mýrdalssandur, and that is just what it is. The steep-sided morphology and overall geology of Hjörleifshöfði, like Pétursey which was noted in the "On Route" section between Stop 4.4 and Vík, bear a distinct similarity to the islands of the Vestmannaeyjar from Day 4. Hjörleifshöfði has been studied in detail by Watton et al. (2012, 2013). Hjörleifshöfði formed by eruptions when this area was south of the shoreline. The eruptive process will have been like Surtsey in 1963–1967, with submarine construction then phreato-magmatic subaerial eruptions, and some subaerial eruptions giving rise to 'a'

Ā lava flows like the one highlighted on the drive in as well as an intact cinder cone on the upper surface. Areas of silicic accretionary lapilli are found on the upper surface, and chemically match the Solheimar ignimbrite (Watton et al., 2012). The cliff at this stop (Fig. 62) exposes three lithofacies of Watton et al. (2013): massive volcanic breccia (VB) low in the cliffs, overlain by imbricated planar cross-bedded hyaloclastite breccia (GHip), unconformably overlain by trough cross-bedded volcaniclastic sandstone/ breccia (VStcb). None of these facies here is interpreted as a primary volcanic deposit. In the interpre-ation of Watton et al. (2013) these facies represent: VB = eroded remnant of an older edifice (distally reworked deposit); GHip =delta deposits from material leaving a submarine channel; and VStcb = material reworked by tidal and/or wave processes. As in the Vestmannaeyjar, the steep margins of Hjörleif-shöfði reflect wave erosion reaching the more palagonitized core of the volcano. Since the formation of Hjörleifshöfði and the erosional oversteepening of its margins, outwash of Mýrdalssandur has aggraded, pushing the shoreline southward leaving this former island >2 km from the sea. The shoreline may have been at Hjörleifshöfði at the time of settlement (Björnsson, 2017). Deposition during the jökulhlaups of the 1918 Katla eruption pushed the shoreline >600 m south (estimated from Tómasson, 1996) making this area (Kötlutangi) the new southernmost point of the mainland of Iceland.

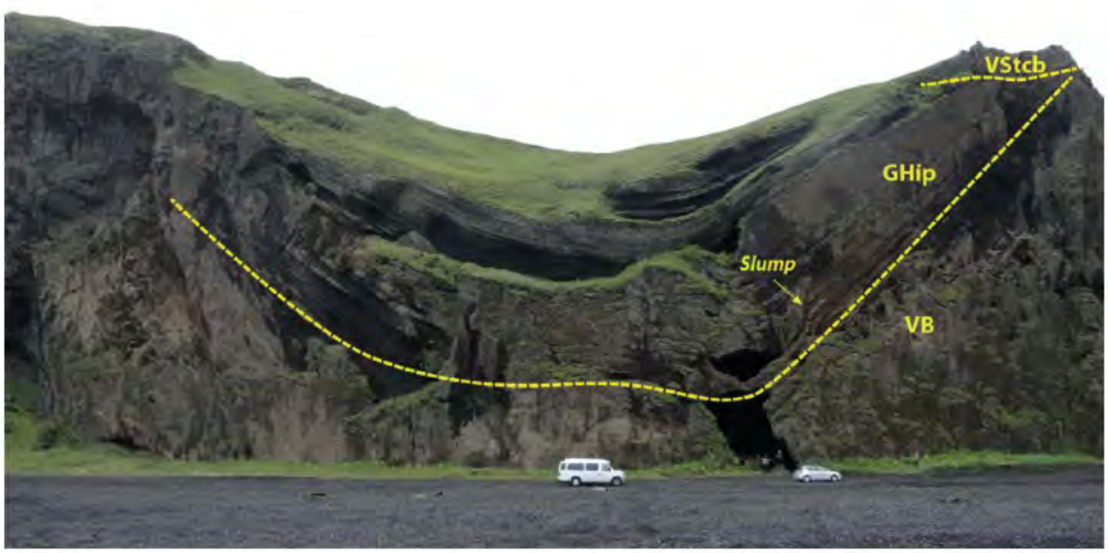


Figure 62. The southeastern end of Hjörleifshöfði, a steep-sided hill, and former island, within Mýrdalssandur. The units exposed here are: massive volcanic breccia (VB) low, overlain by imbricated planar cross-bedded hyaloclastite breccia (GHip), and unconformably overlain by trough cross-bedded volcaniclastic sandstone/breccia (VStcb).

Stop 4: 2 hour 21 minute drive to **Hotel Laugarvatn**

Parking: 64.2180989799842, -20.733260720389463 – *plenty of parking available*

References:

Watton, T.J., Thordarson, T., Jerram, D.A., and Brown, R.J., 2012, The Geol- ogy and Volcanic Evolution of the Hjorliefshofthi Outlier, Iceland: A 3D exposure of a Surtseyan Volcano?:

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June 6: Golden Circle
(Mel, Alex & Sally)

Summary

Stop	Location	Time
Þingvellir	64.279629, -21.088375	2-3 hours
Pillow basalt	64.2158°N, 20.8836°W	30 min-1hr
Gullfoss	Main parking lot 1: 64.325271, -20.129666 Smaller parking lot (along road): 64.324814, -20.125532	30-45min
Geysir and Strokkur	64.3089°N, 20.3031°W	1-2 hours

Proposed day schedule:
Start (8am): Hótel Laugarvatn, breakfast. Leave by 9am
Stop 1a: 28 min drive to the Almannagjá tension fractures (9:30 am), spend 10-15 min
Stop 1b: 5 min drive to Þingvellir (9:50 am), spend 2-3 hours. Leave ~12:30pm
Stop 2: 22 min drive to Pillow basalt (GSA Stop 2.2). Arrive ~1:00pm. Eat lunch at this stop, leave by 1:30-2:00pm.
Stop 3: 45 min drive to Gullfoss (arrive ~2:30 pm). Spend 30min-45min.
Stop 4: 10 min drive to Geysir and Strokkur (Arrive ~3:00/3:15pm). Spend up to 2 hours at this stop.
End: 23 min drive back to Hótel Laugarvatn, dinner. Return ~6:00pm.

Overview of driving stops

Stop Information

Stop 1a: Almannagjá tension fractures and Þingvallavatn overlook
Park coordinates: 64.23742199824675, -21.152121347555944
(See **Fig. 1**: Turn off of Road 36 onto gravel at 64.24662284075977, -21.16831466341565).

This is an overview of the landscape of the Þingvellir area, including the beautiful Þingvallavatn and its islands, and view tension fractures up close. In addition, this stop provides a good look (to the northwest, see **Figure 2** and inset for orientation) at the depression or valley Gagnheiði between the mountains Botnsúlur and Ármannsfell that is analogous to the valley of Þingvellir itself (**Fig. 2**). The only difference is that the valley of Gagnheiði is located in rocks considerably older, and partly of a different type, than those at Þingvellir. Both valleys are formed by subsidence of the land between two major normal faults and are considered grabens.

The tension fractures are present at the southern end of the large fracture that we will be hiking.

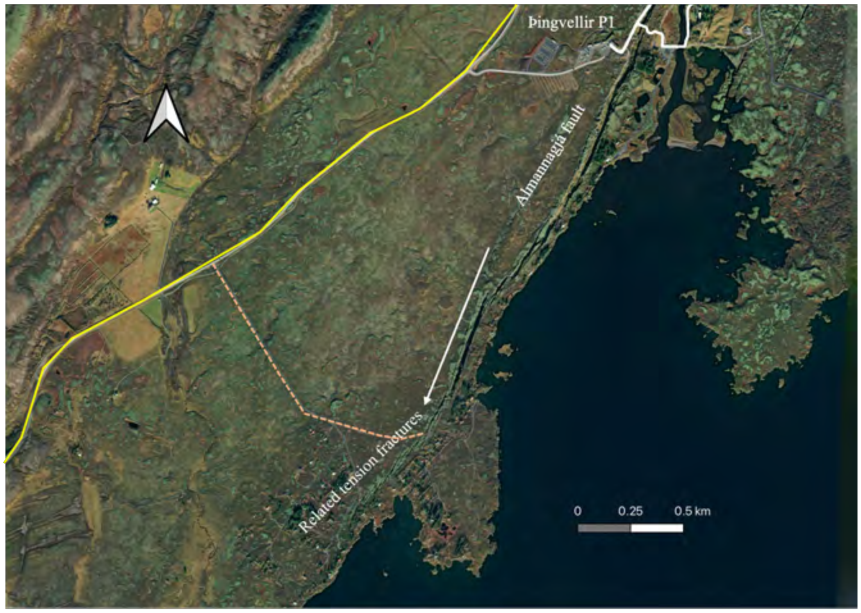

Figure 1. Map of Rt 36 (yellow) and turn off (orange dashed line) to Stop 1a.

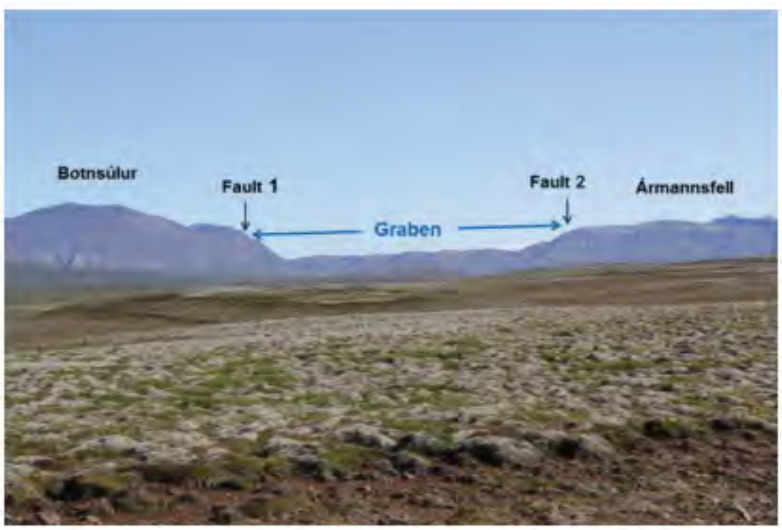

Fig. 4.12 Gagnheidi, the depression between the mountains Botnsulur and Armannsfell, is a graben, that is, a trough formed by the subsidence of land in-between two normal faults (explained in Fig. 4.14). The main boundary faults, Fault 1 and Fault 2, are indicated. Fault 1 (Sulnaberg, Súlnaberg) is one of the largest normal faults in Iceland, with a vertical displacement or subsidence of about 400 m

Figure 2. View from Stop 1a looking NNW (Gudmundsson, 2017)

Stop 1b: Þingvellir National Park

Park at Þingvellir National Park, P1 (64.25544, -21.132538)
This is a good bathroom stop!

We will be walking a 2.5 mi loop on mostly paved paths in the most popular part of the park. **Figure 3** shows a map with the hiking route and the features discussed below.

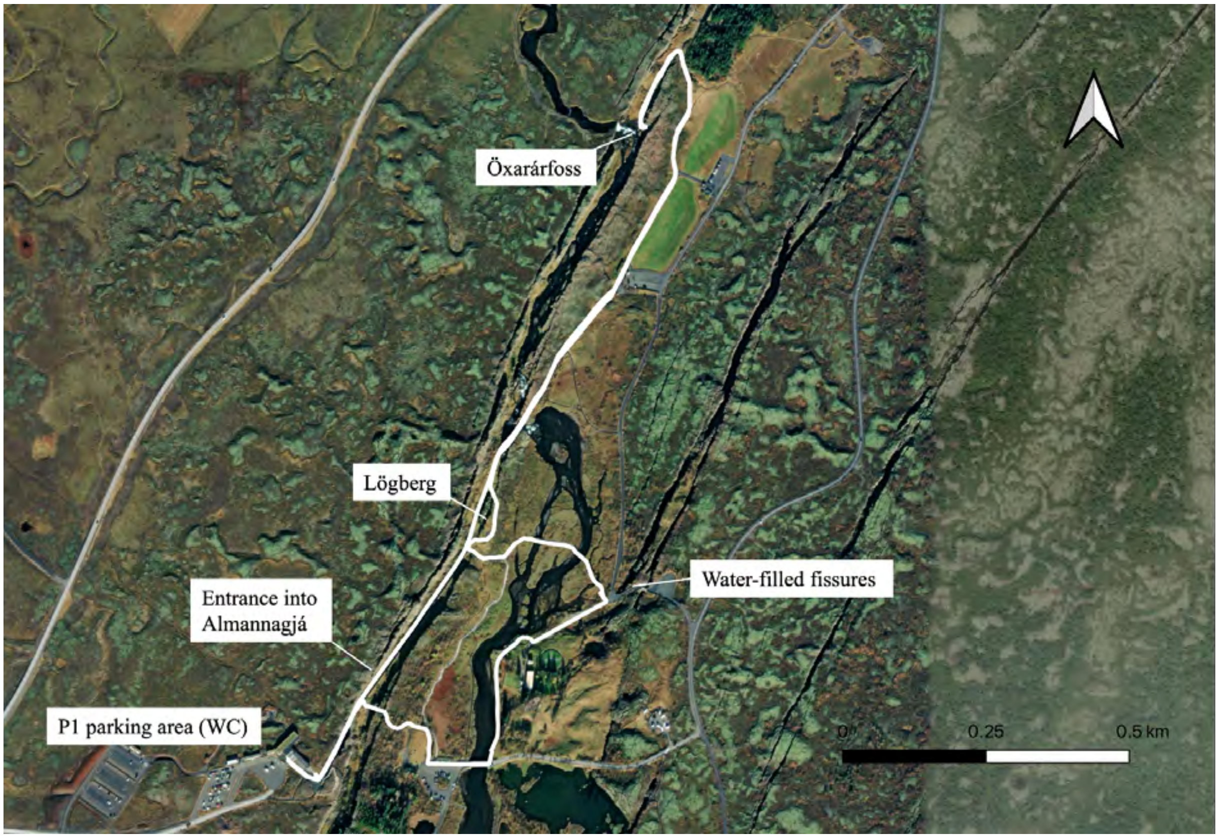

Figure 3. Satellite map (ESIR citation) of Þingvellir hiking loop with labeled points of interest mentioned in the text.

Introduction

(Text for this stop taken from Gudmundsson, 2017)

Þingvellir 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 Þingvellir 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**). Þingvellir constitutes a graben that forms a part of the West Volcanic Zone. More specifically, the Þingvellir Graben is located in the northern part of the Hengill Volcanic System (**Fig. 4**). 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.

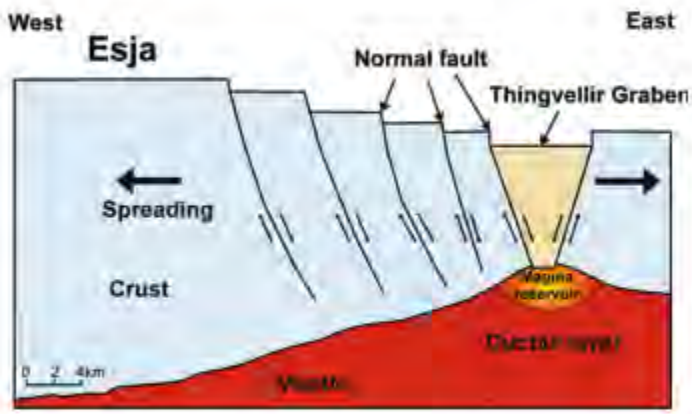

Fig. 4.5 The rocks, primarily lava flows, that constitute the mountain Esja were initially formed in the part of the West Volcanic Zone now occupied by the Thingvellir Graben. Esja itself is largely formed by lateral westward drift of some 28 km from this volcanic zone over the past 2.8 million years combined with deep glacial erosion and uplift. The top layers of Esja have risen by some 800 m as they drifted to the west, partly through normal faulting. The crust (or, strictly, the lithosphere) is floating on the magma or melt-rich ductile mantle. The crust/lithosphere increases in thickness with distance from the volcanic zone (here the Thingvellir Graben) because part of the magma in the mantle solidifies and becomes added to the lithosphere. At the same time, the glacier erosion wears away part of the surface through the generation of numerous valleys and lowlands, lessening the weight or vertical load on the ductile mantle. Both factors contribute—primarily through so-called isostasy—to the remaining parts of the crust rising (partly along faults) to form mountains such as Esja

Figure 4. Schematic drawing of the location of the Þhingvellir Graben within the divergent plate boundary (Gudmundsson, 2017). Note Mt. Esja that we will visit June 7.

