ICELAND SPRING BREAK TRIP 2016

UNIVERSITY OF PITTSBURGH AT JOHNSTOWN
DEPARTMENT OF ENERGY AND EARTH RESOURCES


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

Flights

Departing Flight
Departure: Sat 5 Mar 2016, 19:45, Washington Dulles International (IAD)
Icelandair (FI 644) Boeing 757-200, Duration: 05:45
Arrival: Sun 6 Mar 2016, 06:30, Reykjavik Keflavik International (KEF)

Return Flight
Departure: Sun 13 Mar 2016, 17:00, Reykjavik Keflavik International (KEF)
Icelandair (FI 645) Boeing 757-200, Duration: 06:30
Arrival: Sun 13 Mar 2016, 19:30, Washington Dulles International (IAD)

Iceland Basics

Emergency Number: 112
USA embassy: 595-2200

- *Currency:* Icelandic króna (IKR)
- *Exchange Rate:* 1 USD = ~130 IKR ($10 = 1,300)
- *Time zone:* GMT (5 hour difference from EST)
- *Credit Cards:* Accepted at most locations, even in rural areas. VISA and MasterCard are ubiquitous, AmEx less so
- *ATMs:* Available in all towns
- *Electricity:* 220 V/50 Hz, 2-pronged (CEE-type) – these are rounded prongs, not NEMA like our prongs
- *Tipping:* None
- *Etiquette:* Smoking is illegal in enclosed public spaces, bars, and restaurants. Remove shoes when entering homes. Shower thoroughly before entering spas and hot springs
- *Temperature:* March weather and climate: daily highs average around 37°F (3°C) and lows around 28°F (-2°C)
- *Cloud Cover:* The median cloud cover is 89% (mostly cloudy) and does not vary substantially over the course of the month
- *Precipitation:* The average probability that some form of precipitation will be observed in a given day is 78%, with little variation over the course of the month.
- *Wind:* Over the course of March typical wind speeds vary from 4 mph to 25 mph (light breeze to strong breeze), rarely exceeding 39 mph (gale).
- *Daylight:* ~11 hours of daylight (08:00–19:00)

Icelandic Language

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

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

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

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

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

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

BRIEF ITINERARY

Day 1: Saturday, March 5th, 2016 – Board flight

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

Day 2: Sunday, March 6th, 2016 – Reykjanes Peninsula

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

7:30: After clearing customs, we will pick-up the vehicles

8:00: I think it will be best to have breakfast at the airport

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

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

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

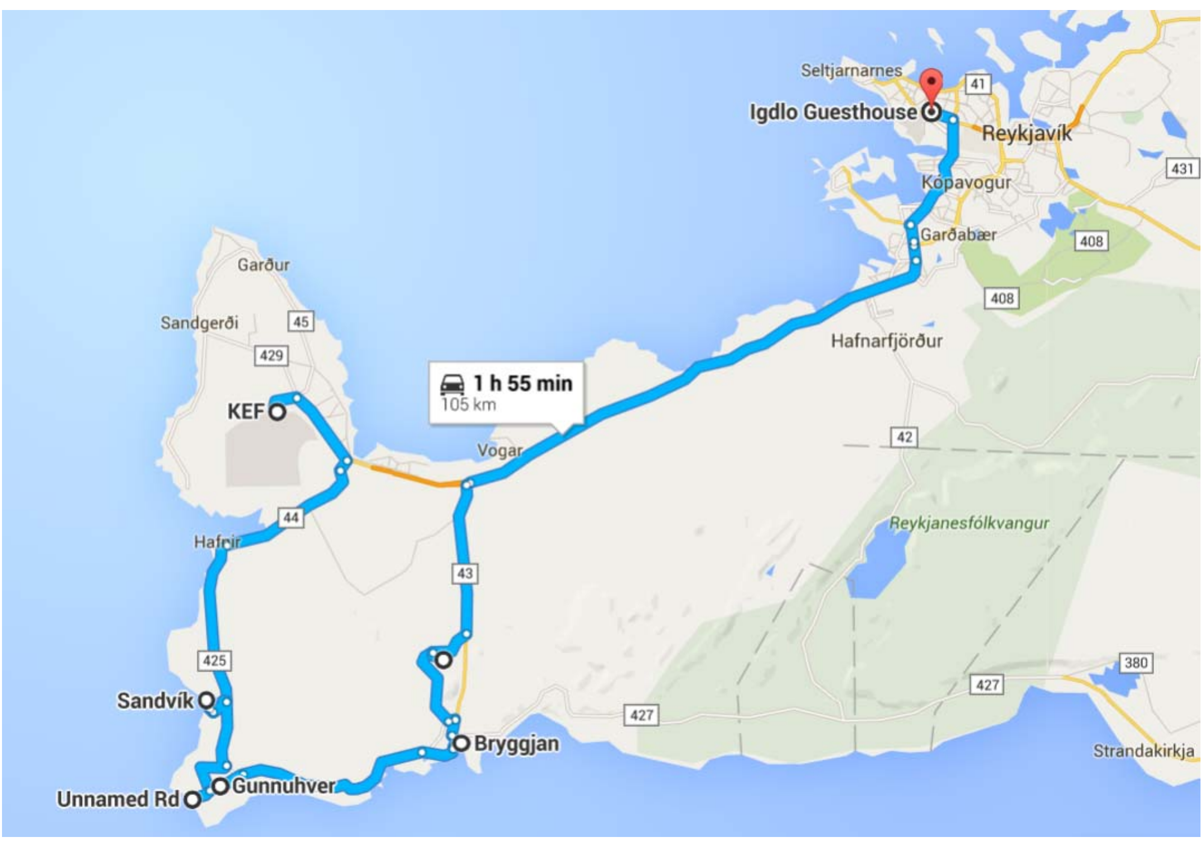
12:30: Lunch in Grindavik – There is a café called Bryggjan (2 240, Miðgarður, Grindavík) near the harborfront that might be good.

There is also a grocery store in Grindvik called Netto, this might be a good opportunity pick up some groceries and such.

2:00PM: Blue Lagoon – the basic package is $45 dollars, that really just gets you entrance into the pools, looks like you can add on towel for $5. They list other packages up to $80 that include drinks, mud masks, etc.

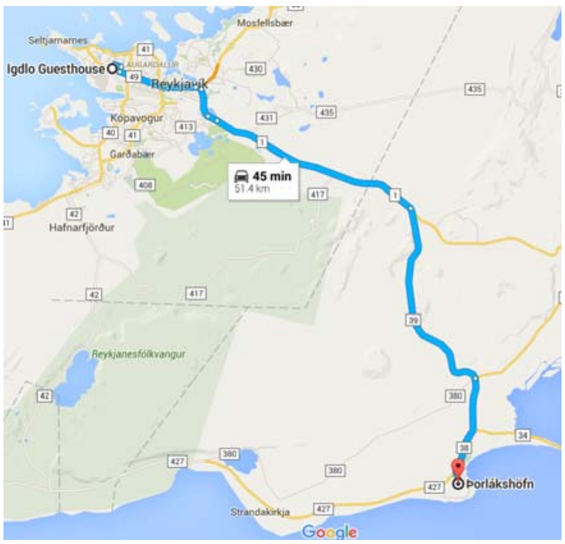
It is about 40 minutes to the hostel, we can stay as long as people want but I would suggest we hit the road by 5.

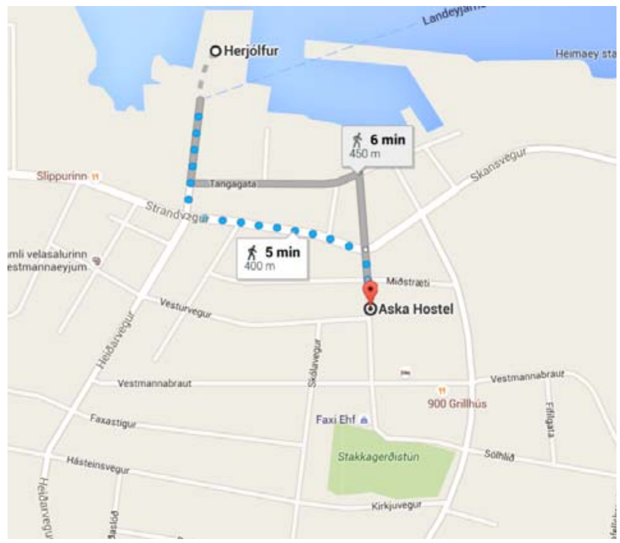
6 or 7 PM: Get to the hostel (Igdlo Guesthouse, Gunnarsbraut 46, 105 Reykjavík). Stay there for one night. Fend for yourself for dinner? Or we could cook a group meal, the hostel has a kitchen that we can use.



Day 3: Monday, March 7th, 2016 – Reykjavik to Heimaey

The morning is free and the hostel will provide breakfast.
10:15: Leave the hostel and head toward Þorlákshöfn for the ferry
11:30: Board the ferry and depart for Vestmannaeyjar, Heimaey.
12:00: Lunch on the boat
2:30PM: Arrive Vestmannaeyjar, Heimaey and check in with the hostel (Aska Hostel, Bárustígur 11, Vestmannaeyjar, 900, Iceland).
Rest of the day: Walk around, hang out, relax, whatever… On our own for dinner, there might be a kitchen at the hostel, we could do a group meal.





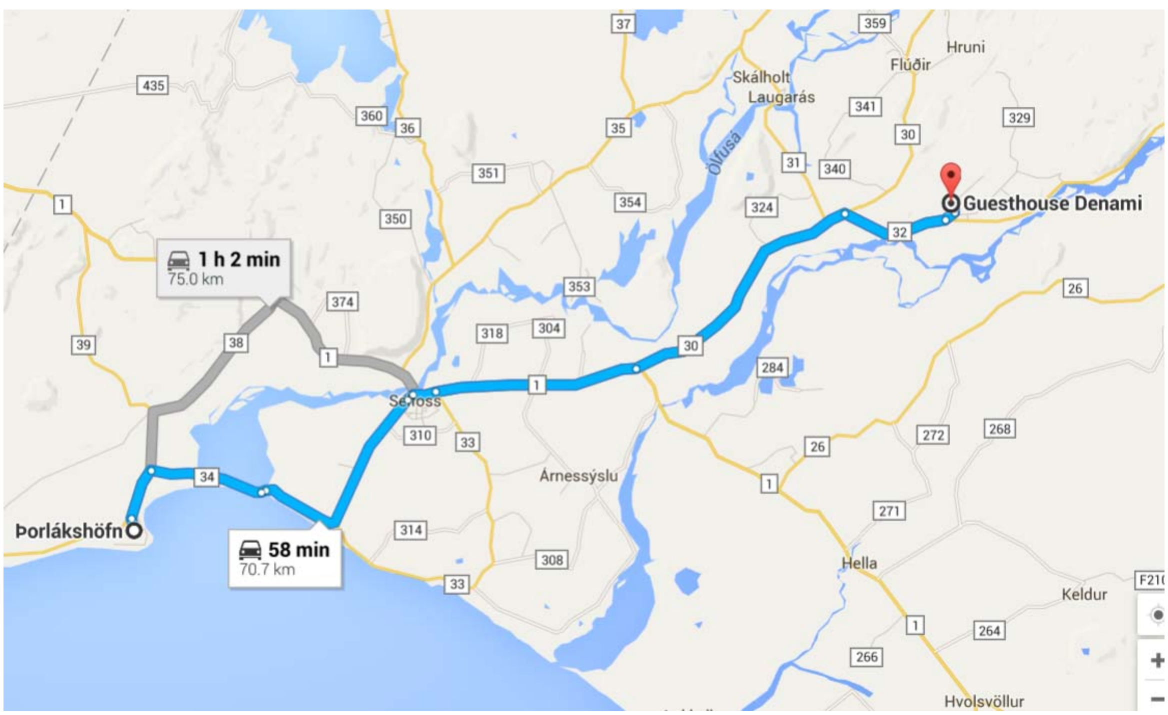
Day 4: Tuesday, March 8th, 2016 – Heimaey to the Rift Valley

8:00: Make breakfast in the hostel
9:00: Drive to the south edge of the island, hike around and get a view of Surtsey
There is enough hiking to make that our full day, there is a lot to see here. Terry has a good loop hike that would bring us past a lot the cool stuff.
There pictures of Elephant Rock on the internet from this island, it looks really cool, hopefully we can figure out where it is, I'd like to see that…
If weather becomes an issue there are indoor activities available as well.

Indoor Activities: Eldheimar Volcano Museum (10, Gerðisbraut, Vestmannaeyjabær, opens at 11AM, $14) – seems like this give a descent history of the island and the volcanic issue. This also has overview of the buried portions of the town.

The natural history museum and aquarium gets good reviews (Saeheimar Aquarium, Heioarvegur 12 900, Vestmannaeyjar, close to the ferry terminal, opens at 1PM, $8). Other than that people could just hike around or wait for the ferry in a café or something.

3:00PM: Board the ferry and depart for the main land
6:15PM: Reach Þorlákshöfn and drive to the Guesthouse in the rift valley
7:30PM: Get to Guesthouse Denami (Háholt, Iceland), they will have a traditional Icelandic meal of lamb stew and Icelandic breads

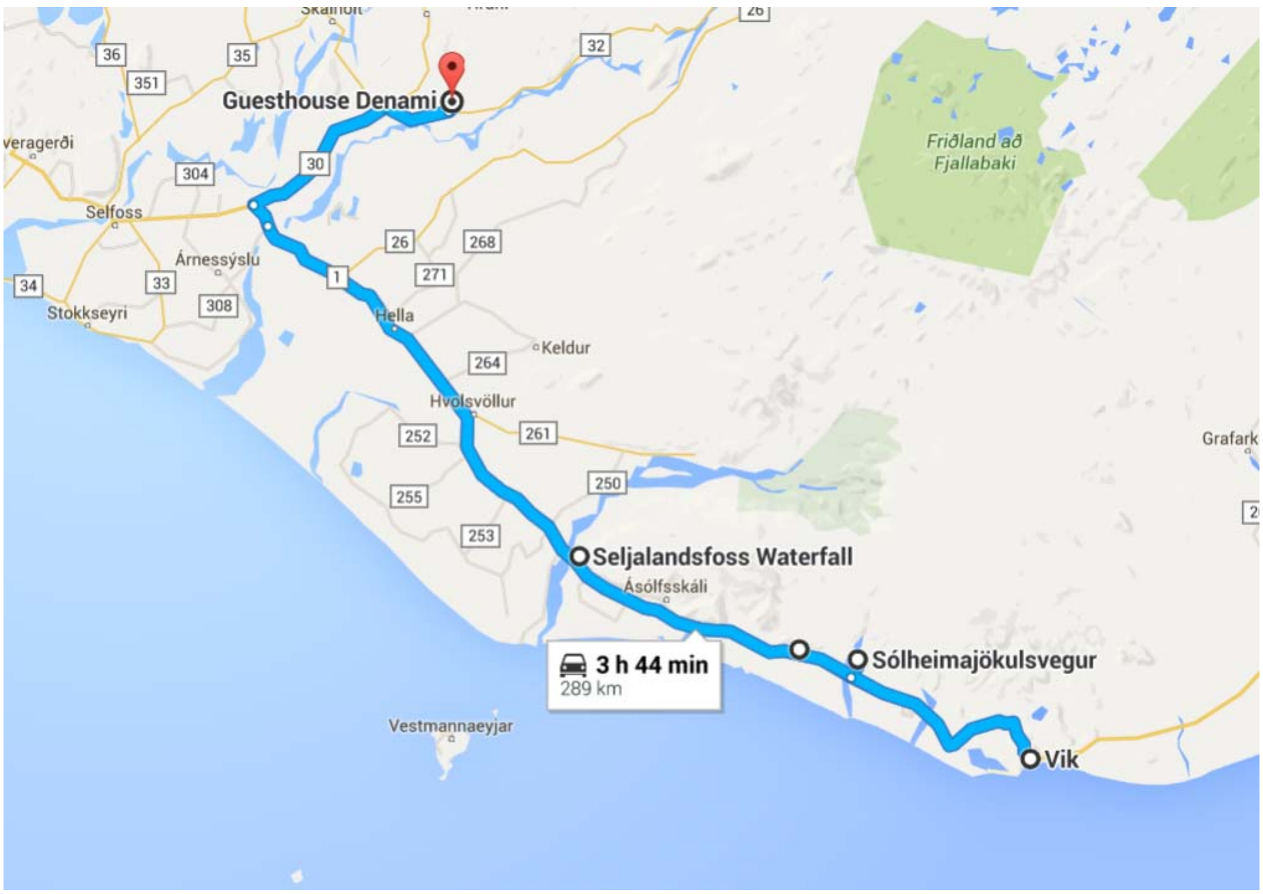


Day 5: Wednesday, March 9th, 2016 – Waterfalls, Glaciers and Vik Beaches

7:00: Wake-up.
7:30: Make Breakfast.
8:30: Depart
9:30: Arrived at Seljalandsfoss waterfall.
10:15: Arrived at Skogafoss waterfall.
12:00: Sólheimajökulsvegur Glacier, Lunch at the Glacier
2:30PM: Arrive in Vik walk the beaches and check out Vik.

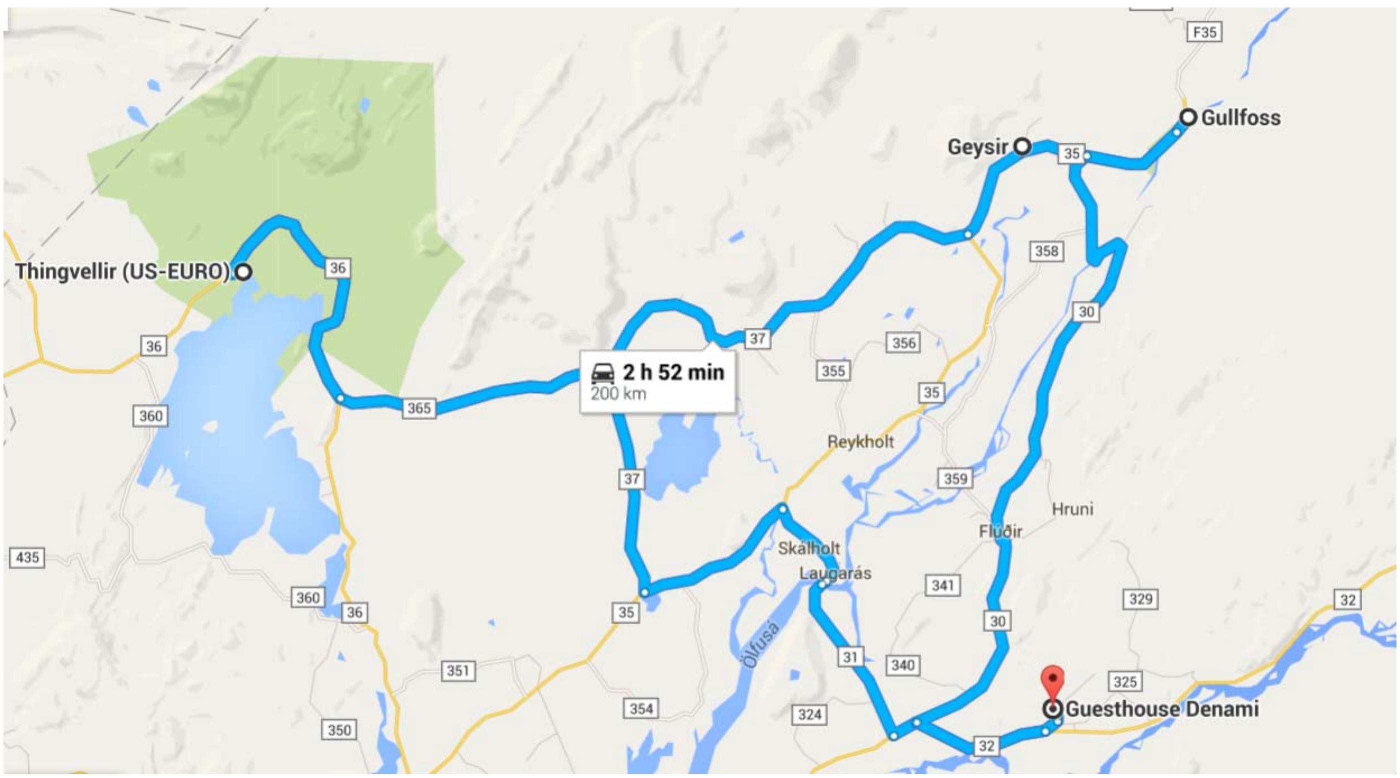
This would be the best day for the Ice Cave tour people have mentioned.

This evening we are on our own for dinner, we will need to figure that out.



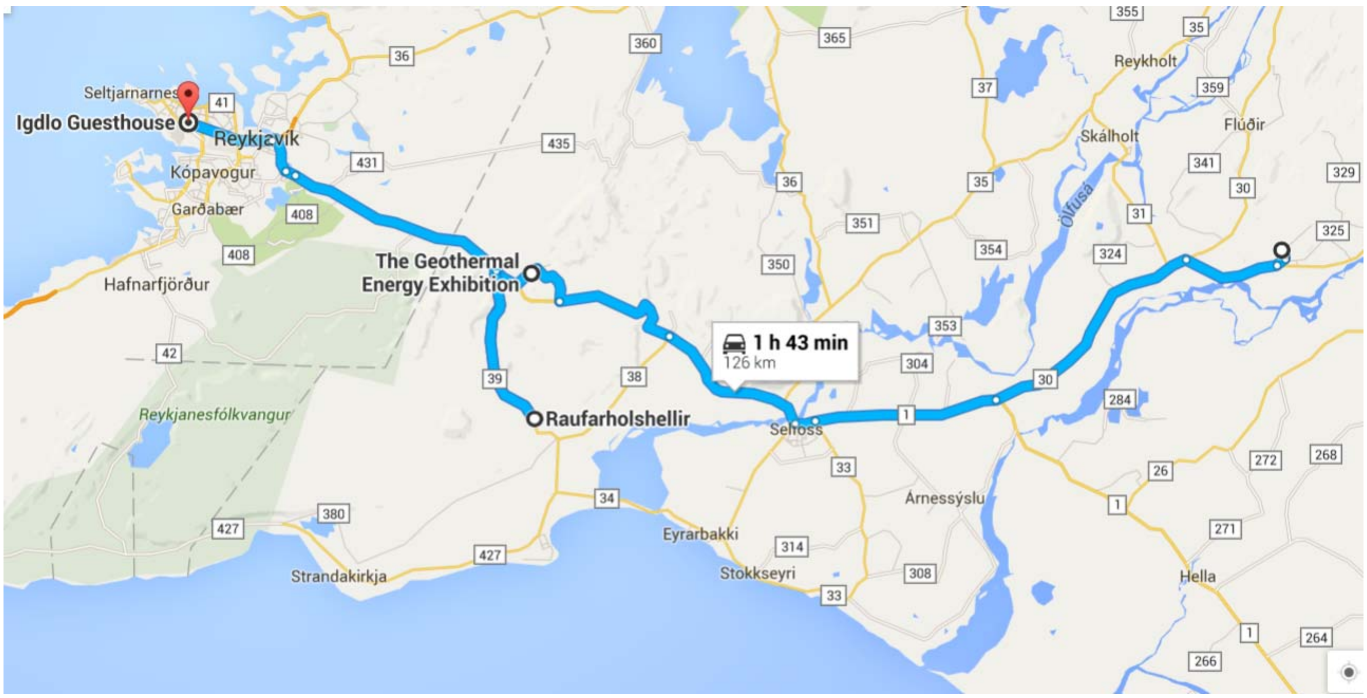
Day 6: Thursday, March 10th, 2016 – Þingvellir, Geysir, Gulfoss

7:00: Wake-up.
7:30: Make Breakfast.
8:30: Depart for Þingvellir
9:30: Arrived at Þingvellir
10:00: Walk to the Law Rock and through the rift valley.
12:00: Make lunch
1:00PM: Depart for Geysir.
2:00PM: Arrived at Geysir (site of hydrothermal springs and geysers). Walk around the site
3:30PM: Leave for Gullfoss (Golden Waterfalls)
4:00PM: Arrive at Gullfoss visit the fall and visitor's center
5:30PM: Depart to return to the hostel
6:15PM: Get to Guesthouse Denami (Háholt, Iceland), they will have a traditional Icelandic meal of lamb stew and Icelandic breads



