

Department of Earth & Environmental Sciences

Iceland field guide

DEES Graduate Student Field Trip



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Front page photo: Fjallsjökull glacial tongue, Vatnajökull ice cap (credit N. Zakharova)

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Preface

Iceland is a unique place to study a great variety of geologic and climate-driven processes, and to observe how interactions between these processes create unusual and diverse environments. High rates of volcanic activity, crustal deformation, rapid erosion, interplay of glacial and volcanic forces, and dramatic climate effects make Iceland an attractive destination for a wide range of Earth scientists.

This guide is based on the Columbia University graduate student field trip to Iceland in August 2010 (Fig. 1). It was made possible by the Storke Memorial Fund, designated to support educational activities at Lamont-Doherty Earth Observatory, Columbia University. The participants on this trip consisted of Ph.D. students in the Earth and Environmental Sciences and Master students from the Climate and Society Program. This group of students represented a full spectrum of sub-disciplines, which allowed us to cover a wide variety of scientific topics including geophysics, tectonics, seismicity, volcanism, petrology, geothermal power generation and carbon sequestration, glaciology, climate and ecology as well as how these have shaped Icelandic culture and history.

A student-led seminar series based on extensive literature reviews was a critical component of the preparation for this field trip. Each of the participants presented a topic of interest to the rest of the group. The seminar laid a good foundation for our field studies and helped to foster the discussion of various features and phenomena we observed in the field. The seminar also provided a basis for general overviews included in this guide.

This guide summarizes the amazing field experience and the information we learned before, during, and after the trip. In addition to the broad overviews of Icelandic geology, ecology, etc., the guide also contains detailed day itineraries, trip expenses, and dinner menus. We hope that this will be useful in planning future trips to wonderful and beautiful country of Iceland.

Trip Itinerary

DAY 1 - August 19th, 2010:

- Arriving to Keflavík early in the morning
- Exploring Reykjanestá
- Visiting Blue Lagoon
- Camping in Reykjavík

DAY 2 - August 20th, 2010:

- Exploring Hellisheiði power plant and CO₂ sequestration site
- Hiking Raufarhólshellir lava tube
- Exploring Þingvellir National Park and camping there

DAY 3 - August 21st, 2010:

- Visiting Geysir and Gulfoss
- Driving to Eyjafjallajökull and camping in Thosmork

DAY 4 - August 22nd, 2010:

- Long hike to Eyjafjallajökull
- Driving to Skaftafell and camping

DAY 5 - August 23rd, 2010:

- Glacial hike on Öræfajökull
- Short hike to Svartifoss
- Camping in Skaftafell

DAY 6 - August 24th, 2010:

- Visit Jökulsarlón glacial lagoon
- Explore glacial features of Skaftafell
- Camping in Skaftafell

DAY 7 - August 25th, 2010:

- Driving through eastern Iceland (fjords)
- Stop at Petra mineral museum
- Arriving to Mývatn and camping there

DAY 8 - August 26th, 2010:

- Exploring Krafla caldera and Leirhjúkur geothermal vents
- Hiking in Dimmuborgir lava lake
- Hiking up the Hverfjall tephra cone
- Bathing in Mývatn Nature Baths
- Camping by Mývatn

DAY 9 - August 27th, 2010:

- Transfer to Reykjavík - driving through central Iceland
- Stop in Akureyri
- Stop at Goðafoss
- Stop at Kjölur hot springs
- Camping in Reykjavík

DAY 10 - August 28th, 2010:

- Exploring Reykjavík
- Flying home in the afternoon

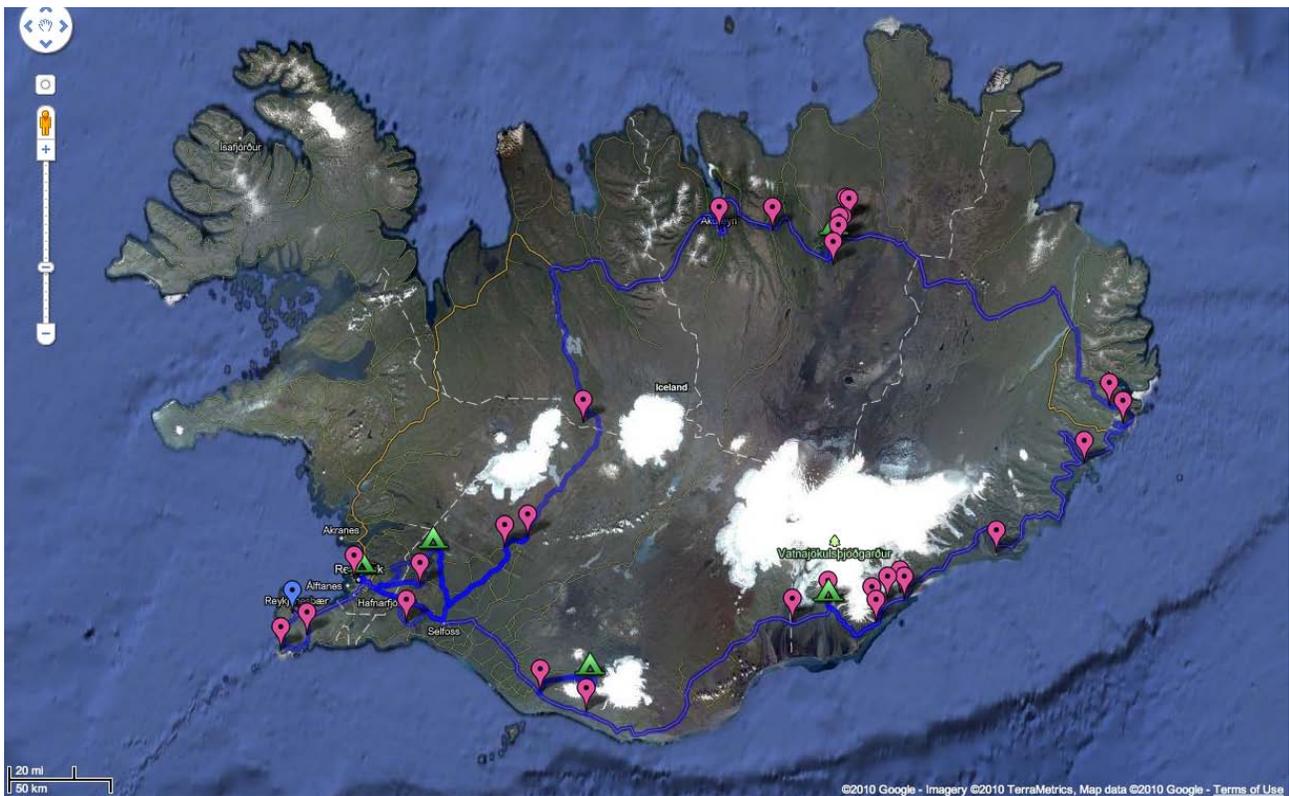


Figure 1. Schematic route of the trip and major sites visited.

Introduction

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°24'N and 66°33'N and between longitudes 13°30'W and 24°32'W. The closest countries are Greenland (286 km), Scotland (795 km), and Norway (950 km). The total area of Iceland is 103,000 km² (39,756 mi²), which is about the size of Kentucky. The distance from the north to south coast is approximately 300 km (185 mi) and from east to west is approximately 500 km (305 mi). The coastline is 4,970 km long. The average elevation of Iceland is 500 m above sea level with the highest point being Hvannadalshnukur at 2,119 m (6,950 ft) on the Öraefajökull 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° C (51° F) in July, with average highs of 24.3° C (76° F). The average winter temperature in Reykjavík is about 0° C (32° F) in January. In general, the southern and western lowland coastal areas enjoy milder temperatures than the central highlands due to the warm waters of the Gulf Stream. The annual precipitation varies from 3,000 mm on the south coast to 400 mm in the highlands. Coastal areas tend to be windy especially in winter.

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

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

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

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

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

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Geologic Overviews

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 features¹. At least 21 of the 30–50 identified present-day hot spots appear to be interacting with mid-ocean ridges². 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 mantle³. 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

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 $^{87}\text{Sr}/^{86}\text{Sr}$ and $^3\text{He}/^4\text{He}$ 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.

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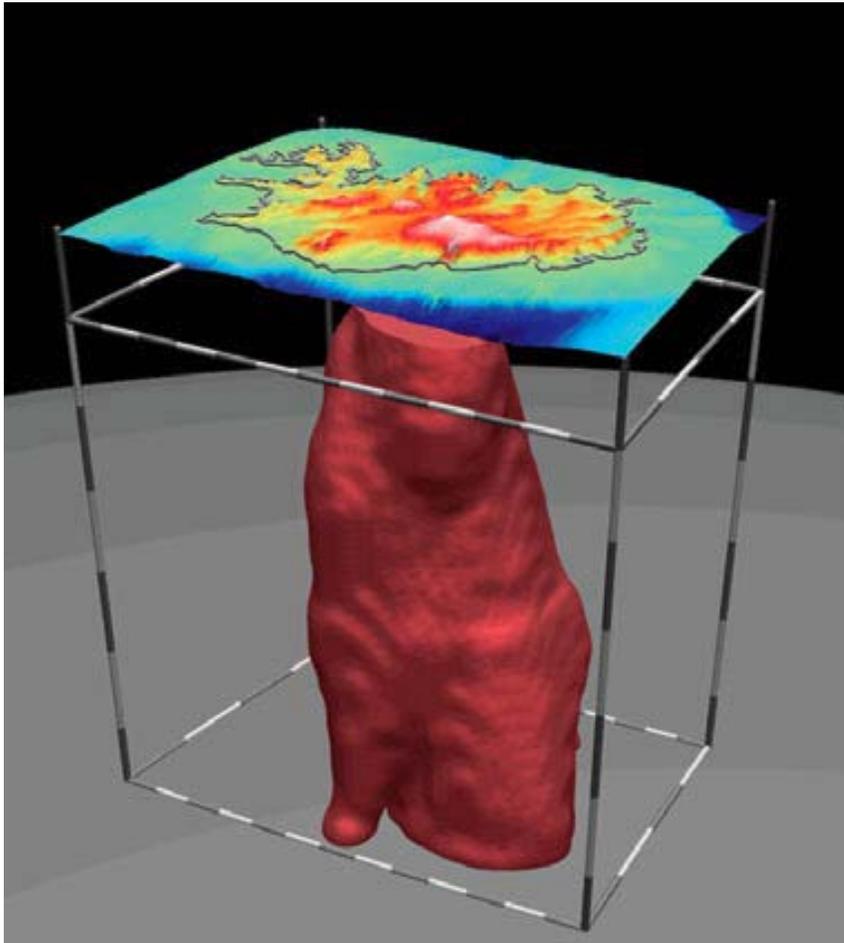


Figure 2. Seismic image of the upper mantle beneath the Iceland hotspot (Wolfe et al, 1997).

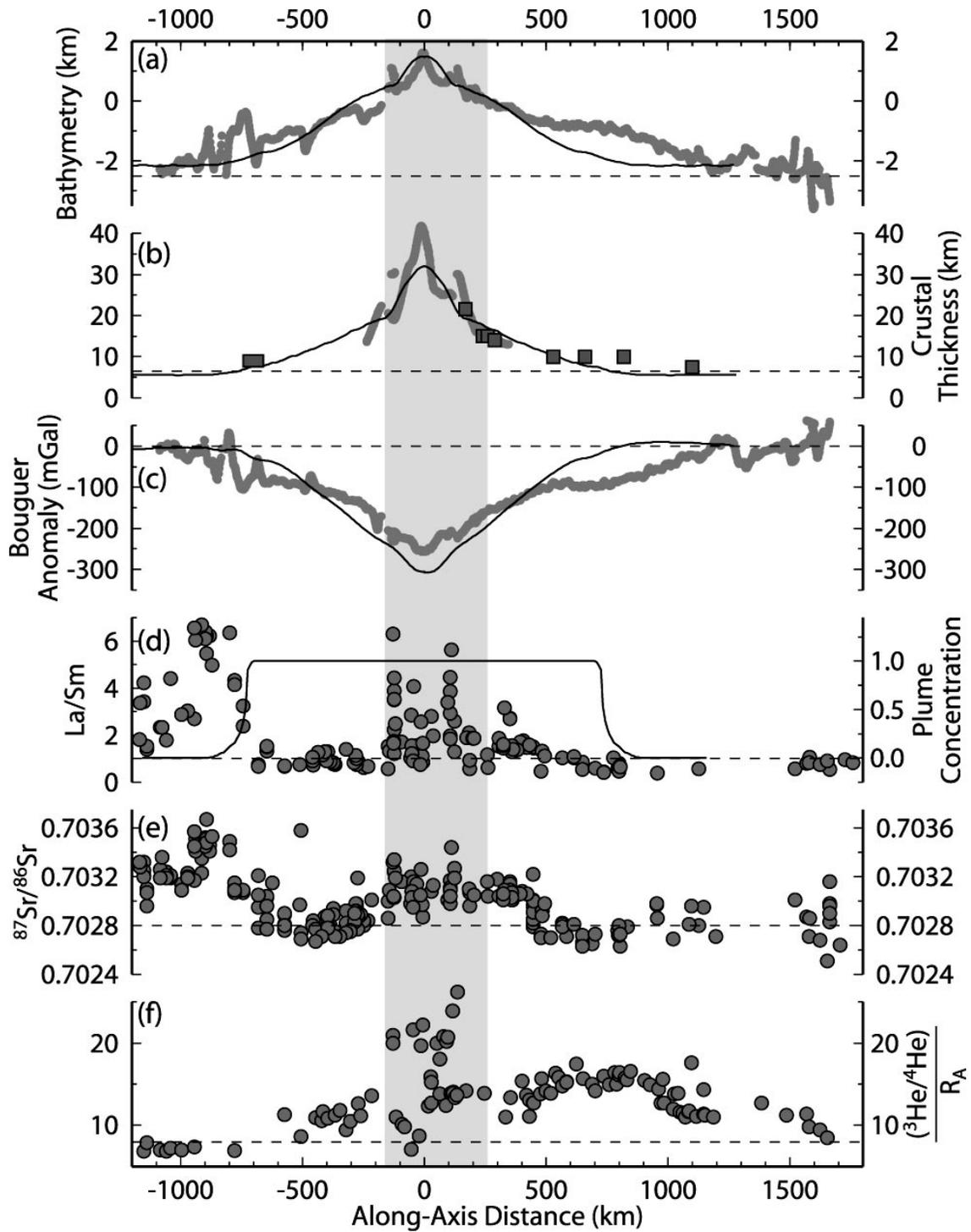


Figure 3. Profiles along the Mid-Atlantic ridge centered on Iceland of (a) bathymetry, (b) crustal thickness, (c) Bouguer gravity, (d) La/Sm ratio, (e) $^{87}\text{Sr}/^{86}\text{Sr}$ ratio, and (f) $^3\text{He}/^4\text{He}$ normalized by atmospheric ration. Form Ito et al (2003).

