Around the Hengill Triple Junction

A three-plate fieldtrip on October 16, 2019

A field guide compiled by Páll Einarsson

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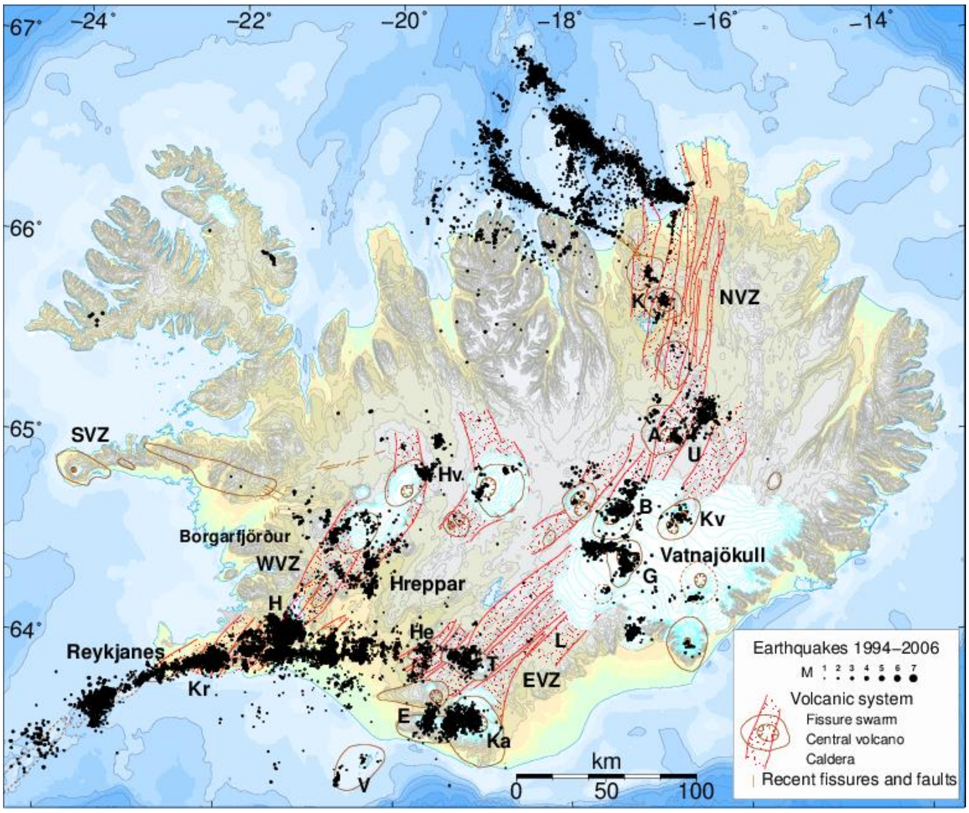
Leave Selfoss at 13 h

The triple junction

The interaction of the Iceland hot spot with the Mid-Atlantic plate boundary leads to frequent ridge jumps. New rift zones are generated when the plate boundary drifts too far from the central part of the hot spot. Such a rift jump is in progress at the present time in South Iceland. A crustal fragment generated as a part of the Eurasia Plate has been separated from it by the new rift, the Eastern Volcanic Zone, whereas the old rift, the Western Volcanic Zone, is gradually becoming inactive. This fragment qualifies as a microplate, the Hreppar Microplate, forming two triple junctions with the two major plates, the North America and Eurasia Plates. On our field trip we will visit all three plates and cross all three arms of the southern triple junction. Selfoss is located right at the plate boundary between the Eurasia Plate and the Hreppar Microplate, a bit on the south side so our trip begins on the Eurasia Plate.