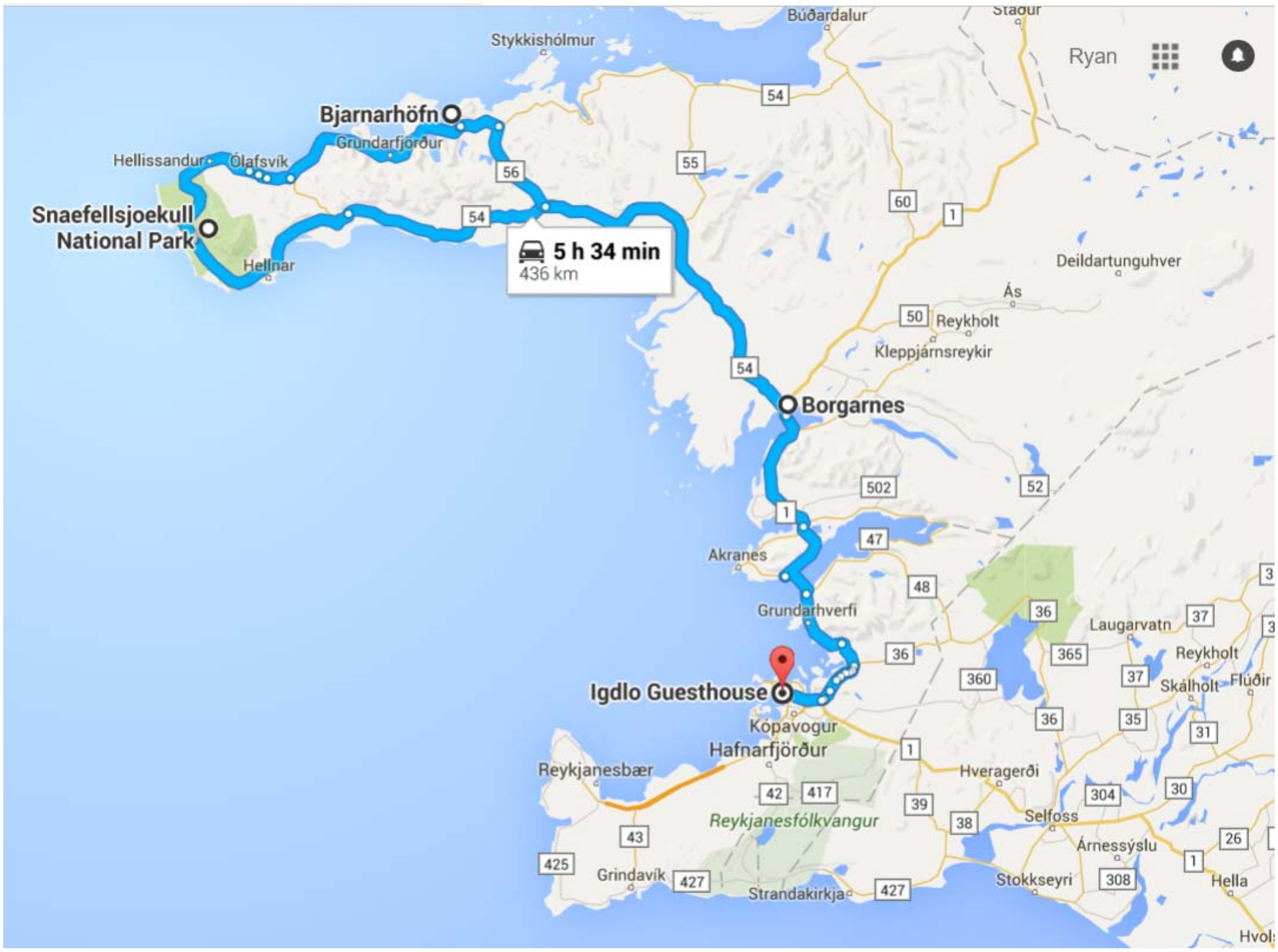
Day 7: Friday, March 11th, 2016 – Hellisheiði Power Plant, Raurfarholshellir Lava Tube, and back to Reykjavik

7:00: Wake-up, pack our things and load the vans.
7:30: Make breakfast.
8:30: Depart for Hellisheiði Power Plant (Hellisheiðarvirkjun, Iceland)
9:30: Take a tour of the geothermal museum and a "behind-the-scenes" tour of the power plant ($20 each).
12:00: Finished tour. Have lunch.
1:30PM: Arrived at Raurfarholshellir Lava Tube, ate lunch. Hike some of the lava tube. THIS REQUIRES STURDY BOOTS AND A FLASHLIGHT (or headlamp).
3:00PM: Returned to the van and head into Reykjavik. We will be staying in the same accommodations (Igdlo Guesthouse, Gunnarsbraut 46, 105 Reykjavík).



Day 8: Saturday, March 12th, 2016 – Borgarnes and the Snaefellsness Peninsula

8:00: Wake-up and have breakfast (provided by the hostel)
9:00: Depart for Borgarnes
10:00: Arrive in Borgarnes
11:00: Drive around the Snaefellness Peninsula
1:00 PM: Snæfellsjökull Volcano – the lonely planet guide has good descriptions of stuff.
5:00 PM: Return to Reykjavik
6:00 PM: Group Dinner?



Day 9: Sunday, March 13th, 2016 – Reykjavik and return home

Also this is daylight savings time, this not observed in Iceland but it should be noted.

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

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

2:30PM: Return the rental vehicles
3:00PM: Arrive at the airport
5:00PM: Boarding Icelandair Flight 645
7:30PM: Arrive in Dulles, Washington DC

INTRODUCTION

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

General Information about Iceland

Contributed by Nevin Singh

Iceland is located in the Northern Atlantic Ocean, on the edge of the Arctic Circle, between latitudes $63^o24'$N and $66^o33'$N and between longitudes $13^o30'$W and $24^o32'$W. The closest countries are Greenland (286 km), Scotland (795 km), and Norway (950 km). The total area of Iceland is 103,000 km2 (39,756 mi2), which is about the size of Kentucky. The distance from the north to south coast is approximately 300 km (185 mi) and from east to west is approximately 500 km (305 mi). The coastline is 4,970 km long. The average elevation of Iceland is 500 m above sea level with the highest point being Hvannadalshnukur at 2,119 m (6,950 ft) on the Öræfajökull glacier. There are several islands that surround the coast, some of which are inhabited. These include the Westman Islands to the south, Hrisey in the north, and Grimsey in the Arctic Circle.

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

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

Iceland is the most sparsely populated country in Europe with an average of about 3 inhabitants per square kilometer. Almost 80 percent of the country is uninhabited, with most people living on the coasts, valleys, and southwest corner of the country. In 2008, the population was 313,000 with 2/3 of them living in the capital of Reykjavík . The life expectancies for men and women (78 and 82 years, respectively) are among the world's highest averages. The country's written and spoken language is Icelandic, a Nordic language very similar to that of the original settlers. Icelandic and Norwegian did not become markedly different until the 14th century. Icelanders have resisted change to their language and, still today, Icelandic is very similar to the language that existed in the 12^{th} century. The literacy rate is 99.9%, the highest in the world.

Iceland's currency is the krona, which in September 2010 traded at 114 krona to the dollar. Iceland's economy had an estimated GDP of $12.2 billion in 2009, with a GDP per capita of $39,800. The economy is based on a Scandinavian-type social market economy that combines a capitalist structure with an extensive welfare system. Iceland's economy is highly export-driven with marine products accounting for the majority of exports. The fishing industry provides 70% of export income and employs 6% of the workforce. Other exports include aluminum, machinery, electronic fishing equipment, software, and woolen goods. Through hydroelectric and geothermal resources, Iceland is able to generate 70% of its primary energy and 99.9% of their electricity from renewable energy sources. Their goal is to be completely energy independent, using 100% renewable energy by 2050.

Historical and Cultural Background

Contributed by Chris Hayes

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

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

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

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

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

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

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

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

GEOLOGIC OVERVIEWS

Ridge-Hotspot Interaction – The Origin of Iceland

Contributed by Shuoshuo Han

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

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

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

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

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

References:
[1]Dyment, J. Lin, and E.T. Baker, (2007). Ridge-hotspot interactions - How mid-ocean ridges tell us about deep Earth processes, Oceanography, Vol. 20, No. 1, 102-115.
[2]Ito, G., J. Lin, and D. Graham (2003). Observational and theoretical studies of the dynamics of mantle plume-mid-ocean ridge interaction, Rev. Geophys., 41(4), 1017.
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[5]Thordarson, T. and Larsen, G., 2007. Volcanism in Iceland in historical time: Volcano types, eruption styles and eruptive history. J. Geodynamics 43, 118-152.
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[7]C. Wolfe, I. Bjarnason, J. VanDecar and S. Soloman, (1997). Seismic structure of the Iceland mantle plume, Nature 385, pp. 245–247.

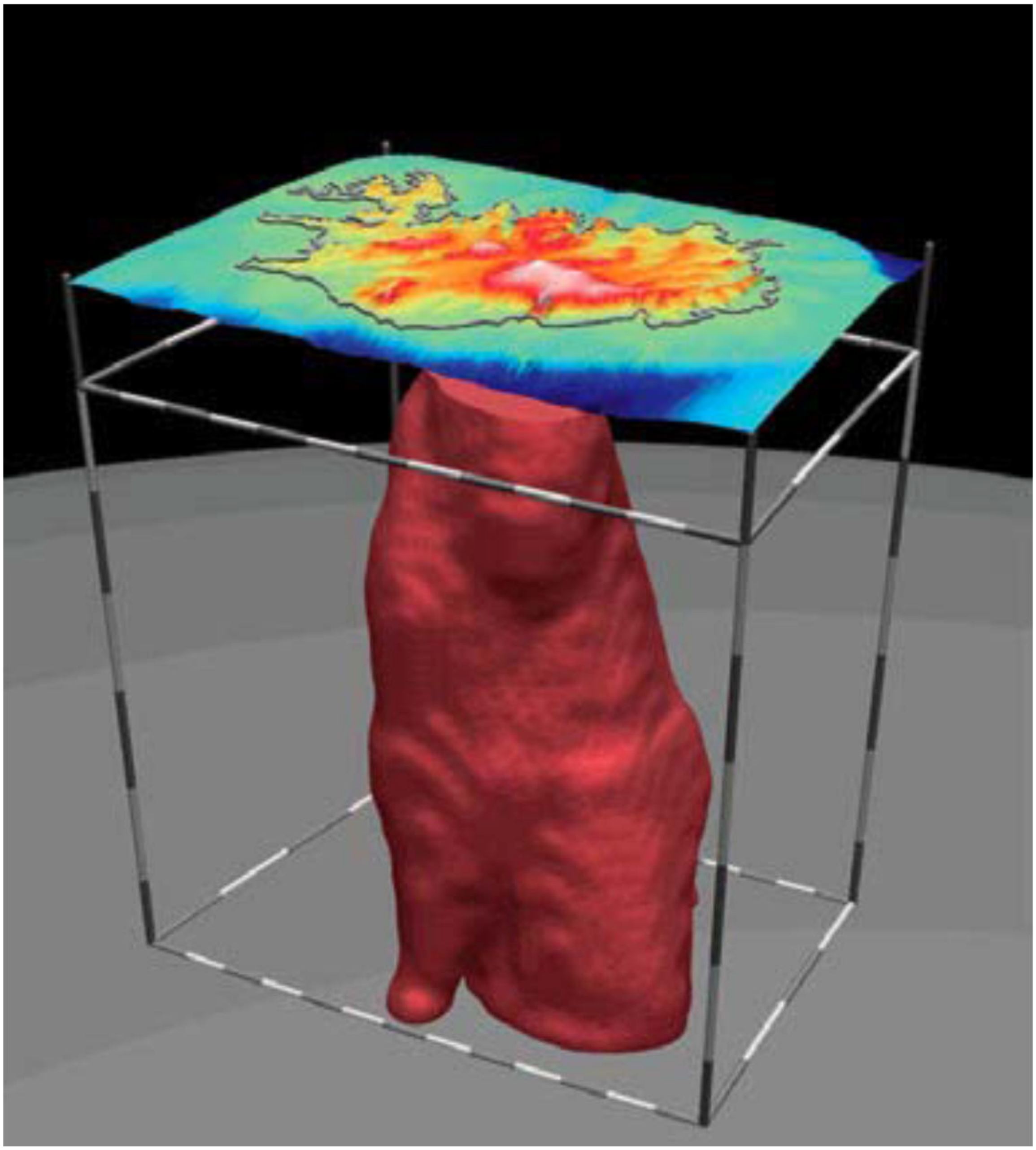

Figure 2. Seismic image of the upper mantle beneath the Iceland hotspot (Wolfe et al, 1997).

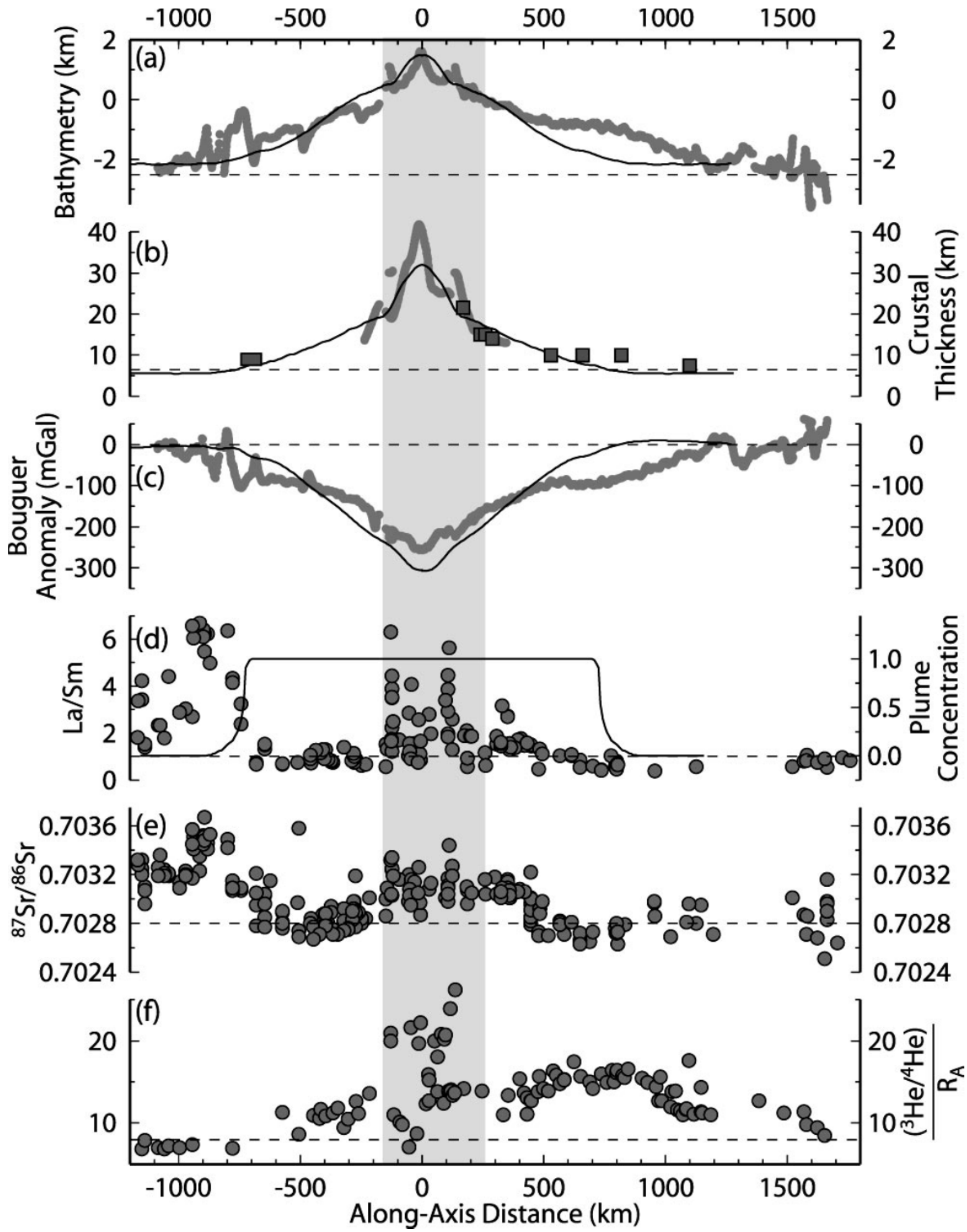

Figure 3. Profiles along the Mid--Atlantic ridge centered on Iceland of (a) bathymetry, (b) crustal thickness, (c) Bouguer gravity, (d) La/Sm ratio, (e) $^{87}Sr/^{86}Sr$ ratio, and (f) $He/^4He$ normalized by atmospheric ration. From Ito et al (2003).

Seismicity

Contributed by Pritwiraj Moulik

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

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

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

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

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

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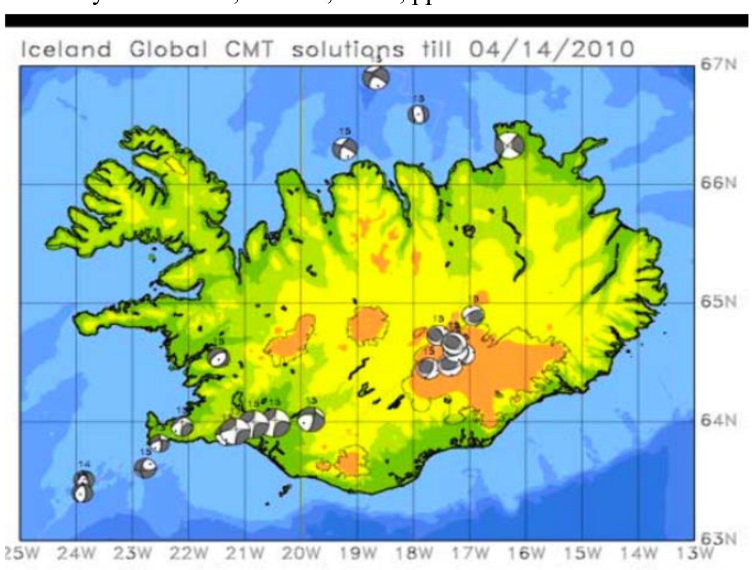

Figure 4. Iceland Global CMT solutions until 04/14/2010.

Petrology and Geochemistry

Contributed by Jason Jweda

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

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

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

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

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

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

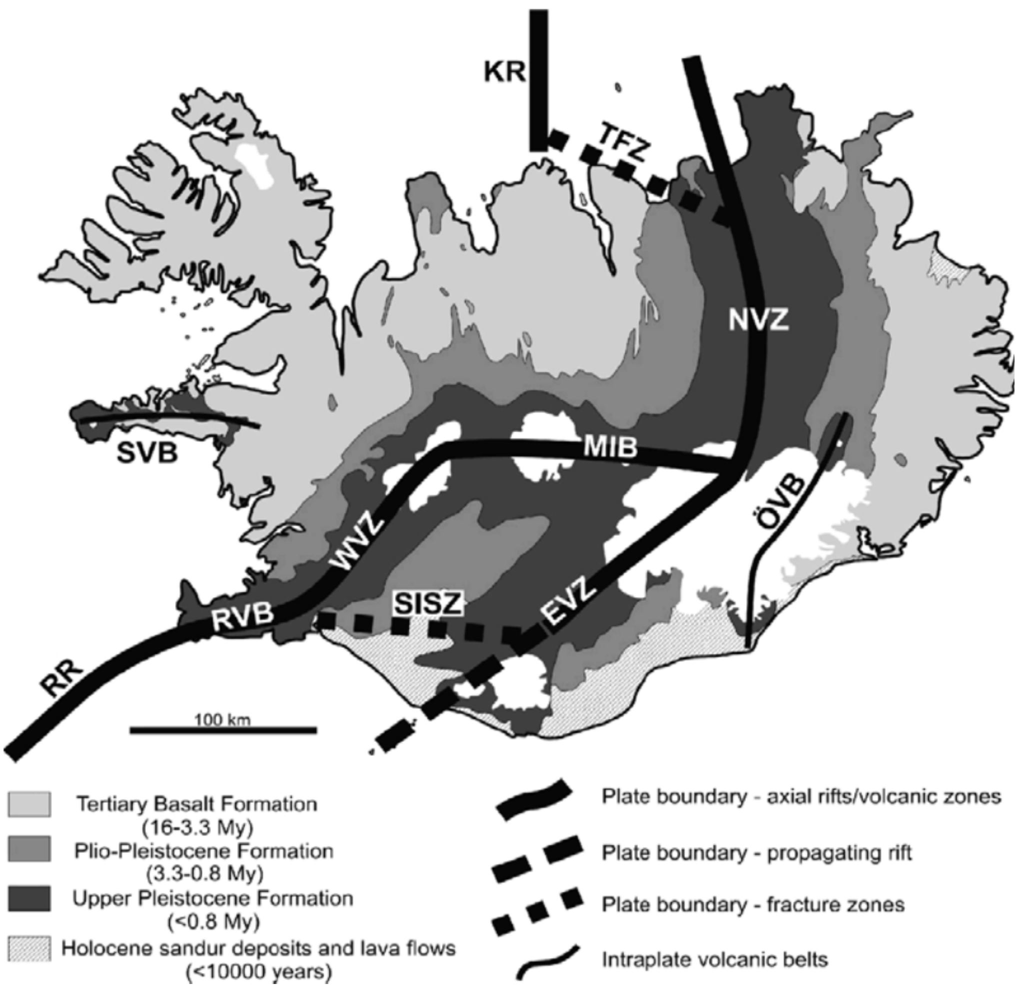

Figure 5. General Areas of Icelandic Volcanism (from Thordarson and Larsen, 2007).

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

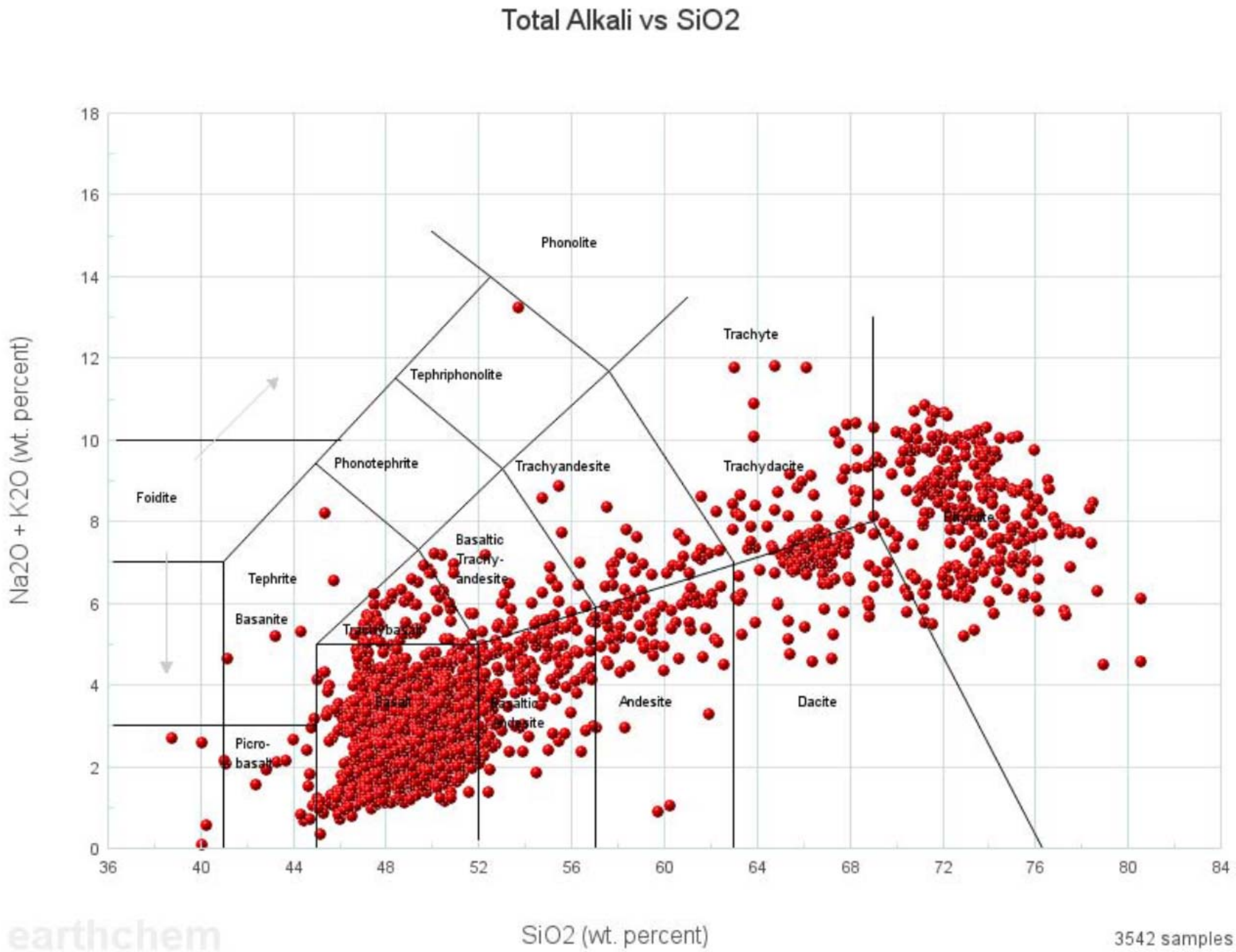

Figure 6. Classification and distribution of igneous rocks from Iceland (from Earthchem).