Seismicity

Contributed by Pritwiraj Moulik

The relative motion of the MAR ridge (spreading ~ 18 mm/yr at 105° 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 anelastic 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 Iceland⁷. 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 rifting⁸, 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 swarm⁹. 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, Bárðarbunga 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 Bárðarbunga with magmatic activity at Krafla¹⁰, 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 Bárðarbunga caldera¹¹.

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 tectonics¹⁰. 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) project¹².

Apart from the usual seismicity associated with volcanic zones and transform fracture zones, the other types of observed seismicity in Iceland include some micro-earthquakes 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 edge¹⁰. 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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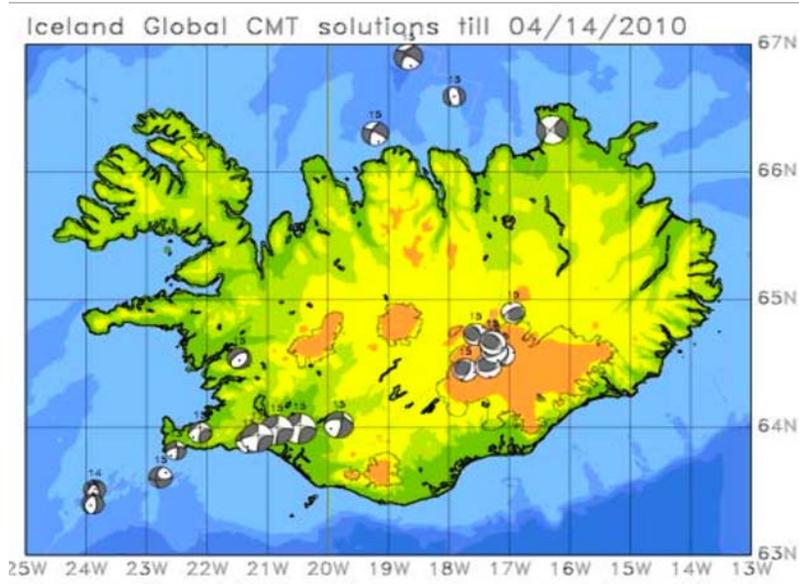


Figure 4. Iceland Global CMT solutions until 04/14/2010.

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 processes¹. 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 period². Active volcanism, which occurs over ~30% of the area of Iceland, is concentrated along zones of neovolcanic rifting and two off-axis intraplate volcanic zones³ (Fig. 5) [further discussion of volcanism in following section]. Although the majority of Icelandic lavas are basalts (~85%), rhyolites (~12%) and intermediate rocks (~3%) are present across the island, especially within large central volcanic complexes⁴. 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 erupted⁵. 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 $\text{Na}_2\text{O} + \text{K}_2\text{O}$ 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 \approx 33 km depth). Subalkaline rocks can be further subdivided into calc-alkaline and tholeiitic rocks, where tholeiites plot higher in FeO than calc-alkaline rocks on an alkali, FeO, MgO (AFM) ternary diagram⁶. 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 $^{87}\text{Sr}/^{86}\text{Sr}$ 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 Iceland⁷. 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 lavas⁷. Seismic indicators and geo-barometers, as well as the high incompatible abundances and isotope (especially $^3\text{He}/^4\text{He}$, 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 basalts¹². The recycled oceanic crust appears to consist of abundant but variable eclogites 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 ratio¹³. 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 alteration⁴. 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}.

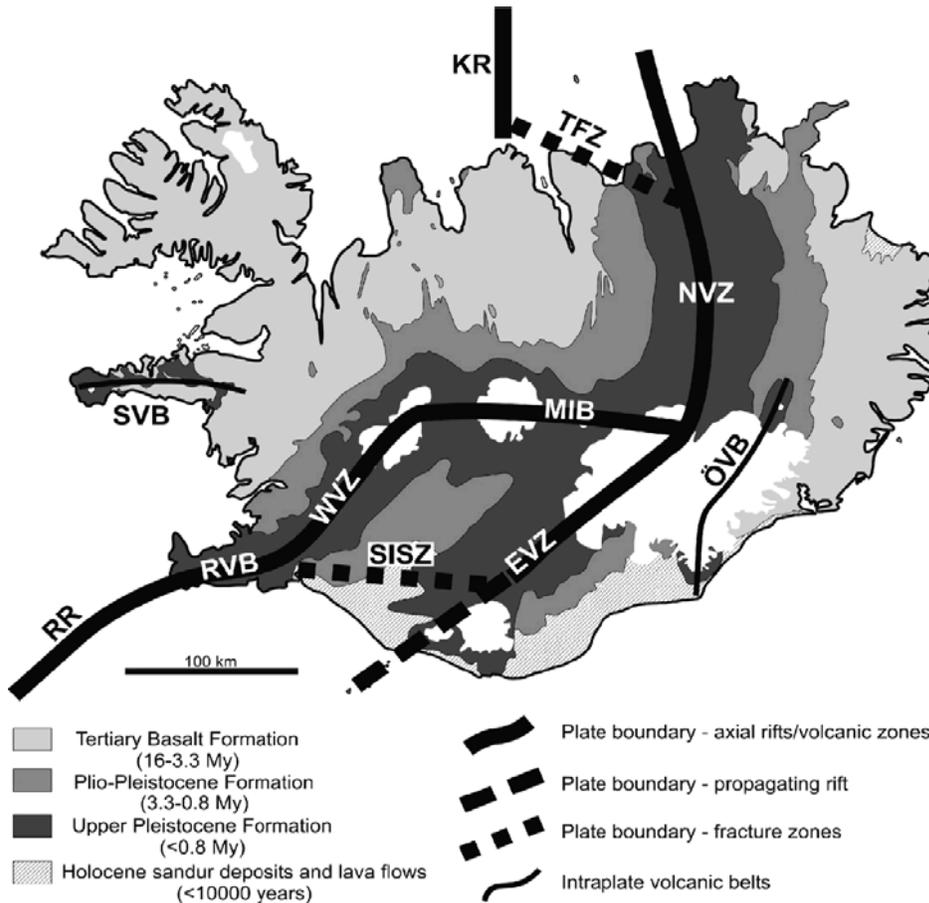


Figure 5. General Areas of Icelandic Volcanism (from Thordarson and Larsen, 2007).

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

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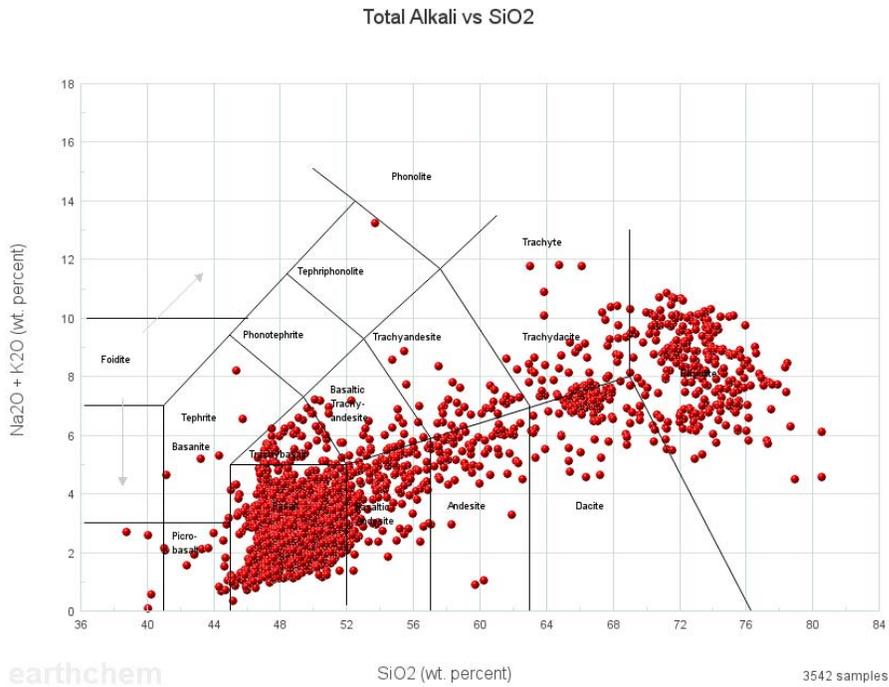


Figure 6. Classification and distribution of igneous rocks from Iceland (from Earthchem).

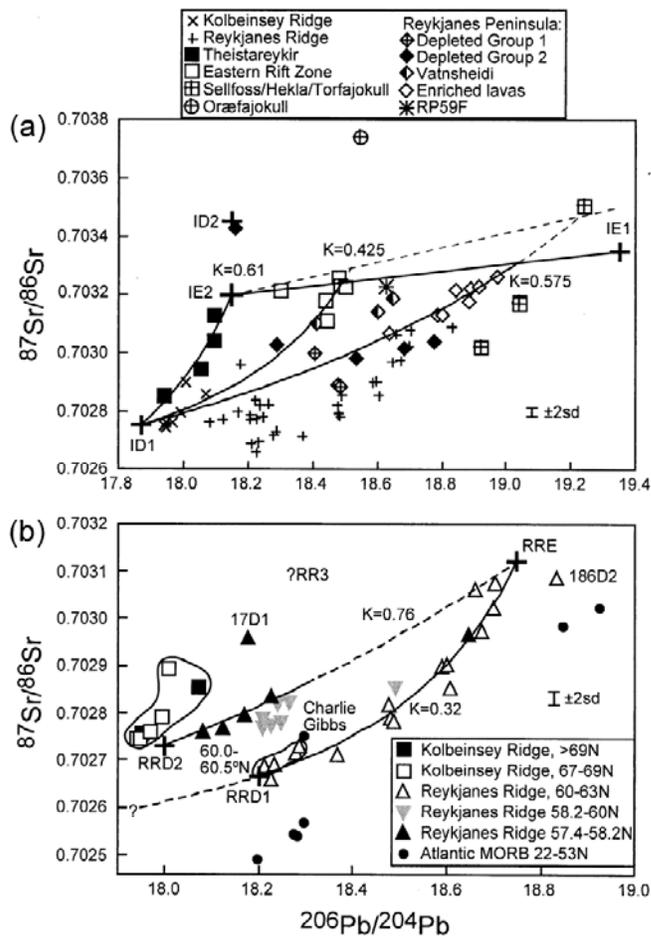


Figure 7. $^{206}\text{Pb}/^{204}\text{Pb}$ vs. $^{143}\text{Nd}/^{144}\text{Nd}$ showing mixing components for Icelandic magmas. Mixing endmembers include the enriched plume source IE1, a low Pb enriched endmember IE2, and the widespread depleted upper mantle endmember ID1. (from Thirwall et al., 2004).

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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 east-west 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, Bárðarbunga-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 Öraefi and Snæfellsness Volcanic Belts) that account for only ~1.5% of the verified eruptions in Iceland. Collectively, these regions cover ~30,000 km³ 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 systems¹⁷. Individual systems range in length from 7 to 200 km and 25 to 2500 km² 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 volcanoclastic 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 products¹². Note that approximately 80% of the 87 km³ 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 Bárðarbunga-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, Vatnajökull. 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. Bárðarbunga-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 Bárðarbunga-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 eruption²⁸. This seismicity suggests there is some degree of connectivity between the Bárðarbunga-Veidivötn and Grímsvötn volcanic systems.

Eyjafjallajökull, 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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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 H₂O, CO₂, SO₂, F, B, Cl etc.), metamorphic (H₂O, CO₂, CH₄ etc.) resulting from dehydration reactions during regional metamorphic events, connate (or water trapped in sediments), meteoric (groundwater, rainwater, river water), and seawater¹. 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 seawater³. 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 surface⁴. 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 yellow². 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 source⁵.