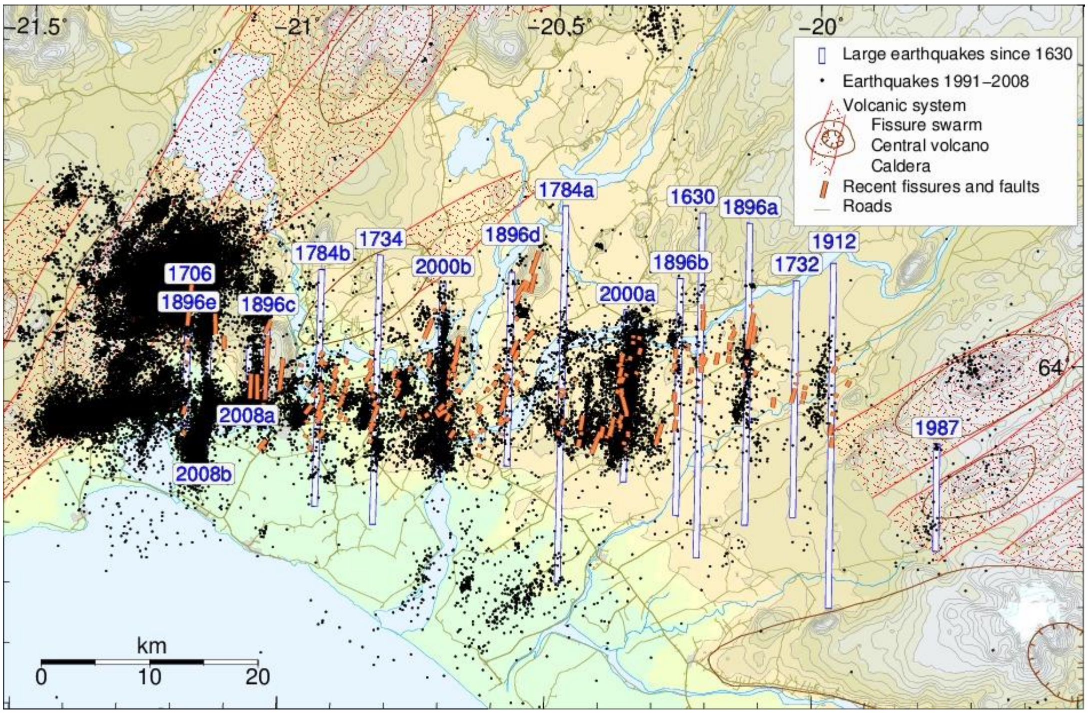


The plate boundaries in Iceland are marked by the volcanic systems and epicenters of earthquakes. Hreppar Microplate is located between the two volcanic zones of South Iceland. The Hengill Triple Junction is marked with H. From Einarsson (2015).

Selfoss – Hveragerði – Hellisheiði

The South Iceland Seismic Zone

Most destructive earthquakes in Icelandic history originate within a zone that bridges the gap between the two subparallel rift zones, the Western and Eastern Volcanic Zones. It marks the southern margin of the Hreppar Microplate and takes up the transform motion between the Reykjanes Peninsula oblique rift and the Eastern Volcanic Zone. It is a zone of high seismicity and large earthquakes (M~7), and has been defined by destruction areas of historical earthquakes, surface ruptures and instrumentally determined epicenters. It is oriented E-W and is 10-15 km wide. Destruction areas of individual earthquakes and surface faulting show, however, that each event is associated with faulting on N-S striking planes, perpendicular to the main zone. Destruction areas are elongate in the N-S direction, and detailed mapping of surface fractures reveals N-S trending arrays of en echelon tension fractures indicating right-lateral faulting. The over-all left-lateral transform motion along the zone thus appears to be accommodated by right-lateral faulting on many parallel, transverse faults and counterclockwise rotation of the blocks between them, "bookshelf faulting". We cross several of these bookshelf faults on our way from Selfoss to Hellisheiði. The first one, active in 1896, passes through the mountain Ingólfsfjall and just west of Selfoss. Another one, active in 2008, crosses the road at Kögunarhóll. You may notice a bump in the road as it crosses the fault.



Source faults of historical damaging earthquakes in the South Iceland Seismic Zone. From Einarsson (2015).

Earthquake sequences. Earthquakes in South Iceland tend to occur in major sequences in which most of the zone is affected. These sequences tend to last from a few days to more than 3 years. Each sequence typically begins with a magnitude 7 event in the eastern part of the zone, followed by smaller events farther west. Sequences of this type occurred in 1896, 1784, 1732-34, 1630-33, 1389-91, 1339 and 1294. The sequences thus occur at intervals that range between 45 and 112 years, and it has been argued that a complete strain release of the whole zone is accomplished in about 140 years. The 1896 earthquakes were followed by a long quiet interval, which in 1985 led to a long-term forecast of a major earthquake sequence within the next decades.

The earthquakes of June 2000. The forecast of 1985 was fulfilled in June 2000 when two magnitude 6.5 events occurred in the central part of the zone. The sequence started on June 17 with a magnitude 6.5 event in the eastern part of the zone which was immediately followed by triggered activity along at least a 80 km long stretch of the plate boundary to the west. The second mainshock of about the same magnitude occurred about 20 km west of the first one on June 21. It was clearly preceded by clustering of microearthquakes in the coming hypocenter.

The mainshocks of the sequence occurred on N-S striking faults, transverse to the zone itself. The sense of faulting was right-lateral strike-slip. The events confirmed the model of “bookshelf faulting” for the SISZ. The two mainshocks occurred on pre-existing faults and were accompanied by surface ruptures expressed by en echelon tension gashes and push-up structures typical for strike-slip faults. The main zones of rupture were about 15 km long, had a N-S trend and coincided with the epicentral distributions. Fault displcements were of the order of 0.1-1 m. Faulting along conjugate faults was also observed, but was less pronounced than the main rupture zones.