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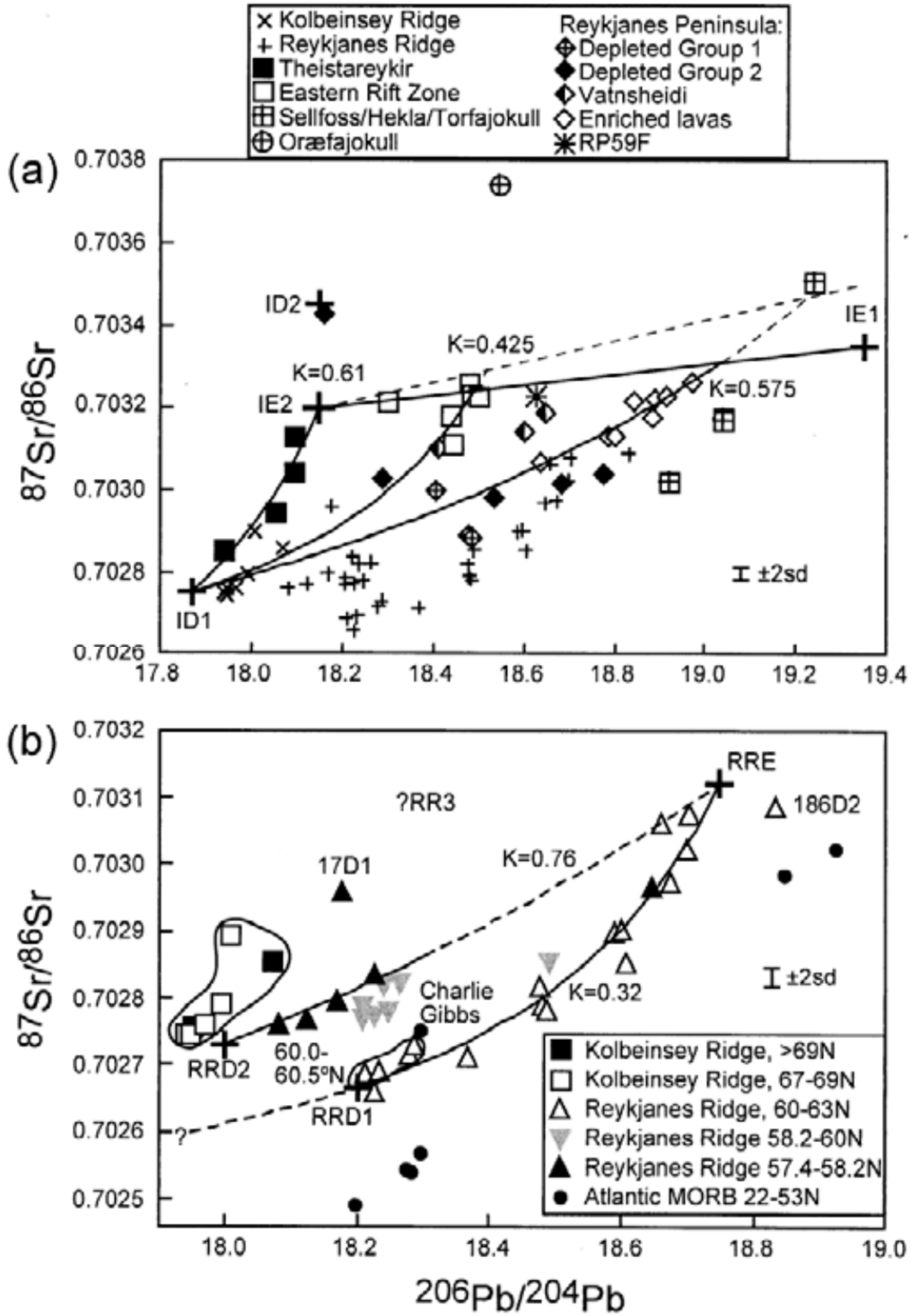

Figure 7. $^{206}Pb/^{204}Pb$ vs. $^{143}Nd/^{144}Nd$ showing mixing components for Icelandic magmas. Mixing endmembers include the enriched plume source IE1, a low Pb enriched endmember IE2, and the widespread depleted upper mantle endmember ID1. (from Thirwall et al., 2004).

Icelandic Mineralogy and Geochemistry

Contributed by Danielle Sumy

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

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

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

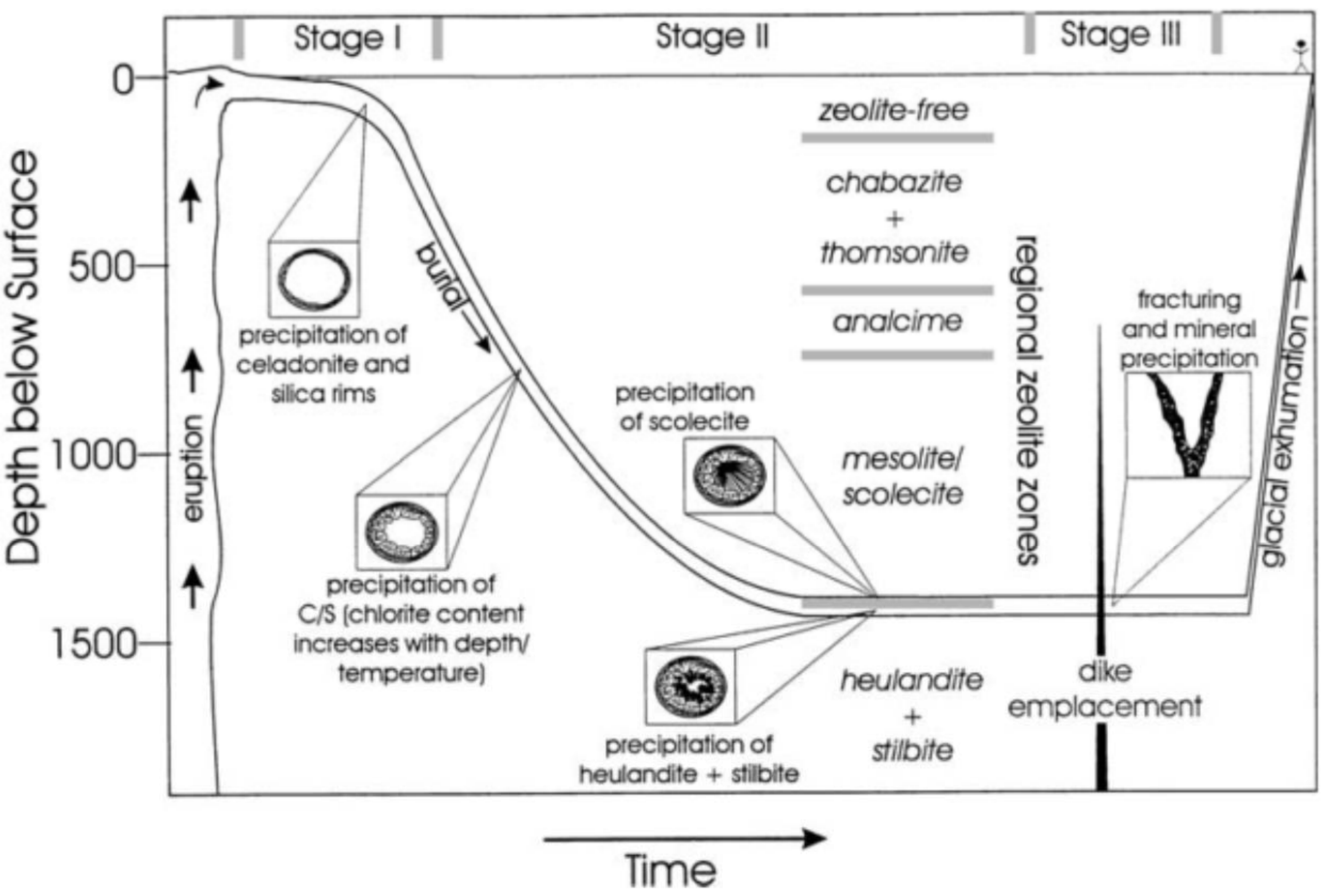

Fig. 13. Spatial and temporal development of pore-filling mineral assemblages at Teigarhorn. The vertical axis depicts depth below land surface at the time of each event depicted in the figure. Time elapsed after eruption increases to the right. No scale is implied on the horizontal axis. The parallel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

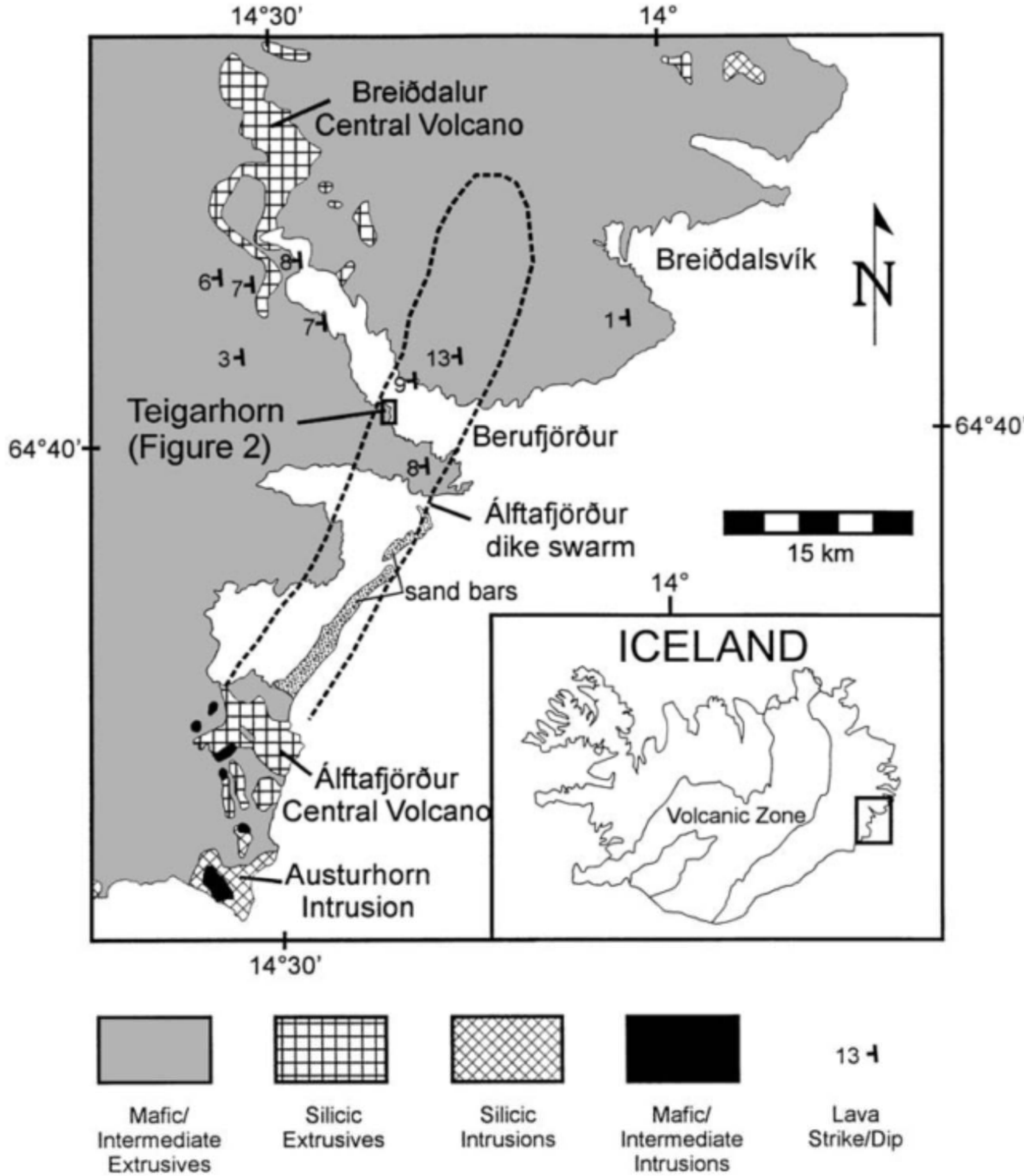

Fig. 1. Generalized geological map of a portion of eastern Iceland (after Jôhannesson and Sæmundsson, 1989) showing the distribution of major rock types, locations of intrusions and central volcanoes, and selected lava orientations from Walker (1963, 1974). Dashed curve outlines the Álftafjördur mafic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

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

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

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

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

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

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Volcanism

Contributed by Danielle Sumy

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

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

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

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

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

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

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

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Recent Volcanism

Contributed by Masha Klescheva

Laki Eruption

In the west area of Vatnajökull National Park, we can visit the site of the deadliest eruption in historical times. Disturbed earth extends out around Mt Laki in parallel fissures for 27 km, now impotent deformed earth, but at one time bringing annihilation to the entire Northern hemisphere. The Laki eruption lasted over an 8 month period between 1783 and 1784. Each of the ten episodes of the eruption ensued by the formation of a fissure, then short lived explosive phreatomagmatic activity (basalt magma interacting with groundwater), then continued gentle flow from the vents, Hawaiian style. Over the 8 month period, 14 km3 of basalt lava poured out from the system (that's enough to pave over Boston 63 meters deep in basalt!)

The real killer, however, creeped out simultaneously with the enraged antics of the lava. Acid haze, clouds of hydrofluoric acid and sulfur dioxide, proved to be much more deadly. Eight million tons of HF and 120 million tons of SO2 were released into the atmosphere alongside the explosion. 50% of Icelandic livestock died of dental and skeletal fluorosis, causing a famine which annihilated a quarter of the Icelandic population. These difficult times in Icelandic history are known as the Mist Hardships.

The Mist, as it were, did not remain in Iceland. Of the 120 million tons of SO_2, 95 million tons made it to the upper troposphere and lower stratosphere, where the jet stream circulated the haze around the entire northern hemisphere. The resulting drop in global temperatures caused crop failures in Europe, and was noticed as far as Egypt, India, and North America. The Laki Eruption is estimated to have killed over 6 million people worldwide.

Figure 1: Laki, photo by Ulrich Latzenhofer

Figure 2: Reynisdrangar basalt columns, photo from www.virtualtourist.com.

Reynisdrangar Basalt Columns

There was no hope. All night the crew struggled against the trolls, but their human ingenuity was no match for the trolls' inexhaustible constitutions. The ship captain defiantly yelled orders into the now dawn, but he heard the ship's bottom scrape the black pebbles of the beach: the trolls had pulled them on shore. It was certain death, until… the morning rays struck the creatures, and they instantly turned to stone: columns of stacked basalt, right on the black beach in Southern Iceland.

So tells us Icelandic Folklore. Reynisfjara is a black pebble beach next to Vik, the southernmost village in Iceland of only 350 people. Reynisdrangar is a cliff of basalt columns on the beach, home to a variety of bird-life. Surrounding the cliffs are caves from twisted basalt, from which puffin chicks belly-flop into the ocean.

Eyjafjallajokull Eruption, þorvaldseyri visitor center

The eruption of Ey-ya-fyad-la-ou-couddle made the news in 2010 not only because none the news anchors could pronounce the name, but also because of the level of travel disturbance it created, the highest since World War II. As a volcanic eruption it was not the most impressive, but it managed to disrupt human travel to such a degree for several reasons. First, it sits directly underneath the jet stream, which is able to swiftly redistribute massive amounts of ash directly into Northern Europe. Second, the eruption happened underneath 200 meters of glacial ice. The melted water flowed right back into the erupting volcano, rapidly vaporized, and elevated the explosive power of the eruption. In addition, the lava cooled very fast, which created clouds of glass-rich ash that shot straight into the jet stream.

The þorvaldseyri Visitor Center opened at the foot of the volcano "when the ash settled." There is a wall showcasing the history of Icelandinc volcanism, and a short film about a family farm in þorvaldseyri. "It’s NOT a typical home-movie, but a dramatic 20-minute film."

Figure 3: Eyjafjallakokull eruption, photo from http://scienceblogs.com/eruptions/2010/04/16/eyjafjallajokulleruption-cont/

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Columnar Basalts: Morphology and Processes

Contributed by Sarah Slotznick

Columnar Basalts: Summary

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

Columnar Basalts: Morphology and Processes

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

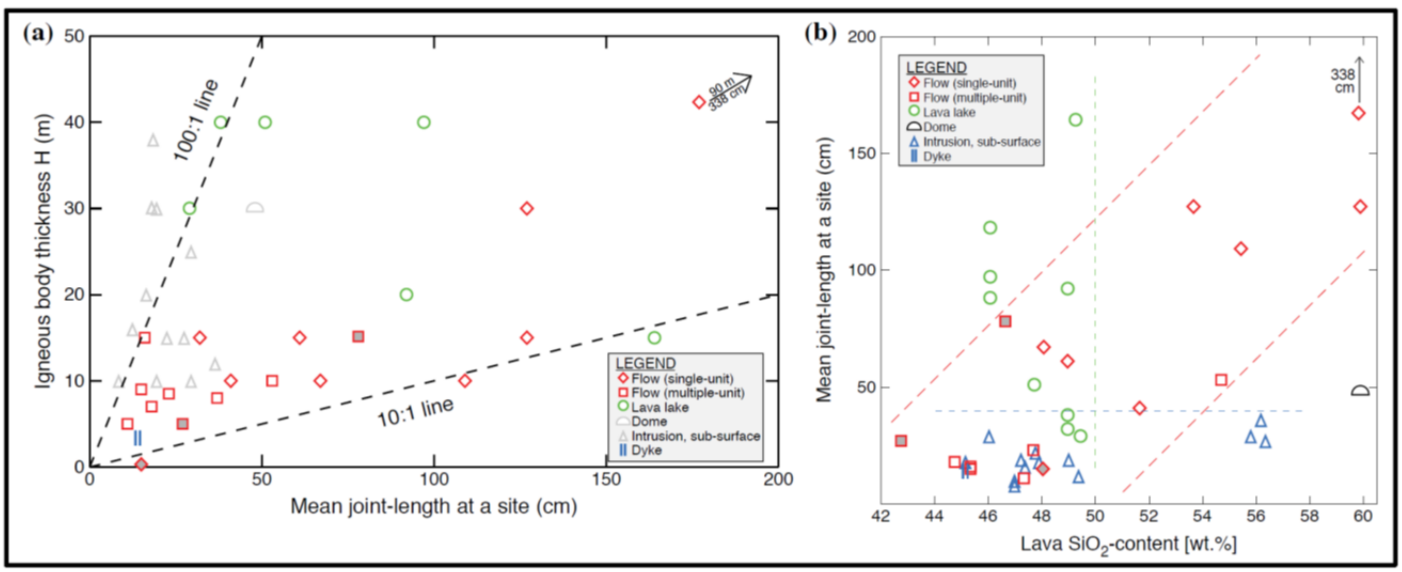


Figure 1: a) Igneous body thickness versus the average side length of columns at 50 different columnar jointing sites in 3 countries. Note that erosion and partial exposure might have reduced the thickness of H and the thickness of the dike site was divided by 1.5 to compare to free flows. Symbols filled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

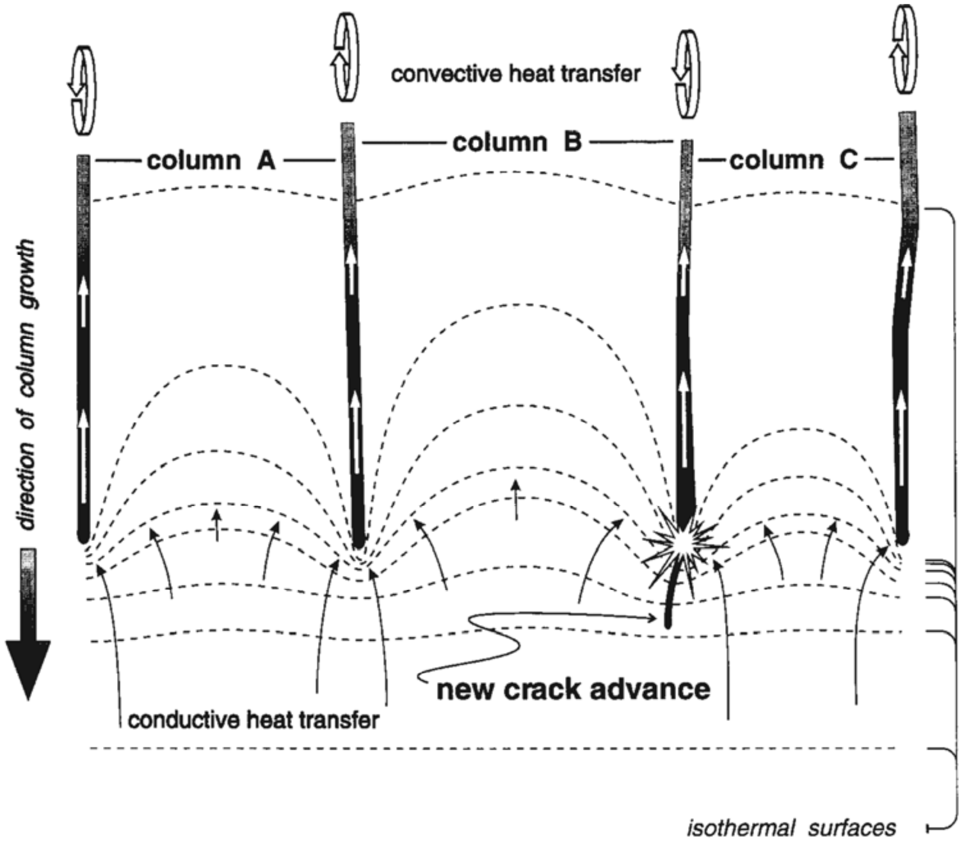


Figure 2: Sketch detauling hypothesis to explain equal-size distribution of columns within a flow unit. (from Budkewitsch and Robin 1994)

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

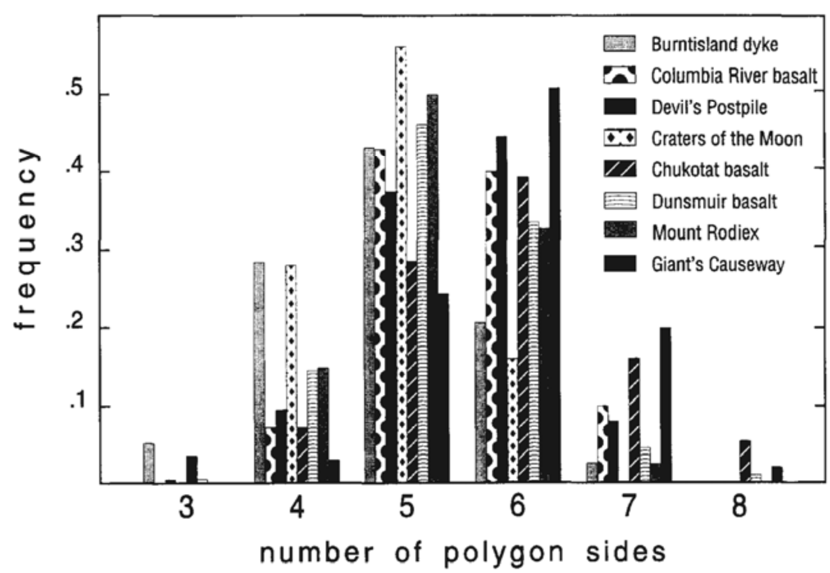


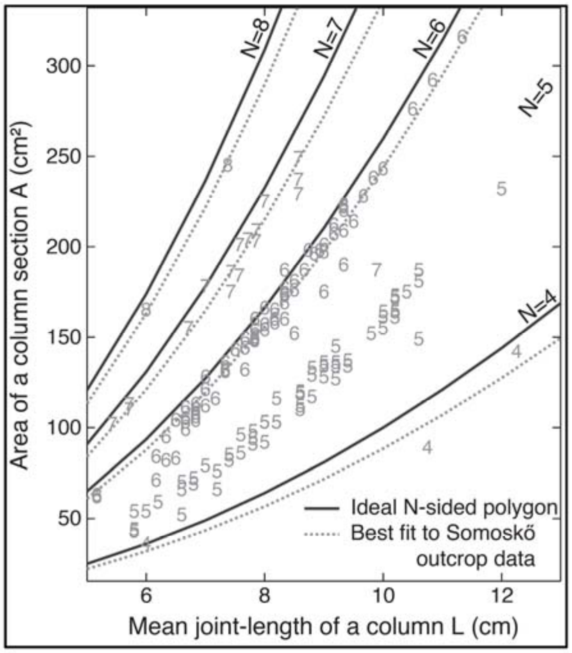
Figure 3: Distribution of number of sides on polygonal cross sections of worldwide columnar basalts. (from Budkewitsch and Robin 1994)

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

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

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

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



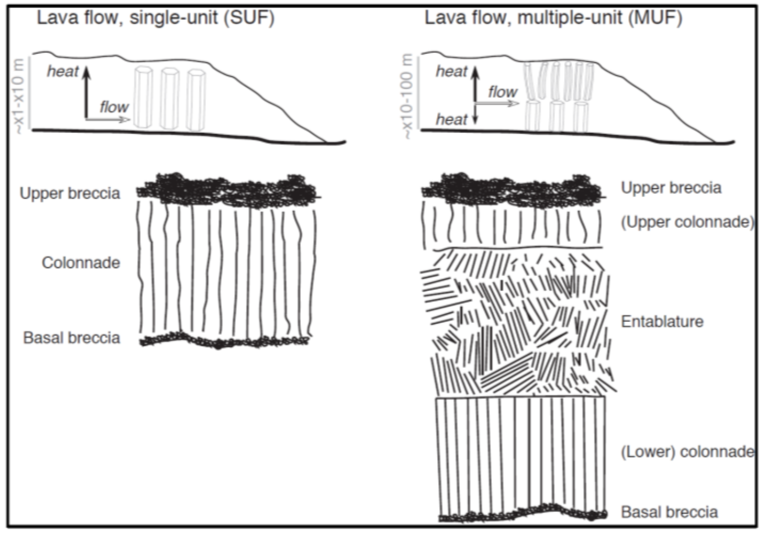
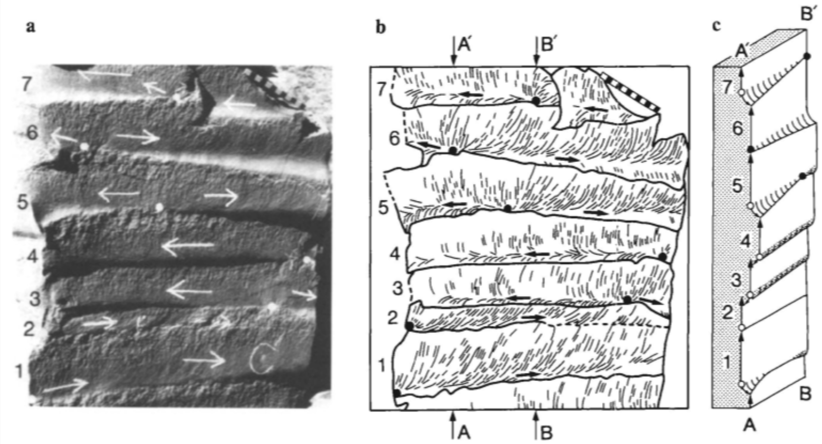


Figure 5: Diagram showing columnar basalt at the outcrop in single unit flows/single tiers and in multiple-unit flows. (from Hetényi et al. 2012).