Fumaroles are openings in the Earth's crust that emit hot gases, such as steam, carbon dioxide, sulfur dioxide, hydrochloric acid, and hydrogen sulfide⁶. 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 intrusions⁶. 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 surface⁶. 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 forms⁷. The gases contained in hydrothermal fluids, such as SO₂ 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 silica⁴. 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 Park². 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 materials¹⁰.

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 geysers (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 are 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 projects¹. 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 Iceland¹.

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 turbines² that generate electricity. Flash steam plants emit small amounts of gasses that naturally occur in the underground reservoirs such as H₂S and CO₂. CarbFix, a project at the Hellisheiði Power Station seeks to re-inject the CO₂ underground where it mineralizes and is thus sequestered, potentially making the plant completely carbon neutral in the future [further discussion in the CO₂ Sequestration section]³. Examples of the single and double flash steam cycle plants can be found at Krafla, Hellisheiði, and Nesjavellir⁴.

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 attraction⁵. Other CHP plants include Hellisheiði and Nesjavellir, both of which provide heat and power to the greater Reykjavík area⁴.

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 fluid⁴.

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 CO₂ 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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CO₂ Sequestration

Contributed by Amelia Paukert

There is now near-universal acceptance in the scientific community of the anthropogenic contribution to global climate change. However, while it is generally acknowledged that emission of CO₂ to the atmosphere from burning fossil fuels is leading to global climate change, the drive to increase the standard of living in developing countries requires that, globally, we continue consuming energy at the current rate or higher. CO₂ sequestration offers a means of CO₂ disposal in order to allow continued development while minimizing the detrimental effects of CO₂ emissions.

Mineral sequestration, in particular, offers a permanent and safe storage mechanism for CO₂ through its conversion into carbonate minerals that are stable at the Earth's surface. The process combines divalent metal cations such as Ca and Mg with dissolved CO₂ to produce solid, environmentally benign minerals such as calcite, dolomite, and magnesite. Ca and Mg are obtained through dissolution of Ca and Mg-rich silicate minerals such as olivine, pyroxene, and Ca-rich plagioclase. These minerals are abundant in continental basalt and basaltic glass, such as that found on Iceland. The high concentration of Ca and Mg in basalt (7-10 weight % Ca and 5-6 weight % Mg) makes Iceland a prime location for mineral CO₂ sequestration.

Iceland's CarbFix project will be the first pilot project for *in situ* CO₂ mineral sequestration. Reykjavík Energy, in collaboration with Columbia University, University of Iceland, and CNRS in Toulouse, is planning to inject dissolved CO₂ into a basalt formation overlying the Hellisheiði geothermal field about 30 km from Reykjavík. The CO₂ will be derived from geothermal steam, which contains 1% geothermal gas with a

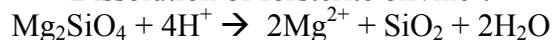
composition of 83% CO₂, 16% H₂S, and 1% combined CH₄, N₂, and H₂ ¹. The CO₂ will be separated out from the rest of the gas using a chiller and injected underground.

The injection site is located 3 km from the main Hellisheiði geothermal power plant. Water in which to dissolve the CO₂ is taken from a nearby well that taps local formation water. According to Hólmfríður Sigurðardóttir, CarbFix project manager, CO₂ will be injected with water to a depth of 550 m, where a dispersion mechanism will help mix the CO₂ into the water and prevent bubbles from rising. The injection area has a flat hydraulic gradient and relatively slow flow, so water will be pumped out of a nearby monitoring well to create space for the injected CO₂-saturated water. This should also help induce a pressure gradient toward the monitoring well and better enable scientists to track the flow of injected CO₂ in the subsurface.

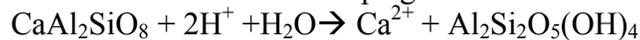
It may seem surprising that a geothermal power company would explore CO₂ sequestration, since CO₂ emissions due to geothermal energy production are much smaller than those of a coal-fired power plant. The Hellisheiði power plant is a 300 MW plant and produces only 60,000 tons of CO₂/year ²; 37 times less than a comparably sized coal-fired power plant ³. However, the CarbFix project embodies Reykjavík Energy's feeling of social responsibility, and of course, if the method works, Reykjavík Energy may be able to sell carbon offsets for CO₂ sequestered on site or market technology it develops in the process.

Reactions controlling the CO₂ mineralization process:

Dissolution of forsterite olivine¹:



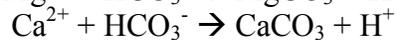
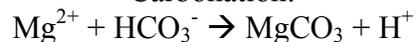
Dissolution of Ca-plagioclase¹:



Dissolution of CO₂ into water:



Carbonation:



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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 km². 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 km² (20,000 mi²) and are currently only found in Antarctica and Greenland¹. 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 mountain². 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 glacier². 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 widening³. 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 compression³, especially near valley walls and bends in the valley. A nunatak is a protrusion of rock that pokes through the surface of the glacier³. 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 time⁴.

A more recent tool, now widely applied to glacial moraines, is in-situ cosmogenic radionuclide dating. As cosmic rays bombard the atmosphere, ¹⁰Be, ²⁶Al, ³⁶Cl, ³He, ¹⁴C and many other radiogenic nuclides are produced on the surface of rocks⁵. 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 the 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 phases⁵.

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, respectively⁶. 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 south⁸.

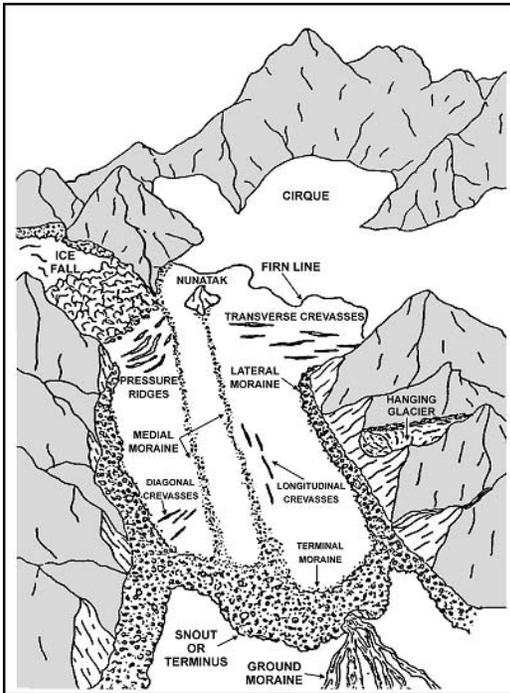


Figure 8. a) Description of features in map view of a glacier, most are mentioned above. a) Cross section of features through a glacier. Source: <http://www.mountain-survival.net/chp10.html>

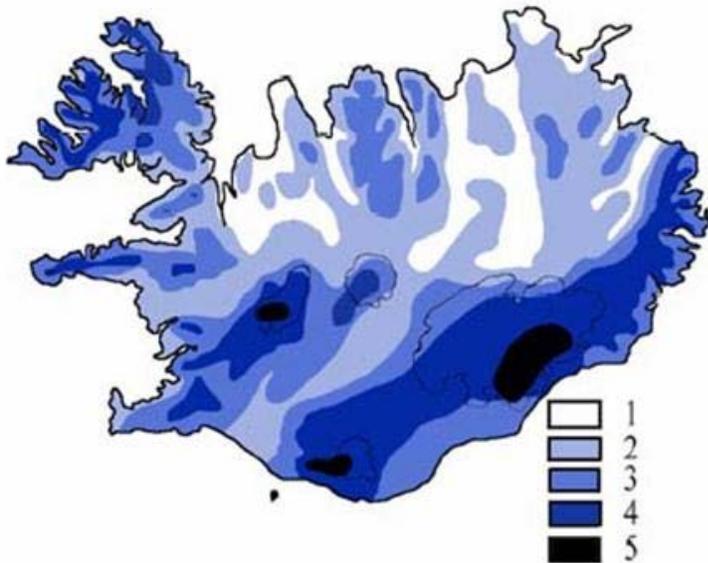
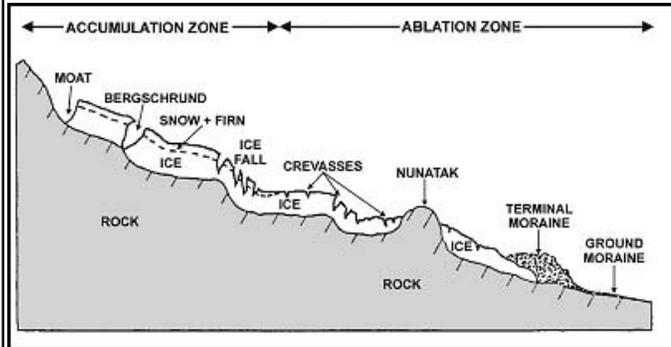


Figure 9. Mean annual precipitation in Iceland for the period 1931-1960: 1. < 600 mm; 2. 600 - 1199 mm; 3. 1200 - 1999 mm; 4. 2000 - 3999 mm and 5. > 4000 mm.

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

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 west⁴. 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 landscape⁴.

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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 km², 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 km² 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 km² 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 km². 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 the 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 ago². 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 rise². 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 post-glacial 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 coast². 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 kya³. 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 coastlines². 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 ky³.

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 cap⁵. Asthenospheric viscosity estimates under Iceland³ 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 productivity⁶. 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.

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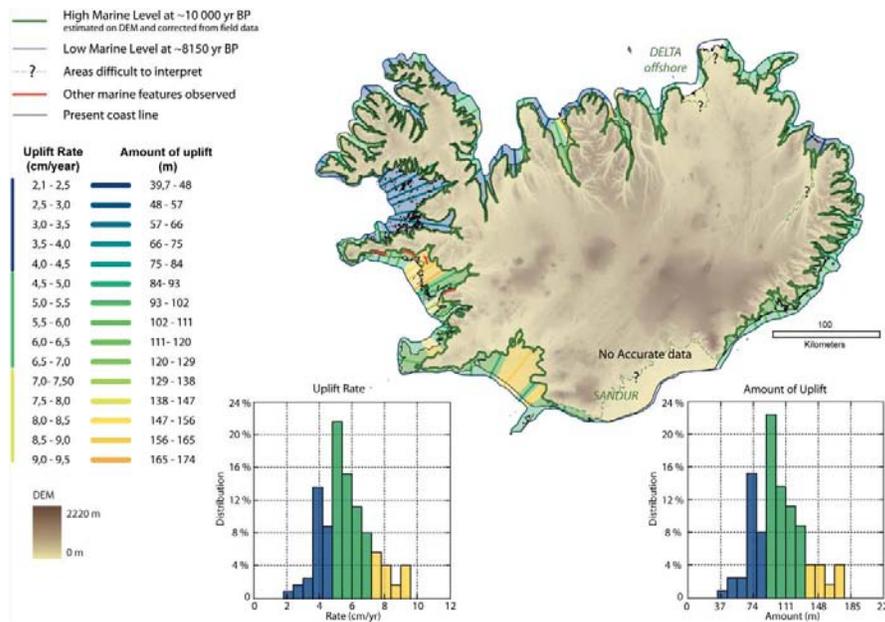


Figure 10. Amount and rate of uplift calculated between 10-8.2 kyr BP (from Le Breton et al., 2010).

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 instrumental 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

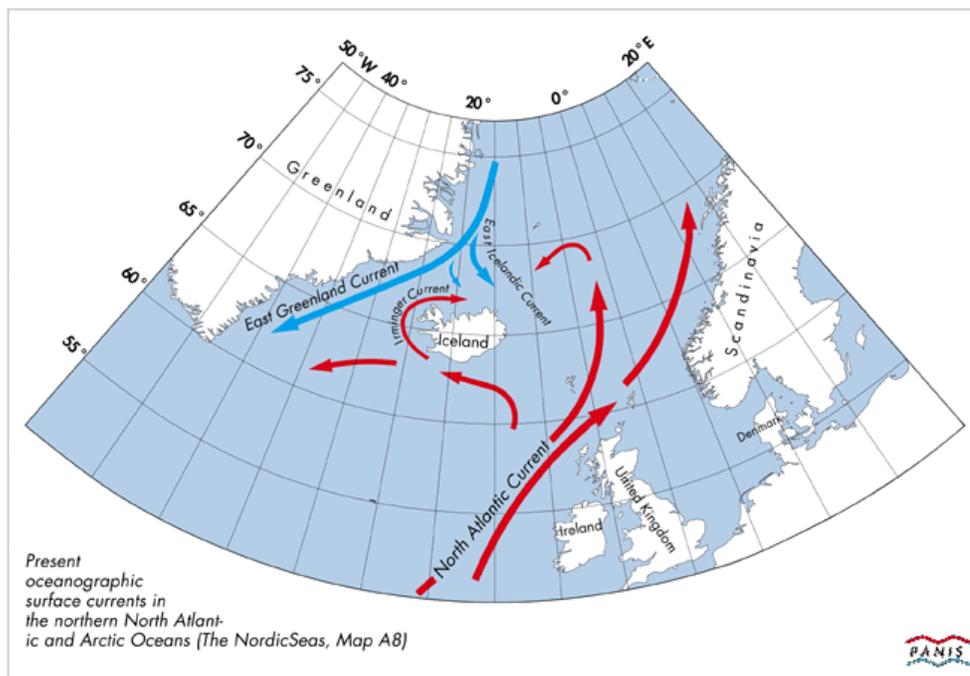


Figure 11. Present oceanographic surface currents around Iceland. Image source: http://www.hi.is/~jeir/panis_currents.html

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 elevation². Although most are rarely found in the country today, the Downy birch, rowan (*Sorbus aucuparia*), aspen (*Populus tremula*), and the tea-leaved willow (*Salix phylicifolia*) are considered to be the only the native Icelandic tree species¹. A sharp decline in woodlands coincides with colonization². 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% landcover³ 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 production².” 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 regrowth⁴. 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 well⁵.