The observed faulting structures were clearly smaller than those observed in association with earlier historical earthquakes such as those of 1630, 1784, 1896 and 1912. These earlier earthquakes were therefore larger than the earthquakes of June 2000.

High acceleration was recorded by a network of strong-motion accelerographs. The highest recorded acceleration was 0.83 g, recorded by an instrument in a bridge abutment within 3 km of the source fault of the June 21 event. Indications of acceleration in excess of 1 g, such as overturned stones, were abundant in the source areas.

In light of the high accelerations the damage to man-made structures was surprisingly low. Only 20 houses were deemed unusable, none of them collapsed, however. Damage was strongly correlated with age of the buildings. There were no casualties and very little injury to humans or animals.

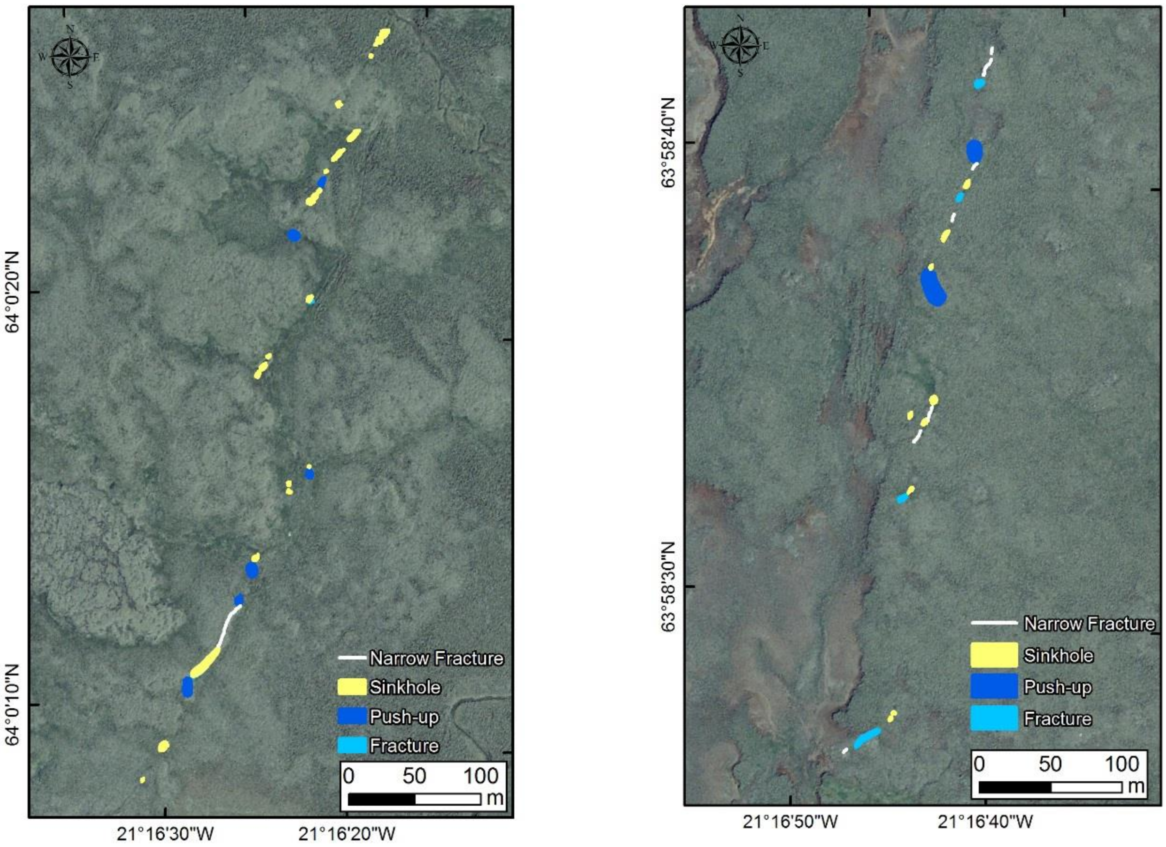
The May 29, 2008, earthquakes. The earthquake sequence of June 2000 was relatively small and only relieved about ¼ of the potential seismic moment accumulated by plate movements since the 1896-1912 sequence. Continuation of the 2000 earthquakes was therefore anticipated. The Ölfus district was considered the most likely source region. The earthquake took place on May 29, 2008 in the afternoon. Foreshocks occurred beneath the SW corner of the Ingólfsfjall mountain, followed about an hour later by a mainshock that was widely felt in Iceland. The mainshock was a double event. The first part occurred on a N-S fault at the location of the foreshocks and was followed within seconds by an even larger slip on another

