Feature

Iceland's best kept secret

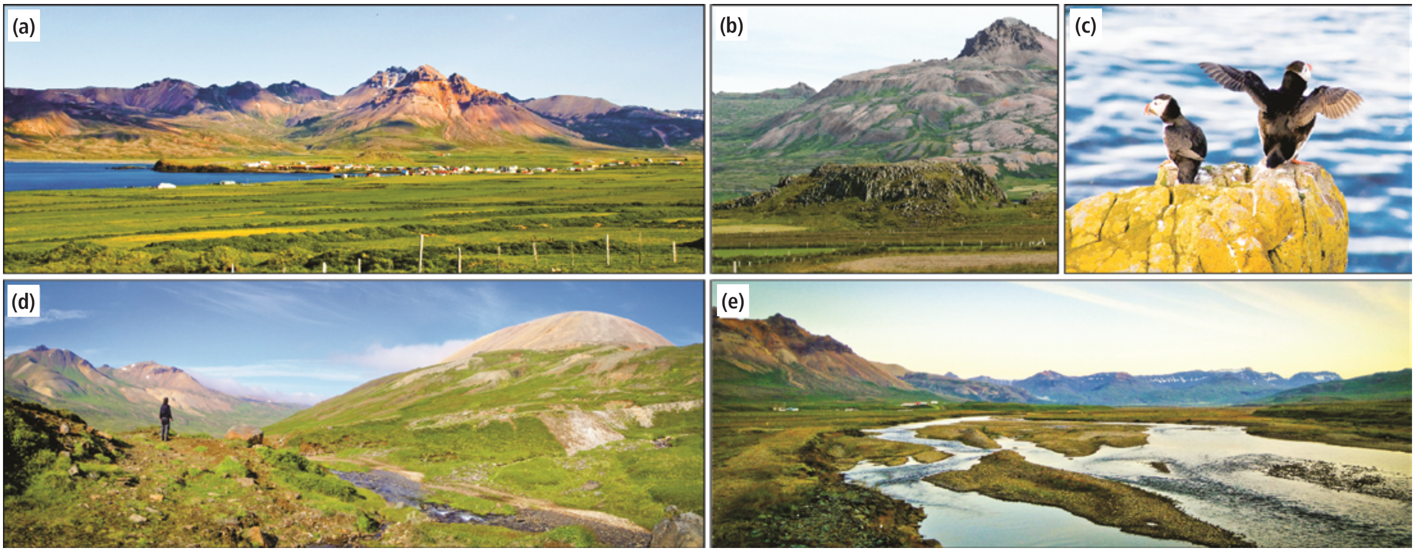
The 'forgotten fjords' and 'deserted inlets' of NE-Iceland, in the region between Borgarfjörður Eystri and Loðmundarfjörður, are not only prominent because of their pristine landscape, their alleged elfin settlements, and the puffins that breed in the harbour, but also for their magnificent geology. From a geological point of view, the area may hold Iceland's best kept geological secret. The greater Borgarfjörður Eystri area hosts mountain chains that consist of voluminous and colourful silicic rocks that are concentrated within a surprisingly small area (Fig. 1), and that represent the second-most voluminous occurrence of silicic rocks in the whole of Iceland. In particular, the presence of unusually large volumes of ignimbrite sheets documents extremely violent eruptions during the Neogene, which is atypical for this geotectonic setting. As a group of geoscientists from Uppsala University (Sweden) and the Nordic Volcanological Center (NordVulk, Iceland) we set out to explore this remote place, with the aim of collecting material that may allow us to unravel the petrogenesis of these large volumes of silicic rocks. This effort could provide an answer to a long-standing petrological dilemma; the question of how silicic continental crust is initially created. Here we document on our geological journey, our field strategy, and describe our field work in the remote valleys of NE-Iceland.