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 factors⁶. 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 phenologies in the Arctic may have an impact on genetic diversity in soil seed banks, increased productivity or habitat expansion, and altered relationships with pollinators⁶.

References:

- ¹Eysteinnsson, Thröstur (2009). Forestry in a treeless land 2009. Updated from: Lustgården 2004: 27-34
- ²Arnalds, A. (1987) Ecosystem disturbance in Iceland. Arctic and Alpine Research 5, 185-189.
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- ⁵ Iceland Worldwide. (1998-2004). <http://www.iww.is/>.
- ⁶ Thrhallsdóttir, T.E. (1998). Flowering phenology in the central highland of Iceland and implications for climate warming in the Arctic. Oecologia, 114 (1), 43-49.

Vegetation in Iceland at present

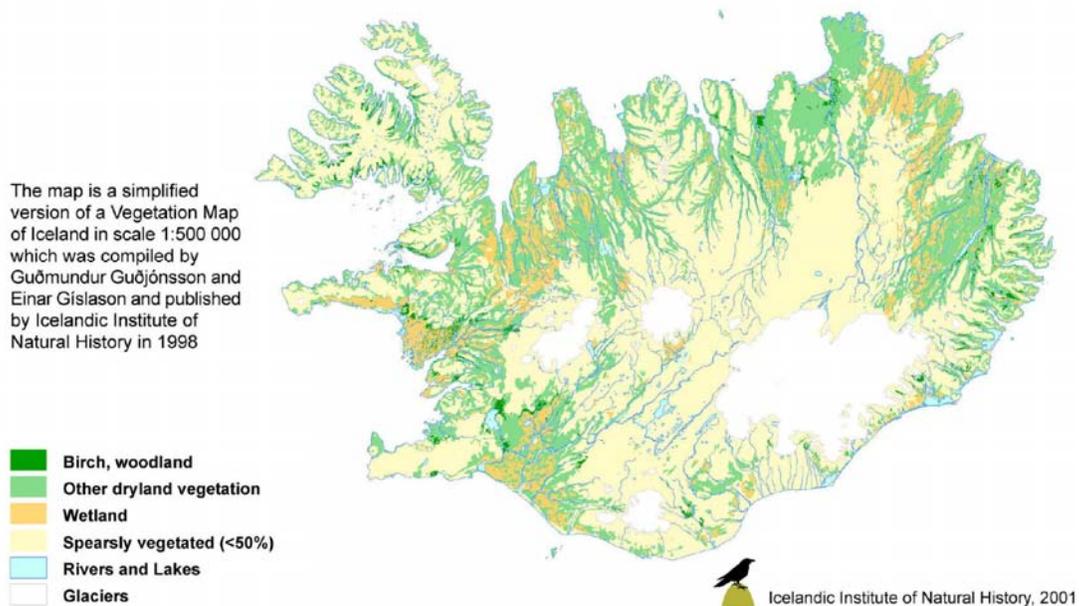


Figure 12. Vegetation in Iceland at present (from Icelandic Institute of Natural History, 2001).

Detailed Itinerary and Descriptions of Visited Sites

Day 0 (Wednesday, August 18th)

Contributed by Shuoshuo Han

17:00 EDT: Gather at 116th Street and Broadway. Get on the vans and drive to JFK.

18:30: Arrive at JFK Terminal 7.

20:35: Icelandair FI614 takes off.

Day 1 (Thursday, August 19th) - Reykjanes Peninsula

(Icelandic Time)

5:45: Icelandair FI614 arrives at Keflavík International Airport.

7:00: After clearing customs, met by Bryndis Brandsdóttir from Institute of Earth Sciences, University of Iceland and our bus driver. Drive to Reykjanes Peninsula.

7:20: Stop at Bridge between Two Continents near Sandvik. Bryndis Brandsdóttir talks about Mid Atlantic Ridge, the boundary between the North American Plate and the Eurasian Plate.

7:50: Breakfast at Valahnukur cliff. Check the contact between tuff and pillow lava.

9:40: Stop at Gunnhver hot spring. Bryndis introduces the geothermal activity in Reykjanes Peninsula.

10:20: Arrive at Blue Lagoon. Spend 4.5 hours there.

15:00: Drive to Reykjavík.

15:30: Stop at GJ Travel Company for 25 min to pick up the rented camping supplies.

16:10: Arrive at Reykjavík Campsite. Set up the tents. Showers located in hostel, running water, and cooking area (with grill) are free for use.

20:00: Dinner at a seafood restaurant in Reykjavík.

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 zone¹. The Reykjanes volcanic system lacks central volcanoes and is characterized by oblique extensional tectonics and episodic fissure eruption volcanism². 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:

- **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 Columbus³. 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.

- **Valahnukur**

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.

- **Gunnhver Hot Spring**

This is one of the most famous high temperature geothermal areas on the Reykjanes Peninsula. The name Gunnhver comes from the witch called Guðrún, who caused a great disturbance until Eiríkur Magnússon, a priest at Vogsógar set a trap that made her fall into the spring⁴. Gunnhver 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 plant⁵. Evaporites and sulfuric minerals can be seen throughout this hydrothermal area. At depth, metal ores are concentrated, especially copper sulfates.



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

- **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.

References:

¹Marks, N., Schiffman, P., Zierenberg, R. A., Franzson, H., Fridleifsson, G. O., (2010). Hydrothermal alteration in the Reykjanes geothermal system: Insights from Iceland deep drilling program well RN-17, *J. Volcanology and Geothermal Res.*, Vol. 189, 172–190.

²Thordarson, T., and Larsen, G., (2007). Volcanism in Iceland in historical time: volcano types, eruption styles and eruptive history. *J. Geodyn.* Vol. 43, 118–152.

³wikipedia: <http://en.wikipedia.org/wiki/Álfagjá>

⁴visiticeland: <http://www.icetourist.is/SearchResults/Attraction/gunnuhver>

⁵Icelandic Geosurvey: <http://geothermal.is/9-gunnhver-hot-springs>



Figure 15. Blue Lagoon

Day 2 (Friday, August 20th) - Hellisheiði Power Plant and Þingvellir

Contributed by Dan Huber and Amelia Paukert

06:30: Wake-up.

07:30: Breakfast.

08:00: Pack up tents

08:20: * Drive from Reykjavík campsite to the Reykjavík Energy headquarters.

08:33: Arrived at Headquarters, picked up Frida (Hólmfríður Sigurðardóttir), CarbFix Project Manager. Continued on to the Hellisheiði Power Plant.

09:00: Arrived at Hellisheiði Power Plant, picked up Einar Gunnlaugsson, Manager of Geothermal Research. Also picked up safety vests and hard hats for the group. Started the tour of the Hellisheiði Power Plant and CO₂ sequestration site.

12:30: Finished tour. Frida and Einar provided us with juice and cookies.

* Note: This is the first day, so breakfast, packing, etc. was slow. We told everyone to be ready to leave by 07:50, but it was another 30 min before we actually left camp.

13:00: Arrived at Raurfarholshellir Lava Tube, ate lunch.

14:00: Started hike into lava tube. THIS REQUIRES STURDY BOOTS AND A FLASHLIGHT.

15:30: Returned to the bus and left for Þingvellir.

16:30: Arrived at Þingvellir. Set up camp. Note: this campsite is *very* windy. Showers have coin operators, but they were disabled so hot showers were free.

18:00: Left on walk to the Law Rock.

Along the walk, we saw multiple fissures and a waterfall. We passed Drekkingarhylur, the drowning pool for women condemned to death during old times (men were hanged elsewhere). Also saw the Lögberg (Law Rock), the site of the annual Alþing (the Parliament). Roger told Egil's Saga. Roger also raised the question of how the west side of the valley came to have a gently sloping ramp while the east side is steep and both sides are bounded by normal faults.

20:00: Arrived back at camp. Started cooking dinner.

22:00: Dinner.

Site Descriptions

- **The Hengill volcanic system** is located east of Reykjavík at the junction of several volcanic zones and covers an area of about 100 square kilometers¹. 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 flows².

- **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 that³. Drill sites are located in metallic geodesic domes dotting the geothermal regions (fig. 4). The borehole taps into a source of two-phase H₂O, as well as a small percentage of gaseous CO₂ and H₂S. 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.

The tour of Hellisheiði Power Plant and CO₂ sequestration site:

Stop 1: Overlook of Lake Þingvallavatn and table mountains.

Einar provided a description of how table mountains are formed and pointed out the 25 km fissure running from Lake Þingvallavatn and southward, between Hengill and Hveradilir. There is a chain of craters along the fissure from eruptions at 2 ka and 10 ka.

Stop 2: Hengill Fumaroles.

We walked to active fumaroles. Einar described the alteration series, from low temperature to high temperature alteration. He also suggested using colors created by alteration to determine where it is safe to walk near the fumaroles and where it is too hot (dark colors are safe, light colors and gray not safe).

Alteration Series:

Fe oxidation – low temperature, looks red or brown

Clay alteration – low temperature alteration (<150 °C), dark color, often smectite

Fe oxides – high temperature, looks light colored or gray; pyrite and pyrrhotite

Zeolites are also low temperature alteration minerals

Epidote is from high temperature alteration, at ~240 °C



Figure 16. Hengill Fumaroles with Einar and outside of the geothermal well we toured.

Reykjavík Energy is going to install a plant relatively near the fumaroles (but out of sight of them). They anticipate harvesting 700 MW of power from the region.

Stop 3: Geothermal wells

We walked through a well house and saw large pipes leading from the well down the hill toward the separating station. Einar describes how, prior to water and steam production, they use individual well separators to test the amount of water and steam coming from the wells.



Figure 17. Visiting a geothermal well (left) and pipelines carrying heat to Reykjavík (right)

Stop 4: Fissure with craters

We stopped at an overlook to the north, of the valley between Hengill and Þingvellir. Here, we saw fissures and cones from the 2 ka eruption.

Stop 5: H₂S injection site

Einar pointed out the well from which they are harvesting water in order to mix with H₂S and inject back into the geothermal field. H₂S sequestration was Reykjavík Energy's original initiative for starting the H₂S and CO₂ injection projects because the smell reduces the quality of life for people who live nearby.



Figure 18. Moisture separators at the Hellisheiði Power Plant (left) and an eruption cone formed during the 2 ka fissure eruption, north of Hengill (right).

Stop 6: Hellisheiði Power plant headquarters

We went to the viewing platform to see turbines, moisture separators, and compressors. Video about geothermal energy was playing but the group did not have time to watch it.

Stop 7: CarbFix CO₂ injection site

Frida showed us the well into which water and CO₂ will be injected. Frida talked about the hydrogeology of the area (relatively flat hydraulic gradient, so slow flow) and described the anticipated subsurface reactions due to injection of CO₂ into basalt.

• **The Raufarhólshellir lava tube** is located about 20 km east of Reykjavík in the Leitastraun 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.



Figure 19. The Raufarhólshellir lava tube; Close-up of bathtub rings (right).

Pingvellir 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 1789⁴. 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 Drekkingsrhyllur, 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 Þingvallavatn. 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.



Figure 20. Water-filled fissure Þingvellir National Park.



Figure 21. The Parliament site, Þingvellir National Park, Lake Þingvallavatn in the distance.

References:

¹Wikipedia: <http://en.wikipedia.org/wiki/Hengill>

²Smithsonian Institution: <http://www.volcano.si.edu/world/volcano.cfm?vnum=1701-05>

³Orkuveita Reykjavíkur: <http://www.or.is/English/Projects/HellisheidiGeothermalPlant/>

⁴Þingvellir National Park: <http://www.Þingvellir.is/english>

Day 3 (Saturday, August 21th) – Geysir and Gullfoss

Contributed by Ivan Mihajlov

- 8:00** Wake up, made breakfast, and packed up tents
- 10:30** Left the campsite near Þingvellir. Drove along the western rift zone which had visible shields and hyaloclastite hills
- 11:15** Arrived at Geysir (site of hydrothermal springs and geysers). Took a walk around the site
- 12:30** Visited souvenir shopping at the Geysir visitor's center. The area was crowded by tourist buses, leaving very little picnic space
- 13:15** Left for Gullfoss (Golden Waterfalls)
- 13:30** Arrived at Gullfoss visitor's center and had lunch on a side bench, followed by a visit to the waterfalls. This is a good lunch spot owing to the large amount of space and spectacular views of the mountains
- 15:15** Left Gullfoss and headed toward the campsite near Eyjafjallajökull
- 17:10** Arrived to Seljalandsfoss (Seljaland waterfall), near the intersection of Route 1 (the road around Iceland's perimeter) and the road to the Básar campsite
- 17:25** Left the falls. The rough drive leads across a glacial outwash plane with braided streams. Erratic boulders, terminal moraines, and glacier tongues are visible as the campsite is approached
- 18:45** Arrived at the Básar campsite in Þórsmörk, near the Eyjafjallajökull glacier.

Site Descriptions

Geysir, Gullfoss, and Seljalandsfoss

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 north¹. 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 graben¹. 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 Geysir') 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 meters² 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.