N-S fault a few kilometers to the west of the first one. The combined event amounts to a magnitude 6.3 (Mw) earthquake. Surface effects of the earthquake were substantial. Rock falls were abundant, sand boils were seen near the Ölfusá river, shattered rock, overturned and moved rocks were observed. Surface ruptures were considerably smaller than in the 2000 earthquakes, consistent with the smaller magnitude. Damage was, however, much larger this time, mainly because of the proximity of the event to two towns, Selfoss and Hveragerði. Beside a few barns no houses collapsed. There were no casualties and only few people suffered injuries in spite of rather heavy material damage.

The major earthquake sequence, 1896-1912. The earthquake sequence of 1896-1912 is sometimes taken as the type example of South Iceland sequences. After a relatively quiet interval of 112 years the sequence began with a M 6.9 earthquake in the eastern part of the seismic zone on August 26. There were apparently no foreshocks or other warning signs, and people were totally unprepared for the disaster. A second earthquake struck in the early morning of August 27. This event apparently was of similar magnitude and originated on a fault west of the first one. The initial burst of activity was followed by a period of relative quiescence. On September 5 two earthquakes occurred within a short interval, one of M 6 near Selfoss and the other of M 6.5 in the Skeið district near the center of the seismic zone. The activity migrated farther west. A M 6 earthquake hit the Ölfus district west of Selfoss the following morning. An earthquake of M 7 occurred in 1912 east of the source areas of the 1896 earthquakes. The destruction area was larger than for any of the 1896 events, but the area was not as densely populated.