Sylvia E. Berg[1,2], Valentin R. Troll[2], Steffi Burchardt[2], Morten S. Riishuus[1], Michael Krumbholz[2] and Ludvik E. Gústafsson[3]

[1]Nordic Volcanological Centre. Institute of Earth Sciences, University of Iceland, Sturlugata 7, Askja, 101 Reykjavik.
sylvia.berg@geo.uu.se
[2]Department of Earth Sciences, CEMPEG, Uppsala University, Villavägen 16, 752 36 Uppsala, Sweden.
valentin.troll@geo.uu.se
[3]Samband Islenskra Sveitarfélag, Borgartúni 30, pósthólf 8100, 128 Reykjavik, Iceland

Iceland makes for an ideal natural laboratory to unravel the occurrence of evolved felsic rocks (e.g. rhyolites) that are associated with basaltic igneous provinces, as it has traditionally been held as a type locality for 'bimodal' (i.e. mafic–felsic) volcanism. The 'Bunsen–Daly' compositional gap was recognized by R. Bunsen in the 1850s and later expanded on by R. Daly in the early twentieth century and by T. Barth and collaborators in the late 1930s. This compositional bimodality of volcanic matter is often identified on ocean islands, and is a fundamental issue in petrology. The apparent bimodal magmatism, and hence scarcity of intermediate compositions in Iceland, is very difficult to reconcile with N. Bowen's fractional crystallization series as the dominant process driving magmatic differentiation. Therefore, hydrothermal alteration and subsequent crustal melting has been also thought to play a significant role in this setting, and it is now widely suggested that rhyolites in Iceland can be generated in at least two ways: (1) by fractional crystallization; and (2) by partial melting of hydrated basalts at shallow crustal levels, e.g. ≥ 2–3 km depth.

This concept was underlined by, for example, the work of MacDonald and co-workers, and Sigurdsson & Sparks in the 1980s, and later by Gunnarson and co-workers in the late 1990s. On the other hand, in the mid-1960s Carmichael documented compelling evidence for closed-system fractional crystallization as the main cause of rhyolite petrogenesis at Thingmúli central volcano in eastern Iceland. According to Bowen's reaction series, however, fractional crystallization is unlikely to produce large volumes of silicic rocks, as only ~5–10 parts rhyolite can be distilled from 100 parts basalt. In our field area in Borgarfjörður Eystri, in the late 1980s Gústafsson recognized that silicic rocks represent 20–25 percent of the total rock mass exposed and, hence, fractional crystallization alone might not to be the sole process responsible for rhyolite petrogenesis here. Crustal melting may also have made a contribution and is thought to occur when voluminous accumulations of basalts in mature rift zones undergo relatively rapid burial during crustal accretion. During this burial the basaltic



lavas experience hydrothermal alteration and an associated metamorphism that can reach up to amphibolite facies. In the vicinity of additional heat sources, e.g. a basaltic intrusion, partial melting will set in locally. This model was put forward by Palmason in the 1970s and 1980s. However, this hypothesis is also, in a sense, problematic. It cannot explain the discrete (i.e. non-continuous) occurrence of rhyolites along the rift zone, as burial and basaltic activity are likely to be ongoing processes along the entire rift.

In addition to these two widely recognized hypotheses above, there may be a third way of generating rhyolite in this part of Iceland: the recycling of old pre-Icelandic crust. Most intriguingly, geophysical sound wave measurements by Foulger in 2006 and by Bjarnason & Schmeling in 2009, have shown that the crust underlying this part of north-east Iceland is abnormally thick compared to the rest of the country and to oceanic islands in general. In view of this anomaly, it has been suggested that a significantly different crustal structure characterizes this area. Partial melting of an underlying fragment of, for example, old continental or oceanic crust, could in part explain the abnormally voluminous silicic output of the area. In 2007, Paquette and collaborators reported on zircons from the region that implied the possible existence of an old, submerged Mesozoic sliver of, e.g. Jurassic volcanics at depth, which could be a part of the southerly extending Jan Mayen ridge (or microcontinent) that was documented by Foulger in 2006. However, there are other theories on the origin and formation of such a crustal sliver. Continental crust originating from Greenland is also possible, e.g. a crustal sliver torn off during the opening of the North Atlantic and subsequently trapped underneath a gradually emerging Iceland. A hidden fragment of Greenland continental crust under north-east Iceland may be comparable to, for example, the microcontinent that Richardson and co-workers propose underlies the Faroe Islands, and could be a key factor in generating felsic magmas in this region of Iceland.

This controversy on rhyolite petrogenesis forms the basis for our in-depth investigation. We employed an integrated petrological, textural, experimental and in-situ isotope approach to produce a comprehensive and quantitative analysis of rhyolite petrogenesis, with the aim of developing a model for the temporal, structural and geochemical evolution of the silicic volcanism in north-east Iceland. This will feed into a broader understanding of magmatic processes and to how the formation of 'felsic crust' in basalt-dominated tectonic settings such as Iceland is achieved. On a more local scale, the results will also likely help us to better understand the processes at work beneath active Icelandic volcanoes such as Katla, Hekla and Askja.