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



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

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

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

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

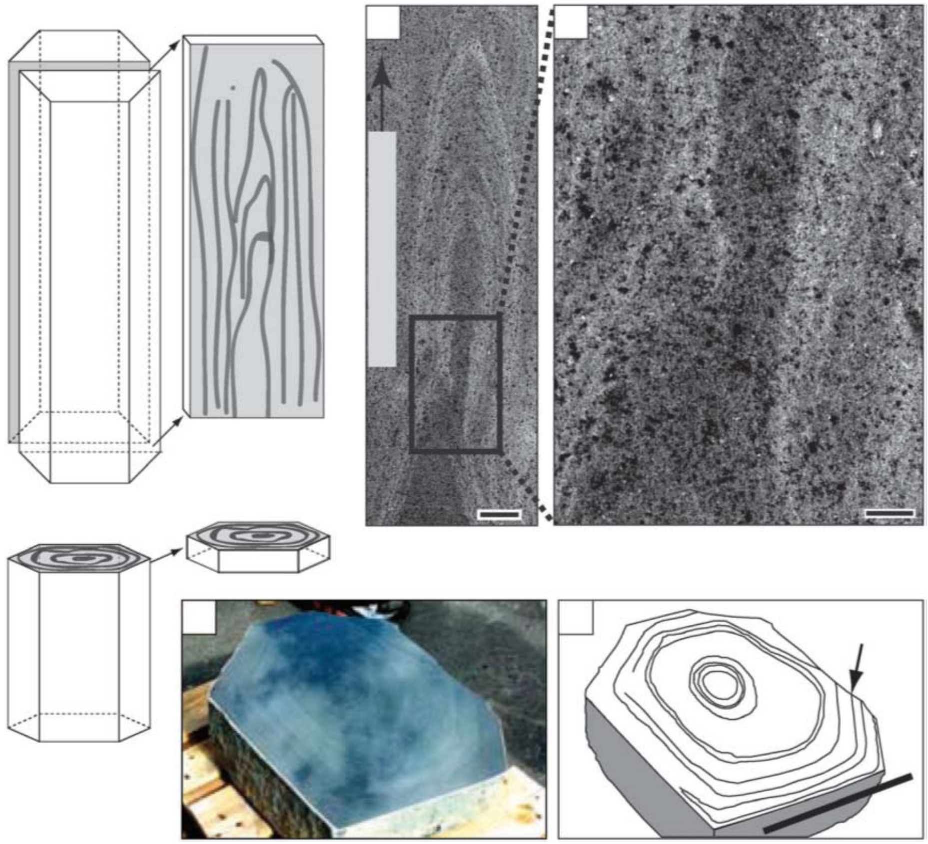


Figure 9: Diagram of how crystallization and pressure loading can force melt-migration in the interior of columns resulting in viscous fingers in the partially crystallized columns. (from Mattson et al. 2011)

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

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

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Rift Valley: Þingvellir National Park

Contributed by Sarah Slotznick

Short summary:

At Þingvellir, which literally stands for assembly field or parliament plains, the general assembly of the nation of Iceland is located. The assembly first came together at Þingvellir in 930 AD and continued to meet there until 1798. Þingvellir National Park was founded in 1930 and remains a property of the Icelandic nation. Today it is one of the most popular tourist destinations because of its historical, cultural, and geological importance.

Long Summary:

After settlement of Iceland in 874 AD, people of Norse (Vikings/people form northern Europe speaking the old Norse language) and Celtic (another ethno-linguistic group of tribal societies in Europe) origin had populated the island to the extent that small regional assemblies were no longer sufficient to deal with political matters and a general assembly was necessary. The Þingvellir region was chosen due to it's relatively convenient location, minimizing travel time and effort to and from the assembly location, and because the land was declared public around the time (conveniently the previous owner was found guilty of murder). The longest travel time was ~17 days for the tribal chief that was in charge of the easternmost region of Iceland. Historians regard the foundation of the general assembly in 930 AD at Þingvellir as the founding moment of the Icelandic nation because it brought the population on a path of common cultural heritage and ultimately to national identity.

The Alþingi is the name of the general assembly of Iceland and remained at Þingvellir until 1271 as Iceland's supreme legislative and judicial authority. The so-called Lögberg was the focal point of the Alþingi and a platform for holding speeches. The Lawspeaker, who was the president of the assembly, was elected to three year terms. His job was to recite the law of the land, which before written-down laws meant orally reciting the laws from memory over the three summers during the Lawspeaker's term. Additionally, he presided over assembly procedures that took place every summer at the Lögberg. Important announcements concerning the nation were made there and anyone attending the assembly was allowed to present his case at the Lögberg.

In addition to inauguration and dissolution of the assembly, new rulings by the Law Council were announced at the Lögberg. The Law Council was the legislative assembly and thus a subinstitution of the Alþingi. The work of the Law Council was not limited to passing new laws only, but it was responsible for settling disputes as well. It thus functioned as a legislative and judicial institution at the same time. Unlike the Alþingi, the Law Council was a closed body in which only certain people enjoyed full rights: chieftains (48 of them) who held the office of "goði", their "Þingmen" (advisors) and later also bishops. However, everyone at the assembly was entitled to watch and listen to the Law Council at work.

Þingvellir: Geologic Setting

Þingvellir: Rifting

Þingvellir is located to the northwest of the shield volcano Hengill that is the location of one of the triple junctions that forms the Southern Iceland microplate (Einarsson 2008). In this location, the Reykjanes Peninsula Ridge (RPR) meets the east-west striking South Iceland Seismic Zone (SISZ) and the Western Volcanic Zone (WVZ) striking to the northwest (Figure 1). Thingvellir thus records rifting activity along the WVZ, which was the primary zone of spreading from ~6Ma until 2Ma when the Eastern Volcanic Zone (EVZ) formed via propagation from the Northern Volcanic Zone (Ivarsson 1992). Based on GPS measurements, today only 20-30% of the total spreading across southern Iceland is

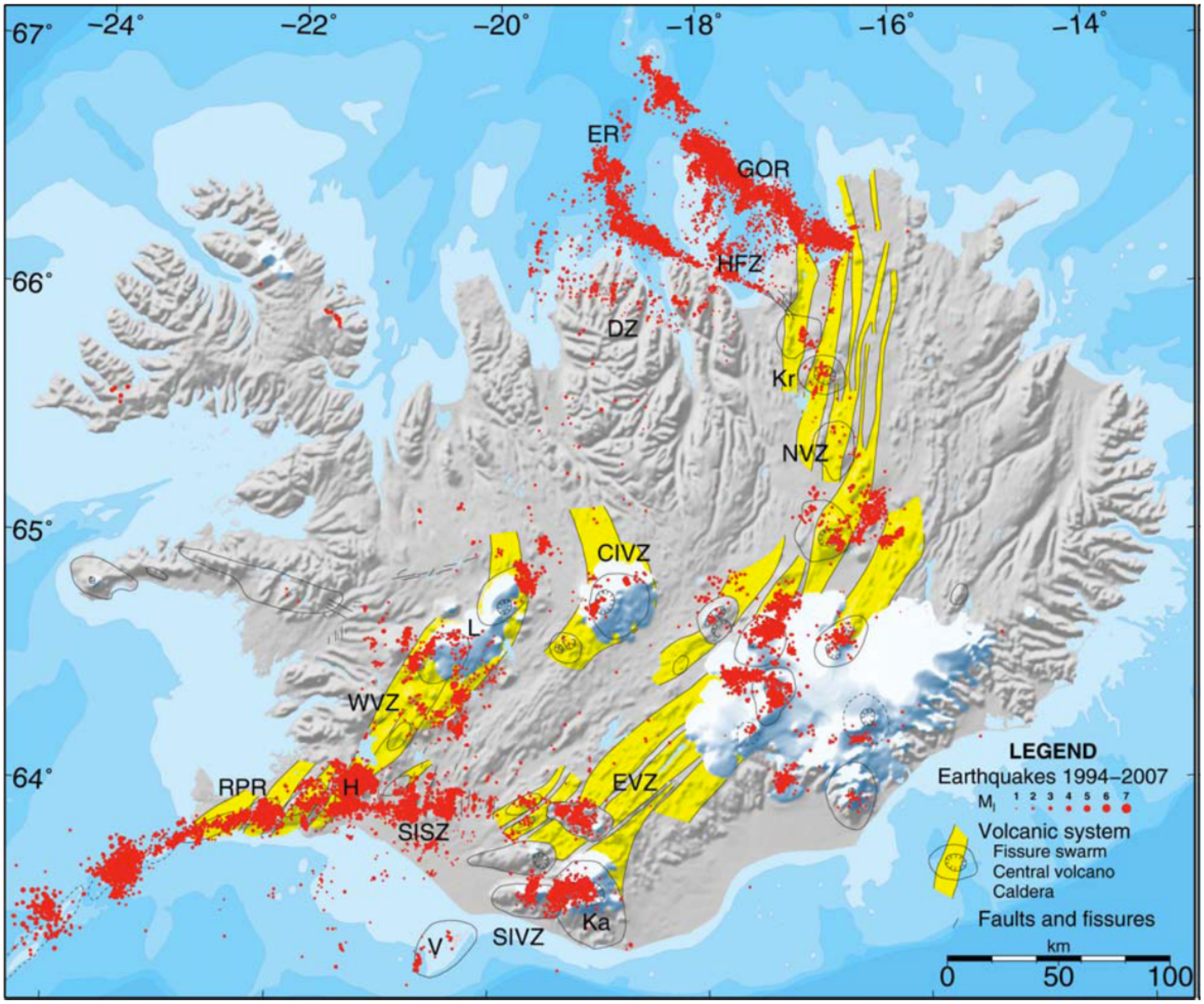


Figure 1: Map of the main fault structures and volcanic belts that form the plate boundaries in Iceland. Plate boundary segments are labeled: RPR Reykjanes Peninsula Rift, WVZ Western Volcanic Zone, SISZ South Iceland Seismic Zone, EVZ Eastern Volcanic Zone, SIVZ South Iceland Volcanic Zone (propagation of the Eastern Volcanic Zone), CIVZ Central Iceland Volcanic Zone, NVZ Northern Volcanic Zone, GOR Grímsey Oblique Rift and HFZ Húsavík-Flatey Zone (Part of the Tjörnes Fracture Zone), ER Eyjafjardaráll Rift, DZ Dalvík Zone. Kr, Ka, H, L, V mark the volcanoes of Krafla, Katla, Hengill, Langjökull, and Vestmannaeyjar. (from Einarsson 2008).

accommodated by rifting on the WVZ; the rest is on the EVZ (Sinton et al. 2005). Based on 9 years of measurements, the spreading rate across the boundary is 3mm/yr in the NE to 7mm/yr in the SW, which classifies the WVZ as an ultraslow spreading ridge (LaFemina et al. 2005, Sinton 2005).

Geologic mapping paired with 14C-dating has identified 44 eruptive units along the WVZ in the past 11,000 years although there has been a decline in volcanism over that period of time (Figure 2, Sinton et al. 2005). 85% of these post-glacial volcanic eruptions have been from volcanic centers of lava shields and cones instead of fissures, which are the majority of eruptions in the other Icelandic volcanic zones. The EVZ lacks any shield volcanoes, while >90% of volcanic production in the WVZ is from these shield volcanoes (Sinton et al. 2005). The lavas seen in Þingvellir are about 10,000 years old, and the lack of recent resurfacing by younger lavas allows us to see the most striking structural feature of the WVZ: the Þingvellir Graben. This tectonic depression, 25km wide in the NW to 10km in the SW, is bound by several successive layers of faults (Figure 3). The large inner graben tectonism occurred around9500-8000 years ago (Sinton et al. 2005), bound on the east by the normal fault Almannagjá and other minor faults with large throws up 40m (at Þingvellir) and on the west by the Hrafnagjá fault system with smaller

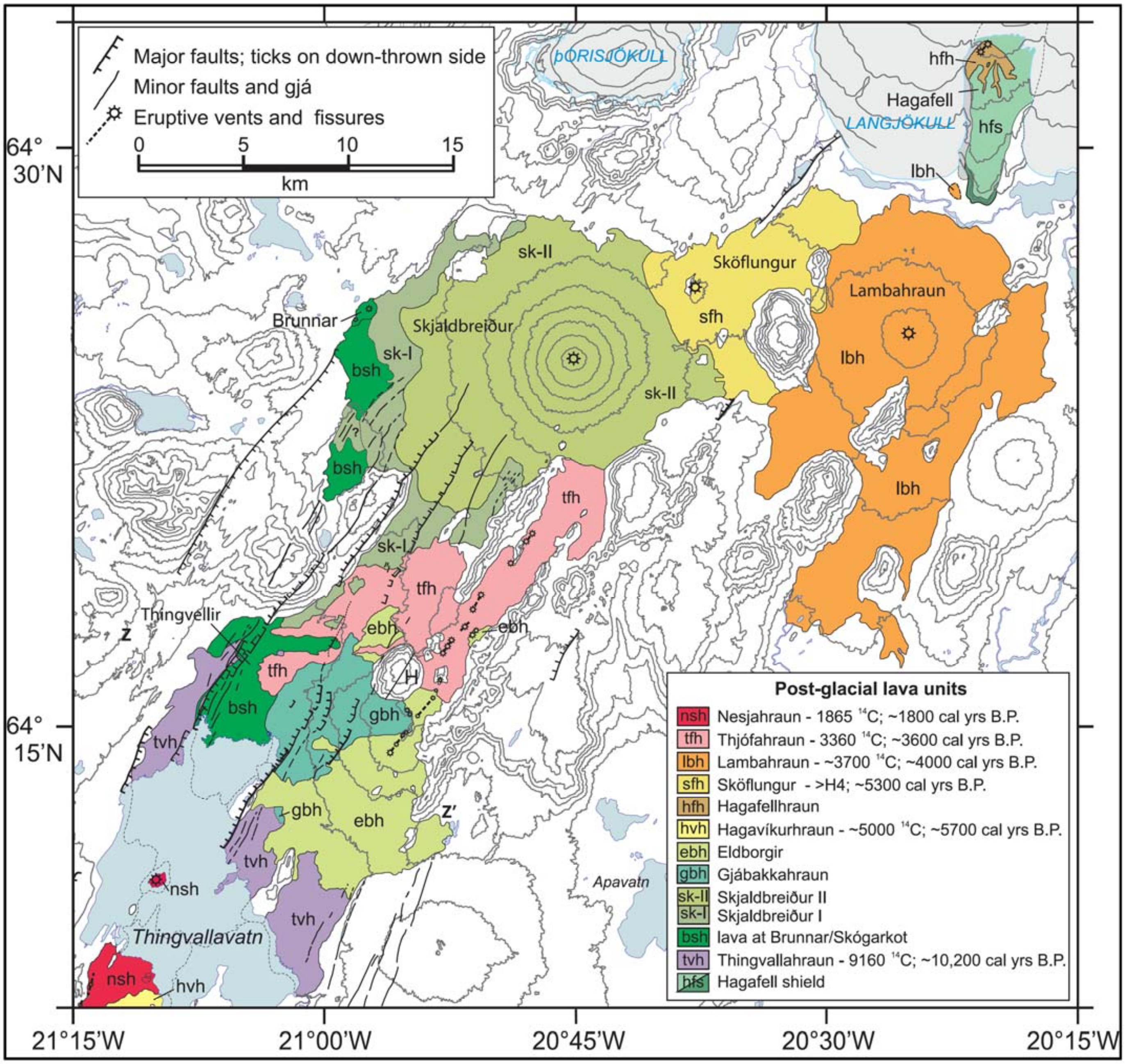
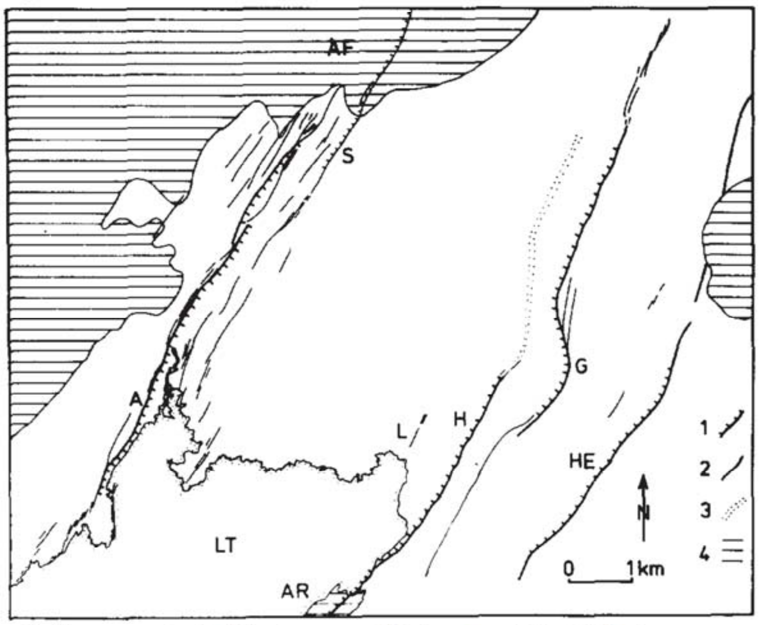


Figure 2: Geologic map of the postglacial lavas and main faults in the northern part of the WVZ. Location of Thingvellir, Thingvallavatn, and Hrafnabjörg table mountain (H) are marked. Topography contours area 100m. (from Sinton et al. 2005).

a)



A, Almannagja; S, Sledaasgja; AF; Armannsfell; LT, Lake Thingvallavatn; AR, Arnarfell; L, Litlagja; H, Hrafnagja; Gildruholtsgja; HE, Heidargja. 1, normal fault (only those with throws of several meters are thus indicated); 2, tectonic fissure (with a small or no throw); 3, deformation zone; 4, Pleistocene rocks (basaltic lavas or hyaloclastites) or alluvium.

b)

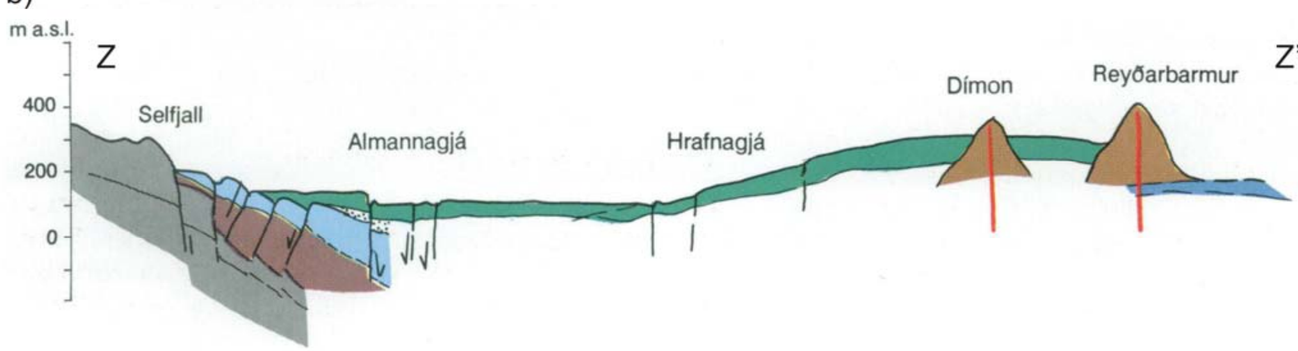


Figure 3: a) Map of the Thingvellir Fissure Swarm. (from Gudmundsson 1987) b) Cross section of Thingvellir Graben near Thingvellier, exact location can be seen in Figure 2 (Z to Z’). msal = meters above sea-level. (from Saemundsson 1992)

vertical offsets (Gudmundsson 1987). Some faults cutting older hundred thousand-year-old units have larger vertical offsets up to 400m indicating a longer history and gradual development of the Þingvellir Graben, the deepest graben with the largest single fault throws in Iceland (Saemundsson 1992).

There has been recent rifting activity on the WVZ. In early June of 1789, following previous events on the EVZ in 1783 and SISZ in 1784, 10 days of significant earthquake activity were felt and recorded by the vicar of Þingvellir along with subsidence and flooding of the lake waters in the center of the graben (~1.4-1.5m) and elevation at the edge of the graben with wells running dry and trails across faults becoming impassable (vertical throws up to 2m reported to the south). To the south of Hengill (in the RPR), a new hot spring appeared but no volcanic eruption occurred, suggesting the event was associated with crustal dike propagation (Saemundsson 2006).

The Þingvellir Graben with its extraordinary deepness, fast subsidence, and large width has been focal point in understanding the nature of rifting along the WVZ since this zone is very different from the other rift zones in Iceland. Its ultra-slow spreading rates, a decline in volcanism, and the deep graben structure at Þingvellir have led many to suggest that the WVZ is a failed or dying rift and all motion will eventually be transferred to the EVZ as it continues its southward propagates (e.g. Pálmason 1981, Einersson 1991). Both in theory and through models it has been shown that the deep graben is a sign of a magma-starved rift with plate divergence being accommodated by crustal stretching and normal faulting instead of volcanism (Saemundsson 1992, Karlsson and Sigmundsson 2008, Sturkell et al. 2013). However, several pieces of contradictory evidence have led to debate about the WVZ in the past several years. Although there has been a decrease in volcanism, production is similar to that seen all over Iceland post-glacially and is constant along the WVZ, whereas a dying rift should be progressively dying from north to south (Sinton et al. 2005). In a counterargument, Sonette et al. 2010 find a decline in tectonic activity along the WVZ (via decreased fissure zone growth rates) and suggest if there is steady-state volcanism still present, it could be due to a decoupling of the Icelandic hotspot and the spreading center/ridge as it moves to the west. Other studies note that this zone is still very seismically active with more earthquakes than the EVZ in the past several decades (Einarsson 1991).

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Hydrothermal Activity

Contributed by Ivan Mihajlov

Hydrothermal systems are responsible for dissipating much of the Earth's internally generated heat near the surface of the Earth1. Three specific requirements are necessary for hydrothermal circulation to occur: a source of heat, the presence of water, and the existence of a plumbing system[1,2]. Virtually all hydrothermal phenomena occur near volcanic zones because this satisfies the requirement of a heat source close to the Earth's surface. Water is heated up by the contact with a hot magma chamber and/or with hot rocks that were themselves heated up by the magma nearby. Water involved in hydrothermal circulation can circulate at great depths (2,000 m)[2] and originate from a variety of sources: magmatic (exsolved H_2O, CO_2, SO_2, F, B, Cl etc.), metamorphic (H_2O, CO_2, CH_4 etc.) resulting from dehydration reactions during regional metamorphic events, connate (or water trapped in sediments), meteoric (groundwater, rainwater, river water), and seawater[1]. Finally, a plumbing system is required for convection of water within the hydrothermal system. This can be any kind of a porous medium, such as sand, gravel, or fractured rocks. Iceland satisfies all these requirements because it is located atop a mid-ocean ridge / hot spot and it has plenty of rainfall and seawater.

