5 Thingvellir (Þingvellir)

Thingvellir is perhaps the best place on this planet to understand the process of rupturing of the crust in response to the pulling forces of plate movements. You will be driving to, and most likely walking inside, the most spectacular example of the effects of the enormous plate-tectonic forces tearing the crust apart. While it is easy to see the open fractures on the ground—and you will see the large ones while walking in the Thingvellir National Park—it is perhaps easier to explain the processes and forces by looking at the area and some of the sites we visit from aerial photographs (Fig. 5.1; see also Fig. 4.1). I therefore include many aerial photographs in this chapter.

Thingvellir constitutes a graben that forms a part of the West Volcanic Zone (Fig. 2.2). More specifically, the Thingvellir Graben is located in the northern part of the Hengill Volcanic System (Figs. 2.3 and 5.2). Although the area is geologically a wonderland, and all the sites are spectacular, it is worth mentioning that great care is needed while walking among the fractures. There are, as we shall see, numerous small fractures adjacent to the larger ones, and many of the fracture walls are unstable. So my strong recommendation is **never ever go to the edge of a large fracture**.

5.1 Almannagja (Almannagjá)

The **fourth stop (4)** on the Circle is normally at the entrance to the largest fracture of the Thingvellir area, **Almannagja (Almannagjá)**, which means the fracture or fissure for or belonging to the general public. It certainly does so today—and you are likely to see many people walking the path along Almannagja. At this stop the classic view is the one in Fig. 5.3 (cf. Fig. 6.1). For comparison, Figs. 5.1 and 5.2 show a larger part of Almannagja from the air. More detailed aspects of this part of

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Fig. 5.1 Aerial photograph showing the location of the four main sites visited at Thingvellir. The numbering refers to the stops indicated in Fig. 4.1. View southwest, the fourth stop (4) is at the entrance to the main fracture in Thingvellir, namely Almannagja. The fifth stop (5) is along the path down Almannagja where the west wall is very high and clear for observations of flow units and related aspects. The sixth stop (6) is at Lögberg, the site for parliamentary meetings when Iceland's parliament was located at Thingvellir, but also geologically an interesting place. The seventh (7) stop has two sites. The first is the popular water-filled fracture Peningagja and its extension Nikulasargja. Both of these, however, are just segments of the main fracture, referred to as Flosagja, which is the second site for the seventh stop. The river Öxara (Öxará) flows to the southwest along part of Almannagja, from the waterfall Öxararfoss (Öxarárfoss)

Almannagja are in Figs. 5.4, 5.5, 5.6, 5.7 and 5.8. In particular, Fig. 5.8 indicates some of the main geological structures associated with Almannagja. The main geological points regarding Almannagja may be summarised as follows (with references to Figs. 5.1, 5.2, 5.3, 5.4, 5.5, 5.6, 5.7 and 5.8):

- The fracture is formed through two main processes: opening and subsidence (vertical displacement). The maximum opening is just over 60 m; the maximum subsidence or vertical displacement is about 40 m (Fig. 5.9). Both processes relate to the plate-tectonic forces that tear the crust apart (discussed further in Sect. 5.3).

- The opening of 60 m by this single fracture gives a spreading rate (Fig. 4.5; Chap. 4) of about 0.6 cm per year. How do we know this? Simply by considering that the fracture is located in a lava flow that is about 10 thousand years old. So if the fracture opens by 60 m in 10,000 years, then we have 60/10,000 or 0.006 m or 0.6 cm per year. When the openings of all the fractures along a line or profile (or section) across the Thingvellir Graben are added up, we obtain 100 m, so that the spreading rate in the past 10,000 years is, on average, about 1 cm per year. This result is generally in good agreement with the spreading rate at Thingvellir measured by other means (such as by satellites) during the past decades.

Fig. 5.2 The fractures of Thingvellir, including Almannagja, are a part of the Hengill Volcanic System, whose central (main) volcano, Hengill, is seen here south of Lake Thingvallavatn. View southwest, this close-up aerial photograph of the southwestern part of Almannagja is taken about a decade later than the one in Fig. 5.1, and the hotel (with a red roof close to the fourth stop) in Fig. 5.1 is no longer seen in Fig. 5.2 (it burned down in 2009). Stops 4, 5 and 6 in Fig. 5.1 can be seen closer here (although not located again). The elevation difference between the western (right) and eastern (left) wall of the normal fault Almannagja is about 40 m, which is the subsidence across the fault in the past 10 thousand years. The last major subsidence was during earthquakes in 1789 when the northern shore of the lake, part of which is seen here, subsided by as much as 2.5 m. The maximum opening or aperture of the fault is about 60 m, close to Lögberg (the sixth stop in Fig. 5.1)