The field area

Iceland is one of the most volcanically active places on Earth, and the volcanic centres and fissure swarms along the present-day rift-zone draw considerable scientific interest. This study is essential to keep the country prepared and warned of future eruptions. However, many of the extinct and eroded central volcanoes created during the formation of Iceland, including those in the northeastern fjords (13–12 Ma), have often been left unexplored from a geochemical perspective. Yet they might hold the key to an understanding of the processes within the interior of the current rift and could offer insight into the formation mechanisms and evolution of the central volcanoes. Indeed, the greater Borgarfjörður Eystri area in north-east Iceland has not been well characterised, geologically. Walker and his co-worker's extensive mapping of the Neogene flood lavas and central volcanoes of east Iceland in the 1960s never ventured

Fig. 1. **a.** The remote village Bakkagerði in Borgarfjörður Eystri, is surrounded by magnificent colourful mountains that consist of mostly silicic rocks. **b.** The elfin hill near Bakkagerði; widely held to be the residence of the Queen of the Icelandic elfins. **c.** Puffins breed at the harbour during the short summer. **d.** Breiðavik valley, with the 'white mountain' Hvítafjall to the right and colourful mountains composed of rhyolite lavas to the left. **e.** Fjardará, the main river running through Borgarfjörður Eystri valley.

this far to the north-east, and neither has this area drawn particular research attention in later years. In the mid-1950s the Scottish geologist Dearnley made some tentative investigations in the area around Loðmundarfjörður, but it was not before the mid-1980s that a detailed geological map and a first petrographic description of the area were produced by Gústafsson. Almost 30 years later, our group began to work in the area, focusing initially on the structures of the volcanoes, and extending now to petrography, mineral chemistry, stable and radiogenic isotope systematics, and to the geochronology of these rocks. The central volcanoes of north-east Iceland are probably amongst the oldest central volcanoes on the island, but have not yet been accurately dated apart from two reconnaissance ages for Borgarfjörður Eystri that were recently determined at 12.5 ± 0.6 and 13.1 ± 0.2 Ma by Martin and collaborators.

The area between Borgarfjörður Eystri and Loðmundarfjörður further south (see Fig. 2) comprises several extinct volcanic centres that were contemporaneously and successively active within a Neogene rift zone. From north to south, these include: Dyrfjöll, Breiðavik, Kaekjuskörð, Herfell and Álftavik-Seydisfjörður. The Dyrfjöll volcano alone had at least two eruptive centres, one in the Dyrfjöll mountains and one in Njarðvik cove, and with at least five different volcanic phases, of which at least two were dominantly silicic. These were explosive and of a degree unusual for Iceland, producing collapse calderas and large volumes of ignimbrites that provide a marked contrast to the dark basaltic rocks common on Iceland (Fig. 1). Several additional ignimbrite sheets south of the Dyrfjöll volcano also bear witness to the explosive past of the Neogene volcanism in this region. Some of them are found in locations so remote from the dirt tracks that they remain virtually unexplored in a petrological and geochemical context. The famed Hvítserkur ignimbrite, however, is a landmark of north-east Iceland, and is one of the largest ignimbrite sheets in the country. The prominent and light coloured mountain exposures (Fig. 3) record the highly explosive volcanic activity that was succeeded by renewed basaltic volcanism evident from basaltic dykes criss-crossing the Hvítserkur ignimbrite. Many of the dykes terminate in a pillow-lava breccia overlying the (caldera-fill) ignimbrite, implying the presence of a caldera lake at some point after its eruption. The area also boasts magnificent exposures of inclined sheet swarms, sub-volcanic rhyolite domes, and silicic feeder dykes, as well as associated eruption sites (Fig. 4), offering a great variety of intrusive and extrusive rock types to be collected, described and analysed.