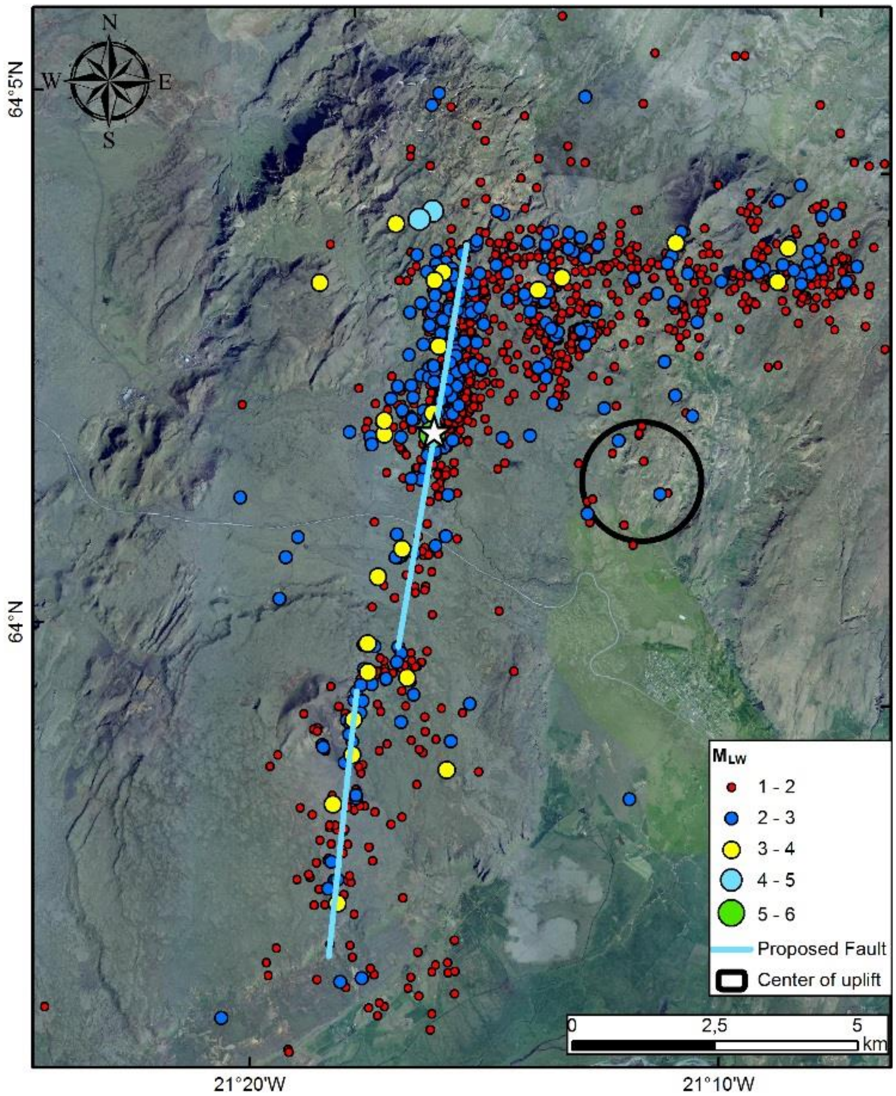
The Hengill Triple Junction area

Our route goes directly through the area where the three arms of the plate boundary join and their deformation areas overlap, i.e. the Reykjanes Peninsula Oblique Rift, the Western Volcanic Zone, and the South Iceland Seismic Zone. The faulting pattern here is complicated and we see both typical rift structures, such as normal faults, graben and open fissures, and strike-slip structures, such as en-echelon arrays of tension gashes and push-up hillocks.



Typical surface expressions of strike-slip faulting along N-S striking faults at the triple junction. From Steigerwald et al. (2018).

1994-1998 inflation and earthquakes of Hrómundartindur. The Hengill area at the triple junction between the Reykjanes Peninsula, the Western Volcanic Zone and the South Iceland Seismic Zone shows persistent seismic activity, mostly of small magnitude. It has been shown that a considerable part of this activity is related to heat mining and thermal contraction of hot crustal rocks due to circulating hydrothermal fluids. The period 1994-1998 was very unusual in this area. The seismicity was very high, with numerous felt earthquakes, particularly in the town Hveragerði. This activity was accompanied by crustal uplift and expansion. It was shown that the increased activity and uplift was caused by injection of a small volume of magma into the roots of the Hrómundartindur volcanic system, at 6 km depth. The activity culminated with a few M~5 earthquakes in 1998 and stopped shortly thereafter. The earthquakes of 1998 had a clear N-S distribution and had fault plane solutions of strike-slip type. Surface ruptures were also consistent with this type of faulting.



Earthquakes of June 1998 at the culmination of the inflation at Hrómundartindur. The circle marks the inflation center according to Feigl et al. (2000). From Steigerwald et al. (2018).

The Hellisheiði power station

A power station harnessing the geothermal power of the southern flank of the Hengill central volcano became operational in 2006. The capacity of the station is 303 MW electrical and 133 MW thermal. Effluent fluid is pumped back into the crust, a procedure that triggers earthquakes on nearby faults. The company´s practice of issuing warnings to the neighboring population prior to expected earthquakes appears to be unique in the world. An experiment to inject CO_2 back into the crust has been conducted at the Hellisheiði plant for more than a decade, the Carbfix Project. CO_2 has been successfully dissolved in water, injected into drillholes and mineralized into solid carbonite in the basaltic crust. This process will be developed into industrial practice in the nearest future in an effort to reduce harmful impact of antropogenic CO_2 in the atmosphere.

The Hellisheiði Power Station supplies energy for space heating in Reykjavík, 133 MW thermal, and generates electricity for the general grid, 303 MW electrical.

Stop: Eruption fissure of 2000 y.b.p. View over triple junction
The latest eruption of the Hengill volcanic system occurred about 2000 years ago. It was a lava eruption from fissures, both on the southern and the northern fissure swarm (Saemundsson, 1992). Lava, the Nesjahraun lava, flowed to the lowland on the south side and into the Þingvallavatn lake on the north side of the central volcano. An island was formed in the lake. We make a short hike to the rim of one of the craters and observe the eruptive fissure, individual craters, and lava flowing from them.

The flat area to the east is the triple junction area. We see a variety of volcanic landforms, both sub-glacial and sub-aerial. Hyaloclastite ridges (tindars) are formed by fissure eruptions under glacier, lava flows and lava shields by eruptions on ice-free ground. A tuya is formed by a central eruption under glacier, producing pillow lava or hyaloclastite. Emerging from the glacier the eruption turns into an effusive eruption forming a lava flow on top of the pillow mount, see the flat-topped Stóri-Meitill.

The Nesjahraun lava is underlain by the Hagavíkurhraun lava, thought to have formed in an eruption about 5000 years ago, also on a fissure on the north fissure swarm. Its eruptive fissure is very near the Nesjahraun fissure and is difficult to separate from it.

An inter-glacial lava shield is visible in the SW, Skálafell – Trölladalur. Also the Bitra ¼ lava shield, in the NE.