Fig. 5.3 Photograph of Almannagja from the fourth stop in Fig. 5.1. View northeast, the surface of the eastern (right) fault wall is inclined by about 11° to the east, whereas the surface of the western (right) wall is horizontal (see Figs. 5.8 and 5.9 for the geometric details). View northeast, the mountain Armannsfell is seen at the end of Almannagja, as well as part of the lava shield Skjarldbreidur (see also Fig. 6.4 for Armannsfell and Fig. 6.6 for Skjaldbreidur)

- The elevation difference between the top of the western wall to the lowest ground of the eastern wall, is about 40 m (Fig. 5.9). It follows that during the past 10,000 years the average rate of vertical displacement, primarily subsidence, across Almannagja has been about 0.4 cm per year. We see therefore that the rate of vertical displacement is about half the rate of opening or spreading in the Thingvellir area.
- While the plate movements are continuous, opening and vertical displacement across fractures such as Almannagja occur in discrete events. During such events, the eastern (lower) fracture wall of Almannagja suddenly subsides relative to the western (higher) wall (Figs. 4.14 and 5.9). Such abrupt displacements normally give rise to earthquakes. The last major subsidence, by close to 1 m at Almannagja, took place during earthquakes in 1789. The earthquakes lasted many days, during which part of the land on the north shore of the lake subsided beneath the water. In the centre of the Thingvelllir Valley

or Graben, the subsidence may have been greater, or as much as 2.5 m. As a result of this subsidence, the Parliament of Iceland was moved from Thingvellir to the capital, Reykjavik.

- All large fractures such as Almannagja—a large normal fault—are formed of smaller parts or segments (Sect. 5.3). As the tearing apart of the crust continues, that is, the spreading continues, the parts or segments of the fracture link together. But the original segments and the linkage between them are normally marked by offsets (Fig. 5.8; cf. Sect. 5.3). When you walk down the road or path inside Almannagja towards the fifth stop, you start your walk at the south end of one of the main segments of Almannagja. And at that lateral end, the fracture does not reach great depth and is made of pure opening—a tension fracture—so that there is no subsidence (Figs. 5.2, 5.4 and 5.8).

Fig. 5.4 The 'entrance' to Almannagja. This part can be seen on the aerial photographs (Figs. 5.2 and 5.8) as being the end of one of the segments of Almannagja. Where the segments end, as here, they are pure tension fractures. That is, the walls on either side of the fracture are at the same elevation. Tension fractures are best seen in Figs. 5.11, 5.12 and 5.15

Fig. 5.5 The lava flow that constitutes the walls of Almannagja is a pahoehoe lava flow. Such flows are basaltic and composed of numerous flow units, commonly with vertical cooling or columnar joints, and can reach thicknesses of several hundred metres, as does the present lava flow. For a vertical section through a thick pahoehoe lava flow, much older than the Thingvellir flow, see Figs. 11.19, 11.20 and 11.21

Walking down the path along Almannagja, we should make the **fifth stop (5)** so as to take a look at the fracture walls (Figs. 5.5 and 5.6). We see that the walls are made of many layers, each one 0.5–2 m thick. All the layers belong to the same lava flow, which at Thingvellir has a thickness of several hundred metres. In the walls we see only the uppermost twenty metres or so (the maximum height of the western wall is about 28 m). The lava flow is about 10 thousand years old and filled a valley, namely the graben that already existed at the time.

The flow is a thick pahoehoe flow of the type very common in the shield volcanoes of Hawaii and other basaltic edifices. Such flows are composed of numerous thin layers of the kind we see in the walls of Almannagja. The layers are called **flow units** (Figs. 5.5 and 5.6). There may be many tens, sometimes hundreds, of flow units in a single thick pahoehoe flow (in Chap. 11 we see a vertical section thorough a thick pahoehoe lava flow). As mentioned in Chap. 2, pahoehoe lavas are made of magma that is very hot (around 1300 °C). When erupted, the magma forms a flowing lava with a temperature of about 1200 °C at the surface (the lava, at the surface, is about one hundred degrees cooler than the magma in the magma chamber). Pahoehoe lava of this type flows very easily, that is, it has a comparatively low viscosity or, more specifically, viscosity similar to that of tomato ketchup or mustard. Each flow unit normally comes from an underground tunnel or tube, a **lava tube**. When the tubes drain at the end of the eruption, they form **caves**, some of which may reach many kilometres in length.