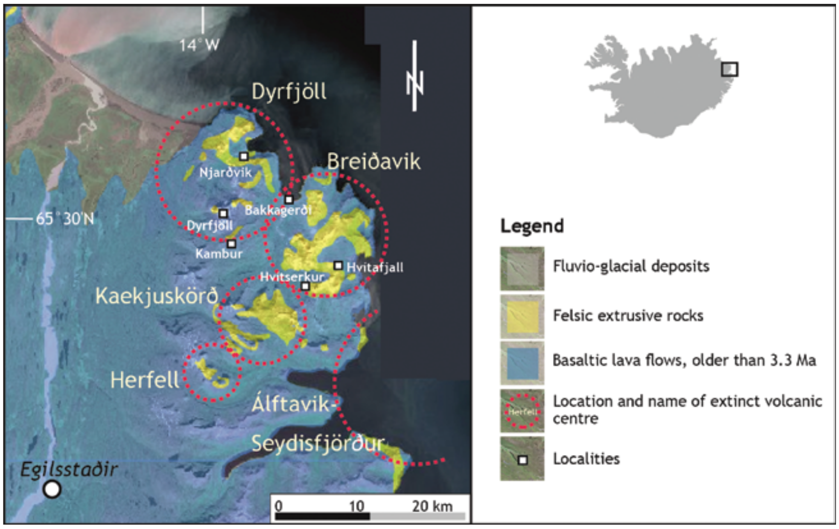


Fig. 2. Simplified geological map of NE-Iceland with locations of extinct volcanic centres according to Walker (1974) and Gústafsson (1992). Geological map by Johannesson and Saemundsson (1998) provided by Nátturuvefsjá (http://www.natturuvefsja.is/vefsja/).

Field strategy and sampling

Two geological expeditions were carried out, one in August 2011 and another in August 2012, and a comprehensive sample suite of intrusive and extrusive rocks, from basaltic to silicic in composition, was collected from the Neogene central complexes in the region between Borgarfjörður Eystri and Loðmundarfjörður (about 60 rock samples and 30 river sands in total). Our research strategy involves testing different hypothesis for the formation of silicic rocks, and therefore samples for a range of different study purposes were collected.

First, a suite of rocks representative of the area is intended for geochemistry, including major and trace elements, mineral chemistry, as well as radiogenic (Sr, Nd, Pb) and stable isotopes (O, H, B). When com-

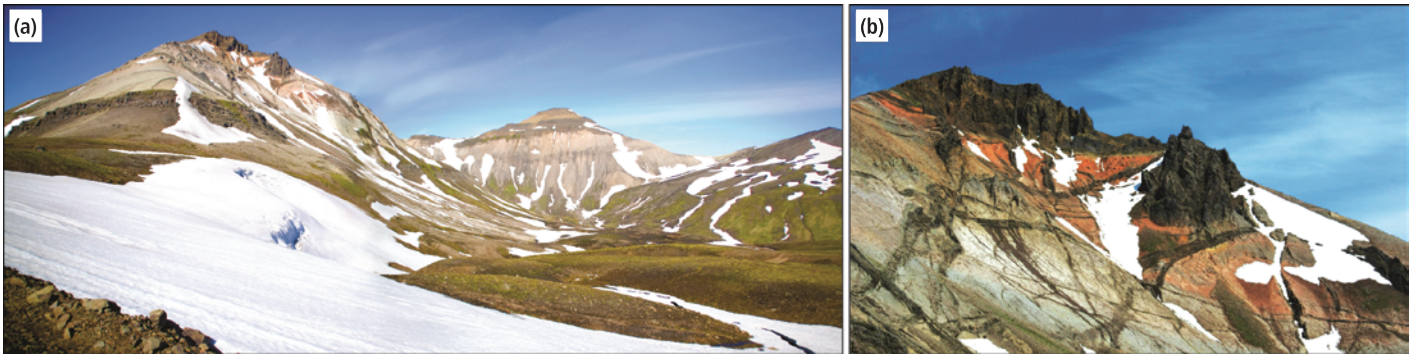


Fig. 3. a. The mountain Hvítserkur consists of one large caldera-filling ignimbrite sheet, which is crosscut by a complex system of basaltic dykes. **b.** Close-up of Hvítserkur with hyaloclastites and pillow breccias seen to overlie the beige to pink ignimbrite.