Almannagjá ("fracture/fissure belonging to the public")

The paved path leads down through an entrance to the largest fracture of the Þingvellir area, Almannagja (Almannagjá). For perspective, **Figure 5** shows a larger part of Almannagja from the air. We will head to Öxarárfoss and then loop back to the parking area.

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. Both processes relate to the plate-tectonic forces that tear the crust apart (briefly discussed above, see **Figure 4**).

The opening of 60 m by this single fracture gives a spreading rate of about 0.6 cm per year. How do we know this? Simply by considering that the fracture is located in a lava flow that is about 10 thousand years old. When the openings of all the fractures along a line or profile (or section) across the Þingvellir 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 Þingvellir measured by other means (such as by satellites) during the past decades.

While the plate movements are continuous, opening and vertical displacement across fractures such as Almannagjá occur in discrete events. During such events, the eastern (lower) fracture wall of Almannagja suddenly subsides relative to the western (higher) wall. Such abrupt displacements normally give rise to earthquakes. The last major subsidence, by close to 1 m at Almannagjá, 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 Þingvellir 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 Þingvellir to the capital, Reykjavik.

All large fractures such as Almannagjá—a large normal fault—are formed of smaller parts or segments. As the tearing apart of the crust continues, that is, the spreading continues, the parts or segments of the fracture link together. But the original segments and the linkage between them are normally marked by offsets. 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.

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

Figure 5. Aerial photograph of Almanngajá. (Gudmundsson, 2017)

Lava flow observations

Walking down the path along Almannagjá, take a look at the fracture walls. 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 Þingvellir has a thickness of several hundred meters. In the walls we see only the uppermost twenty meters or so (the maximum height of the western wall is about 28 m). The lava flow is about 10 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. Notice cavities or vesicles in the different flow units. There is also an offshoot path that quickly leads to an outcrop view of the ropey texture of the pahoehoe lava flows.

Lögberg

Law Rock. This was the main meeting site for the parliament (Alþingi) starting in 930 and continuing until 1789. The reason for choosing this site soon after the settlement of Iceland is partly that the western wall of Almannagja is ideal for projecting the speaker's voice. This was also a central location for the initial inhabitants that settled in southern and southwestern Iceland. This was a place of not only legislative procedure (for example, it was here they decided to officially be Christian in 999) but also for the settling of legal disputes between individuals or families. Many of the sagas based on these original family lineages have action at the Alþingi.

Öxarárfoss

This is a manmade waterfall! The river Öxará was diverted into Almannagjá to allow for easy access to water for the attendees of the Alþingi. This is also where we turn around and head back south on the path.

Water-filled fissures

We will stop at a water-filled fracture named 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. Peningagjá is a part of a larger fissure whose name is Nikulásargjá which, in turn, is a part or segment of a larger fissure whose name is Flosagjá. The latter is the original name of the entire fissure, and Peningagjá and Nikularargjá are just among its southernmost segments or parts.

Flosagjá (and Nikulasargjá and Peningagjá) are clearly different from Almannagjá in that the fracture walls in Flosagjá on either side of the fracture are at the same elevation. By contrast, the eastern wall of Almannagjá has subsided by as much as 40 m relative to the western wall. In geological terms, Almannagjá is a fault, and more specifically a normal fault, whereas Flosagjá 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). On a tension fracture, by contrast, the movement is simple opening, pulling the fracture walls apart. Unlike the tension fractures we observed at the southern extent of Almannagjá, here the fissures go below the water table and are filled with groundwater.

From here, we make our way back to the parking area along the river.

Stop 2: Pillow basalt (Laugarvatnshellir)

64.2158°N, 20.8836°W (Jordan et al. 2019)

Text from Iceland GSA Field guide 2019 (Jordan et al. 2019):

Signage at the parking lot describes the history of habitation of the small cave (Laugarvatnshellir) cut into palagonite just northwest of the parking area. The site is at the base of the mountain Kálfstindar, the southern end of a tindar (móberg ridge) (**Fig. 7**) that extends ~25 km (Jones, 1970). Erosion into the base of this móberg ridge provides an opportunity to see the lower facies of subglacial basaltic volcanism. The first ravine past (northeast of) the cave leads to terrific exposures of pillow lavas. At the farthest point that one can walk up the ravine there is a wall of pillows (**Fig. 6**).

Figure 32. Pillow lavas low in the sequence at Kálfstindar (Stop 2.2).

Figure 6. Pillow lavas (Jordan et al. 2019)

These pillows represent the initial phase of subglacial eruption, while the pressure of meltwater and ice was great enough to suppress explosive expansion of heated meltwater. The pillows exhibit classic characteristics including radial columnar joints, concentric vesiculation bands, glassy rinds, and hyaloclastite/palagonite accumulations between pillows. In the ravine, some hyaloclastite has been weathered out providing an unusually good three-dimensional exposure of pillows.

Walking back out the ravine, one encounters the hyaloclastite and breccia layers that overlie the pillows. These pyroclastic layers are quite varied, reflecting variation in eruption and sedimentation processes. One of the first layers is a ~3-m-thick reversely graded bed. This reflects a high-energy emplacement in a subaqueous pyroclastic density current derived from slope failure higher on the edifice. Breccia units are interbedded with massive and thinly bedded hyaloclastite layers that reflect steady or pulsed (respectively) explosive eruptions under lower pressure as the subglacial volcano built up and the glacial surface melted down.

The eruption of Kálfstindar constructed a volcanic edifice up to the height necessary to erupt subaerially. A sequence of approximately ten subaerial ʻaʻā lava flows is exposed beginning at ~715 m on the north peak of Kálfstindar (Jones, 1970), out of reach of field trip visitors. The ~525 m difference between the base of Kálfstindar and the lowest subaerial lavas represents a *minimum* thickness for the glacier through which it erupted.

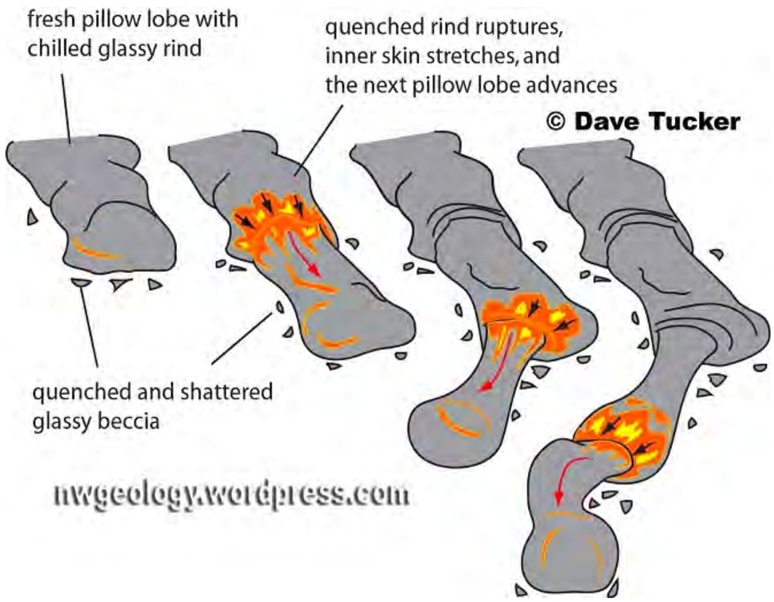

Figure 7. Schematic evolution of pillow lavas (https://nwgeology.wordpress.com/the-fieldtrips/pillow-lava-sites-in-washington/)

Other useful definitions of subglacial volcanism:

Text from (Jovanelly, 2020):

A tuya is as a positive-relief volcano having a morphology that results from ice confinement during eruption and comprising a set of lithofacies that reflect direct interaction between magma and ice/meltwater. More specifically, Russell et al. (2014) separates these glaciovolcanic features into four morphological categories: flat-topped, conical, linear, or complex. Using this as a guide, tindars are generally found in semiregular linear rows having an abrupt peak and a 2:1 ratio (length vs. width) [*Jakobsson and Gudmundsson*, 2008]. Tuyas also have a broad lava cap that is missing from tindars (**Fig. 8**).

Hyaloclastite lava (**Fig. 9**) is hydrated tuff-like breccia rich in volcanic glass and has the appearance of angular flat fragments sized between a few millimeters to a few centimeters. This fragmentation occurs by the force of the volcanic explosion or by the thermal shock during rapid cooling. Subglacial-eruption pillow basalts are formed if the ice to water pressure is adequately high. This process is comparable to the dry formation of pahoehoe lava lobes known as inflation or endogenous growth). Under low-pressure conditions, magma will immediately cool due to the rapid heat transfer from the ice to the magma resulting in glassy mineral textures, like obsidian [*Gudmundsson*, 2005].

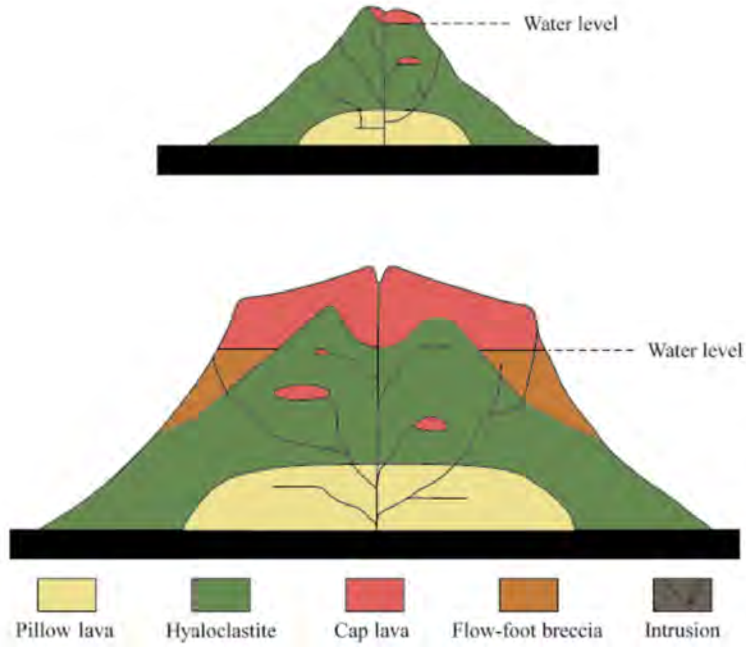

Figure 7.5 Comparison between tindar (top) and tuya (bottom) subglacial structures. [Modified from *Jakobsson and Johnson* [2012]; design credit Nathan Mennen.]

Figure 8. Tindar (top) versus tuyas (bottom) (Jovanelly, 2020)

Figure 9. Example of hyaloclastite. Matrix has altered to palagonite (hydration of volcanic

glass)

Image: [**https://commons.wikimedia.org/wiki/File:Laki_hyaloclastite_03.JPG**](https://commons.wikimedia.org/wiki/File:Laki_hyaloclastite_03.JPG)

Stop 3: Gullfoss - The Golden Waterfall
Parking lot: 64.325271, -20.129666

We will be walking along a trail from the parking lot that is nearly parallel to the main canyon or fault zone. Once we reach the intersection between the first and second step, we will be standing on top of a sediment layer that has been more resistant to erosion, followed by a series of sediment layers, and below that columnar joints.

(Text for this stop taken from Gudmundsson, 2017)

The Gulfoss waterfall consists of two main steps, the top one trending 75 degrees north and the lower one about 15 degrees north (**Fig. 10**). It is situated within a northeast-southwest trending fracture, that is typical for the volcanic systems in the southern half of Iceland.

The waterfall itself is situated within a 2500 m long canyon that has a maximum depth of about 70 m and is composed of primarily basaltic lava flows with columnar joints and sedimentary layers. Over the past several hundred thousand years, lava flows would form during interglacial periods while sediments were deposited during the glacial period when rock fragments were eroded and transported.

These lava flows are different from Almannagja, whose flows are largely pahoehoe lava made of many thin flow units- here we have a'a lava which formed in a single unit. The sediments were deposited during different intervals, and different sediment layers can be distinguished by their resistance to erosion or weathering. Some sediment layers are less easily eroded and thus formed the overhang for visitors to walk on. In comparison, some sediment layers just below have been carved out- these are the soft or easily eroded layers.

Studies have pointed to glacial outburst floods (jokulhaups) as the driver in carving out the main canyon in Gulfoss (Wells et al., 2021). If this 2500 m canyon was carved out following the permanent retreat of ice in this part of Iceland at about 8-9 thousand years ago, it is possible that the growth rate of the canyon is about 30 cm per year, and on average the waterfall is moving this amount further inland each year.