Although the largest number of hydrothermal systems appears on the ocean floor along the mid-ocean ridges, subaerial hydrothermal phenomena are the ones we are the most familiar with. Water in subaerial systems, such as Iceland, originates mostly from meteoric water (rain, rivers, groundwater) and seawater[3]. Initially, river, rain or seawaters are cold and seep through pores or cracks in the ground until they start mixing with warmer waters at depth. At the same time, heated water already sitting at depth has acquired high temperatures and pressures. This water is less dense and starts rising, often arriving at the surface at or even above the boiling point (since high pressure increases the boiling temperature of water). This establishes convection (with cold water and gas sinking and hot water and gas rising) within the hydrothermal system and manifests itself on the surface as hot springs, fumaroles, mud pots, and geysers.

Hot springs, fumaroles and mud pots are fairly common phenomena in all volcanic regions, and we saw them at each of the five hydrothermal sites we visited (Reykjanes peninsula in the southwest, the Hengill area east of Reykjavík, Geysir, Námafjall field near lake Mývatn, and Hveravellir in the center of Iceland). Hot springs form where there is plenty of groundwater and the water table intersects the surface, thus bringing hot (and sometimes boiling) water to the surface[4]. Hot springs, as do the other hydrothermal features, support a variety of interesting prokaryotic life forms (e.g. thermophiles that can live at temperatures up to and above the boiling temperature of water). These thermophiles can help reduce, oxidize, and/or precipitate iron and sulfur minerals, often giving these springs and nearby sediments beautiful shades of blue, red, green or yellow[2]. Hot springs and geysers are also often the sites of siliceous matter precipitation (deposits known as siliceous sinter or geyserite), which can occur abiotically (precipitation due to cooling and evaporation), or be biotically mediated, especially further away from the hot water source[5]. Fumaroles are openings in the Earth's crust that emit hot gases, such as steam, carbon dioxide, sulfur dioxide, hydrochloric acid, and hydrogen sulfide[6]. These gases enter the hydrothermal system during the degassing of magma and hot rocks, and from interactions with groundwater. Fumaroles are not geologically permanent features, often occurring in fresh lava flows or above intrusions[6]. But if they originate deeper in the crust (from a magma chamber or close above it), they might last over centuries or millennia.

Fumaroles can also be called 'solfatara' if they exude sulfur-rich gases, as is the case in the hydrothermal sites we visited in Iceland. From the standpoint of groundwater hydrology, hot springs, mud pots and fumaroles are the expressions of the same phenomenon. Fumaroles are a type of hot springs that boil off their water before reaching the surface[6]. Mud pots, pools of boiling mud, are a special case of hot springs where water is in short supply, thus an emulsion of water, volcanic ash, and clay forms[7]. The gases contained in hydrothermal fluids, such as SO_2 and hydrogen sulfide that react to produce sulfuric acid, often aid the formation of mud pots. Sulfuric acid alters the surrounding rocks, converting them into clays and silica[4]. This fine sediment easily forms mud, the density of which depends on the amount of water available.

Geysers, in contrast to mud pots, fumaroles, and hot springs, are fairly rare phenomena, with only about 1000 geysers known worldwide, and about a half of them are located in Yellowstone National Park[2]. This is because, in addition to the heat, water, and a plumbing system, geysers also require a degree of constriction and impermeability in their plumbing system, allowing for the eruptions to occur. Geysers are very much like regular hot springs, water is abundant and the water table reaches the surface. Hence, geysers are often located near rivers, such as the Hvítá, near Geysir in Iceland. However, they are different from regular hot springs in that they erupt at more or less regular intervals, sending water, steam, and other gases high above the ground. For the eruption to happen, the underground water reservoirs need to be well sealed to allow for pressure build-up, and the reservoir must have a well-defined conduit to the surface narrow enough to prevent convection of water out of the main geyser plumbing system[8,9]. The lower permeability plumbing is created by deposition of silica (geyserite) along the pores and cracks in the subsurface, making the geyser conduit 1000 times less permeable than the surrounding materials[10].

Water that powers geysers stays in the ground for long periods of time and is often several hundred years old at the time of eruption[2,9]. Deep under the surface, water is heated until it boils and small bubbles start rising towards the geyser surface conduit. Water convection would establish a regular hot spring, however, as the bubbles rise, they aggregate, get larger, and get stuck as plumbing constricts, building up pressure and preventing water overturning for a period of time. At that point, a column of water at or near boiling temperature is established and, due to continued heating from below and the pressure of the water column above, water at depth is superheated (heated beyond its surface boiling point). Luckily for the observers near the surface, boiling bubbles eventually do reach the geyser outlet, water domes up, relieving some pressure, which then lowers the boiling point of the water underneath, causing a massive conversion to gas phase, unleashing an eruption of water and steam[2,9].

Geysers erupt at various frequencies (from minutes to days) and their modes and durations of eruption can be widely different, from a few seconds, as for Iceland's Strokkur, to several minutes of steady flow, as for Yellowstone's Old Faithful. Some dependence has been established between eruption frequencies and changes in air pressure, tidal forces, and availability of water; however the strongest relationship in eruptive behavior has been noted with earthquakes[9,10,11]. Earthquakes often alter the frequency of geyser eruptions or completely silence/awaken them, presumably due to changes they cause to the orientation and permeability of the plumbing system (see [9,10,11] for the changes observed for Geysir and Strokkur). Finally, several types of geysers are known, most commonly summarized as fountain geysers and cone geysers[2,9]. Fountain geysers (such as Geysir and Strokkur) erupt from a pool of water and usually have more explosive and variable eruptions, while the cone geyzers (e.g. Old Faithful) erupt from a cone or mound built of siliceous sinter and tend to have steadier eruptions.

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Geothermal Power Generation

Contributed by Dan Huber

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

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

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

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

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

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Glaciology

Contributed by Margaret Reitz

Iceland is famous for its volcanoes and glaciers. Currently, glaciers cover ~10 percent of Iceland's 103,000 km^2. The three largest glacier caps, Vatnajökull, Langjökull, and Hofsjökull, are located in the central highlands. Rifting of the North American and European plates combined with a mantle plume created these highlands as the rift and plume have migrated from western to eastern Iceland. Although Iceland is ~24 Ma, its landscape has only been shaped by glaciers in the last 5 Myr. Iceland's glaciers have advanced and retreated with regional climate shifts as well as local variations, generating the country's spectacular morphology.

Glaciers form when accumulation of ice and snow exceed melting and ablation. There are two main types of glaciers: continental and alpine. Continental glaciers have cold bottoms, meaning the ice is frozen to the bed. Globally, these glaciers cover more than 50,000 km^2 (20,000 mi^2) and are currently only found in Antarctica and Greenland[1]. Alpine, or mountain, glaciers have water at their bases and are the glaciers that currently exist in Iceland. Ice fields feed most of the valley glaciers in Iceland. This is a region of low relief, but it is located above the equilibrium line meaning that nearly all of the precipitation that falls here contributes to glacier growth. Although the ice fields contain the largest volume of ice, outlet glaciers are the predominant sculptors of the landscape.

Cirques, arêtes, and horns are common erosional features made by Iceland alpine glaciers (Fig. 8). A cirque is a semi-circular or amphitheater-shaped bedrock feature at the head of a glacier that forms as the glacier erodes back into a mountain[2]. This is often where snow first accumulates above the equilibrium line. Arêtes and horns are formed when two or three glaciers, respectively, erode into the same mountain from different directions. An arête is a ridge separating two glaciers and a horn is a point separating three or more glaciers. These features are often visible in actively glaciated areas. A hanging valley is a valley carved out by a tributary glacier[2]. Tributary glaciers have less ice than the main valley glacier, which translates to less erosive power. When a valley glacier cuts down faster than the tributary glacier, the tributary valley is left "hanging", making a hanging valley. U-shaped valleys are the most common erosional glacial landform in Iceland. Rivers concentrate their erosive power at the lowest elevation in a valley, creating a "V-shape" in cross section. Glaciers, on the other hand, most efficiently erode along the sides of the valley, creating a valley that has steeper sides than a river valley and a flatter bottom. The erosive power of glaciers is much higher than rivers because it generates potential energy not only from the slope of the land surface, but also from the added mass of the ice. If conditions are right, glaciers can erode below sea level. When the glacier retreats, the ocean then fills in these depressions creating fjords. Some of the fjords in Iceland are 100s of meters below sea level. Jökulsárlón, a proglacial lake at the base of the Breiðamerkurjökull glacier in southeastern Iceland, is an example of glacial erosion below sea level. Erosional features such as striations, grooves, and tarns are not as evident in Iceland because volcanic deposits cover older features and more recent features are currently being formed underneath the glaciers. In terms of depositional features, moraines are by far the most abundant. Moraines are accumulations of till (sediment usually carried within a glacier) at the terminus of a glacier (end moraine), the side of a glacier (lateral moraine), within a glacier (medial moraine), and underneath the glacier (ground moraine)[2].

Glaciers also have recognizable features in the ice. I will only discuss a few here. Crevasses are the most abundant and easily recognized. These cracks in the glacier surface are found in places where there is a large change in gradient of the land surface slope or places where the glacier is widening[3]. An ice fall will form when there is a steepening of the land gradient a few kilometers long. In Iceland, these are common in the transition from the low gradient ice field to the high gradient outlet glacier. As crevasses are formed when the ice is stretching, pressure ridges are formed when the ice is under compression[3], especially near valley walls and bends in the valley. A nunatek is a protrusion of rock that pokes through the surface of the glacier[3]. Often, medial moraines form downslope from nunateks.

Piecing together glacial histories involves mapping the areas covered by glaciers during different time periods in the past. There are two common methods for determining ages and durations of glaciation events. Historically, stratigraphic columns have been utilized most often. In this method, stratigraphic sections of rocks are made in various places. Sedimentologists document lithology and facies with depth in the Earth to reconstruct the different depositional or erosional environments that existed through time. These stratigraphic columns are correlated in space based on sedimentary facies. Age constraints in Iceland come from the numerous volcanic eruptions that deposit sediments within the studied columns. K-Ar dating of ash layers and lava flows allow the correlation of the stratigraphic columns in time[4].

A more recent tool, now widely applied to glacial moraines, is in-situ cosmogenic radionuclide dating. As cosmic rays bombard the atmosphere, ^{10}Be, ^{26}Al, ^{36}Cl, ^{3}He, ^{14}C and many other radiogenic nuclides are produced on the surface of rocks[5]. At depth (e.g. within a glacier where sediment is transported), these nuclides are not produced. Therefore, boulders deposited in glacial moraines begin producing cosmogenic nuclides only after they are deposited and exposed to the atmosphere (i.e. when the glacier retreats). Therefore, the amount (concentration) of any one radiogenic nuclide within a boulder scales with the length of time that that boulder is exposed to the atmosphere. If he nuclide production rate is well known, cosmogenic radionuclides provide a very precise age of glacial retreat. In Icelandic basalts, 36Cl and 3He are more commonly used than the other nuclides because they have the greatest abundance in the olivine mineral phases[5].

Using these two tools to map and date glacial deposits, large-scale and small-scale glacial histories in Iceland have been unraveled. The oldest glacial deposits in Iceland are found in southern Iceland and dated to 4.3 Ma, while glaciation didn't reach western or northern Iceland until 2.6 Ma and 2.4 Ma, respectively[6]. Interestingly, Iceland's climate was cold much earlier than 4.3 Ma[6,7], suggesting that climate is not the only important factor in Iceland's glaciation history. As discussed above, a key factor in glacier growth is the amount of precipitation that occurs above the equilibrium line. The more snow that falls here, the more ice that exists year-round is created. One of the main differences between southern Iceland and northern and western Iceland is the amount of precipitation each region receives (see Fig. 9). This is likely the main reason Icelandic glaciation initiated first in the south[8].

Although in the east glaciations began at 4.3 Ma, a study in the Skaftafell region (an outlet glacier of Vatnajökull, located in the southeast, and where we stayed for days 4-6) show a significant increase in the frequency and intensity of glaciations in the east beginning around 2.6 Ma, coincident with glaciation in the north and west[4]. Another factor, other than climate and precipitation, must have triggered the countrywide glaciation around 2.6 Ma. Current local topographic relief (mountain top to valley bottom) in southeastern Iceland is over 2000 m. Evidence suggests that at 3 Ma, prior to major glaciations, topographic relief here was less than 100 m, but by 0.8 Ma the relief had reached 600 m. Interaction between increasing volcanic activity in the region and the small alpine glaciers led to the formation of this dramatic landscape beginning around 3 Ma. Subglacial eruptions cause lava to cool quickly, and instead of spreading out and flowing over a large area, the lava was confined thereby creating thick volcanic ridges that built up the topography. At the same time that subglacial eruptions were building up the positive relief, glacial erosion was lowering the negative relief. This increase in topographic relief set the stage for the Pleistocene glaciations that further shaped the landscape[4].

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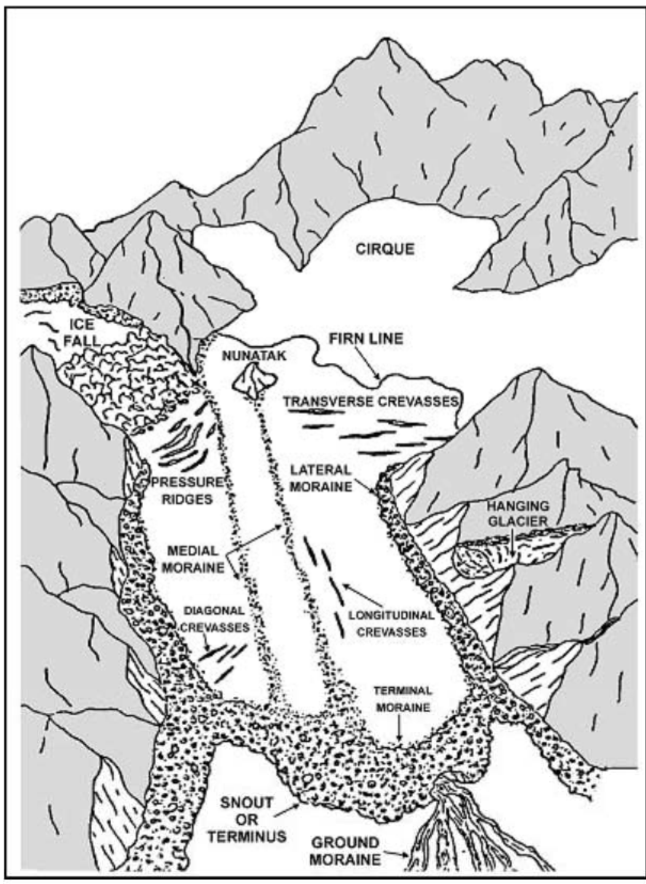

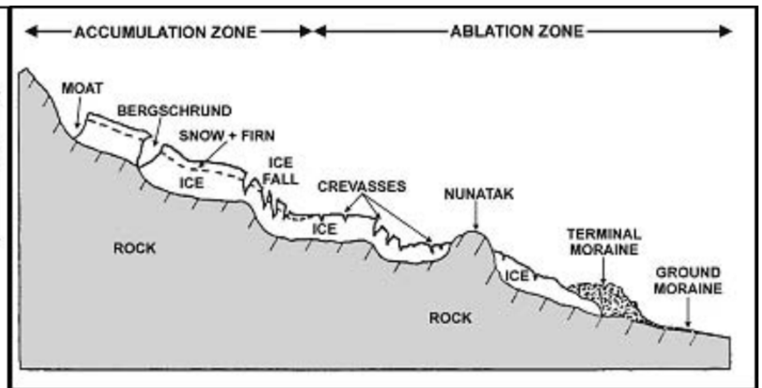

Figure 8. a) Description of features in map view of a glacier, most are mentioned above. b) Cross section of features through a glacier. Source: http://www.mountain--survival.net/chp10.html

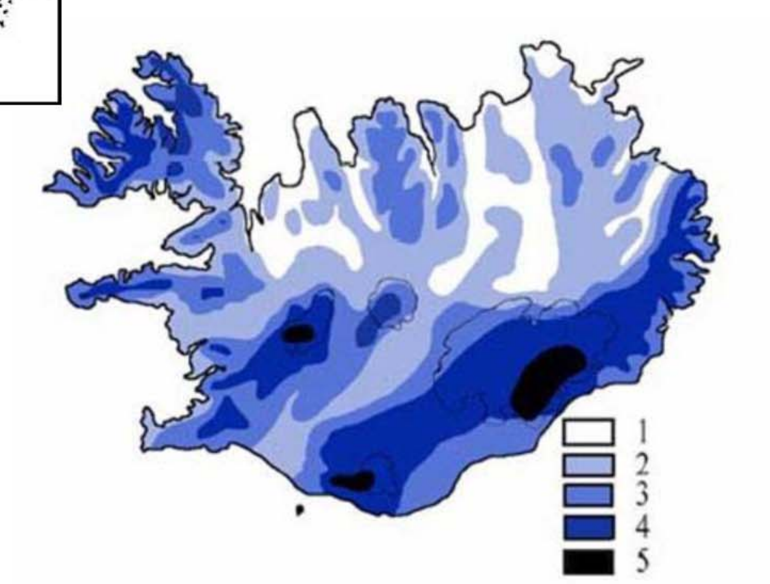

Figure 9. Mean annual precipitation in Iceland for the period 1931--1960: **1.** <600 mm; **2.** 600–1199 mm; **3.** 1200–1999 mm; **4.** 2000–3999 mm and **5.** >4000 mm.

Figure source: http://notendur.hi.is/oi/climate_in_iceland.htm

Glaciers and Jökulhlaups

Contributed by Adrienne Smith

Introduction

Since the onset of Northern Hemisphere glaciation approximately 3 Ma, Iceland has seen between 15-23 glaciations. During the Last Glacial Maximum (LGM) and throughout the Pleistocene Glacials, Iceland was almost entirely covered with ice. End moraines marking the furthest extent of glaciers at the LGM are found 130 km offshore from West Iceland at 150-250 meters below modern sea level (Einarsson and Albertsson, 1988 and references therein).

Today, glaciers cover 10% of Iceland and 60% of that glaciated area overlies active volcanic systems (Björnsson, 2002). This combination of ice and volcanism makes Iceland the unique location of recurring jökulhlaups, floods of volcanic meltwater that rush out from underneath glaciers. Iceland's modern ice caps and glaciers emerged 2.5 ka, coincident with a climatic cooling that caused the decline of once thriving Birch forests. Today, Iceland retains 4 significant Ice Caps, which are (largest first) Vatnajökull, Langjökull, Hofsjökull and Mýrdalsjökull.

Modern Ice Caps and Underlying Volcanoes

Vatnajökull, at approximately 8100 km^2, has an average ice thickness of 400 m but local thicknesses of up to 1000 m. The present volume is sufficient to cover all of Iceland in a 35 m layer of ice, making this the largest glacier in Europe. Beneath Vatnajökull, there are five volcanic systems consisting of central volcanoes and associated fissure swarms. Among these are two large systems with notable modern activity, Grímsvötn and Bárðarbunga. In the past 800 years, more than 80 volcanic eruptions have occurred beneath Vatnajökull. Eruptions under this glacier are often associated with jökulhlaups.

Langjökull, located in Western Iceland, is 925 km^2 in area and averages 580 m of ice thickness. It is underlain by two volcanic systems but no eruptions have taken place under it in the past millennium.

Hofsjökull is located in central Iceland. The ice here is relatively thin, averaging only 215 m (Björnsson, 1985). The ice cap covers 925 km^2 of the country, including Iceland's largest volcano. This volcano has not erupted in the past millennium, largely since Hofsjökull is located west of modern Mid-Atlantic ridge activity (Björnsson, 2002).

Mýrdalsjökull in Southern Iceland covers 600 km^2. Beneath the ice surface lies the Katla volcanic system of craters and calderas. The Katla system has had 20 known eruptions since the settlement of Iceland in ~870 C.E. (Björnsson, 2002). The Katla Volcano is more than 1500 m tall with an ice covering of 200-700 m (http://www.earthice.hi.is/page/ies_katla retrieved on Sept, 14 2010). Eruptions under Mýrdalsjökull are often associated with jökulhlaups.

Also of note is Eyjafjallajökull, the glacier overlying the 2010 C.E.volcanic eruption. This glacier is west of Mýrdalsjökull in southern Iceland, only 25 km from the very active Katla volcanic system. Historically eruptions at Katla are followed by eruptions under Eyjafjallajökull, causing concern over potential continued volcanism in he region (http://news.bbc.co.uk/2/hi/europe/8623239.stm retrieved on Sept, 14, 2010).

Iceland's Jökulhlaups

Jökulhlaups are outburst floods of subglacially stored water. Glacial ice is continuously melting at the bed where it rests on geothermally heated rock. This melting causes draw down of the ice and surface depressions form. Often, the surface depression forms directly over volcanic calderas since these are locations of concentrated geothermal heat. The surface slope of an ice sheet drives the flow of water at the ice-bed interface. Thus, depressions in the surface cause the water to flow in from all directions and pond directly under those depressions. Even without a caldera to hold the water, water can be stored within the ice as long as the surface depression generates a flow gradient. These subglacial lakes are surrounded by ice, which is sealed to the bed under the pressure of its own weight, forming an ice dam. If the dam is broken or if water pressures cause it to float, the stored water is released in outburst floods called jökulhlaups (Björnsson, 2002). Typically, jökulhlaups occur before the water level rises enough to float the ice dam, indicating that water enters conduits under the ice to initiate the flood.

Grímsvötn

Grímsvötn is Iceland's largest subglacial lake and is known to flood periodically at an interval of 1-10 years. At Grímsvötn, hydrothermal activity has created a 300 m deep, 10 km wide depression in Vatnajökull's surface. The lake fills nearly continuously due to hydrothermal activity within the still active caldera and also from the drainage basin at large. Floods tend to occur when the water level reaches a certain threshold elevation relative to sea level, typically just over 1100 m. Nearby seismometers detect ice quakes coincident with the onset of lake drainage. These ice quakes are associated with subsidence of the ice as the lake level drops. Floods from Grímsvötn drain over the world's largest active glacial outwash plain, Skeiðarársandur.

The 1996 Flood Event

In October 1996, Gjálp, a volcano in the Grímsvötn drainage basin began to erupt. The eruption broke through the ice surface within 30 hours but continued under the ice for two weeks. Meltwater accumulated in the Grímsvötn caldera until a historically high lake level of 1510 m above sea level was reached. Then, beginning November 4 and continuing until November 7, a catastrophic jökulhlaup ensued. 3.2 cubic kilometers of water (about the volume of Lake Huron) was released from Grímsvötn in only 40 hours. Like most Grímsvötn floods, the meltwater emerged at Skeiðarárjökul, emitting a sulfur smell and washed over the Skeiðarársandur outwash plain. In this case, the floodwaters reached the outwash plain in only 10.5 hours, as compared to 48 hours on average, and inundated the area, washing out bridges and destroying local infrastructure.

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Post-Glacial Rebound

Contributed by Natalia Zakharova

Post-glacial rebound refers to the rise of landmasses that were depressed by the weight of ice sheets through the process of isostatic compensation. The concept of isostasy describes gravitational equilibrium between the Earth’s lithosphere and asthenosphere. It is based on the idea that the light crust (or lithosphere) is floating on the denser underlying mantle (asthenosphere)[1]. Various geologic processes such as sediment deposition, erosion, formation of ice sheets, and extensive volcanism perturb the state of equilibrium between the crust and the mantle by loading (or removing a load) on the crust. The system then adjusts, resulting in vertical motion (‘sinking’ or rising) of the lithosphere. The way the crust and mantle respond to the disturbances constrains important physical properties of the lithosphere and upper mantle and helps us understand the relations between complex geodynamical phenomena. This section will be focused on the geodynamic relationship between glaciation and volcanism.

Rapid post-glacial rebound of the earth's surface has occurred in Iceland as in other areas of Weichselian ice sheets following the end of the last glaciation approximately 10,000 years ago[2]. The uplift rate estimates in different regions of Iceland vary from about 2 to 10 cm/yr for the period of 10 - 8 ka. The post-glacial rebound resulted in the rise of the earth's surface by 40 - 170 m, about 100 m on average (Fig. 10)[3]. This period of rapid uplift followed by prolonged period of fluctuating vertical displacement since 8200 ka. It is mainly characterized by slow subsidence that is attributed to eustatic sea level rise[2]. Currently, the uplift of 5 - 10 mm/yr is observed at the Vatnajökull ice cap in the southeast of Iceland4, which is attributed to warming and glacial retreat in the 20th century.

While current uplift can be recorded with GPS stations, quantification of postglacial rebound in early Holocene requires making estimates from paleo-shoreline studies. Marine deposits are widely found above present sea level in Iceland, and they cover most of the lowlands. In Southern Iceland they are found more than 100 m above current sea level, and more than 50 km inland from the present coast[2]. Marine shells and driftwood from elevated marine terraces and beach deposits can be dated by radiocarbon to calculate the amplitude and rate of vertical displacement of the surface (after the elevation is corrected for eustatic sea level change). These studies reveal that rapid isostatic adjustment in Iceland occurred from 13 to 8.5 kya[3]. There have been no older or younger shells found, supporting the idea that rapid post-glacial rebound was limited to these 5 ky. Rapid uplift during a short time period can be attributed to the low viscosity of the hot asthenosphere under the island.