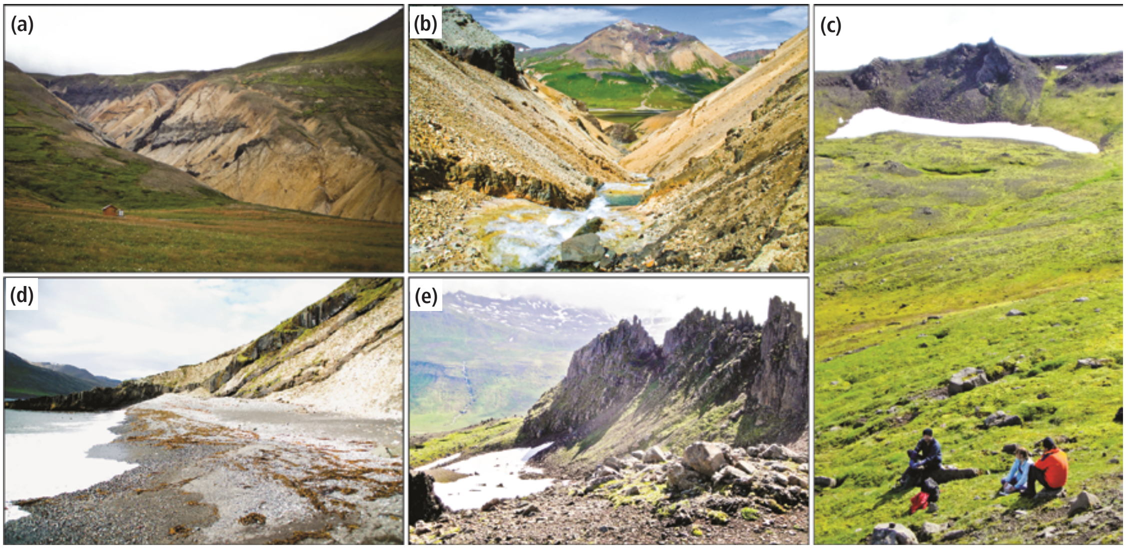


Fig. 4. Impressions of the field area around Borgarfjörður Eystri. **a.** and **b.** Innri Hvannagilsá gully, in the cove of Njarðvik, composed of a subvolcanic rhyolite intrusion, which is crosscut by dykes. **c.** Close to Náttmálafjall, south of Hvítserkur mountain, there are remains of an eruption site (in the background, top of image). **d.** Inclined sheets in Njarðvik cove that crosscut subvolcanic rhyolite. **e.** The pinnacle weathering of a dacite flow gives the mountain Kambur ('comb') its name.

bined, this will allow testing for open- versus closed-system processes, involving tests for fractional crystallization, large scale crustal melting, assimilation with concurrent fractional crystallization (AFC), and magma mixing. In addition, radiogenic isotopes will help to characterise processes such as hydrothermal overprint or, once carefully filtered, source regions of primordial magma genesis. Stable isotopes will complement information on hydrothermal influences, as well as help to quantify the degree of contamination of mantle-derived magmas by wall rock, meteoric water and/or seawater.

Second, prospective silicic (rhyolite) and intermediate rocks (icelandites and dacites), as well as river sands, were collected for zircon separation. Zircon crystals are rather stubborn and largely resistant to alteration and post-crystallization processes, and therefore are a very powerful tool for characterizing the primary igneous environment (e.g. using oxygen isotopes in zircon by SIMS). They are also widely used for U-Pb geochronology, which can reveal the temporal evolution of the central complexes in the area, and we are therefore performing measurements on zircon for oxygen isotopes, and for elemental chemistry, in addition to U-Pb age dating.

Third, hydrothermally altered and zeolitized basalts and rocks with secondary silica-rich mineral precipitates (e.g. jasper) were collected for testing in high pressure/high temperature partial melting experiments, aiming to reproduce and further constrain the melting processes within Iceland's crust. This approach will allow us to determine the composition of partial melts that derive from actual Icelandic crustal rocks under controlled laboratory conditions, e.g. from zeolitized basalts that are buried in voluminous lava piles until they melt with help from external heat sources. The experiments will help us to determine if the partial melting of hydrothermally altered crust is a feasible process for the formation of rhyolites in Iceland, and if this process can produce the compositional spectrum that is recorded here.

