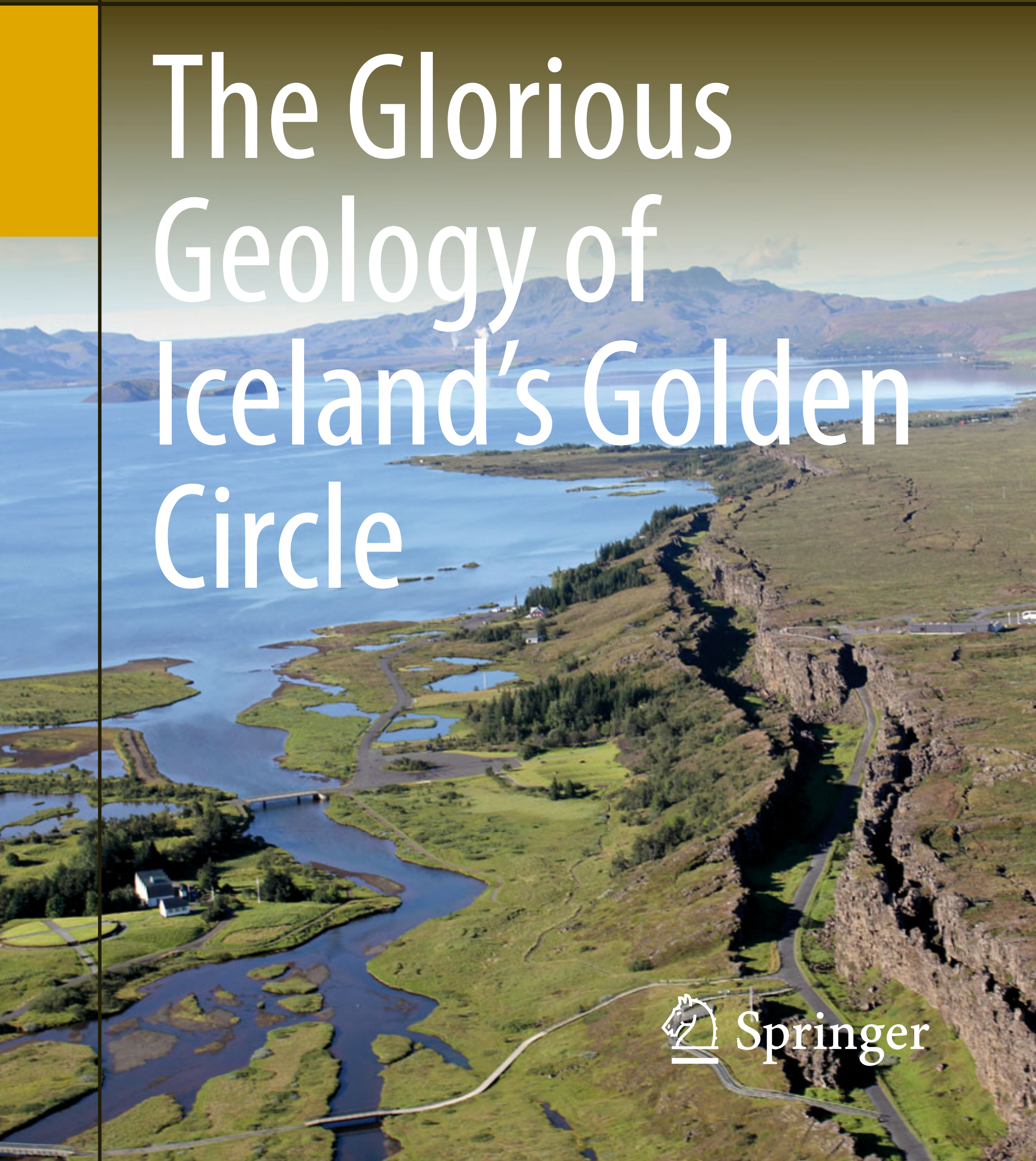
GeoGuide

Agust Gudmundsson

The Glorious Geology of Iceland's Golden Circle



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The Glorious Geology of Iceland's Golden Circle

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Preface

Iceland's Golden Circle provides a unique opportunity to observe and understand many of Earth's natural forces in action. These include those that move the Earth's tectonic plates, rupture the crust, and generate earthquakes and volcanic eruptions. Earthquakes and volcanoes, in turn, provide the paths and the heat sources for hot springs and geysers. These are internal forces which, in combination with external forces, are also responsible for forming the landscape. The external forces relate to the actions of glaciers and rivers that erode the Earth's surface so as to generate waterfalls, river canyons, and, eventually, mountains.

The Golden Circle does not only illustrate natural forces but also natural resources. Among these is plenty of exceptionally clean and readily available groundwater. As humankind moves towards renewable energy, potential or actual renewable energy resources become of gradually greater importance. Those you can see—some from a distance—while travelling the Golden Circle include waterfalls (hydropower), geothermal fields (geothermal power), waves (wave energy) and—perhaps occasionally less welcome—the wind (wind power).

The Golden Circle is normally travelled (driven) in one day. There are many other exciting places that can be visited during one-day excursions. Here I describe four additional excursions that are less well known than the Golden Circle and all of which offer a deeper understanding of the processes that shape our planet as well as places of great landscapes and beauty. Since most visitors to Iceland stay in the Greater Reykjavik area (the Capital Region), all the excursions described here begin and end in Reykjavik. However, these excursions can be made wherever you stay in the southwestern part of the country.

More specifically, the book describes five one-day excursions in the southwestern part of Iceland. The first excursion is the classic Golden Circle, which includes the well-known sites of rifting at Thingvellir (Þingvellir), the geothermal area of Geysir, the waterfall Gullfoss, and the volcanic crater Kerid (Kerið). The second excursion is to the beautiful fjord Halfjördur (Hvalfjörður), north of Reykjavik, where you can observe the deep interiors of volcanoes and volcanic zones as well as a variety of impressive landscape features. The third excursion focuses on the unique landscape, volcanic activity, and geothermal energy of the Hengill Volcano, south of Lake Thingvallavatn. The fourth excursion is to the Reykjanes Peninsula, south of Reykjavik, which contains the Blue Lagoon and the 'Bridge between two continents' and focuses on lakes, explosion craters, geothermal fields, volcanic fissures, and lava fields. The fifth excursion is to South Iceland and includes the main earthquake zone in this part of Iceland but focuses on the famous volcanoes Hekla (erupted in 2000), Eyjafjallajökull (erupted in 2010), and Katla (erupted in 1918), as well as the waterfalls, sandur plains, and the beautiful rock columns at the beach of Reynisfjara.