The interpretation of paleo-shoreline data suggests that, prior to 13 ka, most of Iceland was covered by an ice cap, which depressed the earth's surface and probably extended beyond the present-day shoreline (due to low eustatic sea level during the last glaciation). As the warming began at 13 kya, the ice front retreated, but the surface remained depressed, forming shallow seas. Marine organisms lived in these shallow seas inland the present coastlines[2]. Then, the lithosphere started to adjust to the glacial unloading causing uplift and a forced regression. However, the deglaciation history in Iceland is complex, with at least two glacial re-advances during the Older and Younger Dryas (12 ka – 11.7 ka and 10.8 ka – 9.5 ka, respectively). The increased ice coverage prevented marine sedimentation causing gaps in dates on marine terraces and shorelines. The final deglaciation started at 10 ka and was followed by rapid rebound that was completed in less than 2 ky[3].

Given the estimates of uplift time and elevation change, it is possible to calculate the viscosity of the underlying asthenosphere. Asthenospheric viscosity is one of the major factors defining how fast the rebound can occur because it characterizes the ability of mantle material to flow and 'fill' the depression created by an ice cap[5]. Asthenospheric viscosity estimates under Iceland[3] vary from 8×10^{18} to 3×10^{19} Pa s. These values are generally lower than average mantle viscosity (10^{21} Pa s), which is expected for a hotspot on the Mid-Atlantic ridge.

Glacial loading of lithosphere in Iceland also may have had a strong effect on volcanism. Tephrochronological dating of postglacial volcanism in the Dyngjuföll volcanic complex, a major spreading center in the Icelandic Rift Zone, indicates a high eruption rate in the millennia following deglaciation as compared to the present low productivity[6]. This study suggests that lava production in the period 10 – 4.5 ka was at least 20 to 30 times higher than that in the period after 2.9 ka.

The higher production rate during the earlier period coincides with the disappearance of glaciers of the last glaciation. This phenomenon is explained by the decrease in lithostatic pressure as the glacier melts. Vigorous crustal movements caused by rapid isostatic rebound may trigger intense volcanism until a new lithostatic equilibrium is established.

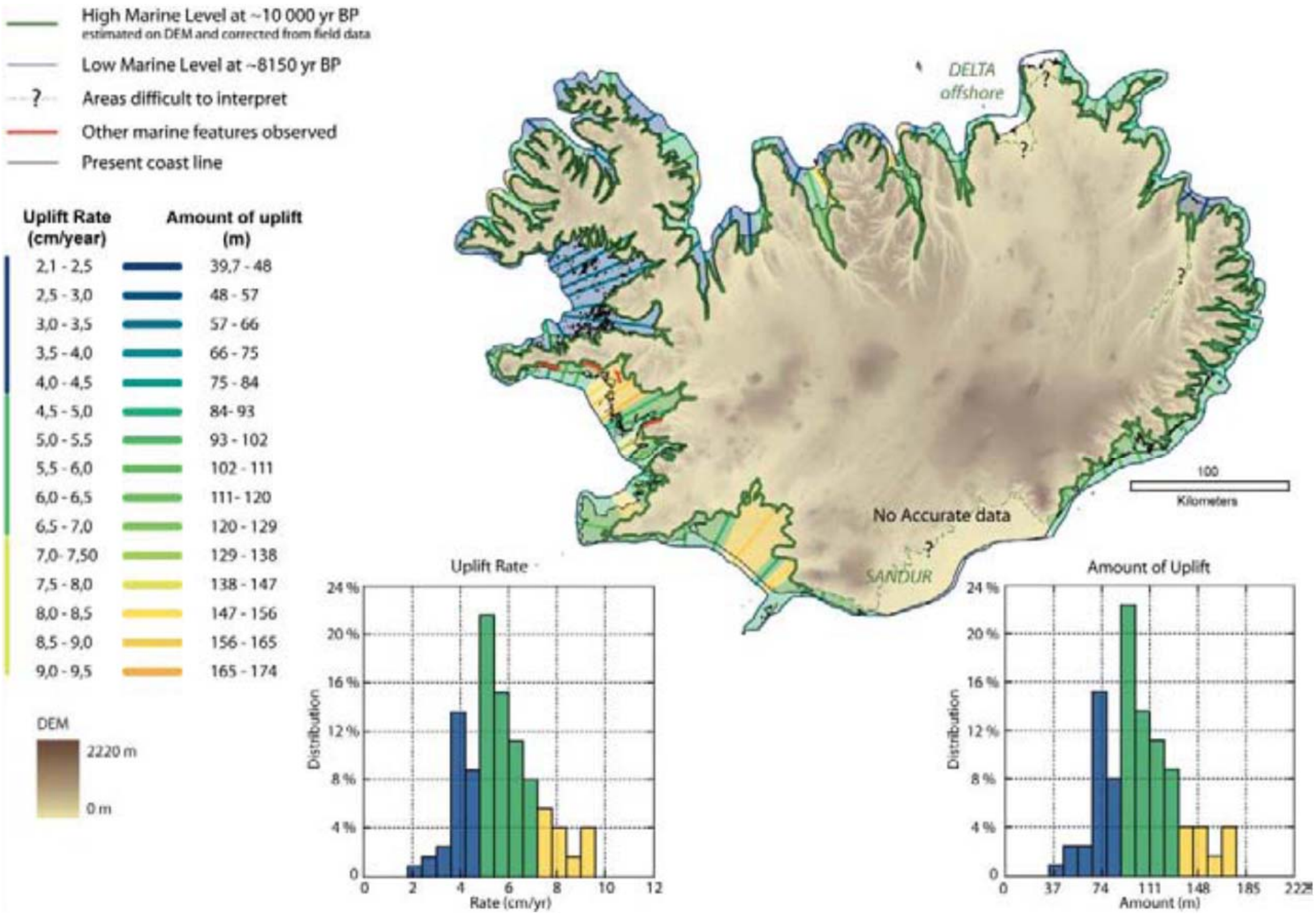

Figure 10. Amount and rate of uplift calculated between 10-8.2 kyr BP (from LeBreton et al., 2010).

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Climate and Climate Change

Contributed by Amy Stypa

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

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

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

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

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

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

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Surface circulation

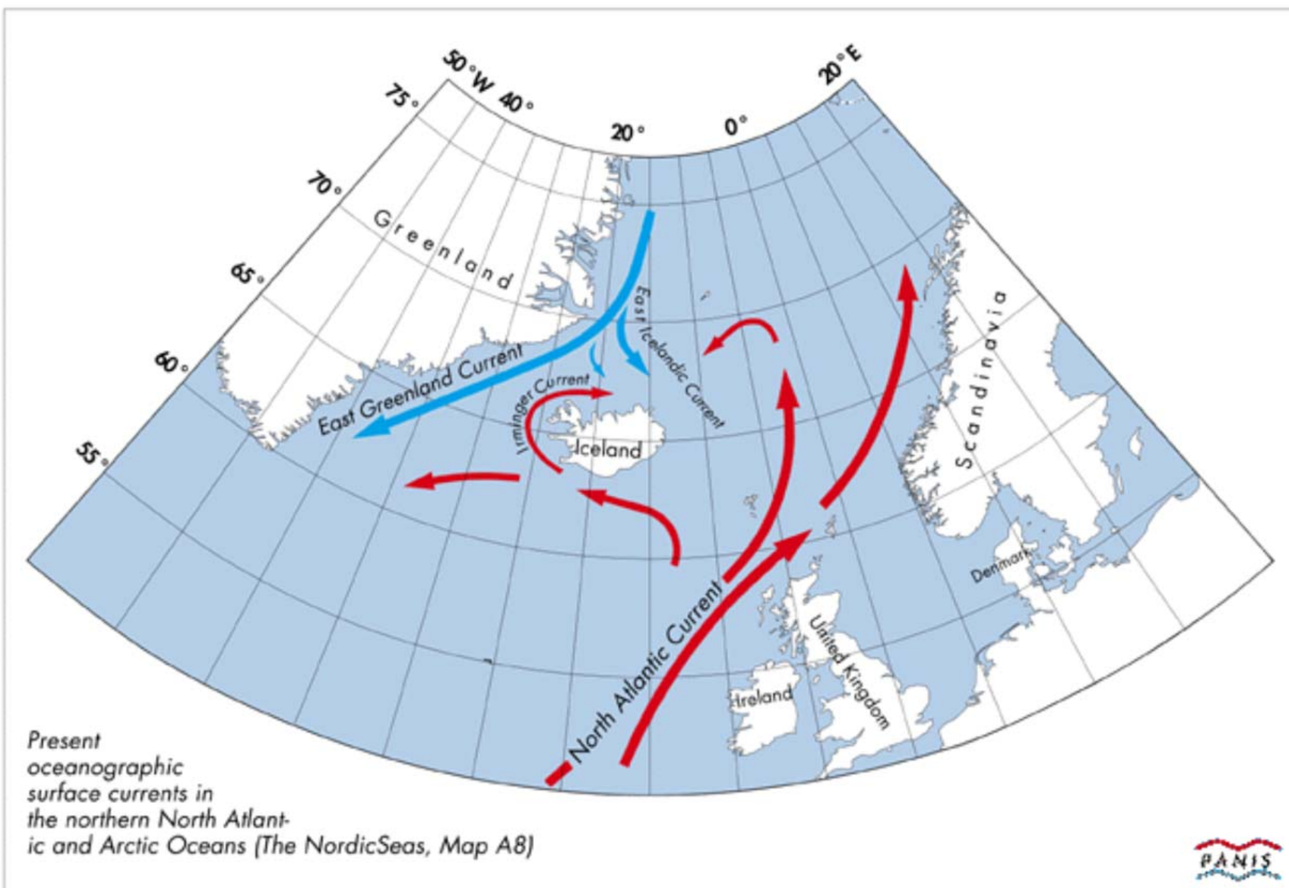

Figure 11. Present oceanographic surface currents around Iceland. Image source: http://www.hi.is/~jeir/panis_currents.html

Iceland Ecology

Contributed by Miriam Marlier and Jennifer Levy

The vegetation history of Iceland has been reconstructed through several methods. Areas that have not been exposed to grazing animals have been studied as remnants of past vegetation communities. Historical records such as farm surveys or sagas as well as terminology used to describe the landscape also aid in vegetation reconstruction. Studies on the rate of succession to protected areas and dating of volcanic ash layers provide timelines for expected soil formation and vegetation colonization. Additionally, pollen records through the soil profile provide information about the plants that occupied the landscape along with the relative abundance of these plants at various points in time.

A synthesis of this type of information suggests that when the country was first settled after the last glaciation in 874 C.E., 65% of the landmass was vegetated. Most of the vegetated area (25-40% of the landmass) was covered by woodlands of *Betula pubescens* (Downy birch)[1]. Sedges and graminoids occupied the wet areas within the woodlands and *Salix* spp. (Willows), along with other small shrubs, occupied extensive areas above 300 to 400 m elevation[2]. Although most are rarely found in the country today, the Downy birch, rowan (*Sorbus aucuparia*), aspen (*Populus tremula*), and the tealeaved willow (*Salix phylicifolia*) are considered to be the only the native Icelandic tree species[1]. A sharp decline in woodlands coincides with colonization[2]. The forests were cut down and burned to clear land for farms. Wood was use for daily living as well as making iron tools. By 1950, the birchwoods were reduced to less than 1% landcover[3] initiating an ecological disaster. Extensive areas of soil erosion soon followed reaching a maximum in the 19th and early 20th centuries[3]. In 1986, the land was characterized as " absence of trees; low density of grasses, forbs, and willows; and abundance of low growing nonpalatable shrubs, sedges, and rushes; and low annual production[2]." This characterization still appears to be fitting (Fig. 12). Driving through the country we observed vast expanses of open land. The ground was either exposed rock absent of vegetation or large areas covered with a layer of low-lying plants. We observed Downy birch at several sights along the trip including Geysir and on our hike from Basi to Skogar. However, the trees were present in small clusters of individual plants instead of the continuous forests that once covered the land.

The Arctic fox, *Alopex lagopus*, is the only native mammal left in Iceland. The blue fox, which escaped from fur farms and interbred with the native foxes, has compromised the genetic diversity of the remaining native population. American mink, Mustela vison, was brought to Iceland in the early 1930's for fur farms but soon escaped captivity, and now prey on a variety of native fish and bird species. Early settlers also inadvertently introduced Norwegian rats and house mice. Reindeer were imported from Norway in the late 1700's, but their distribution is now limited to eastern Iceland after several population crashes in other parts of the country. Early settlers brought domesticated animals such as sheep, dairy cattle, and horses. Sheep have had a particularly strong impact on Icelandic ecology since they actively graze on eroded land, furthering soil erosion by limiting vegetation regrowth[4]. Although we did not focus on marine wildlife or birds during our trip, Iceland is an important habitat for many species. These include a variety of seabirds such as guillemots and puffins, as well as the Icelandic Gyrfalcon. Fish are important to the Icelandic economy, including species such as cod, herring, and capelin. In addition, marine mammals include walruses and a variety of whale and seal species. Polar bears have occasionally been observed in Iceland as well[5].

One immediate concern relevant to Icelandic ecology is how the high northern latitudes might be expected to respond to climate change. In order to further understand this, a study in the central highlands of Iceland analyzed how the timing of flowering has changed for 75 species over 11 years relative to a variety of environmental factors[6]. This study region, south of the Hofsjökull glacier, is home to almost half of the vascular plant species in Iceland including grasses, herbs, mosses, and a variety of shrubs. The timing of flowering is extremely important due to the short growing season, especially since inferior seeds and diminished reproductive success have been found in plants that flower later in the season. This study found that 71 of 75 plants flowered annually, except in two exceptionally cold summers, but that the onset of flowering varied greatly between years. However, there was a correlation between flowering in the first week of July and the air temperature in the five preceding weeks. Although, factors such as light, temperature, and rainfall can stimulate flowering, it was found that snowmelt did not have a significant effect in the majority of years. This study indicates that Arctic species are expected to respond quickly to warmer temperatures and longer growing seasons. Since the species studied have a wide spatial distribution, this study also suggests that accelerated phonologies in the Arctic may have an impact on genetic diversity in soil seed banks, increased productivity or habitat expansion, and altered relationships with pollinators[6].

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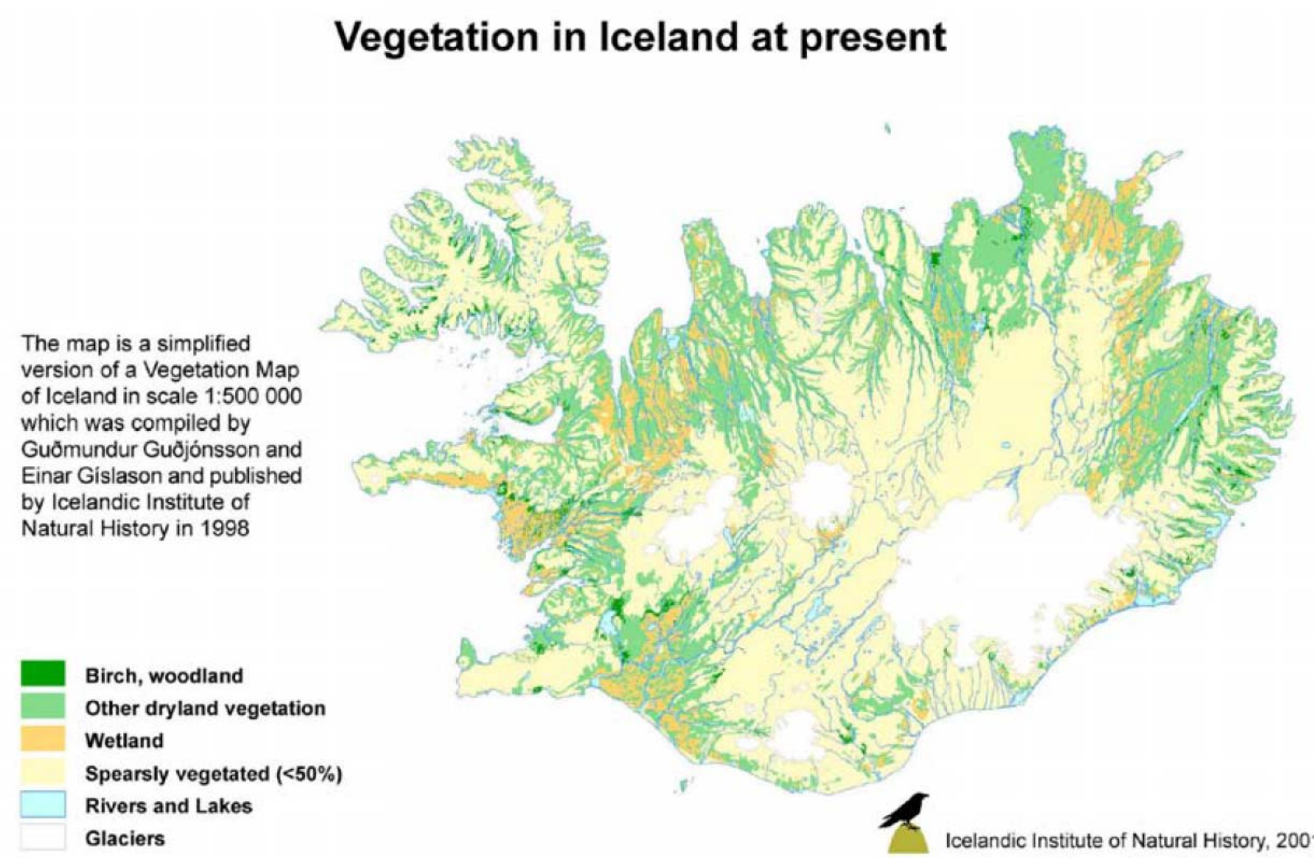


Figure 12. Vegetation in Iceland at present (from Icelandic Institute of Natural History, 2001).

Aurora Borealis

Copied Wikipedia Article on Aurora

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

Occurrence of terrestrial auroras

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

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

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

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

Visual forms and colors

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

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

- **Red:** At the highest altitudes, excited atomic oxygen emits at 630.0 nm (red); low concentration of atoms and lower sensitivity of eyes at this wavelength make this color visible only under more intense solar activity. The low amount of oxygen atoms and their gradually diminishing concentration is responsible for the faint appearance of the top parts of the "curtains". Scarlet, crimson, and carmine are the most often-seen hues of red for the auroras.
- **Green:** At lower altitudes the more frequent collisions suppress the 630.0 nm (red) mode: rather the 557.7 nm emission (green) dominates. Fairly high concentration of atomic oxygen and higher eye sensitivity in green make green auroras the most common. The excited molecular nitrogen (atomic nitrogen being rare due to high stability of the N_2 molecule) plays A role here, as it can transfer energy by collision to an oxygen atom, which then radiates it away at the green wavelength. (Red and green can also mix together to produce pink or yellow hues.) The rapid decrease of concentration of atomic oxygen below about 100 km is responsible for the abrupt-looking end of the lower edges of the curtains. Both the 557.7 and 630.0 nm wavelengths correspond to forbidden transitions of atomic oxygen, slow mechanism that is responsible for the graduality (0.7 s and 107 s respectively) of flaring and fading.
- **Blue:** At yet lower altitudes, atomic oxygen is uncommon, and molecular nitrogen and ionized molecular nitrogen takes over in producing visible light emission; radiating at a large number of wavelengths in both red and blue parts of the spectrum, with 428 nm (blue) being dominant. Blue and purple emissions, typically at the lower edges of the "curtains", show up at the highest levels

of solar activity.[22] The molecular nitrogen transitions are much faster than the atomic oxygen ones.

- **Ultraviolet:** Ultraviolet light from auroras (within the optical window but not visible to virtually all humans) has been observed with the requisite equipment. Ultraviolet auroras have also been seen on Mars,[23] Jupiter and Saturn.
- **Infrared:** Infrared light, in wavelengths that are within the optical window, is also part of many auroras.[23][24]
- **Yellow** and **pink** are a mix of red and green or blue. Other shades of red as well as orange may be seen on rare occasions; yellow-green is moderately common. As red, green, and blue are the primary colors of additive synthesis of colors, in theory practically any color might be possible but the ones mentioned in this article comprise a virtually exhaustive list.

Causes of auroras

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

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

from wave-particle interactions, raises the velocity of a particle in the direction of the guiding magnetic field. The pitch angle is thereby decreased, and increases the chance of it being precipitated into the atmosphere. Both electromagnetic and electrostatic waves, produced at the time of greater geomagnetic disturbances, make a significant contribution to the energising processes that sustain an aurora. Particle acceleration provides a complex intermediate process for transferring energy from the solar wind indirectly into the atmosphere.

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

Auroral particles

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

Auroras and the atmosphere

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

oxygen emissions

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

nitrogen emissions

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

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

Auroras and the ionosphere

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

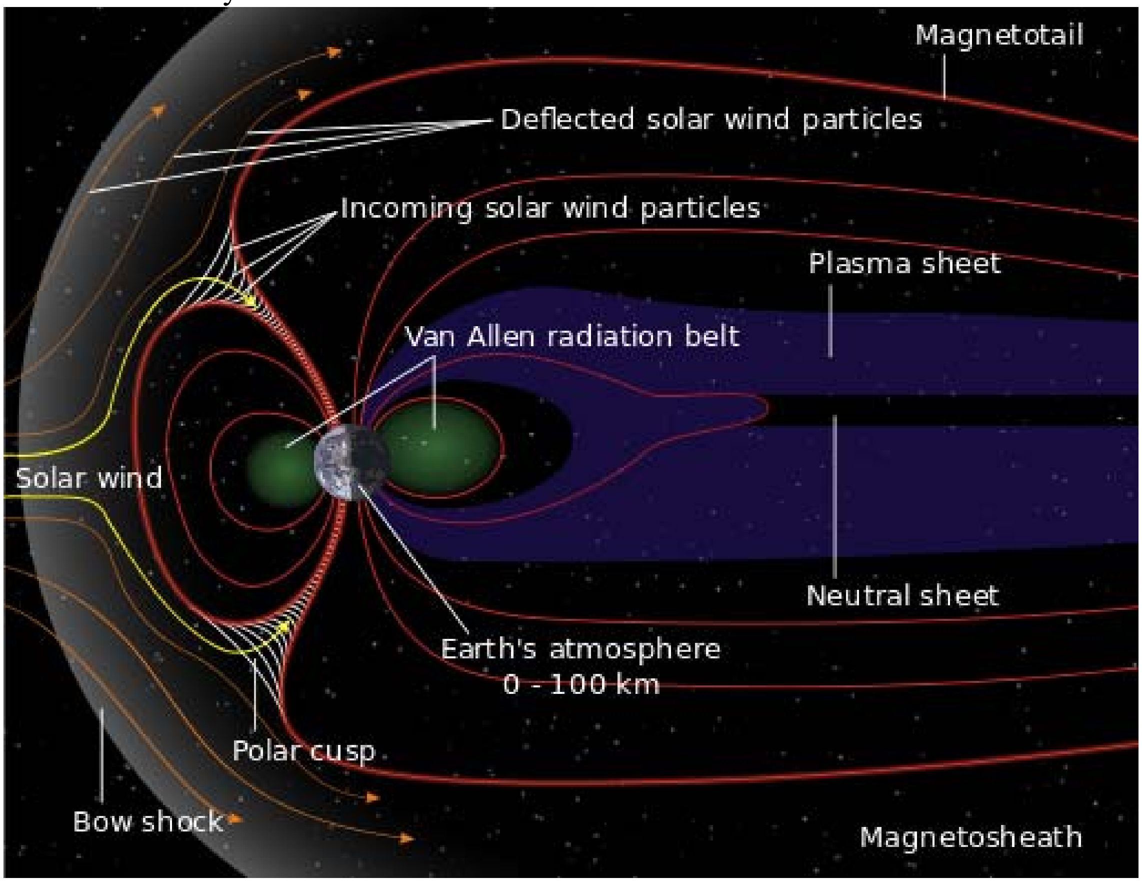
Ionospheric resistance has a complex nature, and leads to a secondary Hall current flow. By a strange twist of physics, the magnetic disturbance on the ground due to the main current almost cancels out, so most of the observed effect of auroras is due to a secondary current, the auroral electrojet. An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

Interaction of the solar wind with Earth

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

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

Schematic of Earth's magnetosphere



Magnetosphere

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

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

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DETAILED ITINERARY

Day 1: Saturday, March 5th, 2016 – Board flight

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

Day 2: Sunday, March 6th, 2016 – Reykjanes Peninsula

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

7:30: After clearing customs, we will pick-up the vehicles

8:00: I think it will be best to have breakfast at the airport

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

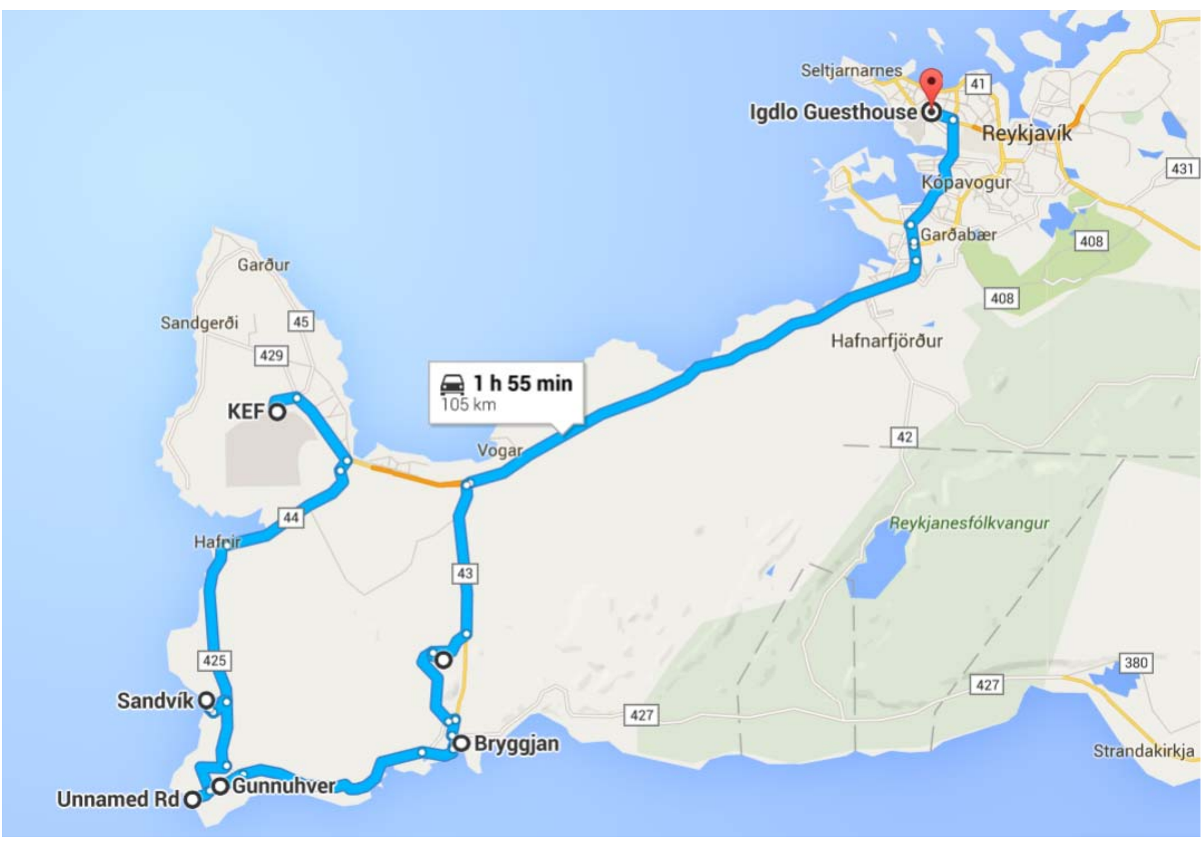
10:00: Valahnukur cliff. Check the contact between tuff and pillow lava.