Field journal

Field expeditions to north-east Iceland habitually commence in Egilsstaðir, the main population centre there (having 2257 inhabitants in 2011), beyond which the silence of nature takes over. After about an hour's drive north of Egilsstaðir, the ragged mountain tops of Dyrfjöll (the 'door mountains'), with their prominent 'door' or scar, appear in the distance (Fig. 5). A steep winding gravel road soon commences and drops into the 'deserted inlets'—the forgotten fjords and relatively unspoiled wilderness of greater Borgarfjörður Eystri. Only two of these fjords are still inhabited: Njarðvik cove and Borgarfjörður Eystri. When arriving in Borgarfjörður Eystri, it is striking how the valley is completely surrounded by mountains of bright coloured silicic rocks with different shades of white, yellow, orange and light brown (Fig. 1). This is unusual in Iceland where the greys and blacks of basalt usually dominate.

The valley has only a few hundred inhabitants, who live in the picturesque fishing village Bakkagerði and on the few farms spread along the valley (Fig. 6). Among tourists the area is highly recommended for its beautiful hiking paths, the castle of the Queen of the Elfins, its highly varied birdlife which includes puffin breeding cliffs, and not to forget, the reindeer herds that live in the mountains (Fig. 7). The region is also known for the special people that live there, who will gladly share some of their knowledge on enjoyable places to visit, on weather predictions and on road conditions, with those not familiar with the area. However, living here must be a serious challenge, particularly in the nine months outside