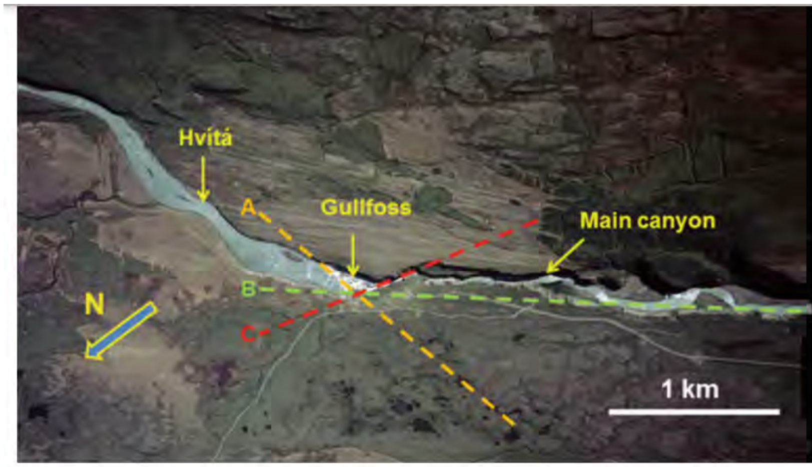

Fig. 8.2 Aerial view of the canyon of the river Hvita (Hvítá), namely Hvitargljufur (Hvítárgljúfur), and Gullfoss. The main steps that constitute Gullfoss have very different orientations, and are also different in orientation from the trend of the main canyon itself. All the three orientations are related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

Figure 10. Aerial view of the river Hvitá and Gullfoss. (Gudmundsson, 2017)

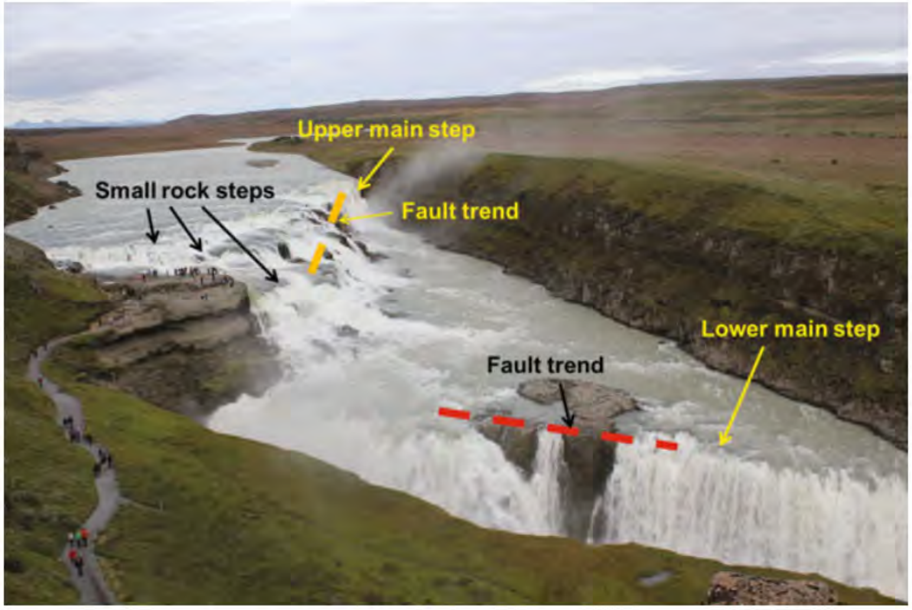

Fig. 8.3 Details of Gullfoss. View east, the main upper step is composed of several smaller rock steps (forming a series of cascades). By contrast, the lower main step is a single one. The upper step is about 11 m in total, whereas the lower step is about 21 m. Also indicated, crudely, are the two fault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

Figure 11. Annotated close up image of Gullfoss. (Gudmundsson, 2017)

Stop 4: Geysir and Strokkur

Parking lot: 64.3089°N, 20.3031°W

Text from Iceland GSA Field guide 2019 (Jordan et al. 2019):

The Geysir geothermal field in Haukadalur comprises several geysers, fumaroles, hot springs, and nearby mudpots (**Fig. 12**). The Geysir area trends NNE-SSW and lies between Laugarfjall, a rhyolite dome on its western edge, and the river Beiná to the east. Geothermal activity here is driven by volcanic intrusions in the roots of a now extinct central volcano. Residual heat from the Laugarfjall system forms a reservoir in the basalt bedrock with temperature of 200–250 °C (Pasvanoglu et al., 2000). Heat is transferred as groundwater at 1–2 km depth that moves through mainly NE-trending fractures. In high-temperature areas, rapid heat transfer leads to geothermal waters rising to the surface. The namesake geyser, Geysir, is rarely active, but its neighbor, Strokkur, erupts a 20–50-m-high (rarely up to 100 m) jet of boiling water every 5–10 minutes or so.

Geothermal waters in the Geysir area are alkaline. Geysir, Strokkur, and Smiður hot springs plot in the bicarbonate water range, but are close to the chloride and sulfate water fields on features at Geysir commonly produce silica deposits called sinter around their openings, and the clear waters at Geysir provide excellent views into the basins of many of the springs. The geothermal area experiences heavy use from tourists; please make every effort to tread lightly and always stay on marked paths.

The chronology of Geysir (also known as “The One who erupts”) has been dated using tephra in sinter deposits (Jones et al. 2007).
Summary: 1) Phase I (>3ka): hot spring waters deposited sinter 2) Phase II 3.3ka: little sinter deposition, ash from Katla and Hekla 3) Phase III 3.0-0.9ka: erosion, palagonitization 4) Phase IV: 900-800 years ago: birth of Geysir.
Geysir has been dormant since 1935.

See a summary schematic of geyer, hot spring, and fumarole formation in **Figure 13**.

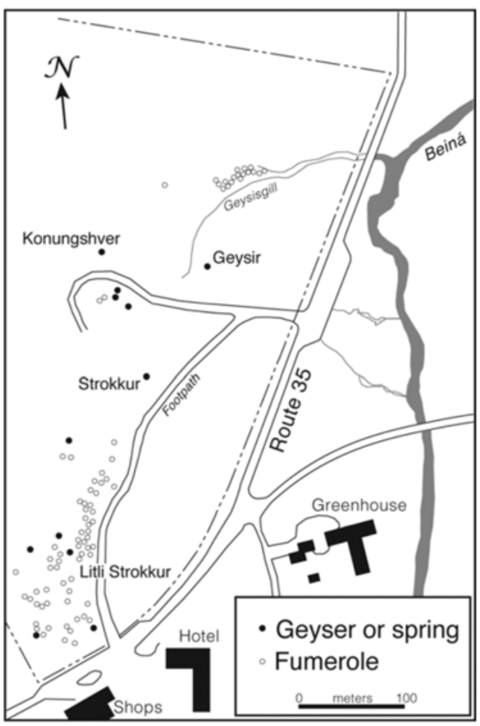

Figure 35. Map of the Geysir geothermal area (Stop 2.3). Modified from Jones and Renaut (2007).

Figure 12. Map of Geysir and Strokkur from Jordan et al. 2019.

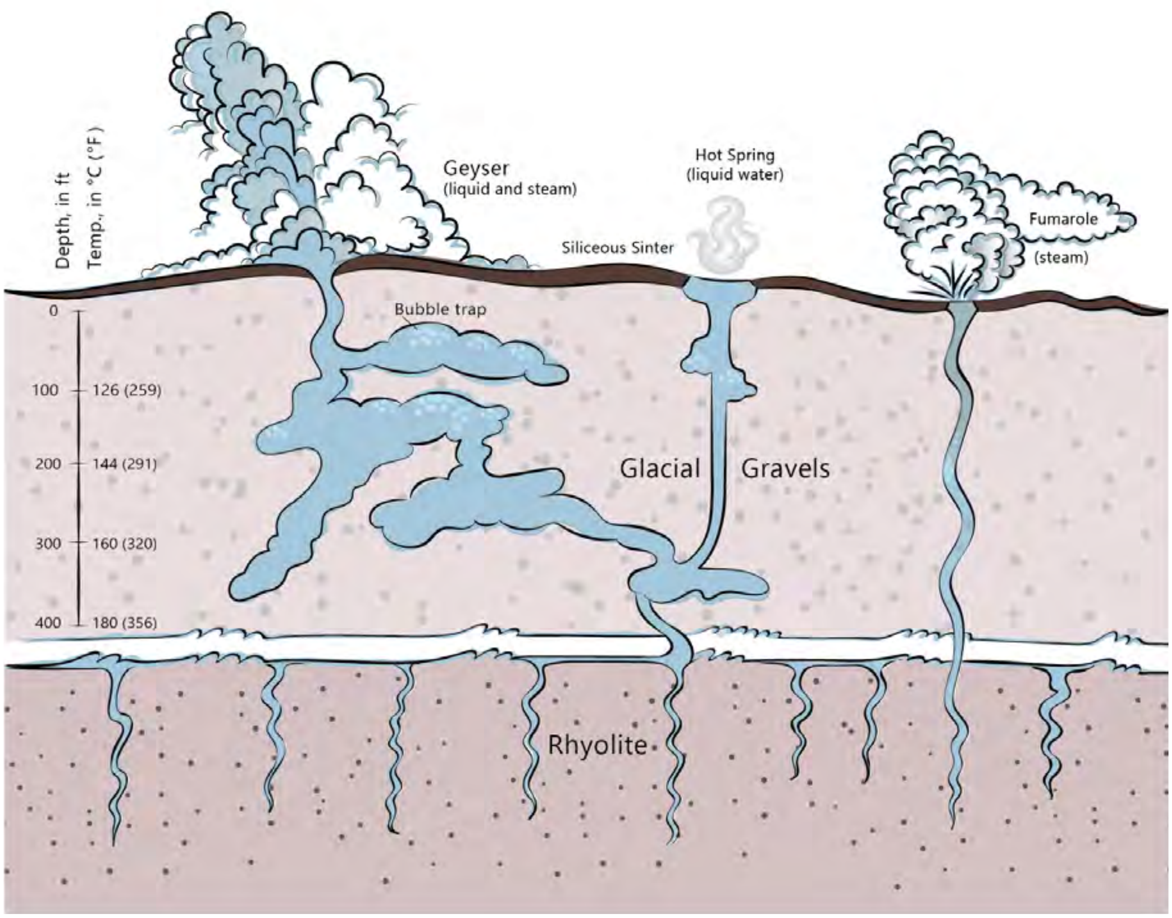

Figure 13. Hydrothermal features
Image: https://www.usgs.gov/media/images/hydrothermal-features

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June 7: Hvalfjörður Area Zeolites & Mt. Esja
(Noah, Fran, Ethan)

Summary

Stop	Location	Stop duration	Topic
Hvalfjörður	64.3327°N,21.7406°W	3-4 hours	Rhyolites + Dikes

Proposed day schedule:

Start: Laugarvatn hostel, breakfast. Leave at 9 AM

Stop 1: Hvalfjörður area (1 Hour Drive)

We will drive for approximately one hour (Stay for as long as desired)

Stop 2: Hvalfjörður area (North side of the fjord) (20-minute drive)

Stop 3: Mt. Esja (Weather and time permitting)
Finish: Eventually drive to KEX Hostel (50-minute drive)

Stop Information

Stop 1: Hvalfjörður area (South side of the fjord) (64.3327°N, 21.7406°W) (1.5+/- hours)

Directions:

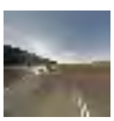
Head southwest on Laugarvatnsvegur/Route 37 toward Lindarbraut

850 m

At the roundabout, take the 1st exit onto Route 365

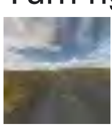
14.4 km

Continue onto Þingvallavegur



27.8 km

Turn right onto Kjósarskarðsvegur



11.4 km

Turn left

600 m

Continue onto Route 461

10.0 km

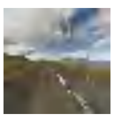
Turn left onto Hvalfjarðarvegur

5.2 km

Stop 2: <u>Hvalfjörður</u> area (North side of the fjord (Akrafjall)) (64.3327°N, 21.7406°W) (1.5+/- hours)

<u>Directions:</u>

Head southwest on Hvalfjarðarvegur toward Route 460



8.2 km

Turn right onto Þjóðvegur

950 m

Continue onto Hvalfjarðargöng

5.9 km

At the roundabout, take the 1st exit onto Þjóðvegur

7.8 km

This route will allow us to travel through the underground/water tunnel spanning the fjord. This is a primary motivation for crossing to the other side (apart from the zeolites)

Hvalfjörður Tunnel -- https://www.youtube.com/watch?v=8gw_EhMk0Vs

WHAT ARE WE SEEING HERE?

Hvalfjörður is an area which is well known to contain zeolites within the beach cliffs of this costal area. This should make for a good walk and scenic beach destination as well for those who don't care to partake in the zeolite hunt.
We should be able to see many zeolite groups at this location including but not limited to:
Analcime, Apophyllite (not a zeolite to many, but to some a zeolite), Chabazite, Heulandite, Laumontite, Mesolite (another favorite), Stilbite, and Thomsonite

Zeolites are a group of minerals belonging to the aluminosilicate family. They are commonly found in volcanic ash deposits and sedimentary rocks. Zeolites are formed through a process known as secondary mineralization, where volcanic activity or hydrothermal alteration of existing minerals leads to the formation of zeolite crystals.
Zeolites are defined and described as such:

1. **Mineral Classification and Composition:**
   - Zeolites belong to the tectosilicate mineral class, specifically the zeolite group, which includes various zeolite minerals with similar crystal structures and properties.
   - The basic composition of zeolites consists of a framework of aluminum, silicon, and oxygen tetrahedra, with additional cations (such as sodium, potassium, calcium, or magnesium) and water molecules occupying the cavities and channels within the structure.

2. **Crystal Structure and Pore System:**
   - Zeolites exhibit a framework structure characterized by an arrangement of interconnected tetrahedra, forming channels and cavities.
   - The framework structure of zeolites consists of various building units, such as sodalite cages, double-six rings, and intersecting channels.
   - The arrangement of these building units gives rise to the unique pore system of zeolites, which allows for the adsorption, exchange, and separation of molecules.

3. **Occurrence and Formation:**
   - Zeolites are found in various geological environments, including volcanic deposits, sedimentary rocks, and hydrothermal veins.
   - The primary source of zeolites is volcanic ash deposits, where alteration processes involving hot fluids and volcanic gasses lead to the formation of zeolite minerals.
   - Zeolites can also form in sedimentary rocks through diagenetic processes, where pore waters rich in silica and alumina interact with pre-existing minerals.

4. **Zeolite Species and Varieties:**
   - There are numerous zeolite species identified, each with its own unique crystal structure, composition, and properties.
   - Some commonly recognized zeolite species include clinoptilolite, mordenite, chabazite, heulandite, and natrolite, among others.
   - Varieties of zeolites are distinguished based on their physical properties, colors, and occurrences in specific locations.

Levyne, Stilbite, and Mesolite collected from the Hvalfjörður area we will be visiting*!*

Déjà vu? This is the same info from June 4! Zeolite literature hasn't changed over a few days ☺

Stop 3: Mt. Esja (Weather and time permitting)
Park here: 64.2089972555036, -21.71597159425157

(Gudmundsson, 2017)

Option to park here (64.17837275257077, -21.668780248351975), just as you turn from Road 1 (the Ring Road, the main highway) to Road 36, the road to Thingvellir, for an overview of the landscape. From the parking place, you can see many interesting geological structures and landscape features.

The mountain south of the parking place, Helgafell (Fig. 4.2), is of an age similar to that of Esja, and the same applies to the mountains south of Road 36 along Mosfellsdalur (the Mosfell Valley, Figs. 4.1 and 4.2). These mountains are partly of hyaloclastite or moberg, and partly of lava flows similar to those seen in Esja. The lava flows all show the same tilting to the east, that is, towards the active West Volcanic Zone as do the lava flows in Esja. The main mountain north of Road 36 closest to the road, Mosfell, is also made primarily of hyaloclastite. This mountain, however, is much younger than the others in its vicinity, or ‘only’ about 150–200 thousand years old. To the north is the beautifully impressive mountain Esja, rising to a maximum height of 914 m above sea level (Figs. 4.3 and 4.4). Esja, whose east-west length is some 20 km, making it one of the larger mountains in Iceland, is formed through two main processes. One is the piling up of lava flows and other volcanic rocks when the mountain area was part of the West Volcanic Zone (Figs. 2.2 and 2.3). The other process is erosion, primarily through the action of the enormous ice sheets active during the Ice Age (the past 2.8 million years). Thus, the primary reason that Esja is a mountain at all is the work of the Ice-Age glaciers—as, indeed, applies to almost all mountains in Iceland that have formed as mountains outside the active volcanic zones. The glaciers erode deep valleys, commonly along weak parts of the crust (often existing fractures), leaving behind the stronger parts which thereby stand as mountains above the valley floors.