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

12:30: Lunch in Grindavik – There is a café called Bryggjan (2 240, Miðgarður, Grindavík) near the harborfront that might be good.
There is also a grocery store in Grindvik called Netto, this might be a good opportunity pick up some groceries and such.

2:00PM: Blue Lagoon – the basic package is $45 dollars, that really just gets you entrance into the pools, looks like you can add on towel for $5. They list other packages up to $80 that include drinks, mud masks, etc.
It is about 40 minutes to the hostel, we can stay as long as people want but I would suggest we hit the road by 5.

6 or 7 PM: Get to the hostel (Igdlo Guesthouse, Gunnarsbraut 46, 105 Reykjavík). Stay there for one night. Fend for yourself for dinner? Or we could cook a group meal, the hostel has a kitchen that we can use.



General Background

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

Site Descriptions:

STOP 1 - *The Bridge between Two Continents (Leif the Lucky Bridge)*

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

Figure 13. View south from Leif the Lucky Bridge.

STOP 2 - *Valahnukur Cliff*

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

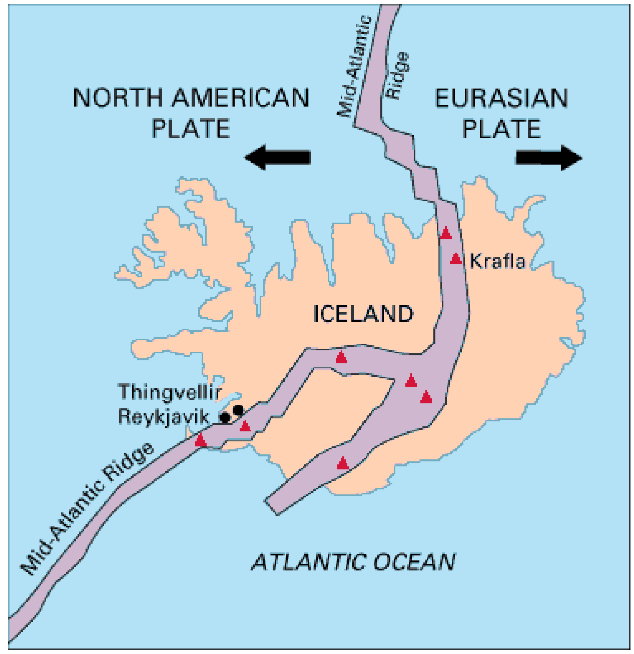


Figure 14. Valahnukur cliff: view south, showing the contact between laminated tephra and pillow basalts.

STOP 3 - *Gunnuhver Hot Spring*

This is one of the most famous high temperature geothermal areas on the Reykjanes Peninsula. The name Gunnuhver comes from the witch called Guðrún, who caused a great disturbance until Eiríkur Magnússon, a priest at Vogsósar set a trap that made her fall into the spring[4]. Gunnuhver is an exception to other geothermal areas because the groundwater here is 100% seawater. Mud pools and steam vents are formed where steam generated in a geothermal reservoir emanates, condenses, and mixes with surface water. The accompanied gases, such as carbon dioxide and hydrogen sulfide, make the water acidic and alter the fresh lavas to clay. Steam released at the surface has increased markedly since 2006 as a consequence of groundwater exploitation by a nearby geothermal power plant[5]. Evaporites and sulfuric minerals can be seen throughout this hydrothermal area. At depth, metal ores are concentrated, especially copper sulfates.

STOP 4 - *Grindavik*

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

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

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

Figure 15. Blue Lagoon

STOP 5 - *Blue Lagoon*

The Blue Lagoon, or "Bláa lónið", is one of the most popular attractions in Iceland. It is a geothermal spa located in a lava field just off the road between Keflavík and Grindavík. It is fed by the wastewater of the nearby geothermal power plant, Svartsengi. The six million liters of milky-blue water in the lagoon is 37-39° C (98-102° F) and is rich in silica and sulfur, along with the natural green blue algae. Tourists all around the world are attracted to Blue Lagoon for its proved healing power of skin diseases and the enhancement of wellness and beauty of the human body. The entrance fee is 28 Euro for adults, 7 Euro for teens.

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Day 3: Monday, March 7th, 2016 – Reykjavik to Heimaey

The morning is free and the hostel will provide breakfast.
10:15: Leave the hostel and head toward Þorlákshöfn for the ferry
11:30: Board the ferry and depart for Vestmannaeyjar, Heimaey.
12:00: Lunch on the boat
2:30PM: Arrive Vestmannaeyjar, Heimaey and check in with the hostel (Aska Hostel, Bárustígur 11, Vestmannaeyjar, 900, Iceland).
Rest of the day: Walk around, hang out, relax, whatever… On our own for dinner, there might be a kitchen at the hostel, we could do a group meal.

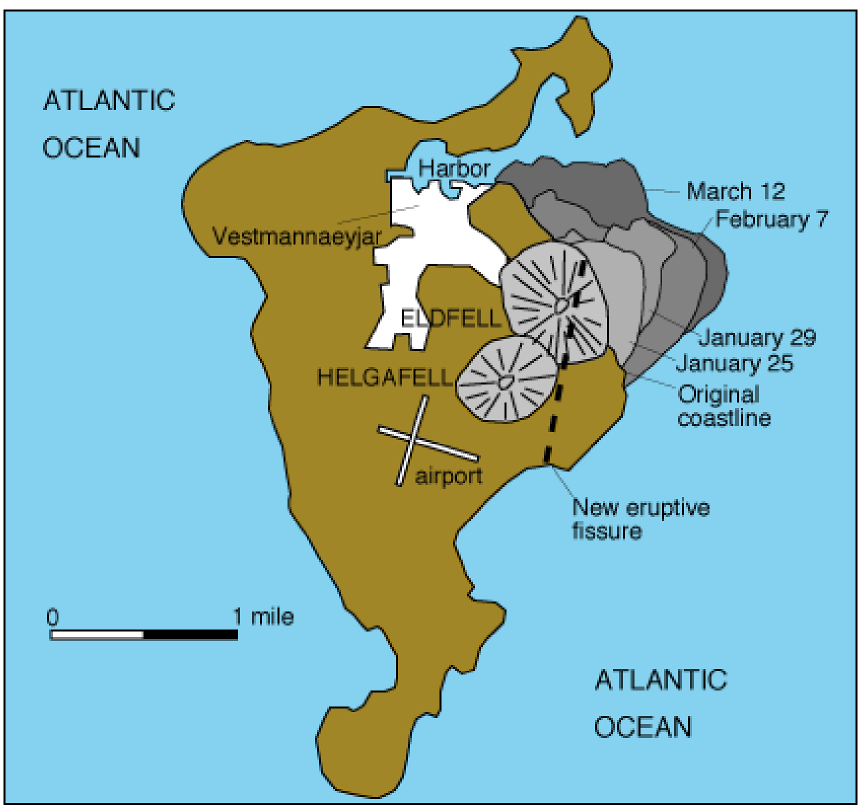
Site Descriptions:

STOP 1 - *Þorlákshöfn*

The town name is named after Þorlákur Helgi who was bishop at Skálholt. Its main importance is as a port as it has the only viable harbour on Iceland's southern coastline between Grindavík in the west and Höfn in the east, and it serves as one of two departure points for ferries to the Vestmannaeyjar archipelago. Services include a restaurant, golf course, motocross field, sport complex and swimming pool.

STOP 2 – *Vestmannaeyjar - Heimaey*

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



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

Day 4: Tuesday, March 8th, 2016 – Heimaey to the Rift Valley

8:00: Make breakfast in the hostel
9:00: Drive to the south edge of the island, hike around and get a view of Surtsey
There is enough hiking to make that our full day, there is a lot to see here. Terry has a good loop hike that would bring us past a lot the cool stuff.
There pictures of Elephant Rock on the internet from this island, it looks really cool, hopefully we can figure out where it is, I'd like to see that…
If weather becomes an issue there are indoor activities available as well.

Indoor Activities: Eldheimar Volcano Museum (10, Gerðisbraut, Vestmannaeyjabær, opens at 11AM, $14) – seems like this give a descent history of the island and the volcanic issue. This also has overview of the buried portions of the town.

The natural history museum and aquarium gets good reviews (Saeheimar Aquarium, Heioarvegur 12 900, Vestmannaeyjar, close to the ferry terminal, opens at 1PM, $8). Other than that people could just hike around or wait for the ferry in a café or something.

3:00PM: Board the ferry and depart for the main land
6:15PM: Reach Þorlákshöfn and drive to the Guesthouse in the rift valley
7:30PM: Get to Guesthouse Denami (Háholt, Iceland), they will have a traditional Icelandic meal of lamb stew and Icelandic breads

From Wikipedia:

Heimaey, literally Home Island, is an Icelandic island. At 13.4 square kilometres (5.2 sq mi), it is the largest island in the Vestmannaeyjar archipelago, and the largest and most populated island off the Icelandic coast. Heimaey is 4 nautical miles (7.4 km; 4.6 mi) off the south coast of Iceland. It is the only populated island of the Vestmannaeyjar islands, with a population of 4,500. The airport and the Vestman Island Golf Course cover a large part of the island.

In January 1973, lava flow from nearby Eldfell destroyed half the town and threatened to close its harbour, its main income source. An operation to cool the advancing lava with sea water saved the harbour.

Eldfell

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

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

Present day

Heimaey is home to around 4,500 people, and eight million puffins every summer. Many millions of other birds migrate there for breeding and feeding.

The island is connected to the rest of Iceland by a ferry and Vestmannaeyjar Airport.

Most people on the island live off fishing. During an annual festival, people are allowed to catch a few puffins to share at the festival, or to eat at home.

Day 5: Wednesday, March 9th, 2016 – Waterfalls, Glaciers and Vik Beaches

7:00: Wake-up.
7:30: Make Breakfast.
8:30: Depart
9:30: Arrived at Seljalandsfoss waterfall.
10:15: Arrived at Skogafoss waterfall.
12:00: Sólheimajökulsvegur Glacier, Lunch at the Glacier
2:30PM: Arrive in Vik walk the beaches and check out Vik.

This would be the best day for the Ice Cave tour people have mentioned.

This evening we are on our own for dinner, we will need to figure that out.

Site Descriptions:

STOP 1 - *Seljalandsfoss waterfall*

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

STOP 2 - *Skógafoss*

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

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

STOP 3 - *Sólheimajökulsvegur Glacier*

STOP 4 - *Vik*

From Wikipedia

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

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

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

Danger from Katla

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

Climate

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

STOP 5 - *Dyrhólaey Peninsula, Reynisdrangar and Black Sand Beaches*

The small peninsula, or promontory, Dyrhólaey (0.192 Miles / 120 meters) (formerly known as „Cape Portland" by seamen)[1] is located on the south coast of Iceland, not far from the village Vík. It was formerly an island of volcanic origin, which is also known by the Icelandic word eyja meaning island.

The view from up there is interesting: To the north is to be seen the big glacier Mýrdalsjökull. To the east, the black lava columns of the Reynisdrangar come out of the sea, and to the west the whole coastline in the direction of Selfoss is visible - depending on weather conditions. In front of the peninsula, there is a gigantic black arch of lava standing in the sea, which gave the peninsula its name (meaning: the hill-island with the door-hole). In the summertime, many puffins nest on the cliff faces of Dyrhólaey.

Reynisdrangar are basalt sea stacks situated under the mountain Reynisfjall near the village Vík í Mýrdal, southern Iceland which is framed by a black sand beach that was ranked in 1991 as one of the ten most beautiful non-tropical beaches in the world. Legend says that the stacks originated when two trolls dragged a three-masted ship to land unsuccessfully and when daylight broke they became needles of rock.

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

Day 6: Thursday, March 10th, 2016 – Þingvellir, Geysir, Gulfoss

7:00: Wake-up.
7:30: Make Breakfast.
8:30: Depart for Þingvellir
9:30: Arrived at Þingvellir
10:00: Walk to the Law Rock and through the rift valley.
12:00: Make lunch
1:00PM: Depart for Geysir.
2:00PM: Arrived at Geysir (site of hydrothermal springs and geysers). Walk around the site
3:30PM: Leave for Gullfoss (Golden Waterfalls)
4:00PM: Arrive at Gullfoss visit the fall and visitor's center
5:30PM: Depart to return to the hostel
6:15PM: Get to Guesthouse Denami (Háholt, Iceland), they will have a traditional Icelandic meal of lamb stew and Icelandic breads

Site Descriptions:

STOP 1 - *Þingvellir National Park (see the write in the Geologic Overview Section)*

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

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

STOP 2 - *Geysir*

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

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

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

Further away is Geysir, the Father of all Geysers. Today it is just a hole encrusted in amorphous, shiny siliceous deposits. Geysir is the tallest geyser in the world with eruptions over 70 meters tall. It is now dormant, unless tourists visit Iceland on the National Day when qualified geologists provoke an eruption of one of Iceland's national symbols. Geysir lent its name to all geysers in the world, being the first geyser known to Europeans (earliest accounts date back to 1294). Its own name comes from the Old Norse (and Icelandic) verb 'to gush'[3]. The activity of Geysir, as well as Strokkur, is intimately linked with seismic events. Eruptions of Strokkur started after an earthquake in 1789 that unblocked its plumbing system. Geysir, on the other hand, was nearly dormant until an earthquake in 1896 caused it to erupt again, but blocked the conduit of Strokkur. Geysir remained active until 1916, after which its eruptions all but ceased. Geysir was later reactivated only by human interventions (such as digging a hole through its silica rim or adding surfactants to the water), although an earthquake in 2000 did cause a short-lived resurgence of natural eruptions. Strokkur, on the other hand, has remained faithful to its eruption interval since the locals cleaned out its conduit in 1963[2,3].

STOP 3 - *Gulfoss*

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

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

Tómasdóttir, a daughter of a local farmer who partly owned the falls, walked all the way to Reykjavík over the sharp rocks of Iceland, in order to prevent the destruction of the falls. She supposedly arrived in the capital, her feet bleeding, and threatened to throw herself into the Gullfoss, should the hydroelectric plant be built [4,5].

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[5]Wikipedia: Gullfoss. http://en.wikipedia.org/wiki/Gullfoss <accessed Sep 12, 2010>

[6]Seljalandsfoss, in World of Waterfalls. http://www.world-of-waterfalls.com/iceland-seljalandsfoss.html <accessed Sep 12, 2010>

Day 7: Friday, March 11th, 2016 – Hellisheiði Power Plant, Raurfarholshellir Lava Tube, and back to Reykjavik

7:00: Wake-up, pack our things and load the vans.
7:30: Make breakfast.
8:30: Depart for Hellisheiði Power Plant (Hellisheiðarvirkjun, Iceland)
9:30: Tour of the geothermal museum & "behind-the-scenes" tour of the power plant ($20 each).
12:00: Finished tour. Have lunch.
1:30PM: Arrived at Raurfarholshellir Lava Tube, ate lunch. Hike some of the lava tube. THIS REQUIRES STURDY BOOTS AND A FLASHLIGHT (or headlamp).
3:00PM: Returned to the van and head into Reykjavik. We will be staying in the same accommodations (Igdlo Guesthouse, Gunnarsbraut 46, 105 Reykjavík).

Site Descriptions:

STOP 1 - *Hellisheiði Power Plant*

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

STOP 2 - *Hengill volcanic system*

The Hengill volcanic system is located east of Reykjavík at the junction of several volcanic zones and covers an area of about 100 square kilometers[1]. The area has numerous northeast to southwest aligned fissure, vents and craters among other evidence of past volcanic activity. Although the last eruption occurred around 2 ka, this is still an active geothermal area dotted with numerous hot springs and fumaroles. The rest of the region is generally covered in postglacial lava flows[2].

STOP 3 - *Raufarhólshellir lava tube*

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

Day 8: Saturday, March 12th, 2016 – Borgarnes and the Snaefellsness Peninsula

8:00: Wake-up and have breakfast (provided by the hostel)
9:00: Depart for Borgarnes
10:00: Arrive in Borgarnes
11:00: Drive around the Snaefellness Peninsula
1:00 PM: Snæfellsjökull Volcano – the lonely planet guide has good descriptions of stuff.
5:00 PM: Return to Reykjavik
6:00 PM: Group Dinner?

Site Descriptions:

STOP 1 - *Borgarnes*

Borgarnes is a town located on a peninsula at the shore of Borgarfjörður in Iceland. It has a population of 1,763 (as of January 2011). The town is located 60 km north of the capital Reykjavík and is connected to other places in Iceland through the second largest bridge in Iceland, Borgarfjarðarbrú. Borgarnes is the biggest town in the Borgarbyggð municipality.

STOPS 2 –*Snæfellsnes Peninsula Overview:*

The Snæfellsnes is a peninsula situated to the west of Borgarfjörður, in western Iceland. It has been named Iceland in Miniature, because many national sights can be found in the area, including the Snæfellsjökull volcano, regarded as one of the symbols of Iceland. With its height of 1446 m, it is the highest mountain on the peninsula and has a glacier at its peak (jökull means "glacier" in Icelandic). The volcano can be seen on clear days from Reykjavík, a distance of about 120 km. The mountain is also known as the setting of the novel Journey to the Center of the Earth by the French author Jules Verne. The area surrounding Snæfellsjökull has been designated one of the four National Parks by the government of Iceland.

The peninsula is one of the main settings in the Laxdœla saga and it was, according to this saga, the birthplace of the first West Norse member of the Varangian Guard, Bolli Bollasson. Other historical people who lived in the area according to the saga include Guðrún Ósvífursdóttir, Bolli Þorleiksson and Snorri the Goði.

Local fishing villages and small towns on the northern shore of Snæfellsnes include Arnarstapi, Hellnar, Rif, Ólafsvík, Grundarfjörður, Stykkishólmur and Búðardalur. Near Hellissandur is the tallest structure in western Europe, the Longwave Radio Mast at Hellissandur.

STOPS 3 - *Snæfellsjökull*

Snæfellsjökull (snow-fell glacier) is a 700,000-year-old stratovolcano with a glacier covering its summit in western Iceland. The name of the mountain is actually Snæfell, but it is normally called "Snæfellsjökull" to distinguish it from two other mountains with this name. It is situated on the most western part of the Snæfellsnes peninsula in Iceland. Sometimes it may be seen from the city of Reykjavík over the bay of Faxaflói, at a distance of 120 km.

The mountain is one of the most famous sites of Iceland, primarily due to the novel Journey to the Center of the Earth (1864) by Jules Verne, in which the protagonists find the entrance to a passage leading to the center of the earth on Snæfellsjökull. The mountain is included in the Snæfellsjökull National Park (Icelandic: Þjóðgarðurinn Snæfellsjökull). In August 2012 the summit was ice-free for the first time in recorded history.

The stratovolcano, which is the only large central volcano in its part of Iceland, has many pyroclastic cones on its flanks. Upper-flank craters produced intermediate to felsic materials, while lower-flank craters produced basaltic lava flows. Several holocene eruptions have originated from the summit crater and have produced felsic material.[1] The latest eruption took place 200 AD ± 150 years, and erupted approximately 0.11 cubic kilometres (0.026 cu mi) worth of volcanic material. The eruption was explosive and originated from the summit crater, and may have produced lava flows.[5]

Snæfellsjökull National Park is Iceland's only National Park to extend to the seashore.[6] The park covers an area of 170 km² (65 sq. miles). The Park's southern boundary reaches to Háahraun in the region of Dagverðará while the northern part reaches to Gufuskálar. The coast is varied and alive with birdlife during the breeding season. The coastal plain is mostly covered by lava that flowed from the glacier or nearby craters. The lava is covered with moss but sheltered hollows can be found in many places, filled with a sizable variety of thriving, verdant plants. Snæfellsjökull has trails of lava and signs of volcanic activity clearly visible on its flanks. On its north side the Eysteinsdalur valley cuts a path up from the plain encircled by alluring steep mountains.

The geology of Snæfellsnes Peninsula is diverse with formations from almost every era of Iceland's past. The more prominent formations in and around the National Park mainly date from geologically "modern" times back to the last ice age. The hills to the north of the glacier, around Bárðarkista, are of volcanic palagonite tuff, formed during eruptions under the glacier or below the surface of the sea. Svalþúfa is most likely the eastern section of a crater that erupted under the sea, while Lóndrangar is a volcanic plug.

Lava is prominent on the landscape of this National Park with two types present – rough, jagged lava ('A'ā) and smooth, ropy lava (Pahoehoe). Most of the lava emanated from the glacier, from the summit crater or from subsidiary craters on the flanks of the mountain. These lava formations are varied and fascinating, and there is a wealth of caves in the area. Visitors are advised not to enter caves unless accompanied by an experienced guide. Smaller volcanoes – Purkhólar, Hólahólar, Saxhólar and Öndverðarneshólar – are in the Park's lowlands, surrounded by lava.

Day 9: Sunday, March 13th, 2016 – Reykjavik and return home

Also this is daylight savings time, this not observed in Iceland but it should be noted.