The book is written for the general visitor to Iceland. In particular, the book is for people who not only wish to enjoy Iceland's unique beauty, but also to appreciate and understand the processes that create that beauty. No geological knowledge is assumed. Technical terms are avoided as much as possible, and those that must be used are explained using non-technical language in main text and in a detailed glossary at the end of the book. I have been a guide on numerous geological excursions in Iceland, including all those described in the book. Some of the excursions have been primarily for people educated in geosciences, whereas others have been for people with no such background. While the book is aimed primarily at people with no background in geosciences, many geoscientists and students may benefit from the well-illustrated field examples and explanations of processes presented in the book. Many readers may neither have the time nor inclination to read the entire book. I have therefore written the chapters so as to make them comparatively independent of other chapters. It is thus possible to go for a single excursion and read the relevant chapter without having to read all the other chapters. For this reason there is considerable repetition of various terms, principles, and processes. To clarify points of interest or under discussion there is, however, much cross-referencing between chapters and, in particular, figures.

In many science books for the general public most of the figures are line drawings, cartoons. This book is unusual in that, while line drawings are used to illustrate certain geological processes, the focus is on explaining the geological structures and processes through annotated photographs. The advantage is that the processes are then explained in terms of structures as you really see them in nature. As a consequence the book has more than 240 illustrations, the great majority of which are photographs. Most of the photographs show the geological features exactly as you will see them during the excursions. There are, in addition, many photographs taken from aircrafts, providing aerial views of the same features. These are meant to explain processes and structures at a different scale from that seen on the ground, as well as to underline and emphasise the unique beauty of the geology of Iceland.

Egham, UK Agust Gudmundsson

Acknowledgements

In working on the book I have received much, and greatly appreciated, help from my wife Nahid Mohajeri. In particular, she has redrawn earlier illustrations and made all the original illustrations in the book. Furthermore, she has read the entire text and made many helpful comments. I would also like to thank Ines Galindo and Sonja Philipp for their meticulous reading of the entire text and for many helpful suggestions.

All the digital elevation models presented in the book are based on data from Landmælingar Íslands (Iceland Geodetic Survey). More specifically, these are Figs. 1.1, 1.5, 2.1, 2.3, 4.1, 10.1, 11.1, 12.1, 13.1, 14.1, 14.12b, and 14.18. Also, the aerial photographs in Figs. 8.2 and 13.7 are from Landmælingar Íslands. These data are made available for free by Landmælingar Íslands through an 'open government licence'. I thank Landmælingar Íslands very much for the free use of these data and aerial photographs.

I gratefully acknowledge being allowed to use photographs taken by the following persons. By Ines Galindo: Figures 13.20, 13.21, 13.23, 13.34, 13.35, 13.36, and 13.39; by Sonja Philipp: Figures 7.1, 9.4, 12.4, 12.5, 12.18, 12.19, 14.25 and 14.28; by Ævar Johannsson: Figure 13.27. All other photographs in the book were taken by me.

Some of the illustrations were modified from my earlier papers and books. The following figures were modified from figures in the listed papers. Figures 2.2, 2.4, 4.10, and 11.14 from the paper *The mechanics of large volcanic eruptions.* Earth-Science Reviews, 163, 72–93, 2016; Fig. 5.9 from the paper *Effects of mechanical layering on the development of normal faults and dykes in Iceland.* Geodinamica Acta, 18, 11–30, 2005; Fig. 11.3 from the paper *How local stresses control magma-chamber ruptures, dyke injections, and eruptions in composite volcanoes*. Earth-Science Reviews, 79, 1–31, 2006; and Fig. 14.20 from the paper

Strengths and strain energies of volcanic edifices: implications for eruptions, collapse calderas, and landslides. Natural Hazards and Earth System Sciences, 12, 1–18, 2012. Similarly, Fig. 13.26 is modified from a figure in the book *Rock Fractures in Geological Processes*, Cambridge University Press, 2011. All the other illustrations were particularly made for the book.

Agust Gudmundsson

Contents

Introduction 1

If you want to understand the natural forces that shape our planet, then the place to go to is Iceland. There is no equally small area on this planet that offers such a variety of easily observed geological processes as Iceland. You can observe the **tectonic plates** that constitute the Earth's surface moving apart, also known as **spreading**, and thereby giving rise to volcanic eruptions, earthquakes, geysers, and geothermal energy. Then there are the large rivers with beautiful waterfalls, as well as the ice caps and the outlet glaciers that have cut or eroded deep valleys and fjords into the land, the surface of the crust, forming tall mountains in-between. All these are easily observed and understood in Iceland.

Because the geological processes and structures are so clear and easily observed in Iceland they can be understood without any geological background. Just looking at the landscapes and the rocks, you should, with the help of this book, be able to recognise the main landforms, by which processes they are generated, and how the processes operate. The aim of the book is to illustrate and explain what main landforms and geological processes can be seen during five **one-day excursions** (described below) in a way that is understandable to those without a formal education in geology. With this in view, I keep technical concepts and jargon to a minimum and use everyday examples and analogies to explain the landforms and processes that you can see in Iceland. Every concept is defined when it is first introduced, and in addition there is a detailed **glossary** at the end of the book, summarising in simple terms the meaning of some common geological and other scientific terms. I use **boldface** type for emphasis and for words that are explained in the glossary. More specifically, boldface is used for important items, technical or semi-technical terms, particularly where first used, and for the stops during the excursions.