When looking very closely at the flow units—which is perhaps best to do as you enter Almannagja where the walls are still low and little danger of rock falls (Fig. 5.4)—you see a lot of cavities in them. Most of the cavities are either circular or somewhat elliptical in shape, and with a common diameter between half and one centimetre. The cavities (named **vesicles** by geologists) are initially gas-filled swellings or bladders within the lava. When the gas escapes out of the hot but solidifying lava and into the air, a cavity is left. The shape of the cavity is an

Fig. 5.6 Close-up of some of the flow units and cooling or columnar joints seen in Fig. 5.5. Here we see three main flow units (and part of the fourth one in the top left corner of the photograph). The cooling or columnar joints are best developed in the topmost flow unit. Vertical columnar joints are typical for horizontal flow units and lava flows in general, but are normally much better developed (more beautiful) in intrusions (see Figs. 11.6, 11.8 and 11.10 for horizontal columnar joints in a dike, and Figs. 14.30, 14.32 and 14.33 for vertical columnar joints in a sill)

Fig. 5.7 The surface of the eastern wall (left) of Almannagja is tilted by about 11° to the east. The tilting is most likely because of friction along the fault at depth (illustrated in Fig. 5.9). The tilting of the eastern wall is along the greater part of Almannagja (Figs. 5.1 and 5.8)

indication of the viscosity of the lava—and thereby the temperature of the lava. If the cavity cross-section is circular or somewhat elliptical, as in the walls of Almannagja, the lava flow had a high temperature and low viscosity. If the cross-section of the cavity is highly elongated or angular, the lava flow had a comparatively high viscosity and lower temperature. The lowest temperatures of basaltic lavas are around 1050 °C. These are **aa** lava flows and easily ten times more viscous than the lava flow seen in the walls of Almannagja. (I provide more discussion on vesicles in basaltic rocks, with close-up photographs, in Chap. 13.)

The **sixth stop (6)** is at the site of Lögberg, which was the main site for the parliament meetings while the parliament still met at Thingvellir (Figs. 5.1, 5.2 and 5.8). The reason for the choose of this site soon after the settlement of Iceland is partly that the western wall of Almannagja is ideal for projecting the speakers voice. One thing that is particularly clear at this site is that the surface of the eastern wall of Almannagja is inclined or tilted down to the east by about 11°. This is clearly seen on the ground (Fig. 5.7) and also from the air (Fig. 5.8). We could also see the sloping eastern wall from the first stop (Fig. 5.3) but perhaps less clearly. By contrast, the surface of the western wall is perfectly horizontal (Figs. 5.2 and 5.8).

So why is the eastern wall tilted while the western wall is not? The primary reason is friction between the walls at a certain depth (Fig. 5.9). Almannagja and other fractures in the volcanic zones of Iceland are open or gaping only to shallow depths. At depths of several tens of metres the walls are closed, that is, in contact with each other. Friction is here a measure of the resistance to relative movement of the closed fracture walls of Almannagja. The part of the eastern wall away from the contact with the western wall can subside through bending of the rocks (Fig. 5.9). At the contact between the walls, however, there is so much friction that