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

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

2:30PM: Return the rental vehicles
3:00PM: Arrive at the airport
5:00PM: Boarding Icelandair Flight 645
7:30PM: Arrive in Dulles, Washington DC

Reykjavik

Contributed by Miki Nakajima, 2014 Caltech Enrichment Trip Iceland

History

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

Geography

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

Weather

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

Energy

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

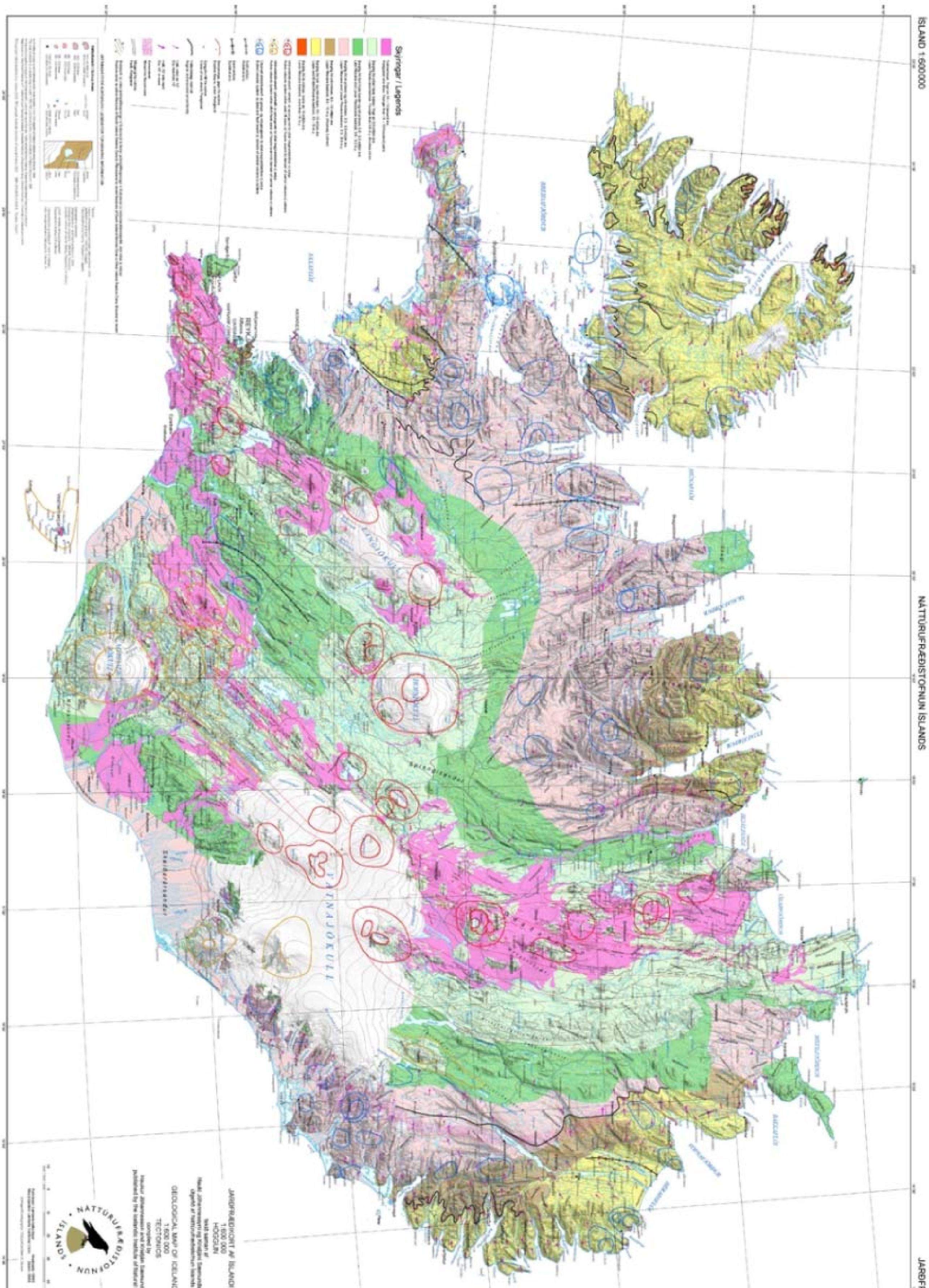
Places to visit

- ***The Blue Lagoon geothermal spa –*** the largest outdoor spa (5000 m2) and one of the most visited attractions in Iceland, located 20 minutes from Keflavik airport and 40 minutes from Reykjavik by car. It is an artificial lagoon and is fed by the water output of the geothermal power plant, Svartsengi. The water is rich in minerals (e.g. silica and sulfur) and the water temperature is controlled to 37-39°C (98-102°F). Facility hours: 9am-9pm, price: 40 EUR. Most crowded between 10am-2pm.
- ***Perlan –*** The building has been used to store hot water. It has large space for exhibition/dining/shopping. The restaurant on the highest floor has a great view of the city and rotates every two hours. The Saga museum exhibits the early history of Iceland.
- ***Hallgrimskirkja –*** a Lutheran parish church named after a poet in 17's century, Hallgrímur Pétursson. This is the largest church in Iceland (73 meters, 244 ft). State Architect Gudjón Samúelsson's designed this building in 1937 inspired by columnar jointed basalt. The statute is Leif Erikson, who found the North American continent 500 years before Christopher Columbus. The elevator inside of the church brings you up to top of the building where you can enjoy the great view of the city.
- ***Höfdi –*** a house initially built for the French consul Jean-Paul Brillouin in 1909. It is best known as the location for the 1986 Reykjavík Summit meeting of presidents Ronald Reagan and Mikhail Gorbachev to take a step to end the Cold War.
- ***Bæjarins Beztu Pylsur (4 stores in/near Reykjavik) –*** a small chain of popular hot dog stands in Reykjavik. The British newspaper The Guardian selected this chain as the best hot dog stand in Europe in 2006. A number of celebrities have visited, including Bill Clinton, James Hetfield, and Charlie Sheen.
- ***More –*** Tjörnin (lake), Sun Voyager (Viking monument based on the myth), Laugardalur (spa)[9]

References & Further Reading

[1] *Reykjavik* http://en.wikipedia.org/wiki/Reykjav%C3%ADk
[2] *Iceland,* Lonely planet, 7th edition
[3] *ECTOS, project* http://www.global-hydrogen-busplatform.com/InformationCentre/PhotoGallery
[4] *Blue Lagoon* http://en.wikipedia.org/wiki/Blue_Lagoon_(geothermal_spa)
[5] *Perlan* http://www.barth.com/iceland/reykjavik/pages/dsc_3068.htm
[6] *Hallgrimskirkja* http://en.wikipedia.org/wiki/Hallgr%C3%ADmskirkja
[7] *Höfdi* http://en.wikipedia.org/wiki/H%C3%B6f%C3%B0i
[8] *Bæjarins Beztu Pylsur* http://en.wikipedia.org/wiki/B%C3%A6jarins_Beztu_Pylsur
[9] *Sun Voyage* http://pilgrimito.com/sun-voyager-reykjavik
[10] *Laugardalur* http://www.holidaym.ru/iceland/gid_laugardalur_valley.php

GEOLOGIC MAP OF ICELAND



THINGS YOU SHOULD BRING

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

Most Important:
• Passport

Personal Items:
• Tissues
• Sunscreen
• Lip balm with sunscreen
• Sunglasses
• Toiletries
• Van/Plane Entertainment (iPod, books, cards, small board games, etc.)
• Travel Towel (however, I contacted the hostels and they will have towels and linens for us, so only bring it if you need to)

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

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

BUDGET INFORMATION

(as of 02/20/16)

Total Money collected once everyone has paid balance: **$12,900**

Cost of plane flights ($621 x 9)	**$5,590**
Total cost of lodging	**$2,625**
Vehicles (2 - 5 passenger light SUV)	**$1,200**
Ferry to Heimaey	**$596**
Tour of Hellsheidi Geothermal Power Plant	**$182**
Total Expenditures so far	**$10,193**
Funds Remaining	**$2,707**

Estimation of gas costs **$1000**
Hopefully gas prices are falling there too!

Remaining funds for food **$1,707**

or ~$23.50 per person per day
based on the 9 people and the 8
days on the ground in Iceland

BOOKING RECEIPTS

Order confirmed - Sadcars

info@sadcars.com

Thu 12/10/2015 2:51 PM

To:Kerrigan, Ryan <kerrigan@pitt.edu>;

DEAR MR RYAN KERRIGAN

Congratulations!
Your reservation has now been placed.

Your reservation details
Booking reference: **#50347**
Booked on: **2015/12/10 19:50**

Your details:
Name: **Mr Ryan Kerrigan**
Street address: **810 13th St**
City: **Windber**
Country: **USA**
Postcode: **15963**
Email: **kerrigan@pitt.edu**
Mobile phone: **612-229-6810**
Optional message: **Yes, this is the second car. Our group is 9 people total. I would to rent two of the RAV4 vehicles. Thanks!**

Travel information:
Collection Date/Time: **06/03/2016 08:00**
Collection Location: **Keflavík Airport Bogatröð 2 235 Reykjanesbær**
Return Date/Time: **13/03/2016 15:45**
Return Location: **Keflavík Airport Bogatröð 2 235 Reykjanesbær**
Flight number: **FI644**
Flight time: **06:30:00**

Vehicle information
Vehicle make/model: **Group N**

Totals:
Total price for car: **€ 584**
Optional extras:
- Extra driver:
€ 10
Discount:**€ -88**

Total price: **€ 506**
The reservation is fully paid and confirmed

Deposit:
Paid: **€ 506**
Card: **Mastercard**
Card Number: **XXXX-XXXX-XXXX-4505**

Order confirmed - Sadcars

info@sadcars.com

Thu 12/10/2015 2:47 PM

To:Kerrigan, Ryan <kerrigan@pitt.edu>;

DEAR MR RYAN KERRIGAN

Congratulations!
Your reservation has now been placed.

Your reservation details
Booking reference: **#50346**
Booked on: **2015/12/10 19:45**

Your details:
Name: **Mr Ryan Kerrigan**
Street address: **810 13th St**
City: **Windber**
Country: **USA**
Postcode: **15963**
Email: **kerrigan@pitt.edu**
Mobile phone: **612-229-6810**
Optional message:

Travel information:
Collection Date/Time: **06/03/2016 08:00**
Collection Location: **Keflavík Airport Bogatröð 2 235 Reykjanesbær**
Return Date/Time: **13/03/2016 15:45**
Return Location: **Keflavík Airport Bogatröð 2 235 Reykjanesbær**
Flight number: **FI644**
Flight time: **06:30:00**

Vehicle information
Vehicle make/model: **Group N**

Totals:
Total price for car: **€ 584**
Optional extras:
- Extra driver:
€ 10
- GPS Navigation system:
€ 80
Discount:**€ -88**

Total price: **€ 586**
The reservation is fully paid and confirmed

Deposit:
Paid: **€ 586**
Card: **Mastercard**
Card Number: **XXXX-XXXX-XXXX-4505**

Booking Details for Igdlo Guest House

Reference Number:	BB1512101473254
Date Of Booking:	10 Dec 2015
Check In Date:	06 Mar 2016
Check Out Date:	08 Mar 2016
Hotel Address:	Gunnarsbraut, 46, ., ., ., Iceland
Hotel Phone:	+354 5645555
Alternative Hotel Phone:	+354 5645555
Guest Name:	Ryan Kerrigan
Guest Email:	kerrigan@pitt.edu
Guest Phone:	612-229-6810
Guest Address:	810 13th St, Windber, PA, 15963, United States
Guest ETA:	02:00 PM
Guest Comments:	

Room 1: Family room / Family room

Ryan Kerrigan

4 adults, 0 child

Family room

Date	Rate	Inclusion
06 Mar 2016	€79	
07 Mar 2016	€79	

Room 2: Family room / Family room

Ryan Kerrigan

3 adults, 0 child

Family room

Date	Rate	Inclusion
06 Mar 2016	€79	
07 Mar 2016	€79	

Booking Summary

Accommodation:	€316
Grand Total:	€316

Prices are in EUR

Booking Details for Igdlo Guest House

Reference Number:	BB1512101473250
Date Of Booking:	10 Dec 2015
Check In Date:	06 Mar 2016
Check Out Date:	08 Mar 2016
Hotel Address:	Gunnarsbraut, 46, ., ., ., Iceland
Hotel Phone:	+354 5645555
Alternative Hotel Phone:	+354 5645555
Guest Name:	Ryan Kerrigan
Guest Email:	kerrigan@pitt.edu
Guest Phone:	612-229-6810
Guest Address:	810 13th St, Windber, PA, 15963, United States
Guest ETA:	02:00 PM
Guest Comments:	

Room 1: Single room / Single room

Ryan Kerrigan

1 adult, 0 child

Single room

Date	Rate	Inclusion
06 Mar 2016	€39	
07 Mar 2016	€39	

Room 2: Single room / Single room

Ryan Kerrigan

1 adult, 0 child

Single room

Date	Rate	Inclusion
06 Mar 2016	€39	
07 Mar 2016	€39	

Booking Summary

Accommodation:	€156
Grand Total:	€156

Prices are in EUR

EIMSKIP

Confirmation

You have booked the following trip:

Booking code: 677876

Password: FCQL
This password is valid only to log in to this booking. Registered users can log in using their own password and review all their current bookings

Þorlákshöfn - Vestmannaeyjar
Herjolfur

Departs:	11:45 07/03/2016
Arrives:	14:30 07/03/2016

Passengers:	
9 Adults	ISK 30780.00
Vehicles	
1 Car less than 5 m lower than 2.15m	ISK 3420.00
1 Car less than 5 m lower than 2.15m	ISK 3420.00
Total for journey:	ISK 37620.00

Vestmannaeyjar - Þorlákshöfn
Herjolfur

Departs:	15:30 08/03/2016
Arrives:	18:15 08/03/2016

Passengers:	
9 Adults	ISK 30780.00
Vehicles	
1 Car less than 5 m lower than 2.15m	ISK 3420.00
1 Car less than 5 m lower than 2.15m	ISK 3420.00

Total for journey:	ISK 37620.00

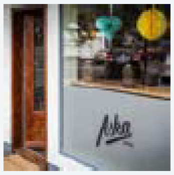
Total price: ISK 75240.00
ISK 0.00

Thank you for traveling with us!

Booking.com

Booking Confirmation

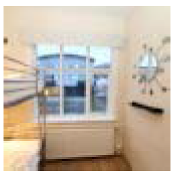
BOOKING NUMBER: 185.212.161 PIN CODE: 1415



Aska Hostel

Address: Bárustígur 11, 900 Vestmannaeyjar, Iceland
Phone: +354 662 7266
GPS Coordinates: N 063° 26.465, W 20° 16.132

CHECK-IN	CHECK-OUT	ROOMS / NIGHTS	PRICE
7 MARCH *Monday* 2:00 PM - 10:00 PM	8 MARCH *Tuesday* 8:00 AM - 12:00 PM	9 / 1	approx. **$379** 9 dorm beds 11 % VAT € 0.70 City tax per night Options € 0



Bed in 5-Bed Dormitory Room

Guest name: Tyler Norris / for max. 1 person.
Meal plan: There is no meal option with this room.

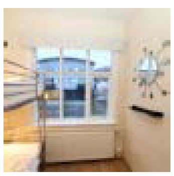
Shared bathroom • Heating • Shared toilet • Towels/Sheets (extra fee) • Wardrobe/Closet • Clothes rack

Bed Size(s): Twin (35-51 inches wide), Full (52-59 inches wide), Bunk beds ().

$25 € 22
Dorm bed
11 % VAT is included.
€ 0.70 City tax per night is included.

Prepayment :
15 percent of the total amount may be charged anytime after booking.

Cancellation cost:
until March 3, 2016 11:59 PM [Vestmannaeyjar] : € 3.30
from March 4, 2016 12:00 AM [Vestmannaeyjar] : € 22
This reservation cannot be canceled free of charge.



Bed in 5-Bed Dormitory Room

Guest name: Matthew Leger / for max. 1 person.
Meal plan: There is no meal option with this room.

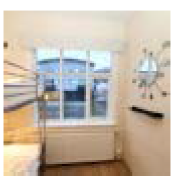
Shared bathroom • Heating • Shared toilet • Towels/Sheets (extra fee) • Wardrobe/Closet • Clothes rack

Bed Size(s): Twin (35-51 inches wide), Full (52-59 inches wide), Bunk beds ().

$25 € 22
Dorm bed
11 % VAT is included.
€ 0.70 City tax per night is included.

Prepayment :
15 percent of the total amount may be charged anytime after booking.

Cancellation cost:
until March 3, 2016 11:59 PM [Vestmannaeyjar] : € 3.30
from March 4, 2016 12:00 AM [Vestmannaeyjar] : € 22
This reservation cannot be canceled free of charge.



Bed in 5-Bed Dormitory Room

Guest name: Alexandra Marra / for max. 1 person.
Meal plan: There is no meal option with this room.

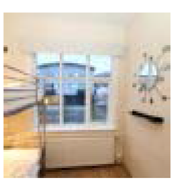
Shared bathroom • Heating • Shared toilet • Towels/Sheets (extra fee) • Wardrobe/Closet • Clothes rack

Bed Size(s): Twin (35-51 inches wide), Full (52-59 inches wide), Bunk beds ().

$25 € 22
Dorm bed
11 % VAT is included.
€ 0.70 City tax per night is included.

Prepayment :
15 percent of the total amount may be charged anytime after booking.

Cancellation cost:
until March 3, 2016 11:59 PM [Vestmannaeyjar] : € 3.30
from March 4, 2016 12:00 AM [Vestmannaeyjar] : € 22
This reservation cannot be canceled free of charge.



Bed in 5-Bed Dormitory Room

Guest name: Luke Layton / for max. 1 person.
Meal plan: There is no meal option with this room.

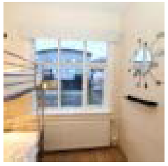
Shared bathroom • Heating • Shared toilet • Towels/Sheets (extra fee) • Wardrobe/Closet • Clothes rack

Bed Size(s): Twin (35-51 inches wide), Full (52-59 inches wide), Bunk beds ().

$25 € 22
Dorm bed
11 % VAT is included.
€ 0.70 City tax per night is included.

Prepayment :
15 percent of the total amount may be charged anytime after booking.

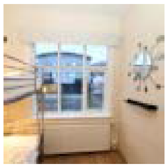
Cancellation cost:
until March 3, 2016 11:59 PM [Vestmannaeyjar] : € 3.30
from March 4, 2016 12:00 AM [Vestmannaeyjar] : € 22
This reservation cannot be canceled free of charge.



Bed in 5-Bed Dormitory Room

Guest name: Lorin Simboli / for max. 1 person.
Meal plan: There is no meal option with this room.
Shared bathroom • Heating • Shared toilet • Towels/Sheets (extra fee) • Wardrobe/Closet • Clothes rack
Bed Size(s): Twin (35-51 inches wide), Full (52-59 inches wide), Bunk beds ().

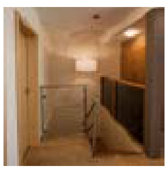
$25 € 22
Dorm bed
11 % VAT is included.
€ 0.70 City tax per night is included.
Prepayment :
15 percent of the total amount may be charged anytime after booking.
Cancellation cost:
until March 3, 2016 11:59 PM [Vestmannaeyjar] : € 3.30
from March 4, 2016 12:00 AM [Vestmannaeyjar] : € 22
This reservation cannot be canceled free of charge.



Bed in 5-Bed Dormitory Room

Guest name: Catherine Bert / for max. 1 person.
Meal plan: There is no meal option with this room.
Shared bathroom • Heating • Shared toilet • Towels/Sheets (extra fee) • Wardrobe/Closet • Clothes rack
Bed Size(s): Twin (35-51 inches wide), Full (52-59 inches wide), Bunk beds ().

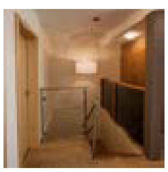
$25 € 22
Dorm bed
11 % VAT is included.
€ 0.70 City tax per night is included.
Prepayment :
15 percent of the total amount may be charged anytime after booking.
Cancellation cost:
until March 3, 2016 11:59 PM [Vestmannaeyjar] : € 3.30
from March 4, 2016 12:00 AM [Vestmannaeyjar] : € 22
This reservation cannot be canceled free of charge.



Twin Room with Shared Bathroom

Guest name: Teresa McConnell / for max. 1 person.
Meal plan: There is no meal option with this room.
Radio • Shared bathroom • Heating • Shared toilet • Sea view • Garden view • Mountain view • Towels • Linens • Clothes rack
Bed Size(s): Twin (35-51 inches wide)

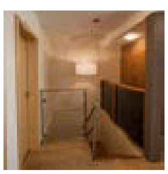
$77 € 67.50
Dorm bed
11 % VAT is included.
€ 0.70 City tax per night is included.
Prepayment :
The total price of the reservation may be charged anytime after booking.
Cancellation cost: € 67.50
This reservation cannot be canceled free of charge.



Twin Room with Shared Bathroom

Guest name: Steven Lindberg / for max. 1 person.
Meal plan: There is no meal option with this room.
Radio • Shared bathroom • Heating • Shared toilet • Sea view • Garden view • Mountain view • Towels • Linens • Clothes rack
Bed Size(s): Twin (35-51 inches wide)

$77 € 67.50
Dorm bed
11 % VAT is included.
€ 0.70 City tax per night is included.
Prepayment :
The total price of the reservation may be charged anytime after booking.
Cancellation cost: € 67.50
This reservation cannot be canceled free of charge.



Twin Room with Shared Bathroom

Guest name: Ryan Kerrigan / for max. 1 person.
Meal plan: There is no meal option with this room.
Radio • Shared bathroom • Heating • Shared toilet • Sea view • Garden view • Mountain view • Towels • Linens • Clothes rack
Bed Size(s): Twin (35-51 inches wide)

$77 € 67.50
Dorm bed
11 % VAT is included.
€ 0.70 City tax per night is included.
Prepayment :
The total price of the reservation may be charged anytime after booking.
Cancellation cost: € 67.50
This reservation cannot be canceled free of charge.

Hotel policies

Guest parking
- Free private parking is available at a location nearby (reservation is not needed).

Internet
- WiFi is available in public areas and is free of charge.

Special Requests

" Approximate time of arrival: between 02:00 and 03:00 hours
You have a booker that prefers communication by email"

Booking Details for Igdlo Guest House

Reference Number:	BB1512101473265
Date Of Booking:	10 Dec 2015
Check In Date:	11 Mar 2016
Check Out Date:	13 Mar 2016
Hotel Address:	Gunnarsbraut, 46, ., ., ., Iceland
Hotel Phone:	+354 5645555
Alternative Hotel Phone:	+354 5645555
Guest Name:	Ryan Kerrigan
Guest Email:	kerrigan@pitt.edu
Guest Phone:	612-229-6810
Guest Address:	810 13th St, Windber, PA, 15963, United States
Guest ETA:	02:00 PM
Guest Comments:	

Room 1: Single room / Single room

Ryan Kerrigan

1 adult, 0 child

Single room

Date	Rate	Inclusion
11 Mar 2016	€39	
12 Mar 2016	€39	

Room 2: Single room / Single room

Ryan Kerrigan

1 adult, 0 child

Single room

Date	Rate	Inclusion
11 Mar 2016	€39	
12 Mar 2016	€39	

Booking Summary

Accommodation:	€156
Grand Total:	€156

Prices are in EUR

Please retain this for your reference
Prices are in EUR

Booking Details for Igdlo Guest House

Reference Number:	BB1512101473268
Date Of Booking:	10 Dec 2015
Check In Date:	11 Mar 2016
Check Out Date:	13 Mar 2016
Hotel Address:	Gunnarsbraut, 46, ., ., ., Iceland
Hotel Phone:	+354 5645555
Alternative Hotel Phone:	+354 5645555
Guest Name:	Ryan Kerrigan
Guest Email:	kerrigan@pitt.edu
Guest Phone:	612-229-6810
Guest Address:	810 13th St, Windber, PA, 15963, United States
Guest ETA:	02:00 PM
Guest Comments:	

Room: Twin room / Twin room

Ryan Kerrigan

1 adult, 0 child

Twin room Two Single Beds Weekly Room Service

Date	Rate	Inclusion
11 Mar 2016	€49	
12 Mar 2016	€49	

Booking Summary

Accommodation:	€98
Grand Total:	€98

Prices are in EUR

Please refer to the Payment Policy below for information about the processing of your payment

Terms and Conditions

Payment Policy

Payment on arrival unless otherwise stated.

Booking Details for Igdlo Guest House

Reference Number:	BB1512101473270
Date Of Booking:	10 Dec 2015
Check In Date:	11 Mar 2016
Check Out Date:	13 Mar 2016
Hotel Address:	Gunnarsbraut, 46, ., ., ., Iceland
Hotel Phone:	+354 5645555
Alternative Hotel Phone:	+354 5645555
Guest Name:	Ryan Kerrigan
Guest Email:	kerrigan@pitt.edu
Guest Phone:	612-229-6810
Guest Address:	810 13th St, Windber, PA, 15963, United States
Guest ETA:	02:00 PM
Guest Comments:	

Room 1: Family room / Family room

Ryan Kerrigan

3 adults, 0 child

Family room

Date	Rate	Inclusion
11 Mar 2016	€79	
12 Mar 2016	€79	

Room 2: Family room / Family room

Ryan Kerrigan

3 adults, 0 child

Family room

Date	Rate	Inclusion
11 Mar 2016	€79	
12 Mar 2016	€79	

Booking Summary

Accommodation:	€316
Grand Total:	€316

Prices are in EUR

LAST YEAR'S SPRING BREAK GROUP

SPRING BREAK 2015 – NORTH CAROLINA

Picture taken at Ray Mine Pegmatite mine, Spruce Pine, NC
Left to Right: Kris Miller, Luke Layton, Leah Marko, Andrew Barchowsky, Matt Gerber, and Ryan Kerrigan