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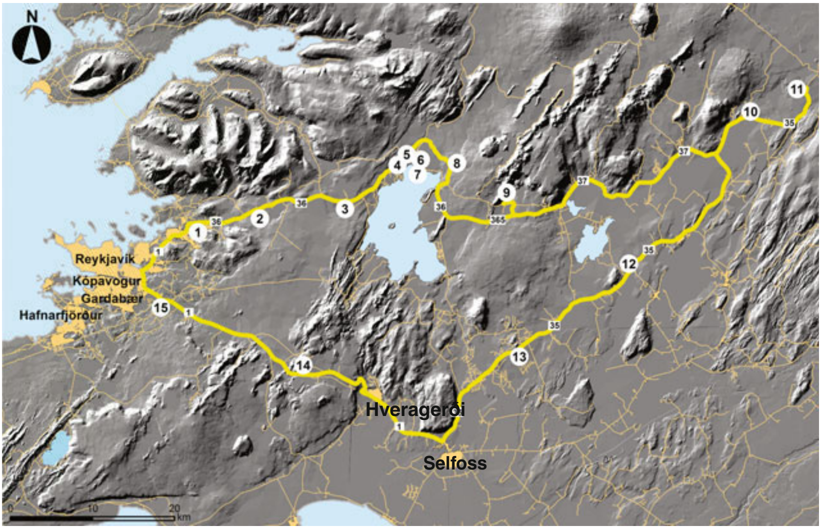

Fig. 1.1 The location of the Golden Circle, shown in yellow. The large encircled numbers, here and on other similar maps, refer to the main stops during the excursions. The small numbers in squares indicate the road numbers. The orientation of north is shown by an arrow in the upper left corner, whereas the scale is indicated in the lower left corner. The city of Reykjavik and the main towns are indicated in orange-brownish colour. The location of the Golden Circle within Iceland as a whole is provided in Fig. 1.5 and a larger version, with more details, in Fig. 4.1. Although the real geometry of the Golden Circle is that of a triangle rather than a circle, the name is traditional and use here. Fig. 4.1 is a larger version of this figure

All the processes mentioned above and their products can be seen in the southwestern part of Iceland, and many along the so-called 'Golden Circle'. While there are somewhat different definitions of the Golden Circle—which is geometrically not really a circle but rather closer to a triangle (Fig. 1.1)—to most people the Circle is composed of the following trips:

- From Reykjavik to the Thingvellir Graben.
- From Thingvellir to the Geysir geothermal field.
- From Geysir to the waterfall of Gullfoss.
- From Gullfoss to the crater of Kerid.
- From Kerid to Reykjavik.

Some versions of the Golden Circles include additional stops. For example, some prefer to stop at the Skalholt Cathedral in central South Iceland, an important historical site but geologically of little interest—and thus omitted here. Similarly, some include the town of Hveragerdi and the power plant of Hellisheidarvirkjun. Both are located in geologically interesting places, not only in relation to geothermal fields and geothermal power but also because they are located close to (Hveragerdi) or inside (Hellisheidarvirkjun) active volcanoes (Hengill) and zones of earthquakes. Hveragerdi and Hellisheidarvirkjun are both discussed briefly in the present version of the Circle, and are optional stops.

The Golden Circle described here is the one in Fig. 1.1. It includes 15 main stops or sites and thus many more than listed in the bullet points above. These additional stops are chosen because of their geological interest. I show photographs from some of the main sites in Fig. 1.2. But the descriptions are not confined to the main sites—Esja, Thingvellir, Geysir, Gullfoss, and Kerid. There are many interesting geological features that can be observed between the main sites. Most of these can be seen from the roads that constitute the standard Circle; for others you need to drive a short distance off the main road. For example, on Road 365 from Thingvellir to Geysir, a short drive to north off that road to Laugarvatnshellar (the Caves of Laugarvatn, the ninth stop) offers many geological features of interest. Not only are the caves themselves interesting (they were inhabited in the early part of the 20th century), but nearby is a section through an inactive volcano that allows you to understand how volcanoes and volcanic islands form during eruptions in water, such as the meltwater of ice caps. In particular, the ninth stop is the location of beautiful **pillow lava** (Fig. 1.3), the type of lava commonly formed at great water depths at mid-ocean ridges. The pillows are found here because the mountain formed in deep water, more specifically in the melt water within the ice sheet of the last ice age. Eruptions in deep water, in the sea or under ice caps, are still happening in Iceland. For example, one such eruption occurred in the Vatnajökull ice cap (located in Fig. 2.2) in 1996 (Fig. 1.4), and the 2010 Eyjafjallajökull eruption (Chap. 14) was partly within an ice cap.

The chapters related to the Golden Circle are broadly of two types. One type describes remarkable geological features and processes seen on the way between the main sites (for example, between Thingvellir and Geysir). The other type describes the main sites themselves, the interesting features that can be seen, and by which geological processes they form and develop.

There are many exciting and beautiful geological structures and activities that can be seen in the vicinity of **Reykjavik** in addition to those of the Golden Circle. I presume many who come to Reykjavik would be interested in seeing more of Iceland's fascinating geology than just the Golden Circle. I have therefore added