The Christianity lava
One of the Sagas has a description of an eruption in it. The eruption occurred in the year 1000 and is described in connection with the remarkable event when the issue of a change of faith was discussed at the parlament meeting in Thingvellir, changing from the old Norse faith in Æsir to Christianity. This change was considered urgent by christian people because of the imminent end of the world in the year 1000. The discussion was heated, but as the attendants of the parlament were ready to take to their weapons a messenger brought the news that an

eruption had broken out and the lava was flowing towards the farm of one of the proponents of christianity. "No wonder", the people said. "The gods are angry because we are considering this outrageous thing". To which one of the chieftains responded: "To whom were the gods angry when the lava burned that we are now standing on?" It became clear to everybody present that the gods did not care one way or the other. This story is written in the thirteenth century and is remarkable for several reasons:

1. Icelanders at the time seem to have had a remarkably naturalistic view of eruptions. The argument against the influence of the gods worked.
2. The argument worked not only for the chieftains and leaders, but for everybody.
3. The public knew that lavas were made by eruptions, in this case prehistoric. Learned men in continental Europe were arguing about this several centuries later, e.g. neptunists and plutonists.

We will cross the Christianity lava just west of the Hellisheiði Power Plant.

Stop: The Brennisteinsfjöll fissure swarm

The fissure swarms of the volcanic systems of the Reykjanes Peninsula Oblique Rift extend into the North America Plate, where they gradually die out towards NE. Good examples of normal faulting in a fissure swarm is provided at Sandskeið, where the road crosses the Brennisteinsfjöll fissure swarm. The total trow of the fault here is about 15 m but a step in the middle of the scarp seems to mark the latest displacement of the fault, possibly occurring in the latest known rifting episode, around 1240 AD.

Leitin lava and the Rauðhólar rootless cones

The road towards Reykjavík is almost parallel to a stream of lava, a branch of the Leitin lava flow that issued from a crater near the axis of the Reykjanes Peninsula plate boundary about 4600 years ago (Sinton et al., 2005). This branch flows into the sea in Reykjavík. The main body of the lava flowed southwards and entered the ocean on the south coast of the peninsula. The road (and the lava) crosses two of the fissure swarms of the Reykjanes Peninsula Oblique Rift on the way, the Brennisteinsfjöll fissure swarm and the Krísuvík fissure swarm. A shallow sedimentary basin (Sandskeið) is formed in the former, but in the latter the lava apparently flowed across a swampy area. A group of rootless cones were formed, Rauðhólar. A good part of them was used for construction during WWII, e.g. for the Reykjavík Airport, bu the craters have since been under protection.

Nesjavellir road

Shortly befor Rauðhólar we turn off the main road and head towards Nesjavellir, on the north flank of Hengill volcano. The road is parallel to the hot-water pipeline that brings water from the Nesjavellir Power Plant to Reykjavík for space heating. It takes us across lava plains from warm periods during the Pleistocene, striated lavas erupted on ice-free surface. We cross the Brennisteinsfjöll fissure swarm again. The lava shields of Eiturhóll and Hæðir can be identified before we enter the hyaloclastite ridges (tindars) and heavily faulted area in the northern fissure swarm of Hengill.

The Nesjavellir Power Plant was built in the 1990ies and uses the geothermal power of 21 wells. The electrical power production is about 120 MW and the thermal power of about 300 MW is used to heat houses in Reykjavík.

Stop: Overlooking Nesjavellir

A variety of tectonic and magmatic structures can be viewed from a platform on the west side of the 160 m deep Nesjavellir graban, a part of the northern fissure swarm of the Hengill volcanic system. The floor of the graben is covered by two lava flows erupted from fissures along the western boundary. The younger one is the Nesjahraun lava, considered to be from the same eruption as the lava we visited on the south side of the central volcano, about 2000 years old. We see the Sandey island in the lake, formed in the same eruption. In the eastern part of the graben an older lava flow is exposed, the Hagavíkurhraun lava, erupted about 5000 years ago (Sinton et al. 2005), probably at the same time as a lava on the south side of Hengill. A littoral cone at the shoree of Þingvallavatn lake, Grámelur, probably formed at this time too.

Several lava shields can be observed from this view point. Most prominent is Skjaldbreiður, north of the lake, formed in a slow and persistent eruption about 8000 – 9000 years ago. The very flat Lyngdalsheiði lava shield on the east side of the lake is interglacial in age.

Tuyas and tindars can be seen in various versions, Hrafnabjörg, Ármannsfell, Tindaskagi, Kálfstindar, Miðfell, etc