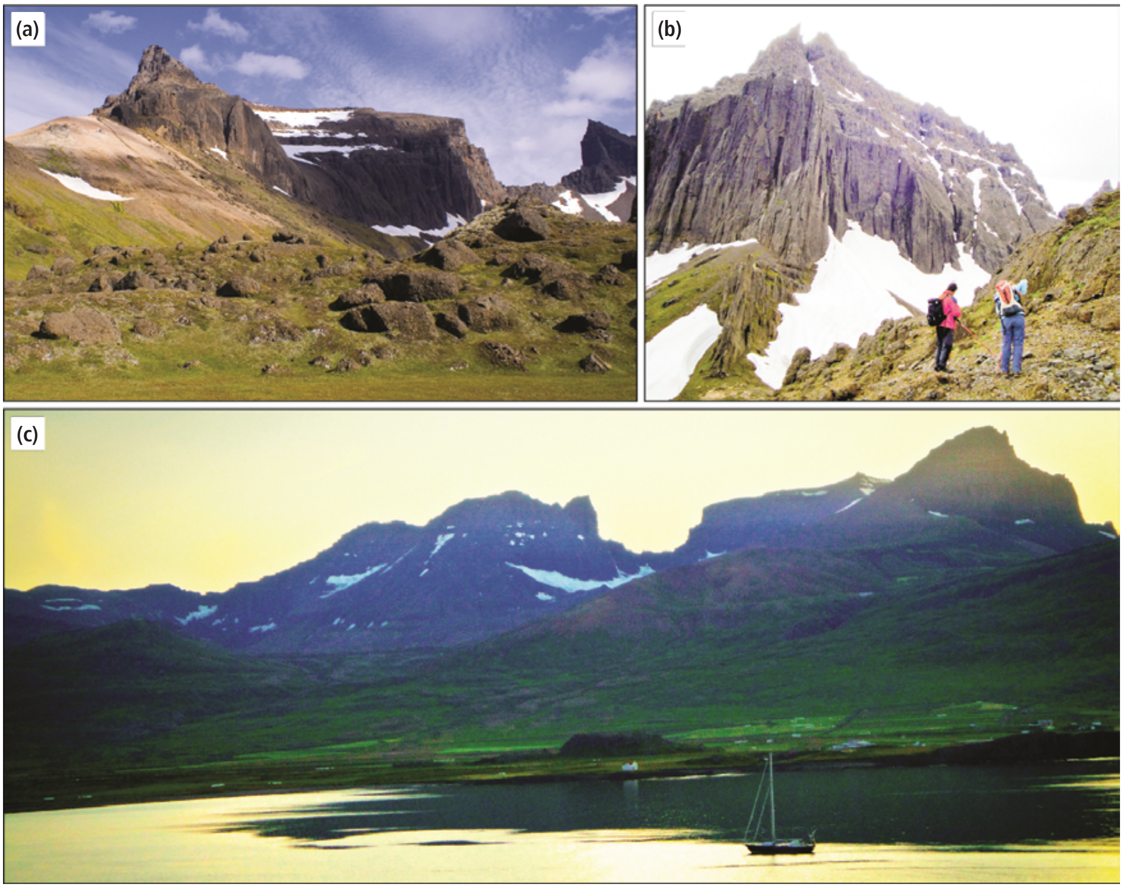


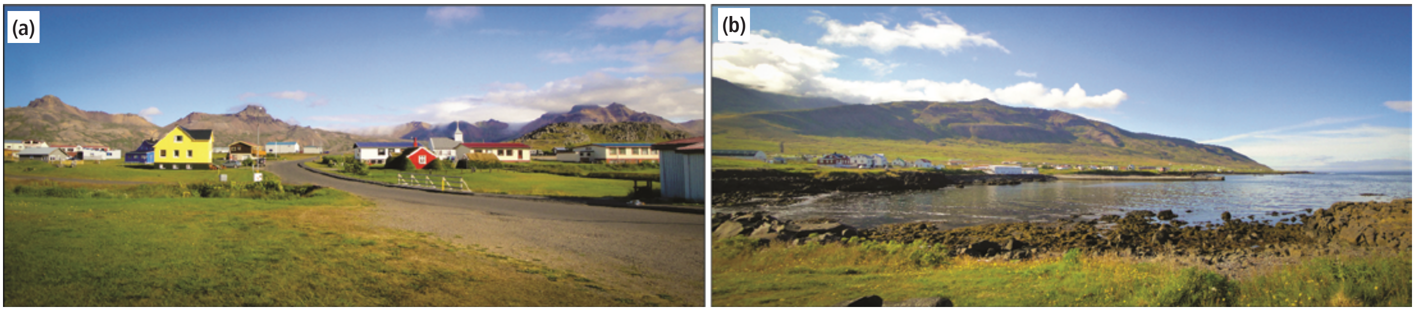
Fig. 5. Dyrfjöll mountains with the characteristic 'door' (right of centre in **a.** and **c.**). This is a well recognized landmark in the area, and is associated with an explosive volcanic episode, edifice collapse and caldera formation. **a.** The pink ignimbrite shines prominently below the brown hyaloclastites that were erupted in a caldera lake. **b.** The massive hyaloclastites are overlain by numerous basaltic lavas. Note the top of the ignimbrite in the foreground. **c.** The Dyrfjöll mountains form an impressive backdrop for the idyllic village of Bakkagerði.

the tourist season. At these times the small shop in Bakkagerði is only open for a few hours a week, and the next pharmacy or hospital is 70 km away (in Egilsstaðir), which is only reachable if the snow and weather permit use of the only mountain pass that leads out of the valley.

The Neogene volcanic centres of Borgarfjörður Eystri were eventually buried under plateau basalts erupted from fissure eruptions in the active rift zone. Subsequent burial metamorphism developed zeolite zones that can be traced through the lava pile. These zeolite assemblages were characterized by Walker in 1960, and he documented that they are commonly sub-parallel to the original land surface and therefore oblique to the tilted lava pile. Zeolite mineral assemblages can also reveal depth of erosion, and estimates by Walker show that a considerable part of the lava pile has been removed. In the north, this amounts to a few hundred metres only, but rises up to nearly two kilometres in the south-east of Iceland. We are therefore looking at the transition from near-surface subvolcanic to subaerial facies of a former cluster of central volcanoes that were in fact buried under a thin cover of basalts after activity had ceased. Therefore, the selection of fresh rock is possible, but requires caution and care when sampling.

Field work in north-east Iceland is strongly weather dependent, especially in the fjords and valleys, and in the ragged mountains that host a few remnant glaciers. Weather conditions can change rapidly there and may cause severe problems and danger to people outdoors, even more so as mobile phone reception is virtually non-existent in these valleys, unless one climbs to the highest mountain tops. Sea fog can rap-

Fig. 6. **a.** and **b.** Bakkagerði fishing village in Borgarfjörður Eystri.