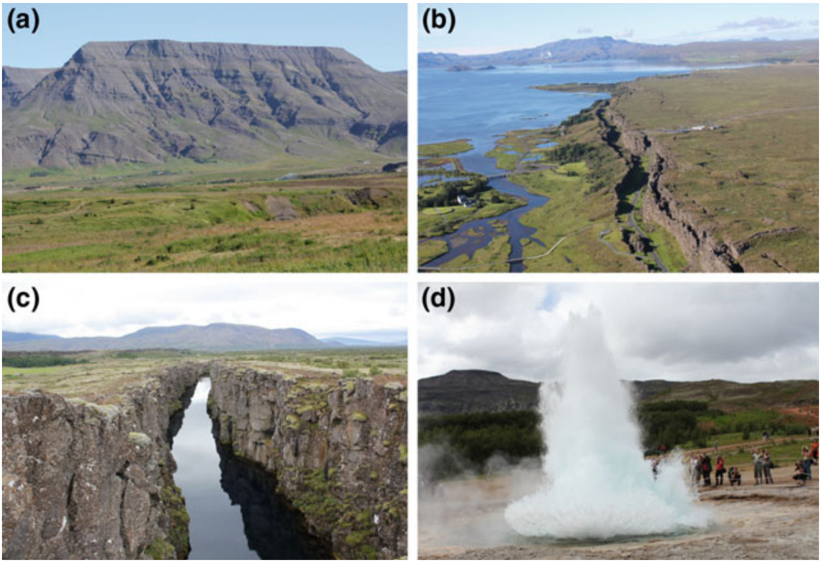

Fig. 1.2 Examples of geological and landscape features seen while travelling along the Golden Circle. All these features are shown again, and discussed in great detail, in Chaps. 4–9. **a** The mountain Esja, which can be seen from Reykjavik (first stop in Fig. 1.1). The rock layers that constitute this mountain originated tens of kilometres to the east, in the volcanic rift zone at Thingvellir, and have been carried through slow spreading (about 1 centimetre per year) to where they are seen now. **b** Part of the active volcanic rift zone at Thingvellir. The photograph is taken from an aircraft, view southwest across Lake Thingvallavatn to the central volcano (stratovolcano, composite volcano) of Hengill—the white 'smoke' is from geothermal fields. The large fracture is an earthquake fault, as wide (open) as 60 m, formed by spreading or plate-tectonic forces (the fourth, fifth, and sixth stop in Fig. 1.1). The land left (to the east) of the fracture has subsided by 40 m. **c** A tension (open) fracture at Thingvellir (the seventh stop in Fig. 1.1). The maximum opening (aperture) of the fracture is about 15 m and the maximum visible depth 25 m, but it may reach to a depth of several hundred metres. The fracture is filled with very clean groundwater. **d** The erupting hot spring, geyser, Strokkur (the tenth stop in Fig. 1.1). The fractures supplying the boiling water for the eruptions maintain their openings or apertures through earthquake activity. **e** The Gullfoss waterfall (the eleventh stop in Fig. 1.1). The total drop is about 32 m and occurs in two steps which follow the directions of the main earthquake fractures in South Iceland. Through erosion, the waterfall is gradually migrating further inland, by about 30 centimetres per year. **f** The crater (volcano) Kerid (the thirteenth stop in Fig. 1.1). It is a collapsed small lava pond, a pit crater, now partly filled with groundwater. Its maximum diameter is about 300 m and depth about 50 m

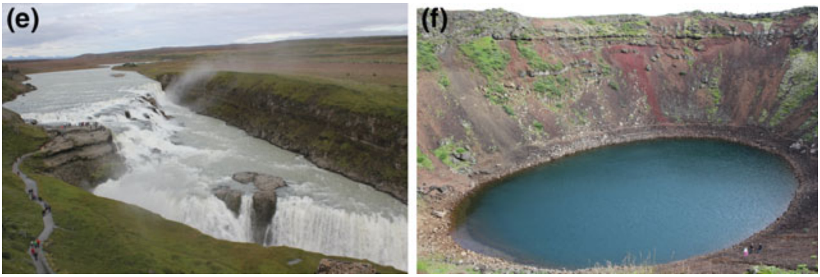

Fig. 1.2 (continued)

several one-day excursions to sites in the vicinity of Reykjavik, namely the following (Fig. 1.5):

- Reykjavik-Hvalfjördur.
- Reykjavik-Hengill.
- Reykjavik-Kleifarvatn-Reykjanes.
- Reykjavik-Eyjafjallajökull-Reynisfjara.

Some of the highlights from these additional excursions are shown in Fig. 1.6. In Hvalfjördur, for example, you can observe the magma-filled fractures (now frozen as solid rock, that is, **dikes**) that supply magma to volcanic eruptions. In Hengill, an active volcano, there is a very unusual and beautiful landscape of valleys and ridges, formed by eruptions and earthquake fractures, that is, **faults**. In the excursions to Reykjanes, you can explore a major geothermal field, explosion craters, the Blue Lagoon, and the fracture referred to as the 'Bridge Between Two Continents'. And in the excursion to Reynisfjara you can observe the famous volcanoes Hekla (from a distance), Eyjafjallajökull, and Katla, in addition to beautiful waterfalls and sets of fractures, referred to as columnar joints, formed when hot molten rock, magma, freezes or solidifies slowly.

Most people who visit Iceland arrive at the Keflavik Airport (Keflavikurflugvöllur). From there most of them drive to the capital Reykjavik or one of its surrounding towns. The Keflavik Airport is located on the Reykjanes Peninsula, which has many interesting geological features in addition to the well-known Blue Lagoon. Some of these features can be seen from the road while driving to Reykjavik. Since this drive provides the introduction of most people to the landscapes and geology of Iceland—although few would describe this part of the country as beautiful—it is logical to start the present book with a brief chapter on the geology seen from the road from Keflavik to Reykjavik (Figs. 1.5 and 2.1).

Before we begin that journey, however, a few words about numbers and spelling of names. As for numbers, particularly the ages of rocks, I commonly give only the first digits and then add the appropriate word, such as thousands or millions. For example, I write 13 thousand years old and 2 million years ago. When the number is presumed very accurate, then I write out the entire number, such as for an eruption that occurred in the year 1000 or the settlement of Iceland which is supposed to have happened in the year 874. I do not use commas in 4-digit numbers, including years. Thus, I write 1200 °C rather than 1,200 °C.

Fig. 1.3 Lava flows that resemble a stack of pillows, that is, ellipsoidal bodies of (mostly basaltic) lava are named pillow lavas (ninth stop in Fig. 1.1). Molten rock, magma, forms pillow lavas under water, the water being meltwater when the eruption occurs beneath a glacier (subglacial eruptions) like here. Individual pillows are commonly about 1 m or less in diameter. Pillow lavas form the lowermost layers in many volcanoes seen in Southwest Iceland, most of which are formed in subglacial eruptions and referred to as hyaloclastite (in Icelandic moberg) mountains. Pillow lavas are also very common at mid-ocean ridges, and some in Iceland are formed in eruptions in the sea (submarine eruptions)

Fig. 1.4 The 1996 Gjalp eruption in the ice sheet Vatnajökull (located in Fig. 2.2) in Iceland. This eruption melted through the glacier, forming hyaloclastite and presumably pillow lava (Fig. 1.3), and caused an enormous flood on the sandur plaines in southern Iceland. Vatnajökull and its volcanoes are outside the scope of the present excursions, but this photograph is a reminder that the processes forming the pillow lavas and most of the volcanoes that you see in the excursions in Southwest Iceland are still operating. The dark, fractured surface is the surface of the ice sheet and the depression and fractures are because of melting from the hot magma beneath the ice sheet. This photograph is from the beginning of the eruption

For 5-digit numbers and higher, however, I use comma, such as in describing a map scale as 1:17,000. As for names, Icelandic has ten letters that do not exist in English. These are the letters á, ð, é, í, ó, ú, ý, þ, æ, and ö. Notice that the letters ö and æ are specific letters and sounds, as are the letters with acute accents, such as á and é. In the book, I transliterate the letters ð as d and þ as th, as is normally done, and æ as ae. Also, I keep ö but omit all acute accents: that is, I write a for á and u for ú, and so forth (as in my own name, which is Ágúst in Icelandic but Agust in English). In the following chapters where the name occurs for the first time (and for some more often) in the main text I give the Icelandic spelling in parentheses following the English spelling. In some chapter headings, I also give the Icelandic spelling when it differs much from the English spelling, such as in the word

Thingvellir, which in Icelandic is Þingvellir. I have translated some of the Icelandic geographical names, particularly those that are geologically interesting, but most are untranslated. In the road maps showing the excursions I use the Icelandic spellings of names because that is the way the spelling is on the topographic and geological maps that you are likely to buy and use.