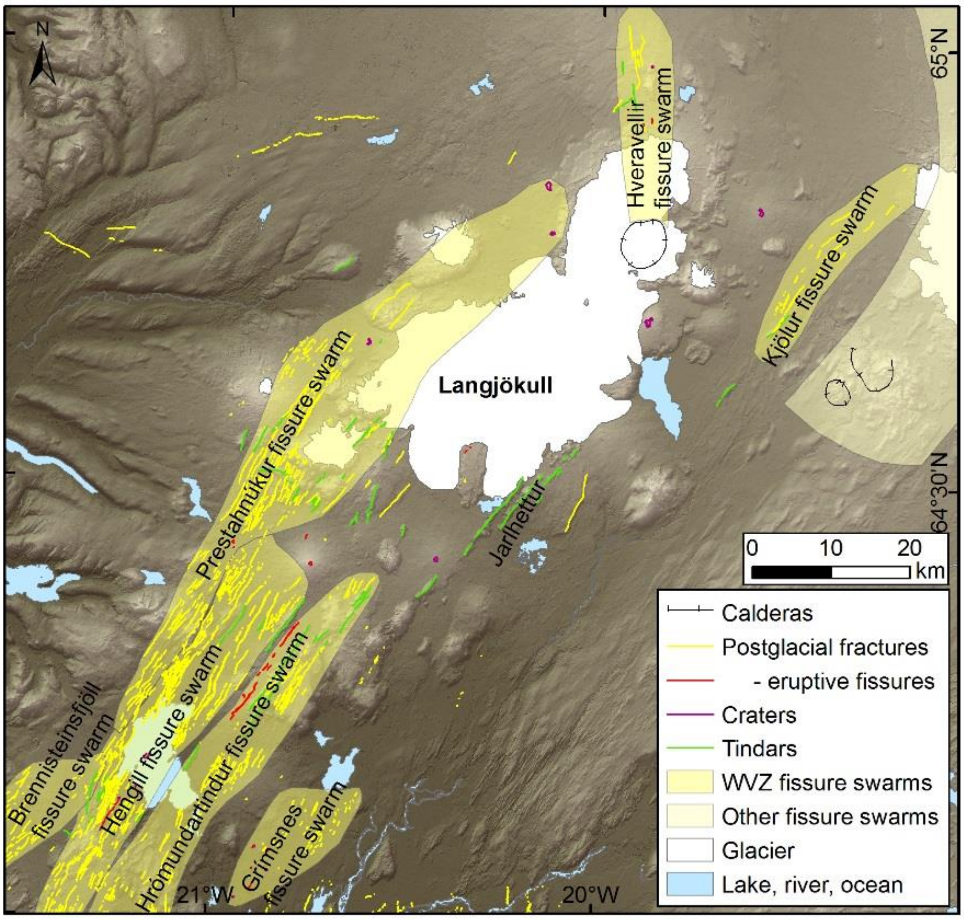
Fault pattern around the Þingvallavatn lake is complex, produced by interfingering of at least three fissure swarms, the Hengill, Prestahnúkur, and Hrómundartindur volcanic systems (Hjartardóttir et al., 2016).

Nesjavellir – Þingvellir

We take the road along the western shore of Þingvallavatn lake and appreciate the throw of the boundary faults of the Hengill fissure swarm, Jórukleif fault. In the distance we see how the fissure swarm dies out towards the north on the slopes of the Skjaldbreiður lava shield.

The faults of the Hrómundartindur fissure swarm can be seen on the east side of the lake, on the gentle slopes of the Lyngdalsheiði lava shield. On the road to Þingvellir we then see the western boundary faults of the Prestahnúkur fissure swarm, and note how they die out towards the south.