Figure 22. Strokkur at the beginning of its eruption (left) and at full force (right)

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}.

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. The horses are available to rent for several hours or days at a time.



Figure 23. Gullfoss (left) drops into a fissure opening as the Hvítá River takes a sharp bend to follow the fissure (right); the scene is completed by a perpetual rainbow in the mist.

Hvítá has its source in the glacier lake Hvítávatn ('white river lake'), 40 km north of the falls, just under the Langjökull glacier⁴. 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 ($80\text{-}140\text{ m}^3/\text{s}$)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 canyon⁵. 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}.

Another 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)⁶, cascading vertically over a former sea cliff. While the falls are not voluminous, their attraction is a walkway that puts visitors behind the falls, creating a

magical show of water droplets, changing sunlight, and a sharp green of the moss-covered rocks and dewy pastures in the distance. The trail is wet and slippery, but only requires 10-20 minutes to complete.



Figure 24. Seljalandsfoss waterfall.

The road to the Þórsmörk campsite follows an outwash plain that drains numerous outlet glaciers from Tindafjallajökull, Eyjafjallajökull, and Mýrdalsjökull. The ride through the glacial outwash landscape is very rough, and often requires driving through braided streams. The sediment is black and varies in size from dust to boulders. The dust is often carried by wind as ‘glacial flour’. In the narrower part of valley, closer to the campsite, very large boulders (‘erratics’) dot the valley, brought there by occasional avulsions (breaches) of the terminal moraines. A glacial tongue with its former moraine (now avulsed at two sites) can be appreciated to the right of the road. The yellow and pink flowers along the road contrast well with layers of black ash and the large boulders. Much of the black ash could have been from the recent (spring 2010) eruption of Eyjafjallajökull. The campsite, reached after an hour long drive across the rubble, is very beautifully located on the valley floor just under a glacier, and provides plenty of tent sites tucked in between trees and bushes.

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

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

⁶Seljalandsfoss, in World of Waterfalls.

<http://www.world-of-waterfalls.com/iceland-seljalandsfoss.html> <accessed Sep 12, 2010>



Figure 25. Glacial erratics on the outwash plain on the way to the Þórsmörk campsite.

Day 4 (Sunday, August 22nd) – Hike to Eyjafjallajökull

Contributed by Danielle Sumy and Ashley Shuler

05:40: Wake-up.

06:00: Breakfast.

07:10: Meg Reitz discusses erosional and depositional glacial features

07:30: Hike along Skógar-Fimmvörðuháls trail. The trail follows blue markings from Básar base camp toward Brattafönn, approximately 8 km each way, with roughly 600 meters of elevation gain. Glacial features such as kames, arêtes, cirques, moraines and glacial outwash plains can be seen throughout the hike.

11:00: We reached lava flows from March 2010 eruption of Eyjafjallajökull; parts are still steaming! Break for lunch. Part of the group scrambles over lava flows to explore fumaroles near a cinder cone and see molten rock! Ash and hand samples of lava are collected. Note that the sulfur is deposited near the fumaroles in new lava flow.

11:30: Hike back to Básar (base camp)

14:30: Leave for Skaftafell.

15:50: ~30 minute stop at Skógafoss, a waterfall that measures 25 meters in width and 60 meters in height.

18:00: Grocery stop at the Kjarval store in Vik (note: this is a small grocery store in a tiny town, so food was much more expensive than at Bonus)

19:30: Continue on our way to Skaftafell.

20:00: Arrived at the Skaftafell campsite. Set up camp. Cook dinner.

22:30: Eat Dinner.

Site Descriptions

Básar- Þórsmörk Area Overview

Básar base camp is located in a glacial outwash plain between two of Iceland's largest glaciers, Eyjafjallajökull to the south and Mýrdalsjökull to the east. Mýrdalsjökull covers an area of roughly 600 square kilometers, including the active subglacial volcano Katla, which contains a large 10-by-14-kilometer-wide caldera. Katla is one of Iceland's most active volcanoes, erupting twice per century on average. Though recent eruptions have been basaltic eruptions from fissures located inside the caldera, there have been multiple explosive dacitic eruptions in the Holocene¹. The eruption in 934 C.E., for example, produced an 18 km³ lava flow, which is one of the world's largest known Holocene lava flows. Katla also produces jökulhlaups, or glacier-outburst floods. The flood discharge at the peak of an eruption in 1918 is estimated at 100,000 – 400,000 m³/s, which is comparable to the average discharge of the Amazon River².

Eyjafjallajökull is an ice cap covering an area of approximately 100 square kilometers; its main outlet glaciers are Gígjökull and Steinhóltsjökull. Underneath the ice cap lies a stratovolcano of the same name. The volcano stands at 1666 meters and has a 2.5 – kilometer-wide summit caldera. Eyjafjallajökull erupts much less frequently than neighboring Katla, having only 4 eruptions in the last millennium, 920, 1612, 1821-1823, and the most recent eruption, which began in March 2010. A distance of only 25 kilometers separates Katla and Eyjafjallajökull, and disregarding the most recent eruption, each of the three eruptions of Eyjafjallajökull has preceded an eruption of Katla by less than one year. However, Katla has also erupted without being preceded by an eruption from Eyjafjallajökull, so this could just be a coincidence^{3,4}.

The most recent eruption of Eyjafjallajökull was preceded by an increase in seismicity and rapid deformation, which was captured by GPS. The eruption occurred in several phases, each with varying eruption characteristics with different implications for volcanic hazards⁵. The first phase consisted of a fissure eruption that began on March 20, 2010, roughly 9 kilometers E-NE of the summit in an area called Fimmvörðuháls. The start of the eruption had Hawaiian-style fire fountains erupting from a ~500-meter-long fissure. Activity spread to 10-12 vents by March 21, and lava fountains exceeding 100 meters were observed by helicopter. As lava flowed over a steep canyon, extremely rare "lava falls" were observed in the Hvannárgil valley. Activity decreased with time and lava emission had stopped at most craters by April 7.

The second, more explosive phase of the eruption began on April 14, 2010 from the subglacial summit caldera. The eruption melted through the ice cap and an eruption plume was observed within a few hours. A radar image on April 15 depicted a series of vents along a 2-kilometer-long fissure. Meltwater combined with debris resulted in a series of jökulhlaups, which damaged nearby roads, homes, and farms. The ash plume from the explosive phase of the eruption caused the closing of airspace over the United Kingdom and large parts of Europe within several days. The eruption products were

largely fine-grained tephra, which was more silicic than the fissure eruption at Fimmvörðuháls. The eruption continued through June 2010 with decreasing explosive activity with time.



Figure 26. Cinder cone and steaming lava flows observed on hike (see trail overrun by lava).



Figure 27. Molten rock observed from a fissure on top of the cone shown above.

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Index of Monthly Reports for Eyjafjallajökull (<http://www.volcano.si.edu/world/volcano.cfm?vnum=1702-02=&volpage=var>)

Day 5 (Monday, August 23rd) – Glacial hike in Skaftafell

Contributed by Adrienne Smith and Natalia Zakharova

7:00: Wake up. (Overnight stay at Skaftafell National Park. No driving this morning.)

8:45: Meet Glacier Guides at their main office (walking distance). Crampons are fitted.

10:00: Begin hiking in crampons on Fjallsjökull, an outlet from Iceland's Vatnajökull coming down from Öräfajökull.

Glacier hike Recommendations: Wear sunscreen, particularly on the underside of the chin. Bring supplementary lunch, especially if vegetarian. Save room in your water bottle for water from a supraglacial stream.

14:00: Return to the bus for transit back to Skaftafell campground.

15:00-on Free afternoon

Many trip participants take the hiking trails from the campgrounds to Svartifoss (<2km), one of Iceland's many stunning waterfalls. The trail is well defined and mostly easy to walk on. The trail also passes another waterfall – Hundafoss, or Dog Fall. From Svartifoss the track climbs up to the Sjórnarsker viewpoint, which offers a panorama of Skaftafellsheiði, Kristinartindar, the mountains on either side of it, and the plain below. The trail from Svartifoss also offers stunning views on the deserted flood plain below (Skeiðarársandur).

21:00: Dinner (cooks were back earlier)

Site Descriptions

Regional background

Öräfajökull is Iceland's largest ice-covered volcano. It is lying under Vatnajökull, Iceland's largest ice cap, and it is part of a chain of volcanic centers that includes

Hvannadalshnúkur, the highest peak in Iceland. Historically, two eruptions from Öräfajökull have caused catastrophic jökulhlaups. The 1362 eruption is the first contemporary record of a jökulhlaup. The flood lasted only one day, but devastated a once thriving farm community that had settled in the lowlands. The flood originated in the stratavolcano's 500 m deep caldera and then flowed out in all directions. Water rushed out under many of the outlet glaciers in the area, including Fjallsjökull the location of today's hike. The historical record describes this event, “several floods of water gushed out, the last of which was the greatest. When these floods were over the glacier itself slid forward over the plane ground.... The water now rushed down the Earth side without intermission, and destroyed what little of the pasture grounds remained....”. This record suggests that subglacial conduits were not able to contain the large amount of water rushing out of Öräfajökull caldera. The water pressure rose until the glacier itself was floated off its bed, causing it to surge forward over the once peaceful outwash plain. The 1727 eruption was less catastrophic but similarly destroyed farms that had resettled the area. Sediment and ice from this flood persisted in the lowland long enough for the names to become permanent though the ice melted away long ago¹.

Guided glacier hike on Fjallsjökull

Each hiker was given crampons, an ice ax and a slim sandwich for lunch².

Transit to the glacier is provided in a classic American school bus. Participants then walk across unconsolidated till and outwash debris to the front of the glacier.

Interesting features seen during the hike:

Crevasses – cracks and openings in the rigid layer of the ice that form in response to tensional stresses. These openings are often associated with rough bed topography or rapid ice velocity. The base of a glacier is warmer and flows more easily than the surface. Relatively high velocities or directional changes at the base of the glacier often occur at a pace that the surface cannot match, thus creating tension and opening crevasses.



Figure 28. Crossing a crevasse on Fjallsjökull.

Moulins (“moo-lawns”) – near-vertical water drainage tunnels formed at the confluence of crevasses. The pre-existing cracks funnel meltwater to these tunnels, which grow in response to frictional heating as meltwater flows down the ice walls.

Glacial Moss – Supraglacial rocks provide a germination location for moss. It can take 30 years for the moss to begin growing, but growth continues as the rock traverses the glacier's surface. Eventually, the moss covers the entire stone making it difficult to detect the stone within the spongy moss layers.

Dead Ice – Glacial ice that is no longer connected to the active, moving glacier becomes dead ice. Typically, these ice bodies are covered in moraine debris. Under the cover of till, these stationary ice blocks can create depressions in the outwash region of the glacier. The depressions often persist and are filled with water, forming shallow lakes.

Ash layers from 2 historic eruptions at Öraefajökull are seen due to the emergent velocity of the glacier. There is increased melting of the accumulated ice layers near the terminus of glaciers. This exposes old ice on the surface of the glacier. Ash layers to look for:
1362 eruption, rhyolitic ash, lighter cream color
1727 eruption, basaltic ash, grey-black color

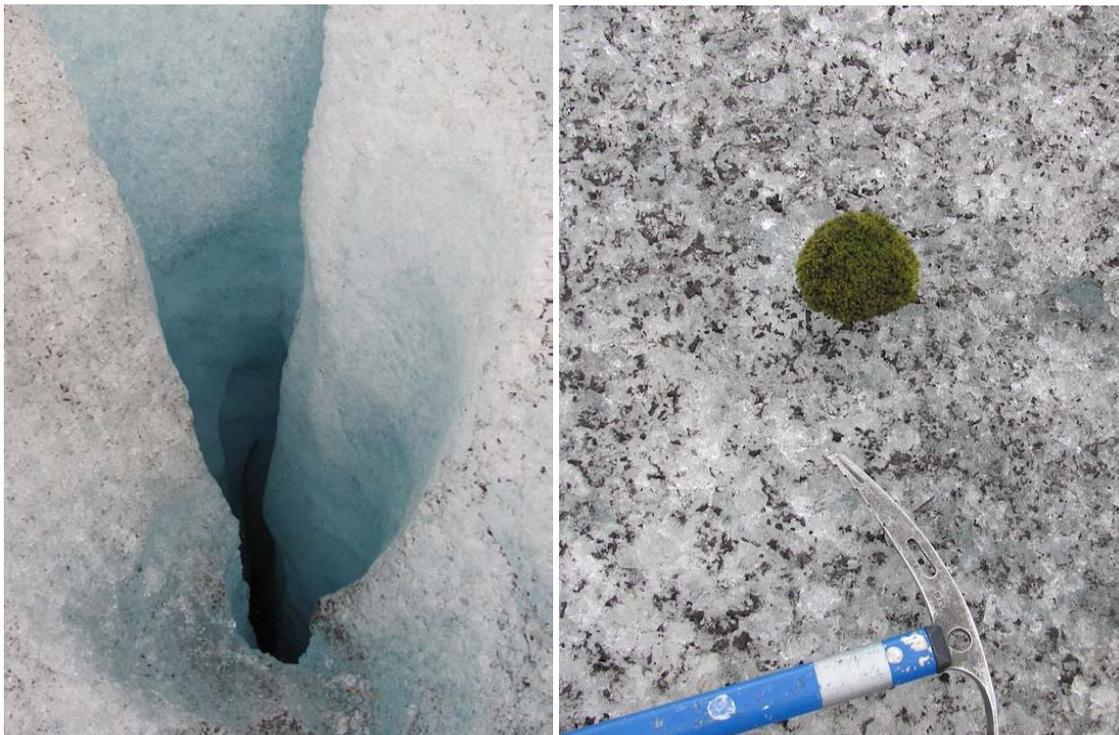


Figure 29. A moulin (left) and glacial moss on Fjallsjökull (right).