Which brings me to the topic of **maps**. While I show all the main roads associated with the excursions, and associated digital elevation (shaded topographic) maps, I do not provide detailed topographic maps. Nor do I provide geological maps, but I give full reference to the most important ones for this book in the list of references at the end of the book. Topographic and geological maps are readily available in bookstores and elsewhere in Reykjavik. In particular, there

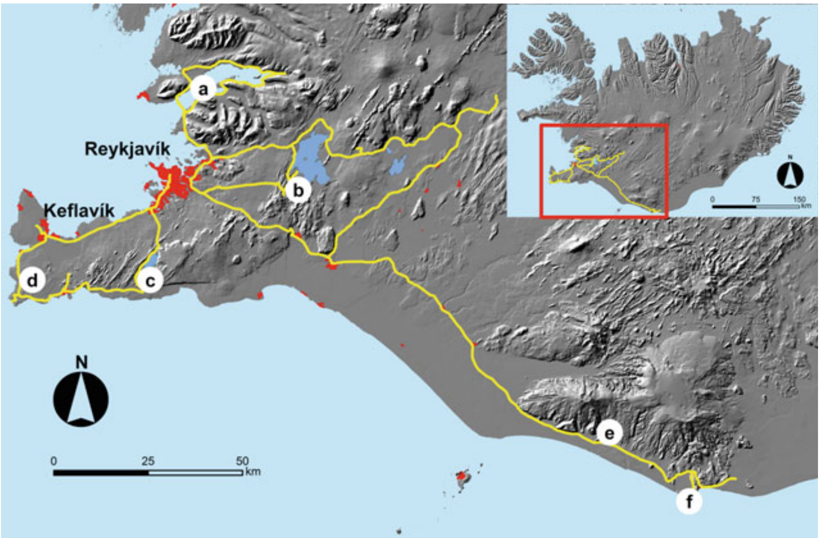

Fig. 1.5 The standard 'Golden Circle' is indicated in Fig. 1.1. To make the book more useful, it covers four additional excursions, shown here in addition to the Golden Circle, in relation to Iceland (inset map). These are to **a** the fjord north of Reykjavik (Hvalfjördur), **b** the Hengill Volcano (seen in Fig. 1.2b), **c**, **d** the Reykjanes Peninsula, and **e**, **f** Eyjafjallajökull (erupted in 2010) and the coast of Reynisfjara (cf. Fig. 10.1). These extra excursions allow you to see deep into the structure of (inactive or extinct) volcanoes, observe geothermal fields and explosion craters, see the famous volcanoes of Hekla and Eyjafjallajökull (located in Figs. 14.1 and 14.12 b) as well as exploring some of the most beautiful waterfalls and beaches of Iceland. Some of the photographic highlights of these excursions are located by the letters **a** to **f**, the corresponding photographs being shown in Fig. 1.6

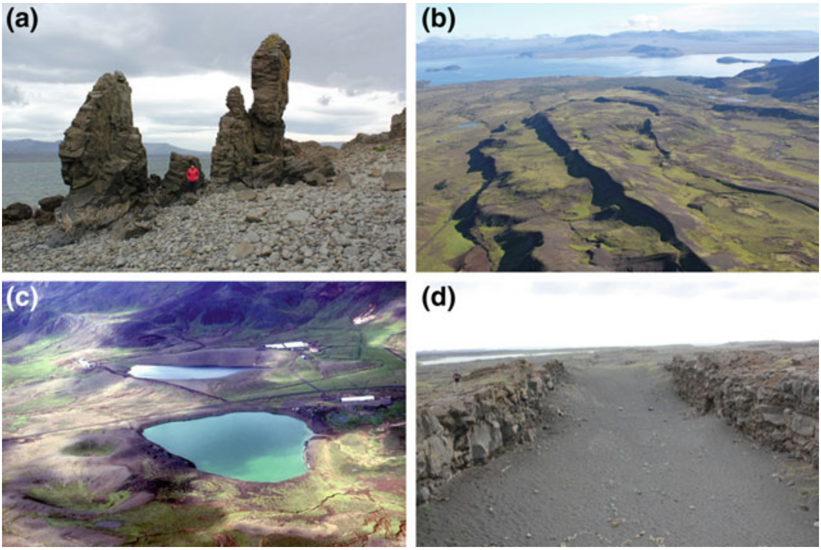

Fig. 1.6 Examples of geological and landscape features seen while making the extra excursions shown in Fig. 1.5. All these features are shown again, and discussed in great detail, in Chaps. 11–14. **a** Molten rock or magma is normally transported in the Earth's outermost solid layer, the crust, along fractures. When the magma subsequently freezes in the fractures, it forms structures named dikes (or dykes). Here is a dike in the fjord Hvalfjördur (located at **a** in Fig. 1.5) which forms a sea stack because it is harder (more resistant to erosion) than the surrounding host rock. The horizontal columns form during cooling of the magma (discussed in **f** below). **b** Aerial view of earthquake fractures (normal faults) in the Hengill area (located at **b** in Fig. 1.5). View north to Lake Thingvallavatn, the faults are large in the old rocks but become smaller in the young lava flow close to the lake. **c** Aerial view of explosion craters, also known as maars, near Lake Kleifarvatn (located at **e** in Fig. 1.5). The one with the green water has a maximum diameter of about 360 m and a depth of 45 m. **d** The tension fracture across which is the 'Bridge Between the Two Continents' (located at **d** in Fig. 1.5). The maximum opening or aperture of the fracture is about 30 m (15 m where the bridge crosses it). **e** The Skogarfoss waterfall (located at **c** in Fig. 1.5) falls or drops vertically about 60 m off an old sea cliff. The cliff was formed some 13 thousand years ago when the sea level was much higher than today. **f** When a magma body cools to form a solid rock (here a basaltic intrusion), the body shrinks and may generate beautiful columns. Here some of the rock columns in Reynisfjara (located at **f** in Fig. 1.5) are seen. The columns are vertical, indicating that they formed in a horizontal sheet-like magma-filled fracture known as a sill

Fig. 1.6 (continued)

exists a very detailed geological map (scale: 1:100,000, meaning that one centimetre on the map corresponds to one hundred thousand centimetres, or one kilometre, in nature) of Southwest Iceland. There are also available geological maps of Southwest and South Iceland (scale: 1:250,000) that cover all the excursions. For those who like great details, perhaps the best are the photomaps, that is, aerial photographs with all the place names and elevation contours shown. Such maps (scale: 1:17,000) are available of the Reykjanes Peninsula, Gullfoss and Geysir, and some other areas. The topographic map Reykjanes-Þingvellir (scale: 1:100,000) is very useful and includes a special and more detailed map of Thingvellir (Þingvellir) itself. In addition, there are many other geological and topographic maps, of parts of Iceland as well as the entire country.