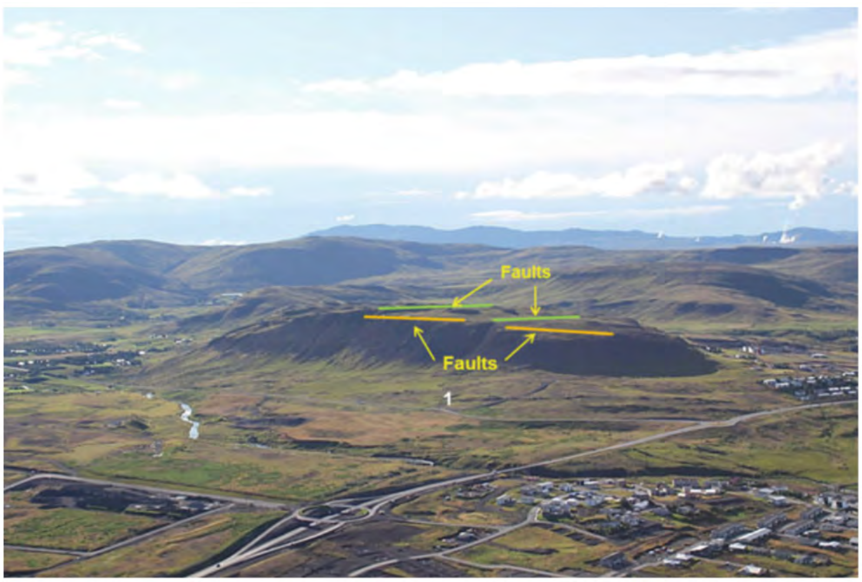


Fig. 4.2 Aerial view of the first stop (marked by 1, the number being at the parking place). View southeast, the tallest mountain in the distance is Hengill (Chap. 12) and the steam further to the south (right) is from the geothermal fields and drill holes of the power plant Hellisheidarvirkjun (both Hengill and Hellisheidarvirkjun are seen later today). From this location, I mainly describe the southern slopes of the mountain Esja (Figs. 4.3 and 4.4). But some additional features are seen on this aerial photograph. First, the mountain itself, Helgafell, is shaped by earthquake fractures, that is, faults, whose main directions, northeast (green) and east-northeast (orange) are indicated. The side of the mountain facing the camera follows an east-southeast trending earthquake fracture, that is, one or more faults (orange), whereas each small depression is the location of a northeast-trending fault. The faults are discussed further in subsequent chapters. Another noticeable feature is that all the layers in Helgafell slope to the east, as is discussed in the main text in connection with the lava flows in Esja (see also Fig. 4.6). The river seen is Kaldakvisl (Kaldakvísl)

The pile of lava flows that constitute the main part of Esja (Figs. 4.3 and 4.4) formed during the past three million years. As mentioned in Chap. 3, the Videy Volcano (Chap. 3) was active 2.8

million years ago, and much of the westernmost part of Esja (Fig. 4.3a) formed at that time (although partly generated by the somewhat older Hvalfjördur Volcano, Chap. 11). Now the eruptions that issued the lava flows that constitute Esja happened at the location of the Thingvellir area or graben (Fig. 4.5), of the Hengill Volcanic System (Figs. 2.2 and 2.3), some 30 km to the east (Figs. 2.3 and 4.1). So how come the lava flows are where they are now? The answer is what used to be called continental drift and is now named plate tectonics. There is a horizontal movement, drift or spreading, across the volcanic zones (Fig. 4.5). At the time of the formation of most of Esja, the rate of movement or spreading rate to the west from the Thingvellir area was about 1 cm each year. It follows that in 2.8 million years (the oldest rocks in the western cliffs of Esja, Fig. 4.3) the lava pile of Esja would be carried some 28 thousand meters, or 28 km, to the west. And that is exactly where the 2.8 million year-old rocks are found today. They have drifted by some 28 km to the west from the Thingvellir Graben because of plate movement or spreading.

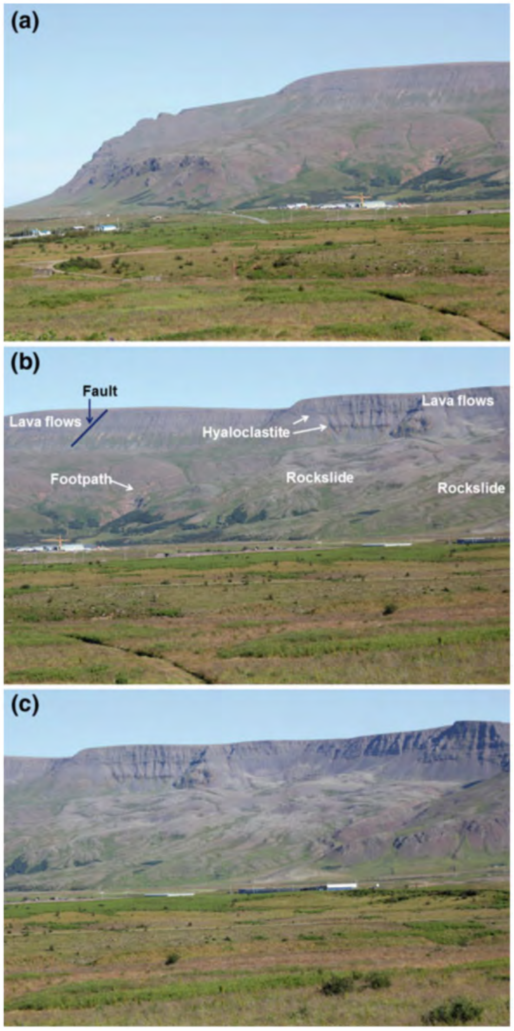


Fig. 4.3 The western part of the south side of Esja. The mountain is mostly of basaltic lava flows (indicated). In addition to basaltic lava flows, there are thick and thin layers of hyaloclastite (basaltic breccia) and many intrusions, both large ones as well as small ones (dikes and small sills, Fig. 4.4b). **a** The westernmost part. **b** The conspicuous brown layers in between the lava flows are hyaloclastite layers. A large rockslide (landslide) is responsible for the smooth undulating surface in the central part of the picture (indicated). **c** The entire rockslide is seen here, forming a 'scar' in the mountain side

But the rocks have not only drifted laterally, they have also risen—that is, their elevation above sea level increased as the rocks moved to the west. Why? Because of the erosion during the Ice Age. As the glaciers scraped and carried away the weaker rocks the load or vertical force by the crust on the ductile mantle below became less so that the entire land rose. The elevation increase towards the west is partly along earthquake fractures, that is, normal faults, as indicated in Fig. 4.5. So, the lava flows that you now see forming the top of Esja at as much as 914 m above sea level (Figs. 4.3 and 4.4) were formerly at the location of the Thingvellir Graben at only 100–150 m above sea level. They have thus risen by some 800 m in the top parts of Esja. The valley (Mosfellsdalur) closest to you in Figs. 4.3 and 4.4, part of which is also seen in Fig. 4.2, contains weaker rocks than Esja itself, rocks that were mostly eroded away by the glaciers. The rocks that constitute Esja were eroded perhaps to a depth of only a few hundred meters. That means that the top layers in Esja that we see today are a few hundred meters below the original top— so a few hundred meters of the lava pile is missing from the Esja area. This top was eroded, and the debris carried by glaciers and rivers into the sea. By contrast, the deepest valleys around the mountain were eroded to depths of more than a kilometer, and the deepest fjords close to Esja, such as Hvalfjördur (Chap. 11), eroded to depths of perhaps 1300 m.

Let us now look at some of the interesting features of Esja. The first thing to notice in Fig. 4.3 is that the top of the mountain is almost flat. In fact, so flat that small aircrafts have landed on the top. It is partly so flat because of erosion, and partly because the top-most layers have not become much tilted or inclined down to the east (towards the West Volcanic Zone and Thingvellir in particular). As I discuss in a moment, the reason is that the uppermost lava flows have been buried under relatively few flows (now eroded away) and thus not been subject to much vertical load. By contrast the lowermost lava flows have been subject to perhaps one kilometer load of lava flows on top of them, and thus been bent down, that is, tilted down towards the West Volcanic Zone (Fig. 4.6).

The top is made of almost horizontal basaltic lava flows, mostly greyish to bluish. The lava flows formed, one on the top of the other (Fig. 4.6), over a long period of time. Commonly the time between successive flows was many thousand years, occasionally tens of thousands of years. In the time periods between the eruption of each new lava flow, vegetation formed on the top on the last one before, similar to the vegetation you see later today on the young lava flows in the Thingvellir Graben and surrounding areas. Old layers of vegetation and soil commonly become red when buried under younger lava flows. There are also brownish layers in-between some of the lava flows. These are made of hyaloclastite or moberg (móberg), that is, basaltic ash, formed in explosive eruptions under glaciers (see Chaps. 2 and 6).

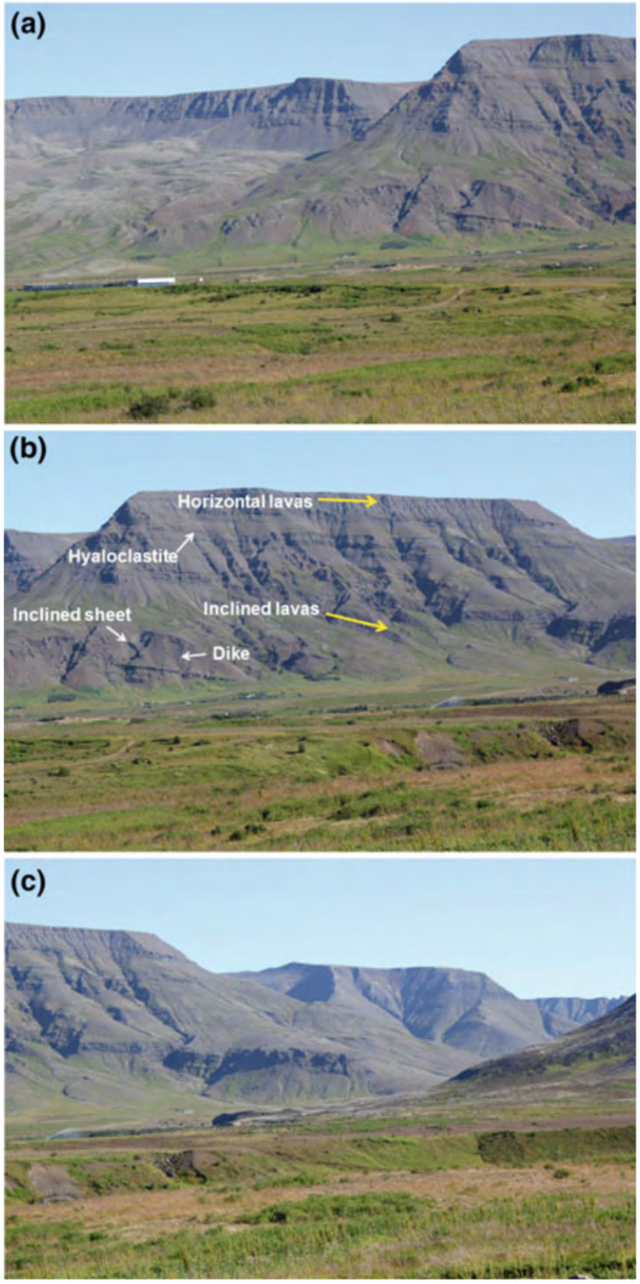


Fig. 4.4 The central part of the south side of Esja. The lava flows are almost horizontal (subhorizontal) at the top but become gradually more inclined down to the east, that is, towards the West Volcanic Zone (and Thingvellir in particular) with increasing depth (decreasing elevation) in the mountain, as explained in Fig. 4.6. **a** The western part. **b** Inclined layers and dikes and inclined sheets are seen and indicated in the lower parts of the slope. This part of Esja is named Kistufell. It has a very even top part. **c** The inclination or tilting of the lava flows clearly increases downslope, that is, with increasing depth below the original surface

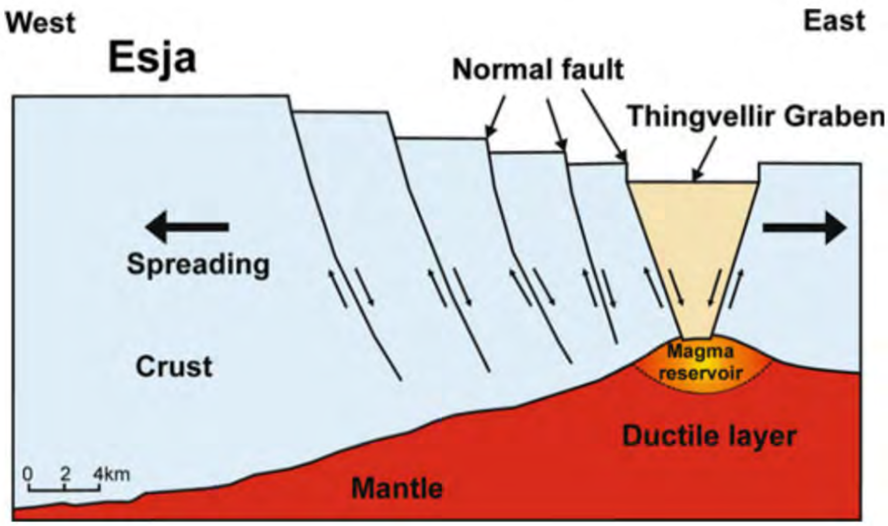


Fig. 4.5 The rocks, primarily lava flows, that constitute the mountain Esja were initially formed in the part of the West Volcanic Zone now occupied by the Thingvellir Graben. Esja itself is largely formed by lateral westward drift of some 28 km from this volcanic zone over the past 2.8 million years combined with deep glacial erosion and uplift. The top layers of Esja have risen by some 800 m as they drifted to the west, partly through normal faulting. The crust (or, strictly, the lithosphere) is floating on the magma or melt-rich ductile mantle. The crust/lithosphere increases in thickness with distance from the volcanic zone (here the Thingvellir Graben) because part of the magma in the mantle solidifies and becomes added to the lithosphere. At the same time, the glacier erosion wears away part of the surface through the generation of numerous valleys and lowlands, lessening the weight or vertical load on the ductile mantle. Both factors contribute—primarily through so-called isostasy—to the remaining parts of the crust rising (partly along faults) to form mountains such as Esja

One remarkable feature, seen most clearly in Fig. 4.3c, is a huge pile of rocks that clearly has broken from the main part of the mountain, leaving a scar. Large slides of this type are named landslides or rockslides. Small rockslides are common in the mountains of Iceland, but rarely of this size. We do not know when it formed—and it need not have been a single slide—but the greatest instability of the mountain edges or slopes occurred when the last glaciers of the Ice Age melted away. Since the main melting of the ice sheet in this part of Iceland occurred some 12–13 thousand years ago, it is possible that the main rockslide occurred at that time.In Fig. 4.4 (particularly 4.4c) it becomes clear that the lava flows, horizontal at the top of Esja, are no longer horizontal in the lower slopes of the mountain, but rather inclined or tilted (dipping is the term used in geology) down to the east. That is, the lava flows, and in fact the whole pile that constitutes Esja, is inclined or dipping towards the active volcanic zone, the West Volcanic Zone, at Thingvellir (Fig. 4.1). This is a universal feature in Iceland: the lava pile almost everywhere tilts or dips towards the closest part of the active volcanic zone. The reason for the tilting of the lava flows at deeper levels (less elevation above sea level) in the mountains is that younger lavas continue to pile up at the surface of the active zone and their weight or load presses the deeper lava flows (Fig. 4.6).

We also see rock layers, or sheets of rock, that are close to vertical (Fig. 4.4b). These are frozen (solidified) magma paths, named dikes (or dykes). We will see many of these close-ups in Chaps. 11 and 13, so that the main discussions about their formation will be in those chapters. Here, however, I can explain dikes briefly as follows. Magma is stored in large cavities, magma chambers, at various depths in the crust. These chambers are partly or totally filled with magma. When the pressure of the magma reaches the strength of the rock around the chamber (so-called tensile strength, namely the pressure or stress that rock being pulled apart can tolerate before it breaks or ruptures) the walls of the chamber—or, most commonly, its roof—rupture. As soon as the rupture occurs, a magma-filled fracture forms which may or may not reach the surface to erupt. When the hot magma eventually freezes or solidifies in the fracture, the resulting structure is called a dike. Most of the dikes we see here never reached the surface of Esja— they stopped on their vertical path to the surface—so that they did not erupt. The word dike is today not only used about the solidified rock in the fracture but also about the fracture when it was filled with fluid, hot magma, and moving (propa- gating) within the crust and the associated volcano.