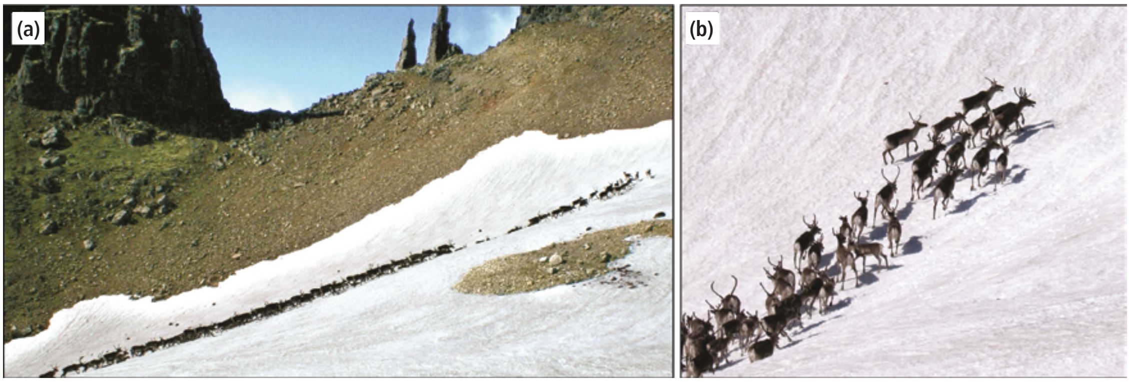


Fig. 7. **a.** and **b.** (close-up), a reindeer herd rushes up the steep mountain side on the top of Kambur mountain.

idly sweep in and completely fill the valleys, leaving one enclosed by an eerie wall of sound-damping mist that decreases visibility so much that manoeuvring your car back to civilization becomes a major adventure. Rainfall can also cause rather severe complications (Fig. 8). Glaciers have carved out extremely steep-sided valleys, and mountain slopes are covered in loose rock produced by frost cracking. Sudden and heavy rainfall can cause rock falls and landslides that can destroy a dirt track in a matter of minutes, which makes geological work in these mountains a never-ending discovery. Rivers can swell drastically in rainy conditions and a river-passage one had taken earlier, by car or by foot, may no longer be usable for the return journey. As we quickly learnt during our fieldwork, it is not worth risking ones safety during bad weather conditions. On these occasions, road side sampling and easily reachable localities close to the road, which had been saved for just these rainy days, are the thing to do. If the worst happens and conditions become unbearable, the (only) local café in Bakkagerði sells a selection of minerals from the local mountains (e.g. jasper, chalcedony, zeolites) and offers a superb fish soup that is truly heart-warming on a wet and stormy day and has a magical ability to considerably soothe the poor geologists' weather frustrations.

In the end, after plenty of driving, hiking, hammering and sample carrying, we managed to collect several hundred kilograms of rock and sand that were sent to Uppsala and Reykjavik for processing and subsequent geochemical analysis. After field expeditions to a place so remote and in a way isolated from the rest of the world, it is nice to return to the comforts of modern urban society. However, there is something special about the calm and quiet countryside in the 'deserted inlets' of north-east Iceland, a place where time slows down somehow and where the castle of the Queen of Elfins seems to hold more than just a legend at times. Where the waves from the Norwegian Sea and the winds on top of the ridges are the only 'noise pollution' one will experience, and where life is just a little bit more the old way, serving as a vivid reminder of the human and societal developments that have led to the almost complete abandonment of the 'deserted inlets' over the last few decades. We are truly excited about the ongoing work that is trying to unravel the history of formation of the volcanic centres that were active when this part of Iceland was under construction some 14–12 Ma ago. After all, the rocks of this remote and unusual place may guard Iceland's best kept geological secrets.

Fig. 8. Fieldwork impressions and working conditions in NE-Iceland. **a.** Dirt-track driving on stony, steep and winding roads. Note the thick fog filling Breiðavik valley. **b.** As we hike close to the Dyrfjöll mountains, we have to pass remnant snow sheets from the last winter. **c.** Locals assist us by pulling our car out of a deep mud hole. **d.** Occasionally we have to share even the main road with the sheep that graze on the slopes of the mountains. **e.** Off-road driving can be adventurous. **f.** It is often necessary to pass streams and small rivers during fieldwork, which usually works well with a 4WD, though exceptions exist (see panel **c.**).

Acknowledgements

We are grateful to the people of Borgarfjörður Eystri, for their hospitality, for their words of wisdom and caution regarding road and weather conditions in the mountains and nearby valleys. Moreover, we are thankful for their rapid assistance in pulling our field car out of a deep mudhole on a particularly rainy day, and ensuring we made it back home safe and sound. We are also greatly indebted to the Swedish Research Council, the Royal Swedish Academy of Sciences, and the Nordic Volcanological Center, Iceland, for generous financial support.

Suggestions for further reading

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