2 Keflavik to Reykjavik

The road we drive from the **Keflavik (Keflavík)** Airport to **Reykjavik (Reykjavík)** is shown in Fig. 2.1. The airport is located on a basaltic lava flow. More specifically, the airport is situated on a smooth lava flow of the type referred to as **pahoehoe** lava. Basalt means that the molten rock, the **magma**, which generated the lava was very hot, about 1300 °C, and of comparatively low viscosity, that is, it flowed easily. When flowing on the surface, the lava itself had probably a temperature of around 1200 °C. The lava hosting the airport, however, lies outside the main active volcanic areas of Iceland (Fig. 2.1).

To clarify this: the parts of Iceland where the tectonic plates move apart and eruptions are possible are defined as volcanic zones. The main zones are mostly 20–80 km wide, covered with rocks formed in the past 800 thousand years, and indicated with a bright yellow colour in Fig. 2.2. Within these zones, however, volcanic eruptions and fracture formation (and earthquakes) are mostly confined to certain areas, named **volcanic systems** (Figs. 2.2, 2.3, and 2.4). The volcanic systems are those parts of the volcanic zones where eruptions have occurred in the past 10–11 thousand years. The volcanic systems thus mark the **main active parts** of the volcanic zones. Volcanic systems are supplied with magma from great depths; in Iceland from depths of 10–20 km or more (Fig. 2.4). In many volcanic systems, but not all, the most frequent eruptions occur in a certain part of the system. This part has a **shallow magma chamber**, commonly with a roof at 1–5 km below the surface, and develops a major volcano, which we refer to as a **central volcano**. The central volcanoes in the active volcanic systems in Iceland are indicated in Fig. 2.2. A typical central volcano, with an associated shallow magma chamber, is shown in the central volcanic system in Fig. 2.4 (cf. Figs. 4.10 and 11.3). Three of the volcanic systems on the Reykjanes Peninsula do not have central volcanoes; only the easternmost system has a central volcano, namely the volcano Hengill (Chap. 12). Most of the famous volcanoes in Iceland and elsewhere in the world are central volcanoes.

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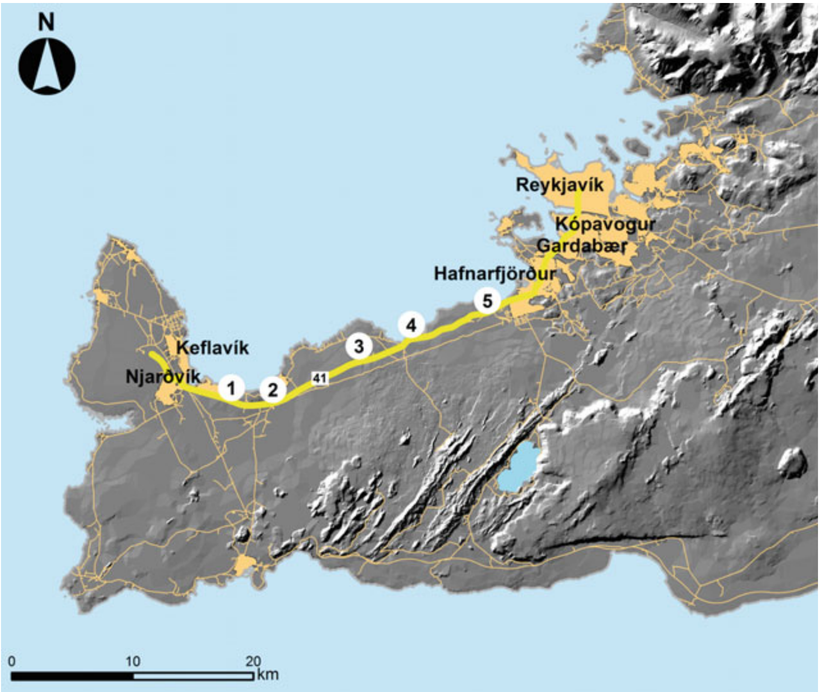

Fig. 2.1 Some geological features of interest can be seen from Road 41 on the way from the Keflavik Airport to Reykjavik. The numbers 1–5 indicate the approximate location along the road where these features are best seen

It is common to define a volcano or a volcanic system as **active**, that is, one that has a reasonable chance of erupting again sometime in the future, if it has erupted at least once during the past 10 thousand years. If no eruption has occurred in a volcano or a volcanic system for more than 10 thousand years, the probability that it will ever erupt again is low. We follow this definition and regard the volcanic systems as the main active parts of the volcanic zones. The other parts are regarded as essentially inactive. The areas outside the volcanic zones (pale yellow colour in Fig. 2.2) are regarded as inactive or extinct.

There are different ways of marking the outlines of the volcanic systems shown in Fig. 2.2. On the Reykjanes Peninsula there are four main volcanic systems. They are shown (more accurately drawn than in Fig. 2.2) in Fig. 2.3. The lava flow on which the Keflavik Airport is built is outside any of the active volcanic systems