Svartifoss (*Black Fall*) is a waterfall in Skaftafell National Park, with spectacular basalt colonnades. It is one of the most popular sights in the park. Svartifoss plunges in

between hanging basalt columns with well-pronounced hexagonal and pentagonal cooling cracks, called columnar joints. It is a common phenomenon in igneous rocks, especially of basaltic composition. The joints form as the rock contracts during slow cooling, and they reflect the thermal history of a lava flow³. In general, large columns signify slower cooling while narrow columns result from faster cooling.

As a magma body cools, the temperature field within it changes in accord with Fourier's law for heat conduction. The cooling front moves inside the body causing thermal contraction cracks to occur perpendicular to isothermal surfaces. The networks of interconnected tension fractures tend to divide solids into prisms bounded by three to eight sides (the pentagons are, in fact, as abundant as commonly known hexagons⁴). The joints in the colonnades also commonly exhibit surface markings known as striae. They represent a single increment of joint growth. As a result, the long slender joint faces of individual columns are built from a stacked succession of short crack segments.



Figure 30. Columnar joints at Svartifoss.

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Day 6 (Tuesday, August 24nd) – Skaftafell Glacier Tour with Helgi Björnsson

Contributed by Kat Allen

9:00: Meet Helgi at the Skaftafell information center. Discuss Vatnajökull glacier and regional geology.

10:15: Leave for Glacial Lake Jökulsarlón

11:00: We climbed up a moraine near the parking lot to get a good view. Helgi gives a short lecture on the history of the Jökulsarlón area. The group explores the moraine area and ice chunks on the beach. Students were free to do a boat tour or walk around the lake. Lunch at the visitor's center.

14:30: Drive to Fjallsarlón

14:45: We explore the moraine area and paleo-shorelines. Roger points out the tilted lava flow sequences to the East.

15:20: Drive to Kvíárjökull, tallest moraine in Iceland.

15:30: We hike up the western branch of the moraine towards the glacier.

16:30: Drive to Kettle Hole at Haalda. The kettle was formed when an ice chunk, transported during the 1727 flood, later melted.

16:50: Briefly discussed kettle hole formation mechanisms.

17:10: Drive out onto the Skeiðarársandur glacial outwash plain (Rt. 139, towards Vik). Crossed the longest bridge in Iceland, above a mostly dry river. Stop at Gigjukvisl to climb to the moraine crest. Discussed the rapid glacier retreat and the 1996 flood event.

18:10: Returned to Skaftafell campsite.

20:30: Dinner

Site Descriptions

Regional overview

Sixty percent of Iceland's glaciers are underlain by volcanoes. Iceland's glaciers collectively contain $\sim 3,600 \text{ km}^3$ of water, which if melted, would raise global eustatic sea level by $\sim 1 \text{ cm}^1$. High geothermal heat, catastrophic melts events, and glaciers' acute sensitivity to precipitation and air temperature make the thickness and extent of these glaciers extremely dynamic. Southeast Iceland is a wonderful location to observe active glacial processes and their corresponding geologic features.

All glaciers are on the move. Ice accumulates at high elevations, moves downslope, and is melted or ablated at lower, warmer elevations. The relative inputs and outputs determine whether a glacier grows, shrinks, or is at steady state. Skaftafell National Park is located at the southern edge of the Vatnajökull glacier, which at $3,100 \text{ km}^3$, is larger by volume than any other glacier in Europe. Prevailing southerly winds bring Gulf Stream-derived moisture to the Skaftafell region, where annual precipitation on high glacial slopes can exceed 5 meters^2 . By contrast, the more northerly inland regions

only receive 0.4 – 0.7 meters, and equilibrium lines (the elevation above which there is net ice accumulation) are higher than those in the south. Today, despite high regional precipitation, Vatnajökull is shrinking by about 1 meter per year (water equivalent).

Not all of this ice loss is due to modern warming air temperatures; catastrophic flooding events called jökulhlaups also play a large role in the mass balance of Icelandic glaciers and leave a distinct mark on glacial landscapes. Jökulhlaups can be caused by gradual geothermal melting, which creates a large pool of water that is released either when it overflows its basin (Helgi’s “coffee-cup” model) or when an ice-dam fails (“blister” model). Volcanic eruptions also cause huge meltwater discharges; the eruption in Gjalp in 1996 alone melted $\sim 4.0 \text{ km}^3$ of ice¹. Events like this can transport massive amounts of sediment to the coastal outwash plains (the “sandur”), which have extended the coastline seawards $\sim 25 \text{ km}$ in the past 1.1 ky. The 1996 flood wreaked havoc on the infrastructure of the south coast, as memorialized by a dramatically twisted bridge support along Route 1.



Figure 31. Glacial lagoon Jökulsarlón with Vatnajökull outlet glacier, Breiðamerkurjökull in the background.

Jökulsarlón is a spectacular example of a feature left behind by a melting glacier. This glacial lake began forming in the 1930s, when one of Vatnajökull’s outlet glaciers, Breiðamerkurjökull, began melting. Moraines of boulders and till that have been dumped by the ablating glacier rim the lake and serve as its southern boundary. Jökulsarlón has grown rapidly during the past few decades, and is now connected by an outlet to the sea. The lake is ~ 300 meters below sea level, contains $\sim 30\%$ seawater and has a daily tidal range of 2 – 3 meters. Large chunks of ice that episodically calve (or break off) from the glacier float quietly on the lake surface. Freshly calved ice is characterized by a deep blue color, indicating very dense ice formed at high pressure. Within a glacier, snow is compacted into ice, a process called “firnification,” which squeezes out air bubbles and creates increasingly dense material (typical glacial ice is 800 kg/m^3 , while pure ice

without air is 915 kg/m^3). Isostatic rebound in this area due to unloading by melting ice is approximately 3 cm per year. Helgi estimates that if all of Vatnajökull's ice were to melt, this area would uplift more than 100 meters³!

During the warm Climatic Optimum 7 kya, Iceland's glaciers almost completely disappeared. Then, ca. 2.5 kya, temperatures cooled and glaciers expanded. Several merged to form Vatnajökull. During human settlement (beginning 874 C.E.), climate was slightly warmer, but in the 1300s (Little Ice Age) the ice re-advanced and devastated much of the vegetation and farmland. Glacial advance culminated in the 1750s, and then began a variable retreat that continues today. Helgi's ice sheet modeling results predict that at current rates of warming, Iceland's glaciers may lose 25% of their volume in 50 years, and they will be reduced to small mountain caps within 200 years³.



Figure 32. Hiking on Kvíárjökull, the tallest moraine in Iceland.

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Day 7 (Wednesday, August 25th) – Eastern Iceland

Contributed by Natalia Zakharova

07:00: Wake-up.

08:00: Breakfast and pack up.

08:50: Leave the Skaftafell campsite and drive eastwards through Tertiary basalts.

10:25: Quick stop at Höfn.

10:45: Leave Höfn, drive through eastern fjörds, look at rhyolite lavas (they are distinguished by lighter and usually more reddish color from the dark basaltic background).

11:20: Passing Eystrahorn, observe a distinct rhyolitic dike.

12:05: Stop at Djúpivogur for lunch. (The town is known for preserved old buildings that lend a distinctive character to Djúpivogur, once the main trading post in the region.)

13:10: Leave Djúpivogur.

14:10: Arrive to Petra museum in Stöðvarfjörður. (The museum is very cozy and has a nice terrace where visitors can repose and have a cup of coffee or tea.)

15:10: Depart Stöðvarfjörður.

15:35: Stop at Fáskrúðsfjörður to observe Sandfell laccolith. Take pictures.

15:45: Drive through tunnel to Reyðarfjörður (the biggest fjörd in Iceland), and continue on the road toward Mývatn.

16:30: Arrive to Egilsstaðir, stop for grocery shopping.

17:45: Depart Egilsstaðir, drive to campsite.

19:45: Arrive to the campsite by Mývatn and begin cooking dinner.

22:00: Dinner.



Figure 33. Langa-Búð, oldest house in Djúpivogur, is made of logs and was originally built in 1790. The building has been renovated and now serves as the cultural center of Djúpivogur.

Site Descriptions

Regional Overview

Eastern Iceland was formed by a continuous succession of Tertiary basalt flows that represent the oldest stratigraphic formation in Iceland. The flows span the time period from 16 My to 3.3 My, and contain nearly 15,000 feet of volcanic rocks, mostly plateau-basalt lavas. Volcanotectonic processes, similar to those operating in the currently active volcanic belt, produced the lavas. Thus, the Tertiary Basalt Formation occurs in two large regions on either side of the active rift zone, covering about half of the island¹. In the east, the Tertiary Basalt formation extends from Skaftafellsfjöll in the southeast across the eastern fords to Bakkafloi in the northeast. The lavas are magnificently exposed and can be well observed from the coastal highway. The change of scenery as you move to the east of Breiðamerkurjökull is remarkable: Tertiary rocks expose layer-cake stratigraphy where one basaltic lava flow is stacked on another, forming a gently dipping succession thousands of meters thick.

One of the most striking features of the area is the great thickness of basalt lavas exposed. The cumulative thickness of the Tertiary Basalt formation is close to 10 km, but the true thickness of the succession at any particular location does not exceed 3 km. The flows are about 10-30 km wide and 50-100 km long². The area has a general westerly dip of a few degrees, which is roughly matched by an opposite dip of the same-age rocks in Western Iceland. Stratigraphic mapping reveals that large faults (with a vertical displacement of more than 100 m) are rare.



Figure 34.
Tertiary basalt
flows in eastern
Iceland.

Approximately 80% of the total volume of the Tertiary volcanic pile (including lavas and subordinate tuffs) have a basaltic composition; the remainder mostly consist of

rhyolite lavas and pyroclastic rocks, with subordinate basaltic andesite lavas³. The basalts were erupted predominantly on land. Between the flows are thin partings of airborne tuffaceous ash that are now bright red in color. Since trees frequently grew on the land between eruptions, remnants of logs are often found enclosed in basalt. Occasional lignite beds are also found and are usually underlain by acid tuff beds. The Tertiary lava piles are cut by numerous, thin (1-10 m wide) dikes. The dikes have a high density and make up to 7% of the total thickness of a 75 km lava sequence. Dikes feed the lava flows and represent the subsurface component of the fissure swarms in active volcanic systems.

One feature of special interest in Eastern Iceland is the abundance of co-existing felsic and basic magmas. Composite dikes are common, in which the more basic edges of the dike were still hot or partially fluid when more evolved lavas were intruded into the center. The felsic rock often contains basic xenoliths, incorporated in the rocks before complete solidification³. A number of examples have been found in which the basaltic and rhyolitic components were evidently extruded simultaneously. Felsic magmas were present in bulk throughout most of the Tertiary history of eastern Iceland. The composition of the Icelandic rhyolites and andesites is consistent with derivation by crystal fractionation from basaltic parent magmas³. It is probable that the felsic magma is too cold and viscous to reach the surface without remobilization by the injection of hot, more fluid, basic magma. Remobilized felsic magma can then be erupted as the centre of a composite dike, composite lava, mix-lava, xenolithic rhyolite, or felsic tuff.



Figure 35. The Sandfell laccolith, on the south side of Fáskrúðsfjörður, is a cone-shaped rhyolite mountain that rises to a height of 743 m.

Petra's mineral museum

The basalt lavas of eastern Iceland have long been famous for their zeolites and other alteration minerals. Many of them can be found in Petra's mineral museum in Stöðvarfjörður.

Petra's museum is the world's largest private mineral collection and it is located in Petra's own house. She became a serious collector more than 60 years ago (in 1946), and has since accumulated a large and beautiful collection of Icelandic rocks and minerals. Most of the stones come from Eastern Iceland, mainly from the Stöðvarfjörður region. The collection contains an impressive number of basaltic rocks and minerals, and

especially secondary minerals and alteration products such as zeolites, halcedones, quartz, etc. The rocks fill both the house and the beautiful garden around it. Petra opened her house for visitors in 1974, and it still remains her home.



Figure 36. Petra's mineral museum.

Eastern fjörds

The main outlet glaciers of the Quaternary icecap enlarged pre-existing fluvial ravines in eastern Iceland and carved deep U-shaped valleys. The outlet glaciers produced a classic alpine landscape. Many of these glacially carved valleys are so deep that they reach below sea level and form fjörds, which is the most distinctive feature of Eastern Iceland. The coastal highway offers excellent views of the fjörds.

The most prominent feature along the southern rim of Fáskrúðsfjörður (a fjörd south of Egilsstaðir) is Mt. Sandfell, a rare example of an exposed rhyolitic laccolith. It attracts immediate attention by its well-defined shape and pale color, in stark contrast with the dark basaltic lavas. The steeply dipping strata adjacent to the rhyolitic body show that it intruded into the basaltic lava series. The slowly rising rhyolitic magma came within 500 meters of the surface and started to accumulate as an intrusion, deforming the overlying strata. It formed a dome-shape hill that eventually rose 400-500 meters above the surroundings².