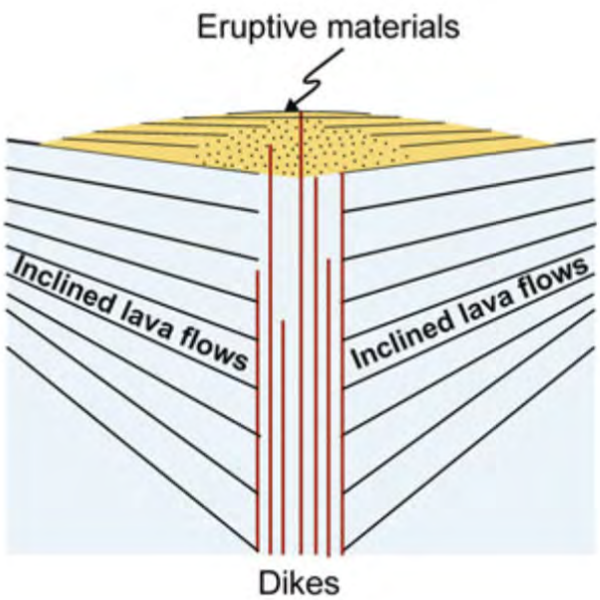


Fig. 4.6 The lava pile in Iceland is normally tilted towards the nearest segment of the volcanic zones. Thus, in East Iceland, the lava pile is tilted to the west (towards the North Volcanic Zone) and to the northwest (towards the East Volcanic Zone—see Fig. 2.2) whereas in West Iceland, such as in Helgafell and Esja (Figs. 4.2, 4.3 and 4.4), the pile is tilted to the southeast, that is, towards the West Volcanic Zone. The tilting or inclination of the lava flows increases with depth in the crust, that is, at less elevation above sea level, in the slopes of the mountains. The reason is that younger lavas continue to pile up at the surface of the active zone and their weight or load presses the lava flows beneath them

(Jovanelly, 2020)

Esja is a mountain complex of three central volcanoes that dramatically dominates the northern skyline of Reykjavík, and is a popular hiking spot as it is only 10 km from the city center. The summit is called Hábunga and sits 914 m above the low-lying area. Esja was created in the late Pliocene, when _during warm periods lava flowed and in the cold periods ridges of tuff were built up under the glacier. The oldest part of the mountain range (dating to 3.2 Ma) can be explored at the base of the western slope and the younger rhyolitic cap deposits dating to 1.8 Ma can be seen on the eastern side, called Móskarðshnúka (64.2431, −21.5278). The 1650 m total thickness of the Esja succession was formed by the extinct Stardalur and Kollafjörður volcanic systems that originated with the initial spreading of the WVZ. Due to erosion, the gabbro intrusions that once were the root of the central volcanoes can be seen at the base of Mount Esja. Fissure eruptions fed by dikes followed earlier volcanic activity [Forslund and Gudmundsson, 1991] and can be seen along the northern slopes of Eyararfjall (64.3191, −21.7261) and Lokufjall (64.2818, −21.8257).

June 7 References

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June 8 (Rek)

(Rachel, Catherine, Lizzi)

Summary

Stop	Location	Stop duration	Type
Geothermal Energy Exhibition	64.0373°N, 21.4011°W	1-1.5 hr	Geothermal
Reykjadalur Hot Spring Thermal River	64°01'15.7"N, 21°12'40.4"W	4 hr	Geothermal
Dalur - HI Hostel & Cafe	64.14655, -21.87474	End of day	Hotel

Proposed itinerary

Start: Dalur Hostel in Reykjavik (breakfast included); depart hostel by 8:45am

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Stop 1: 50 min drive to **Geothermal Energy Exhibition (**64°02'15.4"N 21°24'07.7"W).

Parking: Parking lot, 64.0373°N, 21.4011°W – *plenty of parking.*

Logistics: Carbfix Tour confirmed at 10:00am (1-1.5 hours length) (contact: Kathryn Teeter).

Depature: 12:00 PM

Carbfix tour (CO_2 + H_2S sequestration): A 1-1.5 hour guided tour of the exhibition including a visit out to a Carbfix reinjection borehole. This version of the tour is more in depth, the extra time allows for a more detailed discussion about the Carbfix process. There is a short safety video that must be watched on location before going out to the field to visit the borehole. They are also welcome to further exploration of the exhibition after the tour.

Geologic information, Hellisheiði Geothermal Power Plant
Iceland GSA Field Guide - 2019.

The Hellisheiði plant is one of two geothermal power plants utilizing geothermal fields in the Hengill volcanic system, the other being Nesjavellir to the north. The Hengill volcanic system is the first system, working northeast from where the mid-ocean ridge comes on shore, to have a central volcano, the Hengill central volcano. The exposed geology is dominated by subglacial hyaloclastites, though subaerial lavas are encountered at depth (Franzson et al., 2010). The drilling targets were young volcanic fissures (2–5 ka) and fault structures on the western edge of the Hengill graben (Franzson et al., 2010).

The Hellisheiði plant was commissioned in 2006, and was expanded in 2007, 2008, and 2011. Its installed capacity at the time of writing is 303 MW electric power and 133 MW of thermal energy for district heating, making it the largest geothermal power plant in Iceland (Table 2). The plant is operated by ON Power, a subsidiary of Reykjavík Energy, the former operator.

At Hellisheiði, steam and hot water are collected at 30 production wells (one typically on standby) over an 8 km2 area mostly above the plant (Hallgrímsdóttir et al., 2012). After separation of water and steam, electricity is generated by six 45 MW high-pressure turbines and one 33 MW low-pressure turbine. All are condensing turbines where low pressure is produced by condensation of steam on the outlet side in condensers cooled by freshwater. For the high-pressure turbines the inlet pressure is 6.5–9.5 bar and the condensing pressure is 0.1–0.22 bar. For the low-pressure turbine the design inlet pressure is 2 bar and the condensing pressure is 0.068 bar (Hallgrímsdóttir et al., 2012). Fresh water is initially heated in the condensers and then further heated by heat exchangers interacting with separated water (Hallgrímsdóttir et al., 2012).

There have been some challenges with the Hellisheiði plant. Due to high production density (production rate per unit area) the system has experienced pressure draw-down and reduced enthalpy of the produced fluid (Gunnarsson and Mortensen, 2016). As a result production has been decreasing since 2013. Reinjection wells have not, as of this point, produced desired rejuvenation of the system. Reinjection, started in 2011, has apparently produced increased seismicity and geodetically mea- surable surface deformation (Juncu et al., 2018).

TABLE 2. GEOTHERMAL ELECTRIC POWER PLANTS IN ICELAND				
Plant	Operator	Commissioned	Installed capacity	Volcanic system
Hellisheiði	ON Power	2006	303 MW	Hengill
Nesjavellir	ON Power	1980	120 MW	Hengill
Reykjanes	HS Orka	2006	100 MW	Reykjanes
Þeistareykir	Landsvirkjun	2017	90 MW	Þeistareykir
Svartsengi	HS Orka	1976	76.5 MW	Reykjanes
Krafla	Landsvirkjun	1977	60 MW	Krafla
Bjarnarflag	Landsvirkjun	1969	3 MW*	Krafla
Húsavík	Húsavík Energy	2000	2 MW	–

*Construction is under way to replace with 90 MW plant.

Stop 2: 20 min drive to **Reykjadalur Hot Spring Thermal River** trailhead

Parking: Trailhead, 64°01'15.7"N 21°12'40.4"W – *may be crowded.*

Logistics: Eat lunch upon arrival, 45-60 minute hike to swimming area – *5 mi round trip.*

Depature: ? I propose we get there at 12:30; hit the trail by 1, leave the parking lot by 5, 2 hrs of swimming, 4 hrs total.

Geologic information, Reykjadalur Hot Spring Thermal River
The fluid geochemistry of Ölkelduháls and Hveragerði geothermal areas – SW Iceland (Peñarrieta, 2021).

Reykjadalur is a valley south of Ölkelduháls. The area is well known as a tourist attraction due to the hot river Reykjadalsá which has a comfortable bathing temperature year around. The geothermal activity in Reykjadalur is characterized by steaming ground and hot springs that feed the river running down the valley. East of Reykjadalur lies Grændalur, followed by Gufudalur. Grændalur is separated from the other valleys by agglomerate basalt units, Dalafell on the west and Tindar in the east. Those hyaloclastites are the topographic boundary of the valleys but landslide deposits cover the area within the depression (Kyagulanyi, 1996). The river Grændalsá comes from the Álftatjörn lake, flows through the Grændalur valley and is then joined with Reykjadalsá. The resulting river is from then on called Varmá. Geothermal manifestations in Grændalur and Gufudalur are somewhat similar, characterized by steam vents and hot spring, thermal rivers and streams and mud pools. Hveragerði field is situated south of the three valleys within and around the Hveragerði town. The geothermal activity in Hveragerði is characterized by hot springs, steam vents and mud pools, the water classification based on cations and anions diagram showed Na-HCO3 and NaCl waters. The water manifestations mainly corresponded to steam heated waters and boiled waters recognized in the conceptual model using carbonate-silica mixing models (Geirsson & Arnórsson, 1995) 17 geothermal wells were drilled for commercial and scientific purposes, the geothermal wells are located within this part of the area where the measured temperature goes from 215°C to 230°C on the northern part, and from 167°C to 198°C for the southern part. The conceptual model for the area estimates a maximum reservoir fluid temperature about 250°C (Geirsson & Arnórsson, 1995).

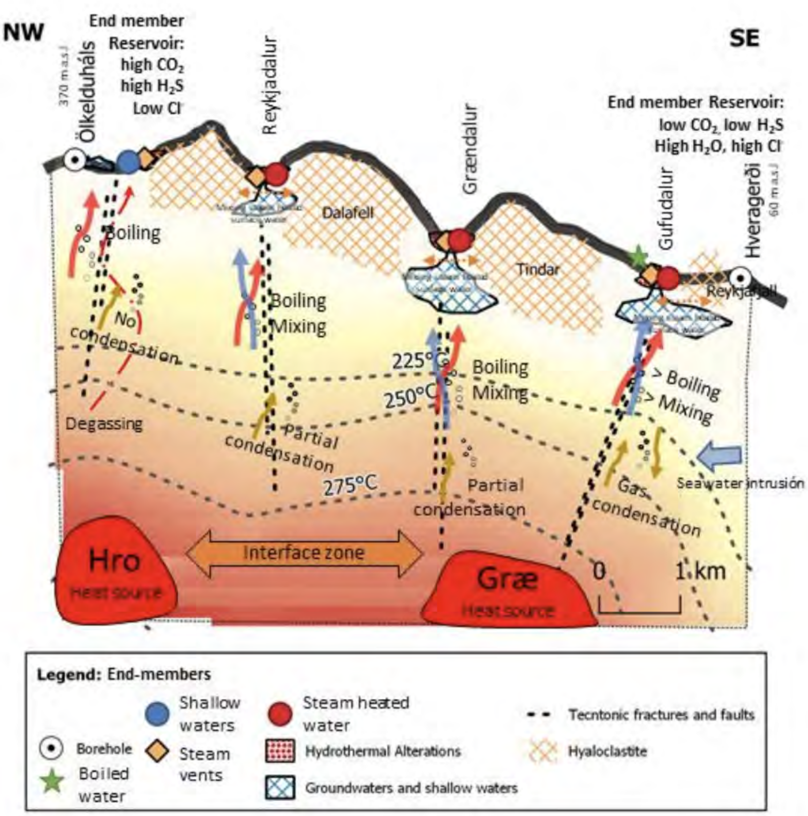

Figure 14. Schematic conceptual model of the the study area (based in Geirsson & Arnórsson, 1995).

The heat source of the geothermal activity might be controlled by two volcanic systems. On the north, Hrómundartindur active volcanic system supplies heat to Ölkelduháls where the estimated temperature is 280-300°C. In the south, Grændalur extinct volcano supplies heat to Hveragerði and Gufudalur where the estimated temperature is 230-280°C. The interface between that two end-members reservoirs are Reykjadalur and Grændalur that are mainly defined by steam heated waters that are formed by mixing between condensed steam and nonthermal waters.

Stop 3: Dalur - HI Hostel & Cafe

Parking: 64.14655, -21.87474

Logistics: Hotel; we fly back tomorrow morning.

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Jordan, B. T., Carley, T. L., & Banik, T. J. (2019). Iceland: The formation and evolution of a young, dynamic, volcanic island—a field trip guide. *Iceland: The Formation and Evolution of a Young, Dynamic, Volcanic Island—A Field Trip Guide*. https://doi.org/10.1130/2019.0054(01)

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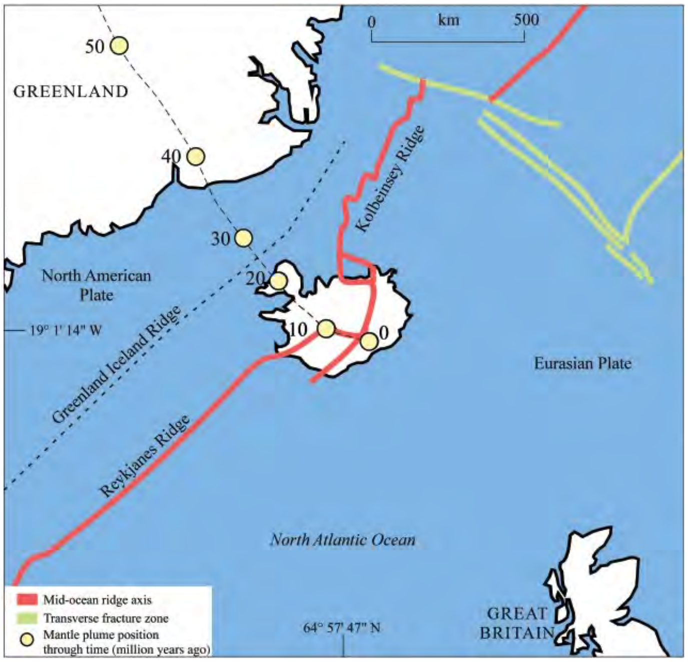
Yerko Figueroa Peñarrieta, 2021, The geochemistry of geothermal fluids of Ölkelduháls and Hveragerði geothermal areas, SW Iceland, Master’s thesis, Faculty of Earth Science, University of Iceland, pp. 66.