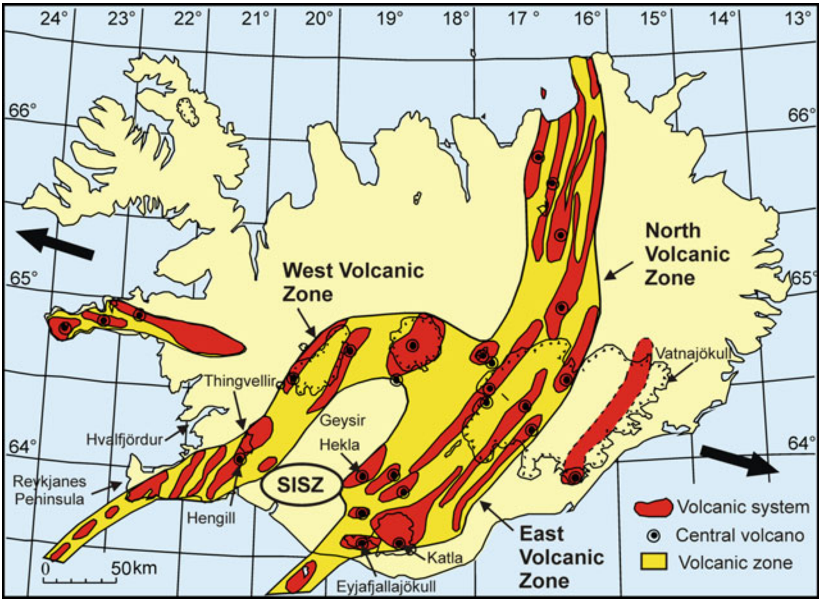

Fig. 2.2 Volcanic zones and systems of Iceland. The zones of possible volcanic eruptions are indicated in bright yellow colour. These are the West, East, and North Volcanic Zones, as well as the Snaefellsnes Volcanic Zone (Snæfellsnes Volcanic Zone), forming the central peninsula of West Iceland. The main active parts of the volcanic zones, however, are the volcanic systems, shown in red. These are mostly zones or swarms of volcanoes formed in single eruptions, such as volcanic fissures (crater rows), lava shields, and various types of single craters, as well as tectonic fractures (tension fractures and faults—discussed in Chap. 5). There are 28 volcanic systems shown here; their number and geometries vary somewhat depending on the criteria used to define them. All, however, have been active in the past 10–11 thousand years. Most volcanic systems, but not all (Fig. 2.4), develop central volcanoes (stratovolcanoes, composite volcanoes, collapse calderas) supplied with magma from shallow magma chambers. The central volcanoes are indicated by encircled dots. Some of the main central volcanoes discussed in the book are indicated (Hengill, Hekla, Eyjafjallajökull, Katla), as well as areas of interest such as the Reykjanes Peninsula, Hvalfjördur (Hvalfjörður), Thingvellir (Þingvellir), and Geysir. The main earthquake zone discussed in the book, the South Iceland Seismic Zone (SISZ) is also indicated. The thick, black arrows indicate how the west and east parts of Iceland are being pulled apart, that is, the regional direction plate-tectonic spreading

(Figs. 2.2 and 2.3). The lava flow is, in fact, well over 100 thousand years old, and may be much older. Volcanic eruptions are thus not expected at the location of the airport.

Driving along Road 41 towards Reykjavik, some of the geological features that can be seen from the car/bus are indicated by number in Fig. 2.1. In contrast to later excursions, we do not go to the structures seen on this drive. I presume you will either see them while driving or, if you stop, look at them from the main road (Road 41), that is, from a distance. However, even when you just look out of the window of a bus, it is worth mentioning some of the geological structures and features that you see (depending on visibility) on the way to Reykjavik.

The first remarkable feature is the comparatively young basaltic lava flow **Arnarseturshraun (1)**. Being mostly an **aa lava flow** (Fig. 2.5; see also Fig. 13.20a), it has rough surface with broken irregular blocks, and the same applies to the adjacent lava flow to the south, **Illahraun**. Both lava flows can be seen from Road 41, and Road 43 which leads to the town Grindavik (Chap. 13), passes through these lava flows. Illahraun is today very well known to millions of

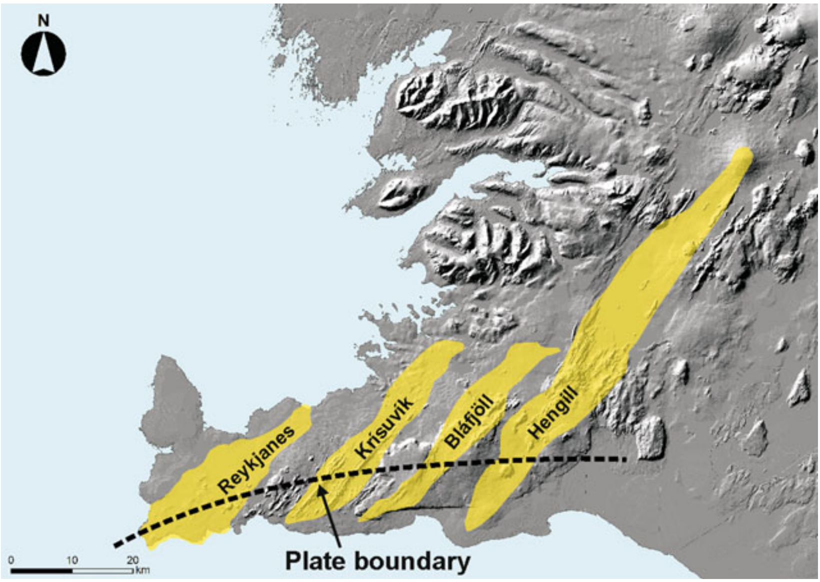

Fig. 2.3 Main volcanic systems on the Reykjanes Peninsula are Reykjanes, Krisuvik (Krísuvík), Blafjöll (Bláfjöll), and Hengill. The Vogar Fissure Swarm constitutes the northernmost part of the Reykjanes System, whereas the Thingvellir (Þingvellir) Graben (Chap. 5) constitutes the northern part of the Hengill system. The broken line shows the highly oblique plate boundary—where most of the earthquakes on the Peninsula occur

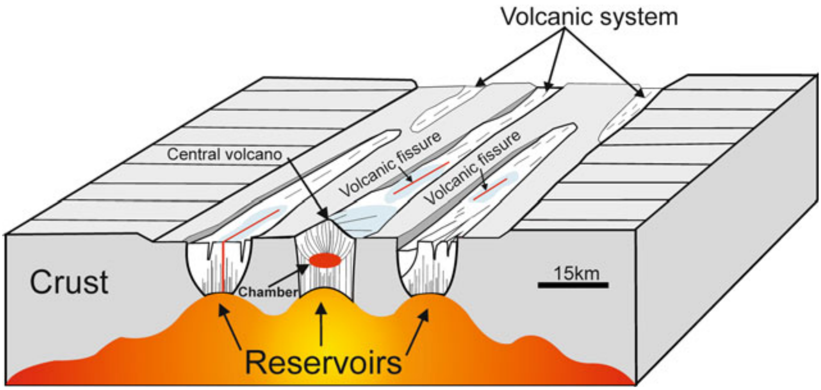

Fig. 2.4 Internal structure of volcanic systems. Only one of the systems, the one in the centre, has a shallow magma chamber in addition to a deep-seated reservoir. Because the central system has a shallow chamber which channels magma to a limited area on the surface, it also has a central volcano, shown here as a central volcano (stratovolcano, composite volcano) of a typical (cone) shape. In the other two systems the magma comes straight from the deep-seated reservoirs. At the surface, the volcanic systems are composed primarily of normal faults (see Figs. 2.5, 2.6, 4.5, 4.12, and 5.8 for clarification and examples), tension fractures (see e.g., Figs. 2.5, 2.6, 5.8, 5.11, 5.12, and 5.13 for clarification and examples) and volcanic fissures (see Figs. 12.21, 13.20e, 13.25, 13.27, and 13.32a for examples)