Fáskrúðsfjörður is connected by tunnel to the head of the largest fjörd in East Iceland, Reyðarfjörður, which stretches for over 20 km and reaches the width of several kilometers.



Figure 37. At the head of Reyðarfjörður, the largest fjörd in eastern Iceland.

References:

¹Walker, 1957. Geology of the Reydarflördur area, Eastern Iceland, Quarterly Journal of the Geological Society. Vol. 114, 367-391.

²Thordarson and Hoskuldsson, 2002. Classic geology in Europe 3: Iceland, Terra Publishing.

³Walker, 1964. Geologic investigation in eastern Iceland, Paper read at the IAV scientific session of Aug.30, 1963 (XIII General Assembly, I.U.G.G.).

Day 8 (Thursday, August 26th) - Lake Mývatn

Contributed by Jason Jweda

07:30: Wake-up.

08:00: Breakfast.

09:10: Drive from Mývatn campsite to the Krafla powerplant.

09:25: Arrive at power plant, but visitor center only open from 13:00-17:00. Drive north to Leirhujukur area where lava from the 1977-1984 Krafla fires erupted.

09:35: Explore geothermal vents and hike the Leirhujukur trail around the most recent lava flows (easy ~2 km). Roger Buck discusses geophysics of dike events and fissure eruptions at Krafla (~45 min).

11:45: Return to bus and drive to Lake Víti.

12:00: After short walk to Víti's rim, have lunch.

12:40: Drive to geothermal area south of Krafla.

12:55: Arrive at Námafjall Hverir geothermal area. Hike around the ~1 km trail.

13:40: Drive to Dimmuborgir (collapsed lava lake).

14:00: Arrive at Dimmuborgir and hike the yellow trail to the “church” (~1 hr) and then hike through the lava lake to the base of Hverfjall cone (~1 hr). Climb to the top of the tephra cone, walk along rim, and then hike to the bus, which was waiting in the parking lot on the NW side (low portion of the rim) of the cone (~1 hr).

17:00: Drive to the Mývatn Nature Baths.

17:15: Spend two hours in the geothermal baths.

19:15: Drive back to campsite.

19:30: Arrive at campsite and begin cooking dinner.

21:00: Dinner.

Site Descriptions

Mývatn Area General Background

The Mývatn area, located in north-central Iceland, consists of a shallow eutrophic lake (the 4th largest natural lake in Iceland) and the Krafla volcanic system¹. The lake and surrounding wetlands take their name from the numerous small flies (midges) that populate the area. Lake Mývatn is recognized as having exceptional waterfowl abundances and one of the most diverse duck species concentrations in the world. This wildlife diversity owes its existence to the relatively mild climate of the region (generally considered to be the most moderate in Iceland), the large insect population, and nutrient-rich lake water. Lake Mývatn covers roughly 37 km², has an average depth of ~4.2 m, and consists of two basins (Ytrifloi and Sydrifloi). Inflow to the lake is mainly produced by groundwater seeps on the eastern shores and outflow occurs mainly as discharge through the River Laxá².

Krafla central volcano, located ~10 km NE of Lake Mývatn, is manifested by a 10 km wide caldera that is cut by a long (~100 km) N-S trending fissure system³. Krafla was the source of several rifting and eruptive events in the late Holocene, including two historical eruptions that were well documented. Postglacial volcanism in the Mývatn area consists of three major eruptive cycles. The first cycle commenced after the ice sheets of the last glaciation retreated at least 6 kya and produced the Lúdent tephra cone (the large cone we saw SE of Hverfjall crater). Around 3.8 kya, the shield volcano Ketildyngja (~25 km SE of Lake Mývatn) produced the relatively large Older Laxá-lava flow (~4 km³), which flowed down the Laxárdalur valley and covered the southern portion of the Mývatn area. The lava also dammed the low-lying areas to form the ancient Lake Mývatn, which was similar in size to the present lake. The Older Laxá-lava is a plagioclase-bearing porphyritic tholeiitic basalt with well preserved pahoehoe surficial structures⁴.

The second cycle of volcanism at 2.5 kya generated the tephra cone Hverfjall, which is ~150 m high and ~1 km in diameter. Hverfjall was produced by a phreatic explosive eruption caused by magma interactions with groundwater. The tephra consists mostly of lithics and older lava fragments, with rare juvenile basaltic grains. The NW side of the cone apparently slumped during the eruption, and a small cone in the center of the main crater represents the last gasps of activity at the locality.



Figure 38. The Krafla caldera. Lava flows in foreground are from the Mývatn Fires.



Figure 39. View of Hverfjall tephra cone from the campsite (left) and the view of the 1 km wide crater from the south rim.

Around 2,300 kya the Younger Laxá-lava flow was erupted and flowed over the Older Laxá-lava flow and down the Laxárdalur valley, once again providing a water dam for the present Lake Mývatn. This eruption produced a row of craters along the eastern boundary of the lava flow, called þrengslaborgir/Ludentsborgir, from which all of the lava flowed west (this was the high ridge we saw to the west of Lake Mývatn). As lava filled up the basin, heating of water-saturated lake bottom sediments generated large steam eruptions that fragmented the lava and brought pieces of the altered sediment to the surface. Repeated explosions created the characteristic pseudocraters that dot the southern end of Lake Mývatn (we stopped to look at these for a few minutes on the morning of day 9). It has been suggested that the pseudocraters dammed a lava lake between the previous lake and the crater row at Dimmuborgir.



Figure 40. View of one of the pseudocraters at the southern shore of Lake Mývatn.

The Dimmuborgir formation consists of lava tubes and pillars formed by the collapse and drainage of this temporary lava lake. The pooled lava may have been as deep as 10 m. Vapor that rose through the lake formed “drainpipe” pillars that were preserved after the lava was drained and the roof collapsed. We stopped at “the Church” structure near the middle of the Dimmuborgir to discuss its formation at length (fig. 25). We concluded that the structure was a lava tube produced concurrent with the formation of the lava lake but before the roof crust of the lake collapsed⁴.



Figure 41. The Church lava tube structure at Dimmuborgir (left) and a panoramic of the “Dark Castles” (below).



The third cycle, including the most recent volcanism, began in 1724 C.E., with the explosion of the Víti crater, and ended in 1729. The Mývatn fires produced fissures and lava fountains near Leirhnjúkur in the Krafla caldera. Lava from the eruption flowed down to the NE corner of Lake Mývatn, forming the rock on which we camped. The lava consists of tholeiitic basalt and has classic Pahoehoe texture. “Mounds” of this lava, called tumuli structures are found within the campground; these are broken lava domes formed by swelling and brittle failure of the lava crust caused by upward pressure of slow moving lava below. The Krafla fires, whose chronology bears a striking resemblance to that of the Mývatn fires, began in late 1975 and lasted until late 1984. The Krafla fires are the best-studied dike intrusion event on a divergent boundary in the world and showed that a central magma chamber repeatedly fed dikes that propagated in opposite directions. The observed pattern included 20 events that produced fissures and sometimes lava flows in and around the caldera. A pattern of gradual inflation and sudden deflation in the caldera accompanied the diking episodes^{3,5}.

Geothermal activity is evident throughout the Krafla fissure system and is most notable at Námafjall geothermal field, located on the northeast side of the Moberg ridge⁴. The field consists of ~1 km² of steaming vents, hot springs, and boiling mudpots. The hydrothermal activity has altered the rocks to clays and formed sulfur deposits.



Figure 42.
Boiling mudpots
in the Námafjall
geothermal field.

References:

¹<http://en.wikipedia.org/wiki/M%C3%BDvatn>

²Kjaraan, S. P., Holm, S. L., Myer, E. M., 2004. Lake circulation and sediment transport in Lake Mývatn. *Aquatic Ecology* 38, 145-162.

³Thordarson, T. and Larsen, G., 2007. Volcanism in Iceland in historical time: Volcano types, eruption styles and eruptive history. *J. Geodynamics* 43, 118-152.

⁴Thorarinsson, S. 1979. The postglacial history of the Mývatn area. *Oikos* 32 (1), 17-28.

⁵Buck, R., Einarsson, P., and Brandsdóttir, B., 2006. Tectonic stress and magma chamber size as controls on dike propagation: Constraints from the 1975-1984 Krafla rifting episode. *J. Geophysical Res.* 111, B12404.

Day 9 (Friday, August 27th) - Drive to Reykjavík via Kjölur (500 Km)

Contributed by Natalia Zakharova and Jennifer Levy

07:15: Wake-up

07:45: Breakfast

08:15: Drive from Mývatn campsite to a nearby gas station

08:30: Arrived at gas station, explore pseudocraters* nearby

08:45: Drive to Goðafoss waterfall

09:15: Stop at Goðafoss waterfall for bathroom and pictures. *Note the stunning geometry of cooling joints in columnar basalts exposed in the riverbanks.*

09:35: Leave Goðafoss

10:10: Arrive at scenic photo stop (Stryturnar nattuervaetti) across the bay from Akureyri; take pictures for 5 minutes. *Read the sign about the area proudly introducing nearby region Höfðahverfi as 'a flourishing district with a population of around 100'.*

10:15: Leave for nearby town of Akureyri

10:20: Arrive in Akureyri, stop for bathroom break and a short walk

11:00: Leave Akureyri

12:05: Stop for lunch at Varmahlið. A café with bathrooms and small gift shop were available.

13:55: Leave Varmahlið. Drive on Kjölur road through the deserted interior Highland of Iceland, passing between Langjökull and Hofsjökull glaciers.

14:35: Arrive at Hveravellir hot springs. This stop had a campsite, a small café, and a hiking path to see hot springs.

15:10: Leave Kjölur road and take a rocky road to Gullfoss waterfall.

17:10: Arrive at Gullfoss waterfall for short bathroom break

17:20: Leave Gullfoss waterfall

19:00: Arrive at campsite in Reykjavík and begin cooking lamb and vegetable dinner.

Site Descriptions

The Goðafoss, one of the most spectacular Icelandic waterfalls, is located in the Mývatn district of North-Central Iceland at the beginning of the Sprengisandur highland road. The water of the river Skjálfandafljót falls from a height of 12 meters over a width

* Description of pseudocraters is in the previous section.

of 30 meters. The name ‘Goðafoss’ means ‘waterfall of the gods’ in Icelandic and refers to the time of conversion of Iceland to Christianity. In the year 999 or 1000 the lawspeaker, Þorgeir Ljósvetningagoði, made Christianity the official religion of Iceland¹. Upon returning from the Alþing, after his conversion, Þorgeir threw his statues of the Norse gods into the waterfall.



Figure 43. Goðafoss: panoramic view of the waterfall, and fanning colonnades in the walls.

Akureyri is a beautiful city in northern Iceland located at the head of Eyjafjörður. Nicknamed "the Capital of North Iceland," Akureyri is an important port and fisheries center, with a population of 17,304 (Iceland's second largest urban area after the Greater Reykjavik area)². The area has a relatively warm climate due to geographical factors, and the city's ice-free harbor has played a significant role in its history. The city has several bars, reputable restaurants and various attractions including museums, churches, the Botanical Gardens (the most northerly botanical gardens), and the most northerly 18 hole golf course in the world.



Figure 44. Eyjafjörður.



Figure 45. Akureyri.

The Kjölur is a highland road in Iceland. It begins in Southern Iceland near Haukadalur, behind the Gullfoss waterfall, and ends in the north near Blönduós. The road traverses the interior between two glaciers, Langjökull and Hofsjökull, and passes through Hveravellir the Hot Spring Fields near the headwaters of the Blanda River³.

Hveravellir is a beautiful geothermal area at the northern edge of the lava field Kjalhraun, with smoking fumaroles and nicely shaped pools of sky-blue boiling water. It is a popular stopover with tourist huts, a meteorological watch (occupied the whole year), and a man made bathing pool. The old route across the lava field continued through the thermal area, which is also frequently referred to in the Sagas. The hot spring area has been protected since 1965 and people are asked to stay on the boardwalk across it. There are a number of walking routes in the vicinity⁴. In the 18th century, the Icelandic outlaw Fjalla-Eyvindur used the Hveravellir hot springs as a settlement. One of the hot spots in this area is still used for bathing.



Figure 46. Hveravellir hot springs and the outlaw settlement memorial.

References:

¹<http://en.wikipedia.org/wiki/Goðafoss>

²<http://en.wikipedia.org/wiki/Akureyri>

³<http://en.wikipedia.org/wiki/Kjölur>

⁴<http://www.hveravellir.is/english.html>

Day 10 (Saturday, August 28th) - Reykjavík

Contributed by Natalia Zakharova

8:00-13:00 Free time in Reykjavík

13:00 Start packing

14:00 Pick-up from the campsite and return the rented camping gear

15:00 Drive to the airport

17:00 Flight FI613 to New York

Site Descriptions

Day highlights:

A group of students attended the Symposium honoring Sigfus Johnsen (a pioneer in ice core research in Greenland) at the University of Iceland. The morning session was devoted to glaciers, ice sheets and climate. Among others, Helgi Björnsson (our guide in Skaftafell on day 6) presented his research on ‘The story of present glaciers in Iceland.’

After the conference, Bryndis Brandsdóttir kindly offered to show the group around the university. We attended a moving science exhibit organized by the Nordic Council and hosted by the University of Iceland at that time. We also visited a new high tech building of the Science Institute.