Geologic History Overview

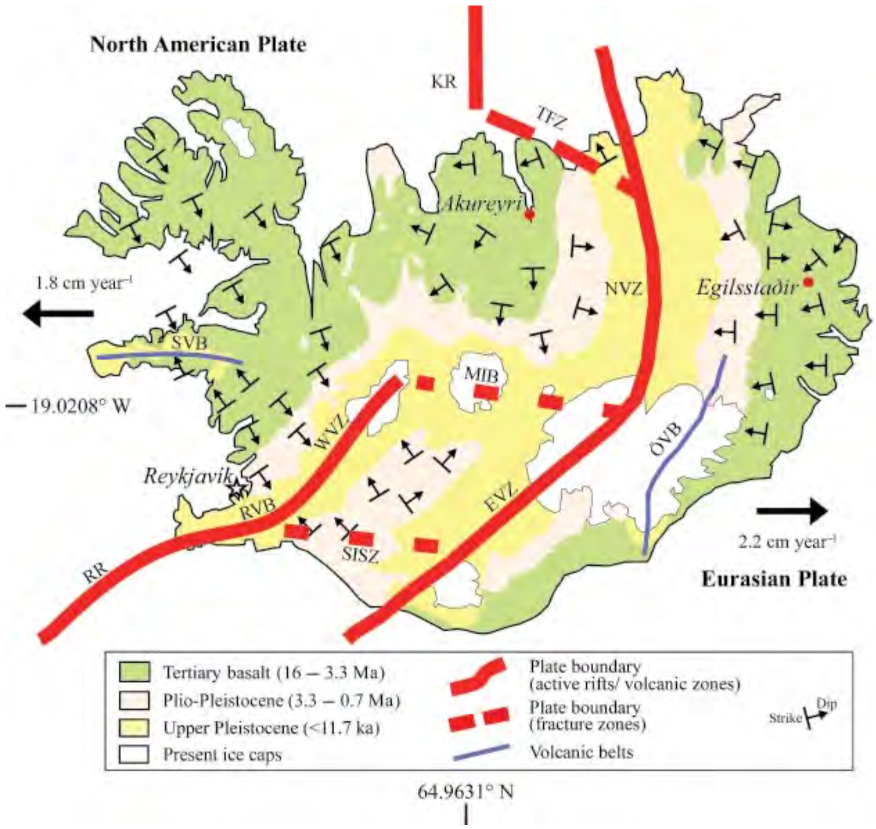
Era	Period	Epoch	Age	Stage	Sub-stage	Formation	Major events
CENOZOIC	**Quaternary**	*Holocene*	0–2.5 ka	Late Bog Period (sub-Atlantic)		Upper Pleistocene Formation	
			2.5–5 ka	Late Birch Period (sub-Boreal)			
			5–7.2 ka	Early Bog Period (Atlantic)			
			7.2–9.3 ka	Early Birch Period (Boreal)			
			9.3–10 ka	Pre-Boreal			Ice Age glaciers melt
		Late Pleistocene	10–11 ka	Weichselian	Younger Dryas		Cooling in northern hemisphere; glaciers grow
			11–12 ka		Allerød		Warmer climate
			12–20 ka		Older Dryas		Icelandic ice sheets quickly retreat
			20–110 ka				Eurasian ice sheet at maximum; last glacial stage
		Middle Pleistocene	115–130 ka	Eemian			Last interglacial stage
			130–300 ka	Saale			Glacial stage
			300–700 ka				
		Early Pleistocene	0.7–2.5 Ma			Plio-Pleistocene Formation	Start of full-scale glaciations
	Teriatery	*Pliocene*	2.5–3.3 Ma				Pacific Ocean fauna arrive in Iceland. Bering Strait opens
			3.3–7 Ma			Teriatery Basalt Formation	Climate begins to cool
		Late Miocene	7–12 Ma				Warm, temperate climate
		Middle Miocene	12–18 Ma				
		Early Miocene	18–25 Ma				Origination of Iceland

Note. ka, thousand years ago; Ma, million years ago. Modified from *Thordarson and Höskuldsson* [2014]; design credit Nathan Mennen.

Tectonic Context



Figures from Jovanelly (AGU 2020)


North American Plate
KR
TFZ
Akureyri
NVZ
Egilsstaðir
1.8 cm year⁻¹
SVB
MIB
— 19.0208° W
WVZ
ÖVB
Reykjavik
RVB
EVZ
2.2 cm year⁻¹
SISZ
RR
Eurasian Plate
Tertiary basalt (16 – 3.3 Ma)
Plio-Pleistocene (3.3 – 0.7 Ma)
Upper Pleistocene (<11.7 ka)
Present ice caps
Plate boundary (active rifts/ volcanic zones)
Plate boundary (fracture zones)
Volcanic belts
Strike
Dip
64.9631° N

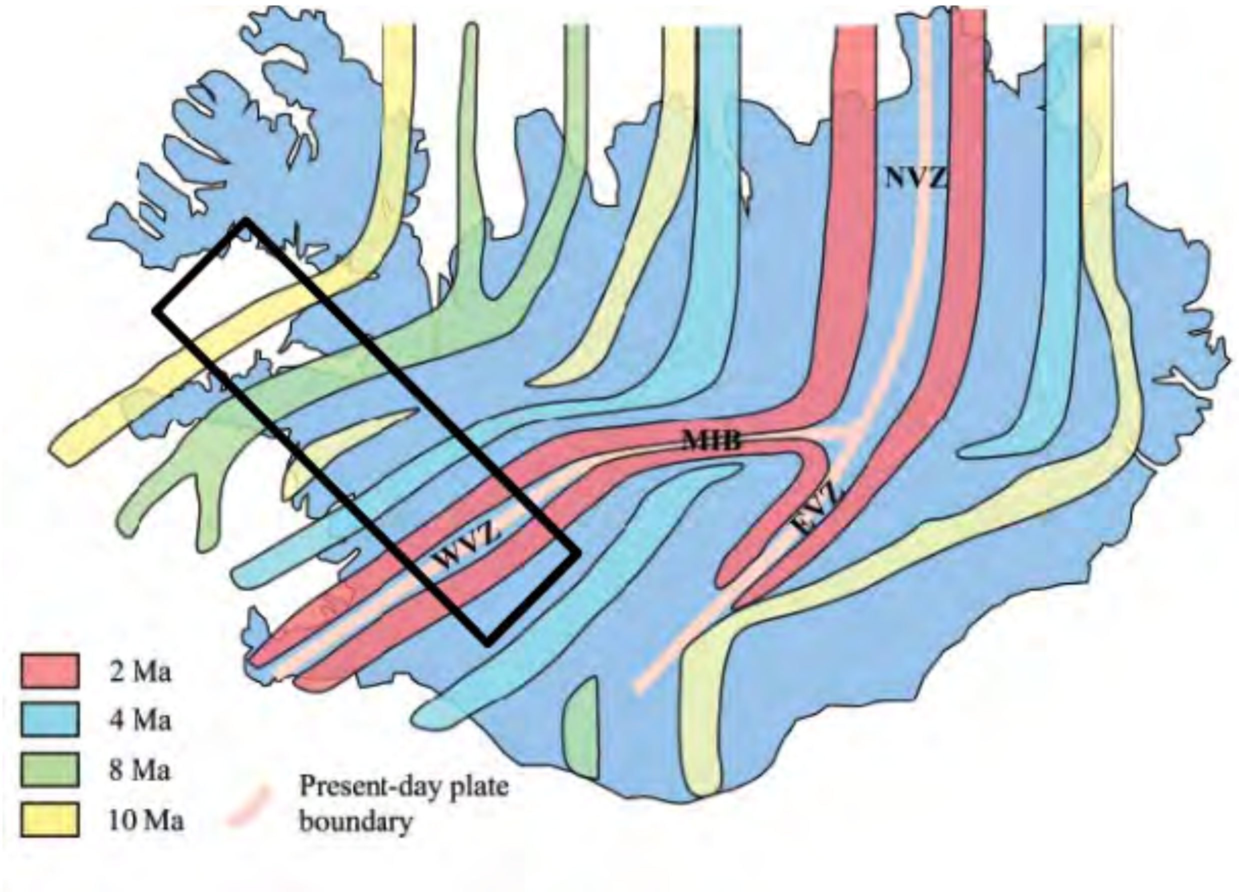
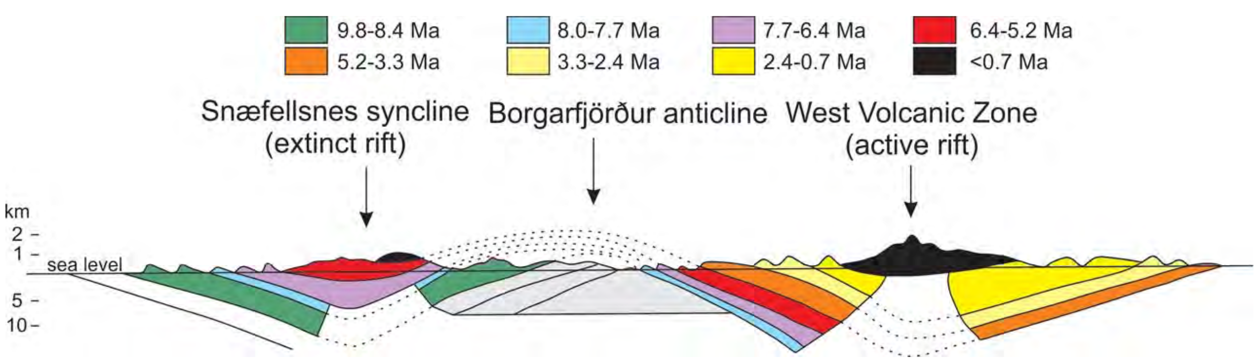
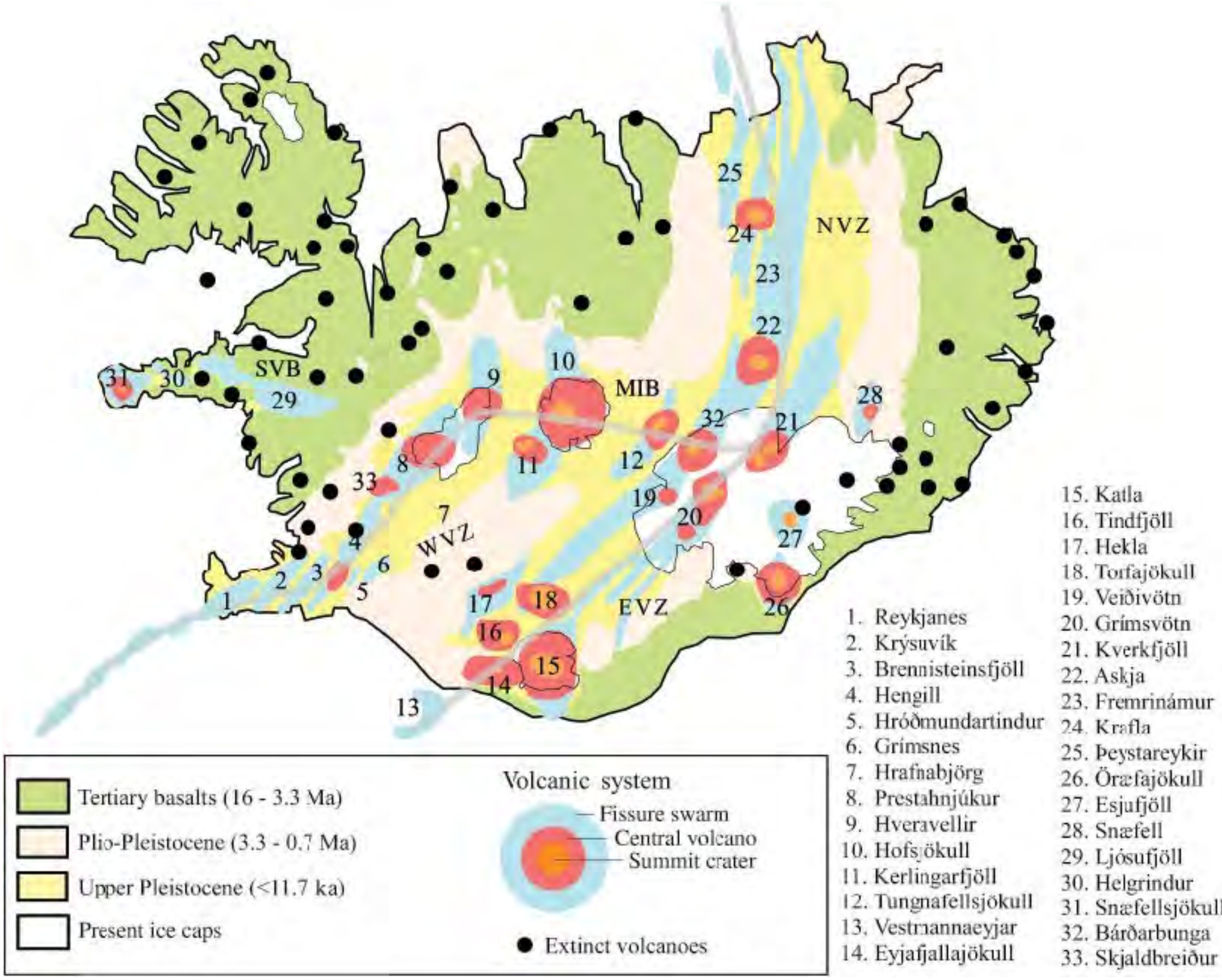


Figure from Jovanelly (AGU 2020)

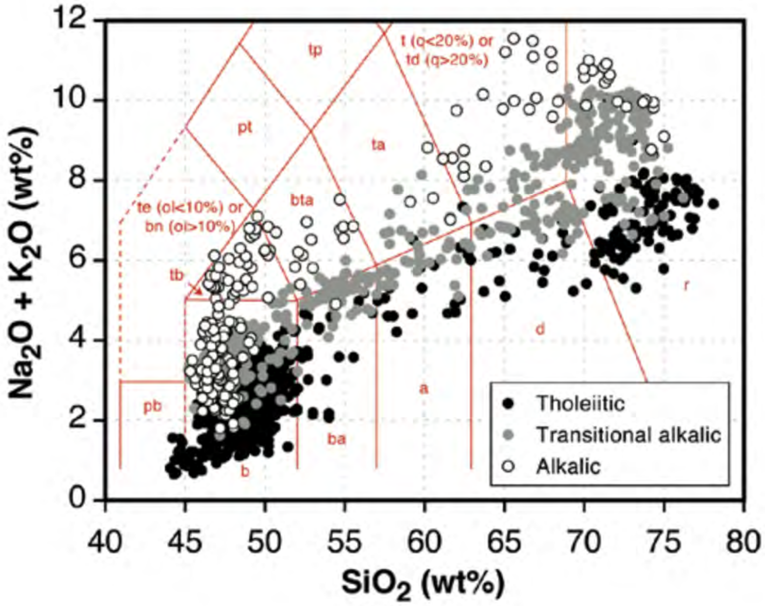


As described by Mittelstaedt et all. (2008) rift jumps are induced by magmatic heating from an off-axis hot spot (at present, under Vatnajökull), which results in a change in the location of the ridge axis. The magma produced by the hot spot thins the lithospheric crust thereby initiating new rifting to form a new ridge axis. In Iceland, this process is combined with east and west divergence of two continental plates, resulting in the rift axes becoming less active as they move away (e.g., relocate) from the hot spot intensity.