tourists who have visited the **Blue Lagoon (Bláa Lónið**; cf. Fig. 13.24; Chap. 13), whose geothermal waters derive from deep wells that pass through Illahraun. Both Arnarseturshraun (Fig. 2.5) and Illahraun are of similar age, formed in the period 1210–1240 CE, that is, somewhere around 800 years ago (CE means **Current Era**, which is also denoted by AD, Anno Domini. I normally drop CE/AD when giving the age of lava flows in this book. Thus, **CE is implied** unless stated otherwise.) These are among the youngest lava flows on the Reykjanes Peninsula. Surprisingly, given the size of the Reykjanes Peninsula and that it has at least four main volcanic systems (Figs. 2.2 and 2.3), there have been no known volcanic eruptions on the entire Peninsula since about 1340 CE, that is, for close to 680 years. Taking into account the general activity on the Peninsula, this is a long hiatus and eruptions are expected in the future.

The geological activity is partly reflected in numerous large earthquake **fractures (2)** in the lava flows on the Peninsula (Figs. 2.5 and 2.6). I discuss how these and other similar fractures form in detail in Chap. 5 about Thingvellir. Basically, all the fractures you see here are formed because Iceland is being pulled apart across the volcanic zones, and particularly across the volcanic systems (Figs. 2.2, 2.3 and 2.4). The pull-apart (or spreading) rate is mostly between one and two centimetres per year. This continuous movement stretches or strains the rock until it breaks and forms a fracture. When such a fracture forms, during the rupture of the rock, there is commonly an earthquake. Most earthquakes associated with the types of fractures you see here, however, are small. The fractures in Figs. 2.5 and 2.6 occur mostly in a pahoehoe lava flow forming a gently sloping, shield-shaped volcano named **Thrainsskjöldur (Þráinsskjöldur)**, which formed more than 10 thousand years ago and possibly as long as 14 thousand years ago. Volcanoes of this type are referred to as **lava shields** and are common in Iceland. They differ from the famous **shield volcanoes** on Hawaii, Galapagos, and many other islands

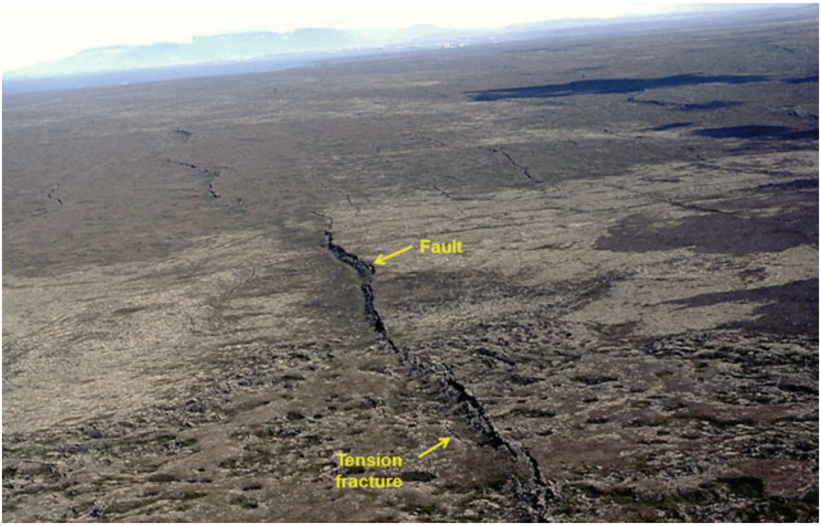

Fig. 2.5 Aerial view of fractures formed by plate-tectonic forces in pahoehoe (smooth-surface) basaltic lava flows of the Reykjanes Peninsula. View (facing or looking) northeast towards the capital region and the mountain Esja. The long fractures are normal faults, the shorter ones tension fractures (their formation is discussed in Chap. 5). The longest fractures reach lengths of many kilometres. These fractures, and those seen in Fig. 2.6, belong to the northwestern part of the Reykjanes Volcanic System (Fig. 2.3); more specifically to the so-called Vogar Fissure Swarm of that system—Vogar is a village close to the second stop in Fig. 2.1. Most of the lava seen here belongs to Thrainsskjöldur, but the closest lava flow, where the main fault in the centre is ending, is the margin of the Arnarsetursharaun lava flow

Fig. 2.6 Aerial view of fractures in pahoehoe basaltic lava flows on the Reykjanes Peninsula. View southeast, the main fracture is a normal fault; the lava surface to the left of the fault (closer to you) has subsided by several metres relative to the lava surface to the right of the fault. Several other normal faults are seen here, but also tension fractures. These fractures are part of the Vogar Fissure Swarm of the Reykjanes Volcanic System (Fig. 2.3). See the caption to Fig. 2.5 for more details

in that the Icelandic shields are much smaller and formed in one or a few eruptions, whereas the large shield volcanoes form in numerous eruptions over tens or hundreds of thousands of years. Thus, the large shield volcanoes are central volcanoes whereas the lava shields are not.

In addition to the fractures and lava flows, there is one very noticeable mountain that can be seen from Road 41 so long as it is not pouring down rain. That mountain is **Keilir (3)**, a cone-shaped mountain that stands as a landmark in the surrounding lava field (Fig. 2.7). The mountain rises about 380 m above sea level and is seen from far away. It is made of basalt, but during an eruption in deep water. When hot magma meets the cold water, the resulting explosions change the magma into fine particles or grains. Each explosion forms one layer of particles or ash. As the layers pile up during the eruption, they form a mountain—hence Keilir. Clearly, the area where the mountain stands today is dry—so where did the water come from? Very likely from a lake in a thick glacier that covered Iceland,