Reykjavík is the capital and largest city of Iceland with a population of around 120,000 (and over 200,000 in the Greater Reykjavík Area). Its latitude, at 64°08' N, makes it the world's northernmost capital of a sovereign state. It is located on the southern shore of Faxaflói Bay.

Reykjavík is believed to be the location of the first permanent settlement in Iceland established around 870 C.E., but there was no urban development until the 18th century. The city was founded in 1786 as an official trading town and grew steadily over the next decades, as it transformed into a regional and, later, national centre of commerce, population, and governmental activities.

The climate in Reykjavík is relatively mild: temperatures very rarely drop below –15 °C (5 °F) in the winter, due to the influence of the Gulf Stream’s warm waters. The city's coastal location makes it prone to wind. Summers are cool, with temperature fluctuating between 10 and 15° C (50 to 59° F), sometimes exceeding 20° C (68° F). The highest ever recorded temperature in Reykjavík was 26.2° C (79° F), recorded on July 30, 2008, while the lowest ever recorded temperature¹ was –24.5° C (–12° F), recorded on January 21, 1918.



Figure 47. Exploring the moving science exhibit (left) and new Science Institute building (right) at the University of Iceland in Reykjavík.

Hallgrímskirkja is a major landmark and the tallest building in Reykjavík. It is a Lutheran parish church, named after the Icelandic poet and clergyman Hallgrímur Pétursson (1614-1674). Hallgrímur was one of the most influential pastors during the Age of Orthodoxy who wrote many important Lutheran hymns and is the author of Passíusálmur ("Hymns of the Passion")². The design of Hallgrímskirkja is the work of state architect Guðjón Samúelsson and is meant to resemble columnar joints (colonnades) in basaltic lavas. The building is 74.5 m (244 ft) high, and its construction took 39 years (the church was completed in 1986)³.



References:

¹<http://en.wikipedia.org/wiki/Reykjav%C3%ADk>

²<http://www.sacred-destinations.com/iceland/Reykjavik-hallgrimskirkja>

³<http://en.wikipedia.org/wiki/Hallgrimskirkja>

Figure 48. Hallgrímskirkja, the tallest building in Reykjavík.

Acknowledgments

We would like to acknowledge the Stroke Memorial Fund that made this trip possible. We thank Professor Steve Goldstein, the chair of the Department of Earth and Environmental Science, and Professor David Walker for considering and accepting the proposal for the Iceland field trip.

An elaborate trip like this can only happen when there is a huge arsenal of helpful and dedicated people. We want to say thanks to everyone who served on the Iceland Planning Committee for the planning effort which shaped this trip and made it happen: Kat Allen, Amelia Paukert, Dan Huber, Meg Reitz, Pritwiraj Moulik, Shuoshuo Han, Sarah Hale, Rafael Almeida, Claire Bendersky, Lisa Streit, Elizabeth Pierce, and Anastasia Yanchilina. Very special thanks go to Kat Allen for her enthusiasm and tremendous amount of work that she put into this trip! Without Kat's inspiration and participation at all stages of its planning and execution, this trip might have never become a reality. We also thank Amelia Paukert for her significant contribution to organizing our everyday field life and taking care of feeding our hungry crowd for 10 days!

We are very grateful to our field trip leaders, Professor Roger Buck and Dr. Timothy Creyts, for providing scientific insights and expert guidance in the field. Roger's geophysical experience and Tim's expertise in physical glaciology were invaluable. Roger's knowledge of Icelandic culture and language, gained after living in Iceland, considerably enriched our trip. We also thank Roger for participating in our discussions at the preparation seminars and for challenging our curiosity and scientific thinking in the field.

A million thanks go to our Icelandic hosts whose warm hospitality and commitment were truly amazing. We thank Bryndis Brandsdóttir for welcoming us to Iceland and sharing her knowledge of Icelandic seismology. We are also grateful for Bryndis's assistance with obtaining invitations for international students, for meeting and guiding us on the first and last days of the trip, and for thoughtfully providing a supply of useful equipment and delicious coffee when we needed it most! We also thank Helgi Björnsson for taking a whole day off to spend with us in Skaftafell National Park in the rain and shine, and for sharing his impressive expertise on Icelandic glaciers. We thank Hólmfríður (Frida) Sigurðardóttir and Einar Gunnlaugsson for the insightful tour of Hellisheiði Power Plant and CarbFix Project. We also thank Guðmundur Jónasson Travel for helping with the itinerary planning. And last, but not least, we thank our knowledgeable and skillful driver, Trygvvi, who always knew the best route to any destination and patiently bore us for 10 days.

Finally, many thanks go to all participants of the trip for making it a fun and memorable experience, and for taking time to contribute to this guide.

Trip Participants

Photo credits: Meg Reitz



From left to right, top to bottom: Ashley Shuler, Adrienne Smith*, Amy Stypa#, Miriam Marlier*, Nevin Singh#, Chris Hayes*, Danielle Sumy*, Ivan Mihajlov*, Shuoshuo Han*, Dan Huber#, Janet Fang`, Tim Creyts\$, Roger Buck^, Pritwiraj Moulik*, Jason Jweda*, Jen Levy#, Meg Reitz*, Natalia Zakharova*, Amelia Paukert*, Kat Allen*.*

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\$ Postdoctoral Research Scientist, Lamont-Doherty Earth Observatory.

Trip Costs

	ITEM	COST (\$)	# needed	TOTAL COST (\$)	Notes
DEES	Flight	\$848.99	20	\$16,979.80	Booked through Empress, paid for directly by DEES. Iceland 2010 invoice #12800
	Group airport shuttle	\$135.00	2	\$270.00	Booked through Carmel services. (Kat)
	1-Bus				
	2-Campsites				
	3-Fuel				
	4-Blue lagoon entrance				
	5-equipment				4 stoves, 1 tent
DEES	... total:	520		\$10,712.00	Booked through Guðmundur Jónasson Travel, Nenty
DEES	Food			\$3,500.00	Travel advance needed (Amelia)
DEES	Glacial safety/tour guide	42	20	840	We are required to have a safety/tour guide on the glacial hike. http://www.glacierguides.is/
Janet	Personal cost	\$1,568.99	1	(\$1,568.99)	Janet is paying for her expenses.
Students	Participation contribution	700	17	(\$11,900.00)	Checks of \$200 and \$500 have been collected.
Total trip cost				\$31,461.80	
Total DEES contribution				\$17,992.81	
Total student contribution				(\$13,468.99)	

Camp Sites Information

Note: Most showers and other facilities at the campsites are operated with coins (usually 50 kronur), so remember to keep change, you'll need plenty of it!

The group stayed at the following campsites:

Aug 19-20, Aug 27-28 **Reykjavík campsite**

Address: Sundlaugarvegur 32, Reykjavík.

Reykjavík Campsite is conveniently located about 3 km from the city center. Free showers and cooking space are available. Internet access can be found at the nearby hostel (and occasionally, on the campgrounds). The site becomes crowded on the weekends.

Aug 20-21 **Þingvellir campsite**

Camping is permitted in two areas in the Þingvellir National Park: Leirar and Vatnskot. We stayed at Leirar, a small and quiet campsite, which is a 5 minute walk from the Information Center and about half an hour from lake Þingvallavatn and the Parliament site. Vatnskot is located right by lake Þingvallavatn.

Note: Leirar campsite was very windy. Showers had coin operators, but they were disabled so hot showers were free.

Aug 21-22 **Básar campsite**

The campsite is located in a scenic valley under glacial caps. It is a relatively large campsite popular among Icelanders located near the trail to Eyjafjallajökull. A warden is in the area during the summer. There are sinks, showers, indoor and outdoor barbeque, sun decks and a playground. Indoor cooking space is available inside large huts, and 4-minute showers in a generator-powered building are a luxury affordable at 3x100 ISK.

Aug 22-25 **Skaftafell campsite**

The campsite has access to electricity (for a fee, but there are also sockets in bathrooms). Toilets are located in a building next to the visitor center and also two buildings by the campsite. Showers are located in a building next to the visitor center and a building in the middle of the campsite. A washing machine and a dryer are located in a building next to the visitor center. No indoor dining or cooking facilities are designated for campsite visitors. Dish washing can be done in kitchen sinks next to the service buildings. Wireless internet is available on the campsite. Access can be bought at the service desk in the visitor center.

Aug 26-27 **Reykjahlid campsite (by lake Mývatn)**

Located 1 km away from the lake so there are fewer mosquitos here than by the lake (we didn't have any). There are free hot showers, electricity, laundry facilities, picnic tables, and a big kitchen tent. There is also a small store on site.

Menus and Food Budget

Daily Menu for 20 people

**Note: Bonus is the cheapest grocery store and we did most of our shopping there. There is at least one in Reykjavík and one in Egilsstaðir. Be sure to tell the driver at the beginning of the day that you will be needing to shop so he can find an appropriate place on the route.*

Breakfast:

1 large bag muesli
1 large bag granola
½ large box Honey Nut Cheerios
20 small skyr (or equivalent amount in larger containers)
3 liters milk
20 bananas
300 g coffee
10 bags tea
2 dozen eggs (to hard boil)

Lunch:

4 loaves bread
2 large packages pre-sliced deli chicken
2 large packages pre-sliced deli ham
3 packages pre-sliced deli salami
2 large packages sliced cheese
½ jar mayonnaise
½ jar mustard
½ head iceberg lettuce or 1 head regular lettuce
10 tomatoes
2 cucumbers
1 ½ jars peanut butter (this gets used for breakfast, too)
1 jar jam
20 apples

Snacks:

4 bags chips
2 boxes crackers
5 large bags cookies
2 large bags peanuts
1 large bag raisins
2 bags chocolate chips
15 packages hot chocolate
2 jugs juice

Dinner:

Entrees differed each night-

Night 1 – Dinner out in Reykjavík at Sjavarbarinn seafood buffet

Night 2 – Chicken fajitas with rice, refried beans and tortillas

Night 3 – Spaghetti

Night 4 – Chili

Night 5 – Fish stir-fry with couscous

Night 6 – Fish curry with rice

Night 7 – Chicken pesto with pasta

Night 8 – Fish tacos with rice, beans, and tortillas

Night 9 – Grilled lamb and zucchini

When cooking dinners, plan on

3-4 kilos meat (depending on whether meat or grain is the backbone of the meal)

2.5 kilos pasta or 1.5 kilos rice

**Note: People are HUNGRY by the end of the day. When in doubt, err on the generous side. Pretty much everything you cook will get eaten eventually.*

Each dinner was also accompanied by salad:

3 heads lettuce

6 tomatoes

2 cucumbers

1 jar salad dressing

Budget

Total food budget: \$2752

Dinner out in Reykjavík \$389

All other food \$2363

Note- this does not include breakfast the first day, which was provided by Bryndis from the University of Iceland

Total cost of food: \$138 per person,
or ~ \$14 per person per day

Cooking Equipment

2 large coolers, lantern, and 12 volt to AC inverter were also purchased for \$242, but are now available for future use for free.

Rented 4 burners and gas from tour company, brought pots and pans and utensils from the US.

Suggested Packing List

Asterisks (*) indicate *mandatory* items

Most Important:

- Passport*
- Sleeping Bag*
- Sleeping Pad (thermarest, etc)*
- Good Hiking Boots (sturdy for cramp-ons)*
- Wool Socks (lots of them)

Personal Items:

- Tissues
- Bug Repellent*
- Sunscreen
- Lip balm with sunscreen
- Sunglasses that wrap around the eyes
- Toiletries*
- Bottle Opener
- Bus/Plane Entertainment (iPod, books, cards, small board games, etc.)
- Travel Towel (or other towel)*
- Baby Wipes
- First Aid Kit
- Folding Chairs
- International phone/sim card for Iceland
- Beer (no beer in Iceland, only just started brewing their own)

Clothes:

- Rain jacket (think polyester and gore-tex)*
- Rain pants*
- Waterproof hiking boots (so important it's listed twice) *
- Wool socks*
- Gaiters (if you have them)
- Sneakers
- Swimming Suit
- Base layer (think Under Armour or polypropylene)*
- Hats (both for sun protection and warmth)*
- Mittens/gloves
- Something for nice (60F and sunny) days
- A normal outfit (one day in Reykjavík)

“Be prepared for horizontal rain/snow as well as nice weather.”

Equipment:

- Tent (with rainfly)*

- Groundcloth for under tent*
- Personal knife, fork, spoon, plate, bowl, cup, coffee mug*
- Equipment you signed up for*
- Camera and batteries
- Universal Adapters
- Field Notebook
- Pencils/Pens
- Headlamp/Flashlight*
- Water Bottles* (or buy in Reykjavík)
- Rock Hammer and Pocket Knife (careful on the plane)
- GPS
- Extra batteries
- Day Pack (to hold water, lunch, camera, notebook, etc.)*

Afterword

Our field trip to Iceland was a very insightful and memorable experience. It provided an exciting opportunity to observe diverse geologic and environmental processes, and enriched our understanding of Earth and Environmental Sciences. The student field trips are crucial for developing observational and interpretational skills, and for learning to plan field activities from scratch. They also provide a unique opportunity for team work and building relationships with peers across disciplines. We are truly thankful to the Department of Earth and Environmental Sciences for supporting the student-led field trips, and we hope that this tradition will continue far into the future.