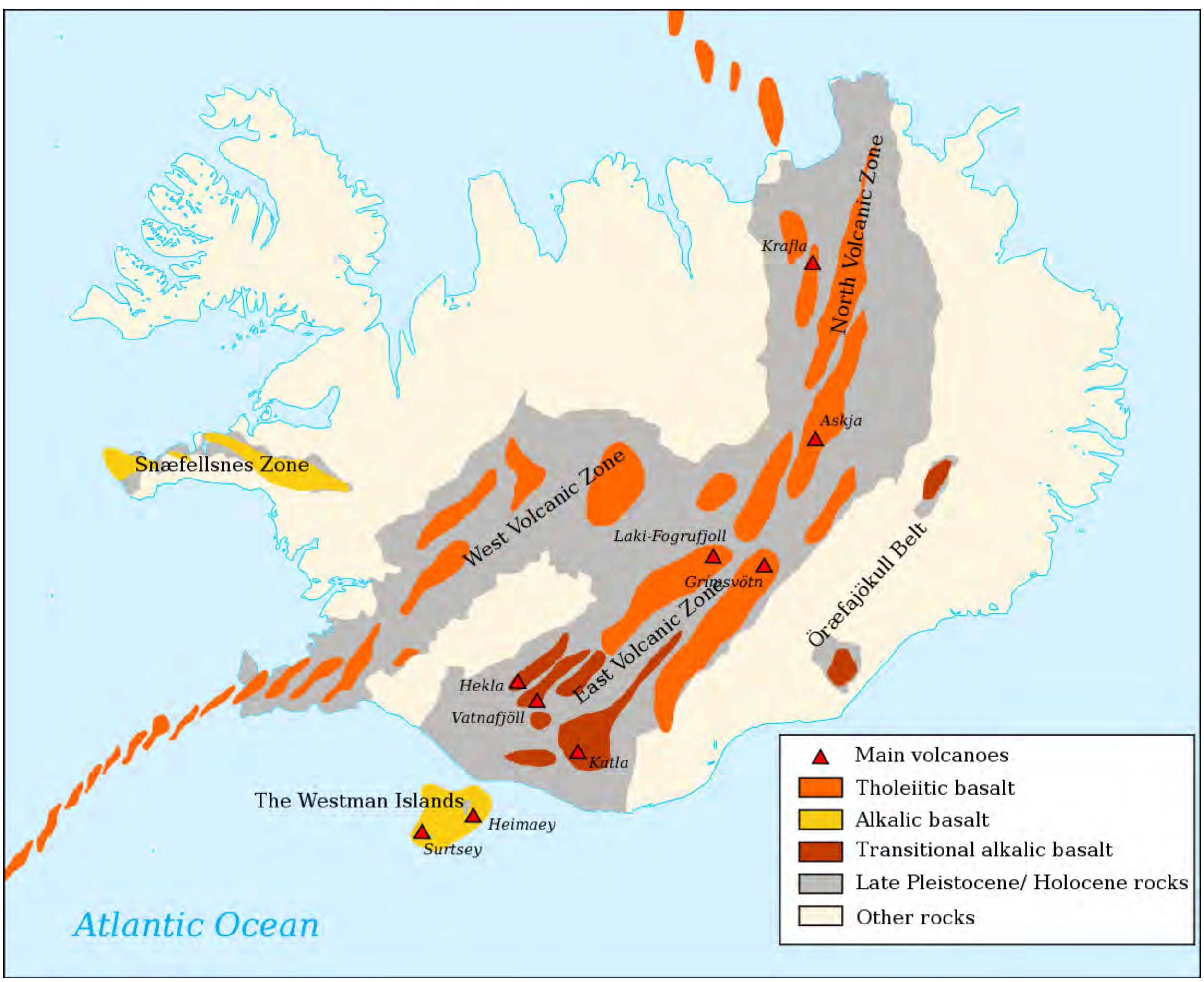
Volcanism



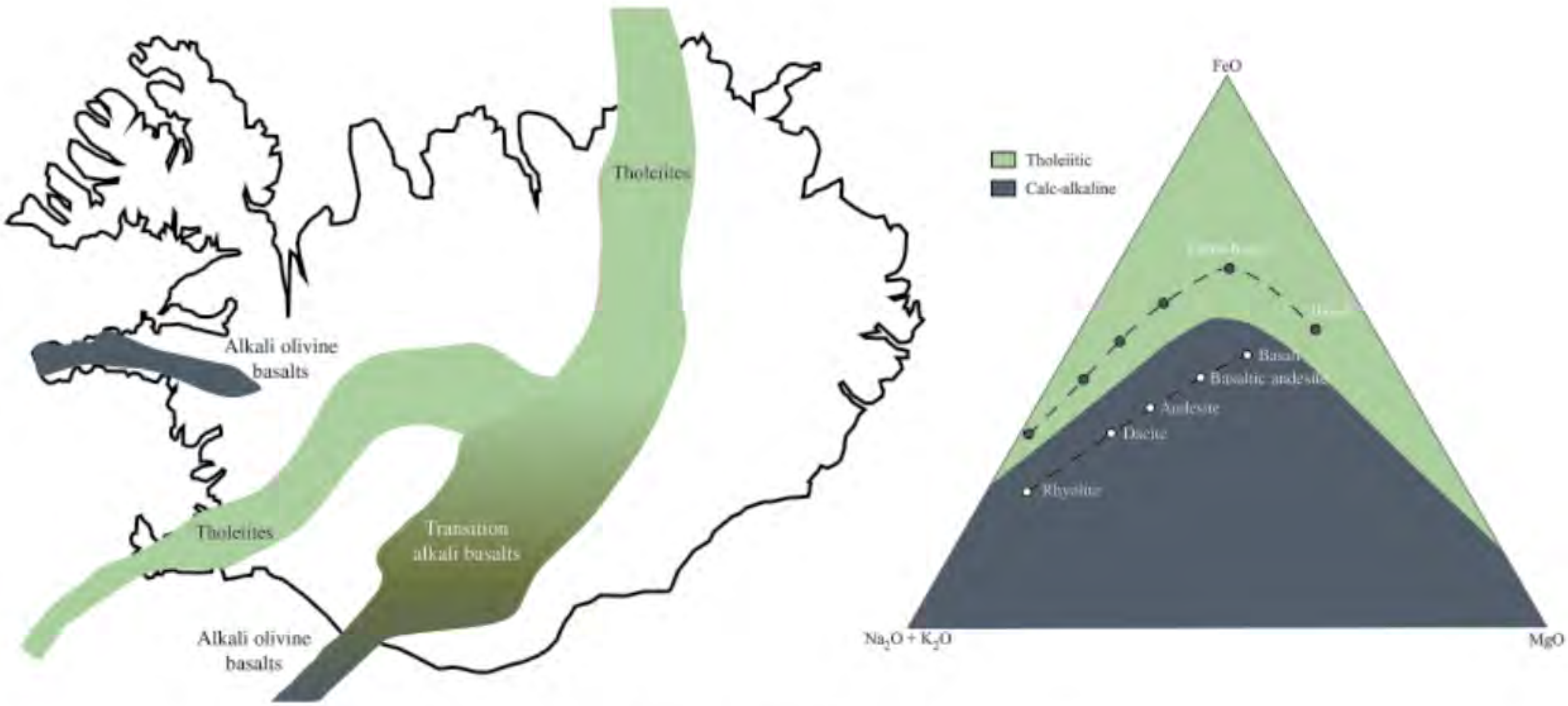
Modified from Jovanelly (AGU 2020): There are three main igneous rock formations in Iceland including: 1) the voluminous Tertiary basalts which have been dated to 14 Ma and have stratigraphic thicknesses up to 10 km in eastern Iceland; 2) late Pliocene and Pleistocene basalts that are characterized by 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. Active volcanism, which occurs over ~30% of the area of Iceland, is concentrated along zones of neovolcanic rifting and two off-axis intraplate volcanic zones3 (Fig. 5) [further discussion of volcanism in following section]. Although most Icelandic lavas are basalts (~85%), rhyolites (~12%) and intermediate rocks (~3%) are present across the island, especially within large central volcanic complexes. The distribution of different igneous rocks in Iceland is shown on the next page.



Na2O + K2O (wt%)
SiO2 (wt%)
tp
t (q<20%) or
td (q>20%)
pt
ta
bta
te (ol<10%) or
bn (ol>10%)
tb
pb
b
ba
a
d
r
Tholeiitic
Transitional alkalic
Alkalic



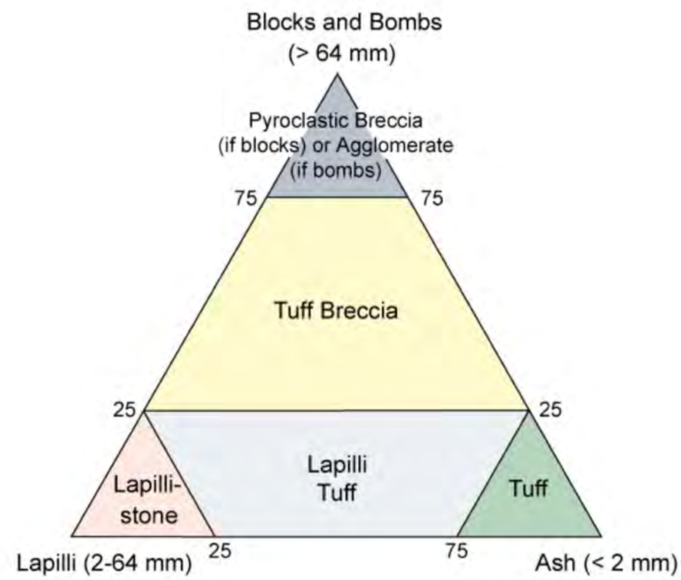
North Volcanic Zone
Krafla
Askja
Snæfellsnes Zone
West Volcanic Zone
Laki-Fogrufjöll
Grímsvötn
Öræfajökull Belt
East Volcanic Zone
Hekla
Vatnafjöll
Katla
The Westman Islands
Heimaey
Surtsey
Atlantic Ocean
Main volcanoes
Tholeiitic basalt
Alkalic basalt
Transitional alkalic basalt
Late Pleistocene/ Holocene rocks
Other rocks

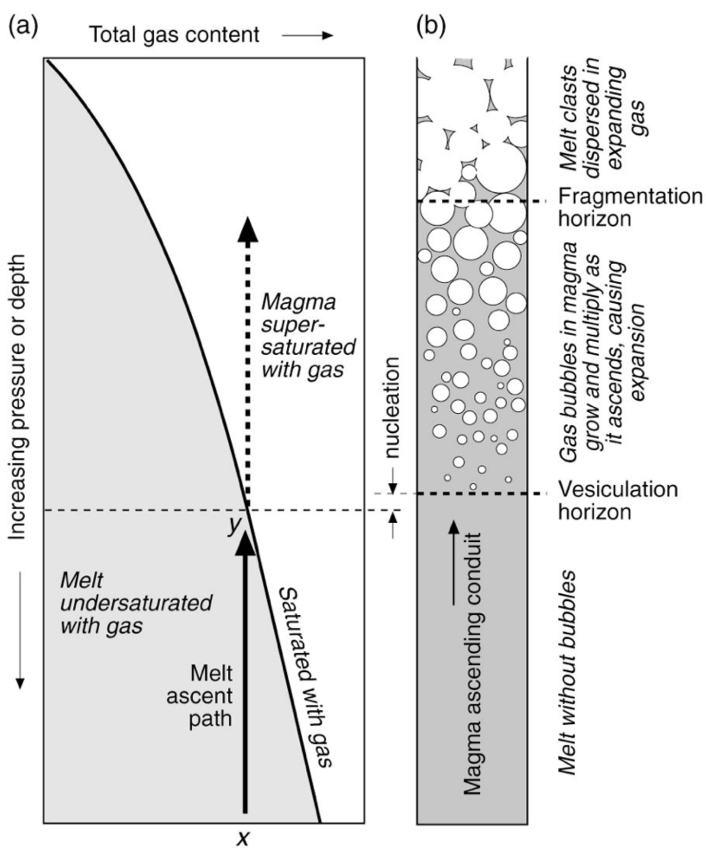


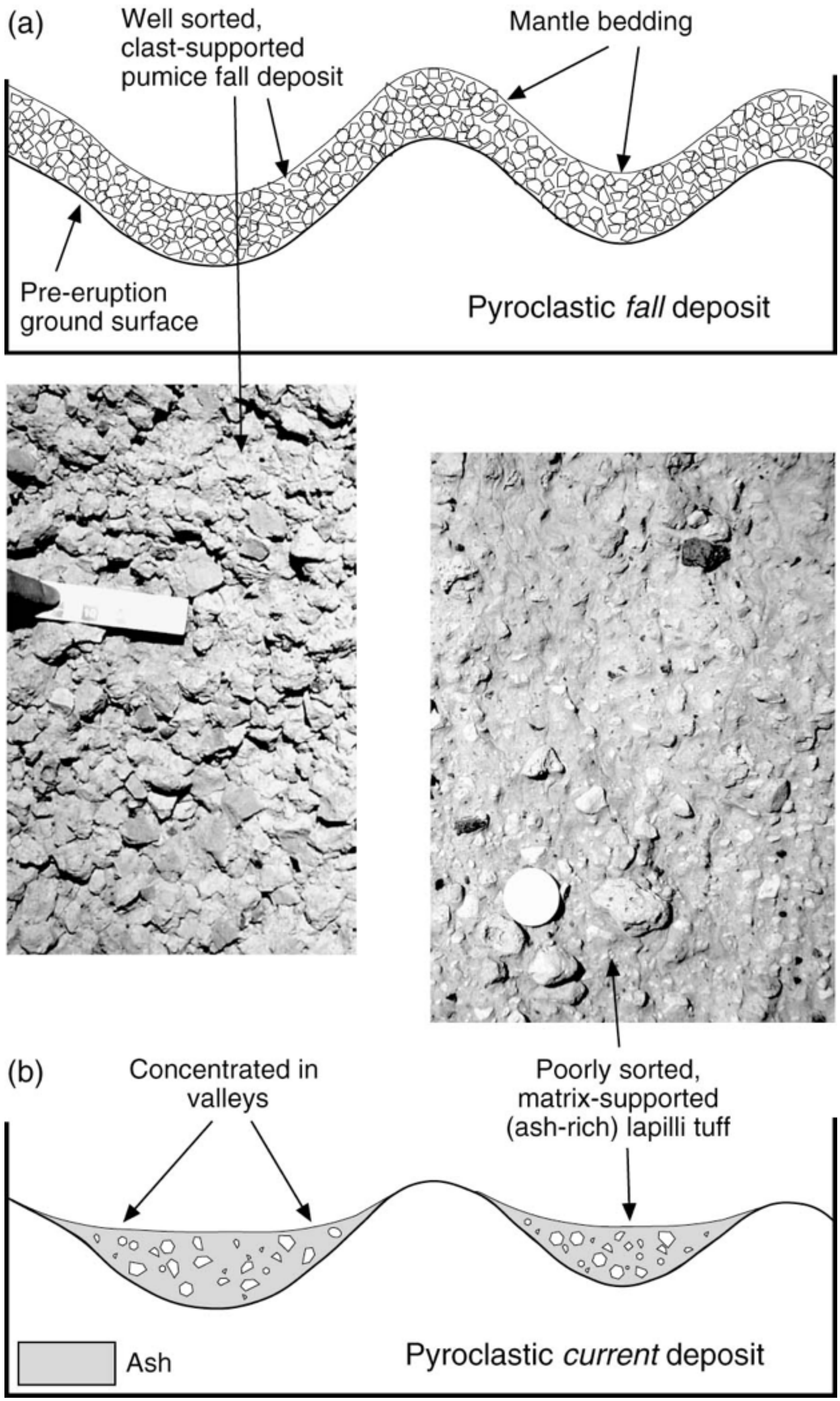
	Tholeiitic series	Transitional alkali series	Alkali series
Basaltic	Picrite Olivine tholeiite Tholeiite	Transitional olivine basalt Transitional basalt	Alkali olivine basalt Alkali basalt
Intermediate	Basaltic icelandite Icelandite	Transitional hawaiite Transitional mugearite Transitional benmoreite	Hawaiite Mugearite Benmoreite
Silicic	Dacite Rhyolite	Transitional trachyte Transitional rhyolite	Trachyte Alkalic rhyolite