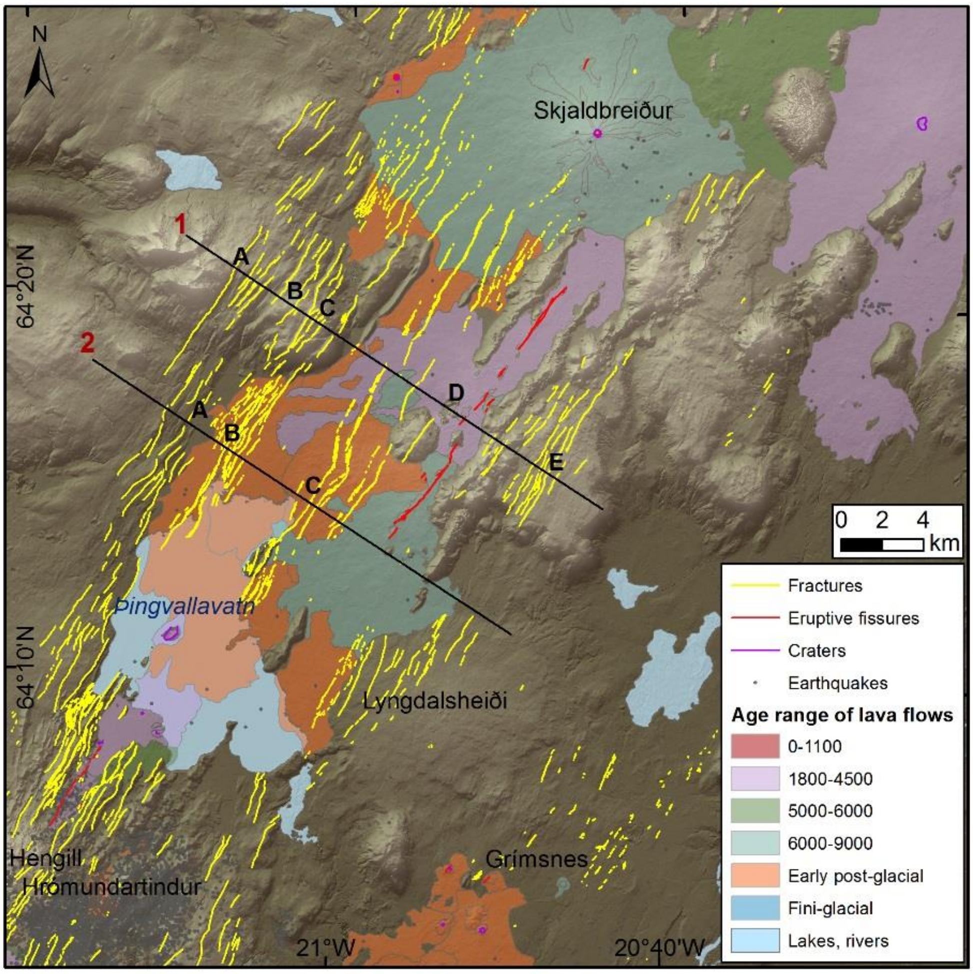
We pass the busy tourist trap of Almannagjá and the historical parlament meeting place, where Alþingi was founded in 930 AD.



Fissure swarms and fractures of the Western Volcanic Zone. From Hjartardóttir et al. (2016).

Stop: Hrafnagjá (near profile 2, site C in Figure)

The road takes us across the 4 km wide and 30 m deep Þingvellir graben, and we stop at the most prominent eastern boundary fault, Hrafnagjá (gjá means fissure in Icelandic). The widening of the Western Volcanic Zone is only a fraction of the relative plate velocity between the major plates, North America and Eurasia Plates. Estimates of this fraction do not all agree. Recent GPS-measurements indicate a widening of 4-5 mm per year, decreasing towards north, becoming almost zero north of Langjökull glacier (LaFemina et al., 2005; Einarsson, 2008). New InSAR studies seem to indicate even lower rates (Drouin and Sigmundsson, 2019).



Lavas and eruption sites around Þingvallavatn lake. From Hjartardóttir et al. (2016). Lava flows from Sinton et al. (2005).

Þingvellir – Laugarvatn – Geysir

We leave the rift zone behind and head into the interior of the Hreppar Microplate, towards Geysir where we have supper. Tuyas and tindars are seen on the left side of the bus, products of sub-glacial eruptive activity during the Pleistocene. The South Iceland lowland is on our right, ancient outwash plains of glacial rivers. Strandlines can be seen here and there along the edge of the highland, evidence of higher sea level at the end of last glaciation. The crust rose by isostatic rebound when the glaciers disappeared, lowering the relative sea level, typically about 60 m in this area. The full rise of the crust appears to have taken place in less than thousand years, evidence for the low viscosity of the lower crust and upper mantle beneath Iceland.

Geothermal activity is common along our route along the margin of the volcanic rift zone. This low-temperature activity is heavily utilized for house heating and greenhouse farming. The most active area is the Geysir area where we have our supper. This area contains several hot springs, including the very active geysir Strokkur that erupts every few minutes, and the Great Geysir of ancient fame.

Supper at Geysir

Geysir – back to Selfoss

We pass several places of interest on our way from Geysir back to Selfoss. ***Skálholt*** was for centuries the cultural center of Iceland. It was the main school of the country and seat of the bishop from the time when the Iceland turned Christian until 1784 when an earthquake devastated the place. Then both the bishop and the school moved to Reykjavík, where a town was beginning to form. A few years later, in 1789, an earthquake swarm hit Þingvellir, most likely caused by a dike intrusion from Hengill. The meeting place of the parlament subsided and became unusable. Alþingi was then also moved to Reykjavík. Thus, within a few years both the political and cultural centers moved to Reykjavík which then became the capital of Iceland.

We drive through the ***Grímsnes volcanic system***, a group of several lava flows erupted from short fissures 6000-9000 years ago. Most of them appear to be from the earlier part of this period. The tectonic position of this system is a bit enigmatic. Most authors consider it to be an outlier of the Western Volcanic Zone, but there also seem to be some relation to the strike-slip faults of the South Iceland Seismic Zone, that is immediately south of Grímsnes.

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