Figure from Jovanelly (AGU 2020)

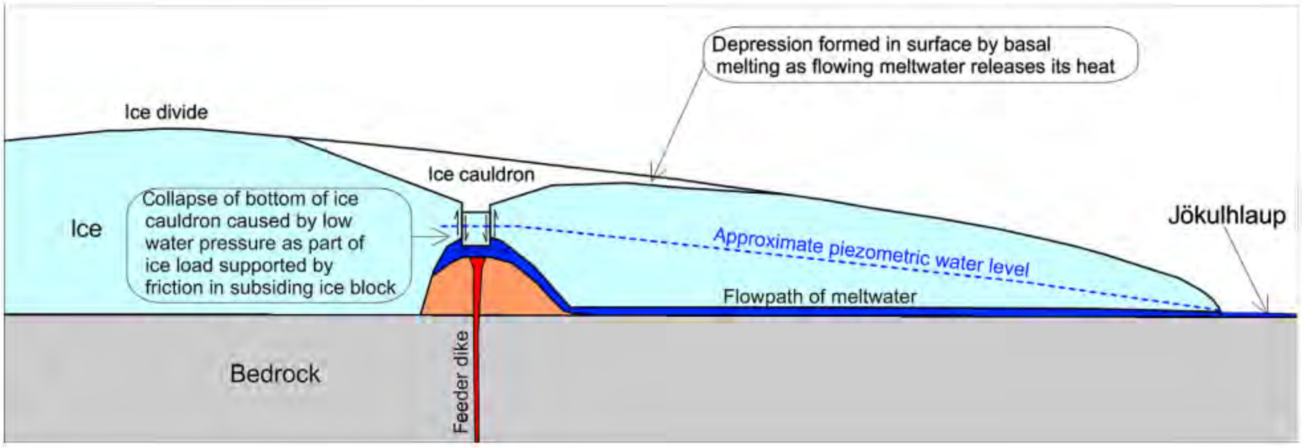
Pyroclastic Volcanism



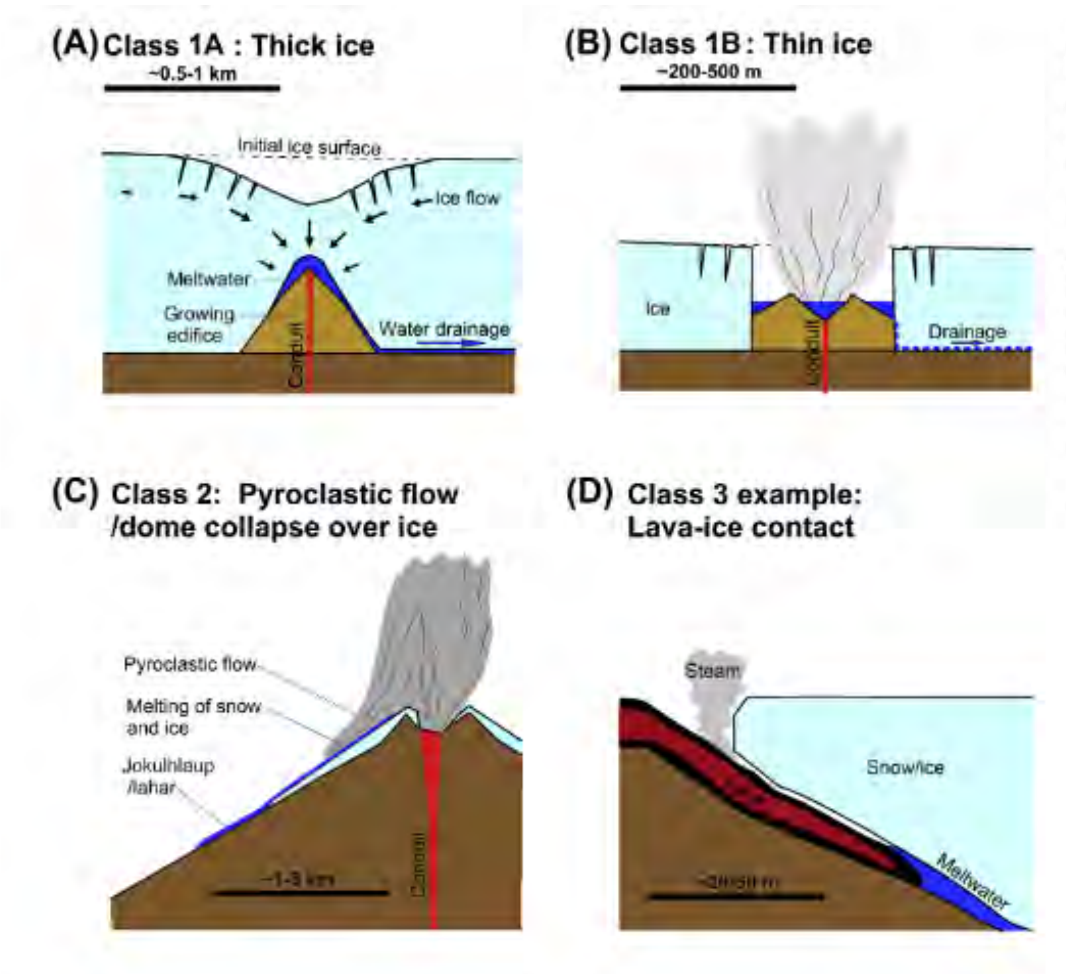


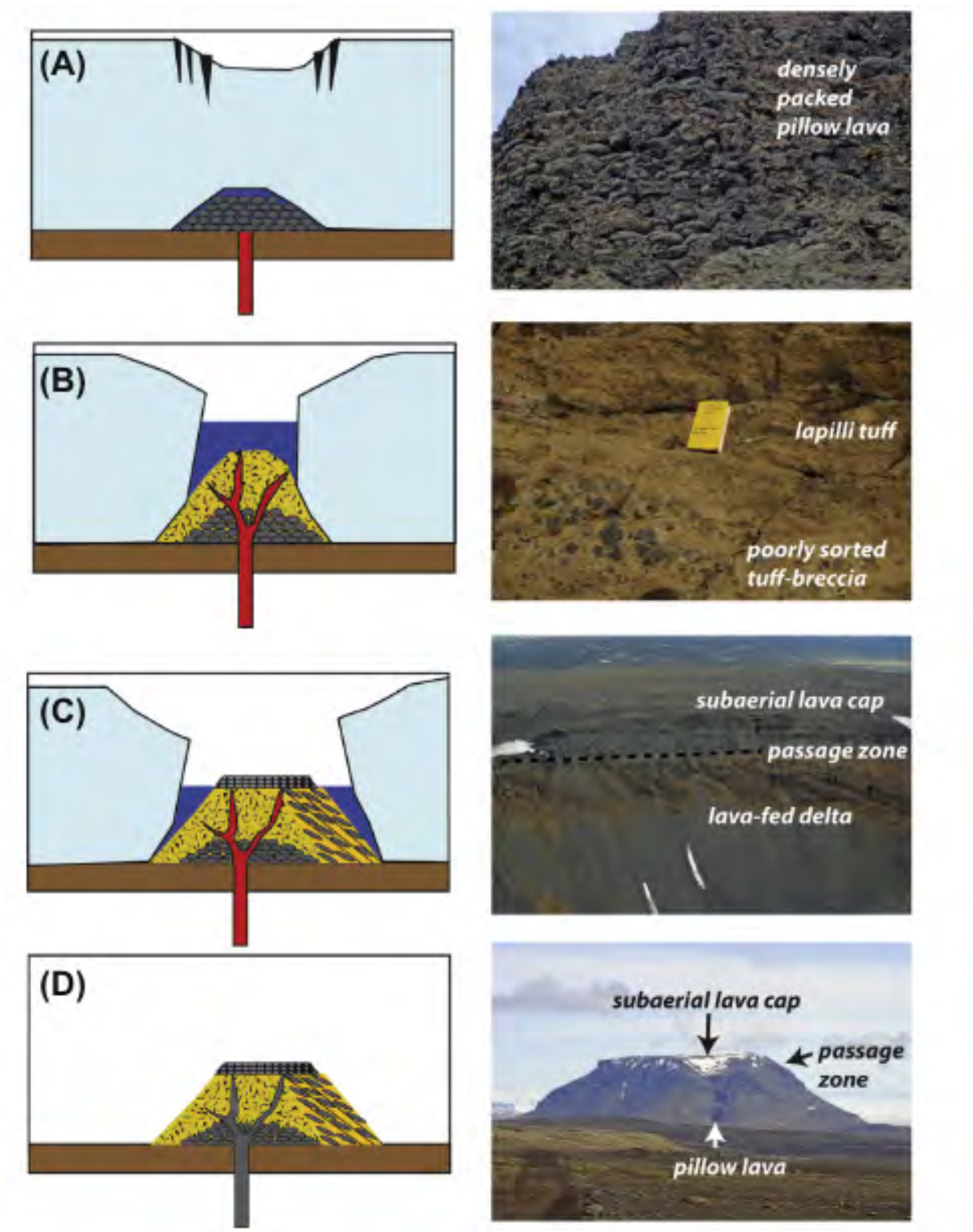

(a)
Well sorted, clast-supported pumice fall deposit
Mantle bedding
Pre-eruption ground surface
Pyroclastic *fall* deposit
(b)
Concentrated in valleys
Poorly sorted, matrix-supported (ash-rich) lapilli tuff
Ash
Pyroclastic *current* deposit

Glaciovolcanism



Edwards, Gudmundsson, Russell, Encyclopedia of Volcanoes (2010)



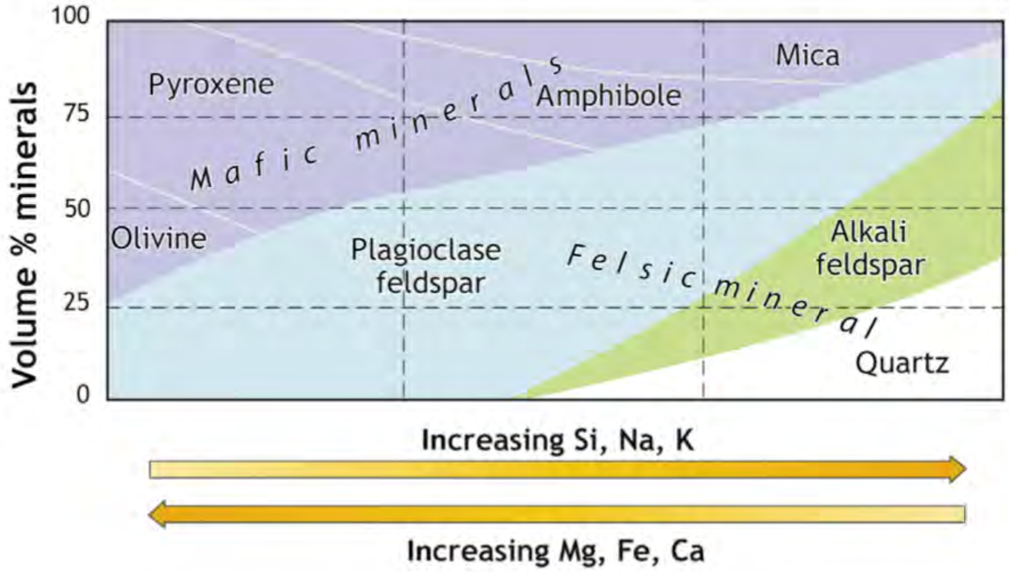


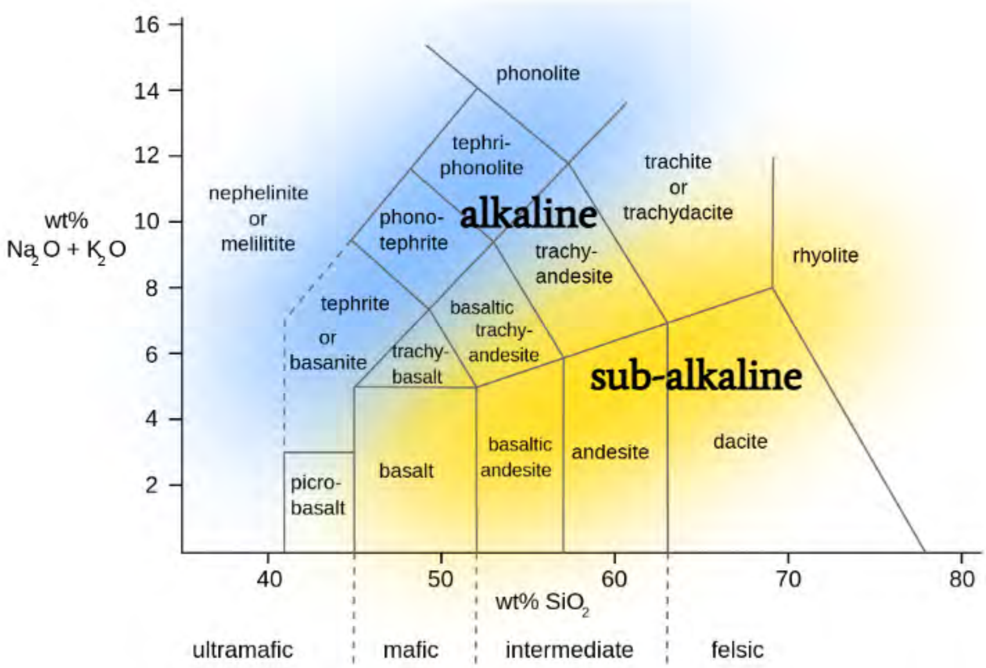
Edwards, Gudmundsson, Russell, Encyclopedia of Volcanoes (2010)

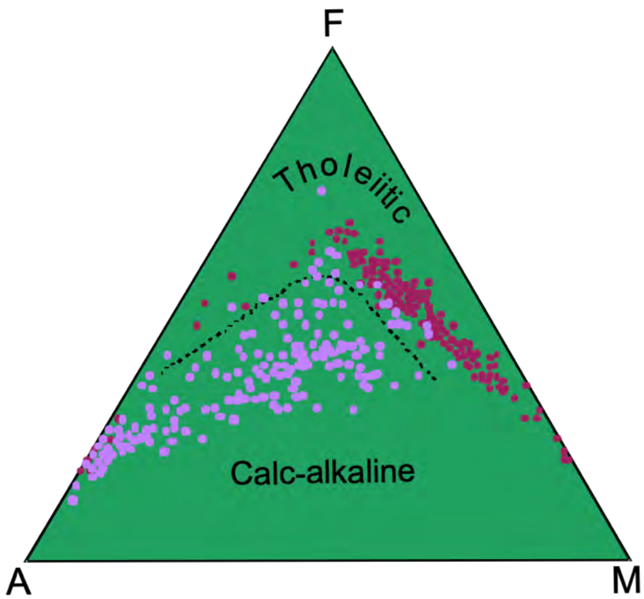
A. Initial eruption under thick ice → pillow lavas
B. Decreased vent pressure (decreased ice thickness) → magmatic fragmentation → lapilli tuff and clasts
C. Passage zone → depositional surface separating subaqueous from subaerial
D. Ice is gone → flat topped Tuya remains!

Additional Petrology Diagrams

	Mafic	*Intermediate*	*Felsic*
Extrusive	Basalt	Andesite	Rhyolite
Intrusive	Gabbro	Diorite	Granite







Further subdivision of subalkaline rocks

- **AFM diagram**
- A = (K_2O + Na_2O); F = (FeO + Fe_2O_3); M = MgO
  - ***tholeiitic*** series
  - ***calc-alkaline*** series