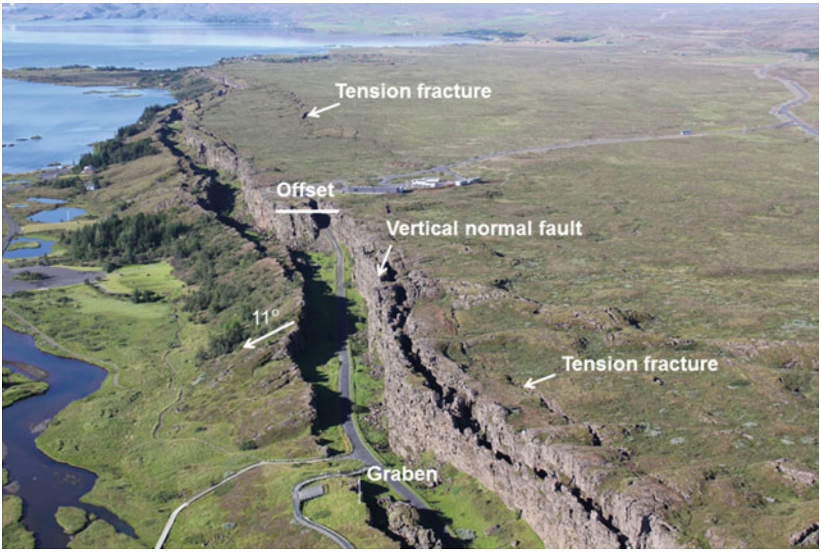

Fig. 5.8 Aerial photograph showing some of the main structures associated with Almannagja. Around Almannagja itself there are many smaller structures. These include small tension fractures (discussed in detail in connection with Figs. 5.11, 5.12 and 5.15) and the inclined eastern fault wall (its surface is inclined by 11° to the east, as shown here). By contrast the surface of the western fault wall is horizontal. Where you enter and start your walk down Almannagja, one segment or part of Almannagja is ending laterally (as a tension fracture). Then there is an east-west offset (indicated) and a new segment takes over and continues to the southwest. While Almannagja is a gaping or open normal fault, its opening is so large (more than 60 m in places) that it resembles a narrow graben (indicated). Compare the vertical section in Fig. 5.9

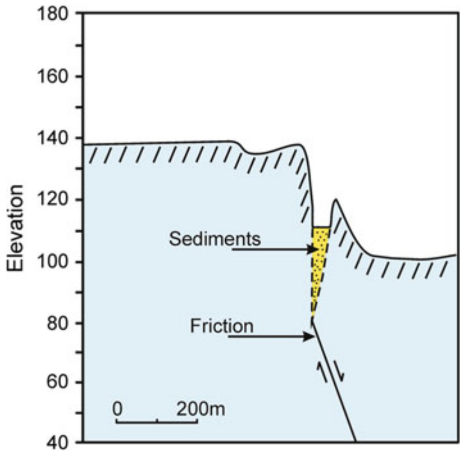

Fig. 5.9 Vertical section through Almannagja (roughly the central part seen in Fig. 5.2). The surface of the western (left) fault wall is at close to 140 m above sea level, whereas the lowest surface on the eastern (right) wall is at about 100 m above sea level. The maximum vertical displacement ('subsidence') across Almannagja is thus about 40 m. The thickness of the 'sediments', which include fractured rocks from the fault walls and gravel, is unknown. Where the fault walls come together at depth, the fault changes from being vertical (originally a tension fracture) to an inclined fault where the eastern wall has moved down relative to the western wall. At this location, the friction between the walls is presumably the reason for the tilting or sloping of the eastern fault wall. The vertical scale is exaggerated about 8-times relative to the horizontal scale

movement can only happen when large forces or stresses make it possible for slip to occur. And when slip occurs, there is an earthquake. The slip along the contact between the walls thus normally lags behind the general subsidence of the Thingvellir Graben, hence the bending or tilting of the eastern wall.

That abrupt slips and earthquakes are comparatively rare on Almannagja is known from recording of earthquakes, and is also indicated by Fig. 5.10. Here we see a stone which is poorly connected to the rest of the wall. In fact, the stone has been in exactly the same position for at least tens of years. During a moderate or strong earthquake the stone is almost certain to fall. But while the entire Thingvellir area is moving or spreading at the rate of close to a centimetre per year, no earthquakes of these sizes have occurred on Almannagja for many decades.

5.2 Peningagja and Flosagja (Peningagjá and Flosagjá)

We now move on to the **seventh stop (7)**. This stop is split in two parts, as explained below, and indicated in Figs. 4.1 and 5.1. It is easy to walk to this stop along the path from stop (6). Part of the path is seen in Figs. 5.1 and 5.2. Alternatively, you may choose to walk back to your car up (south) along Almannagja and then drive to the seventh stop. The seventh stop is one of the most popular in Thingvellir and is at a water-filled fracture named **Peningagja (Peningagjá)**. The name means 'Money Fissure', the money in this case being coins thrown by tourists into the fissure, a tradition established in the early twentieth century. Peningagja is a part of a larger fissure whose name is **Nikulasargja** (**Nikulásargjá**) which, in turn, is a part or segment of a larger fissure whose name is

Fig. 5.10 View west, the uppermost part of the western fault wall of Almannagja at stop 6 (Fig. 5.1). The little stone has been in this position for at least decades, indicating that despite gradual slow crustal movements at Thingvellir, as measured by geodetic instruments, no moderate to strong earthquakes have occurred on Almannagja for many decades and probably not since 1789

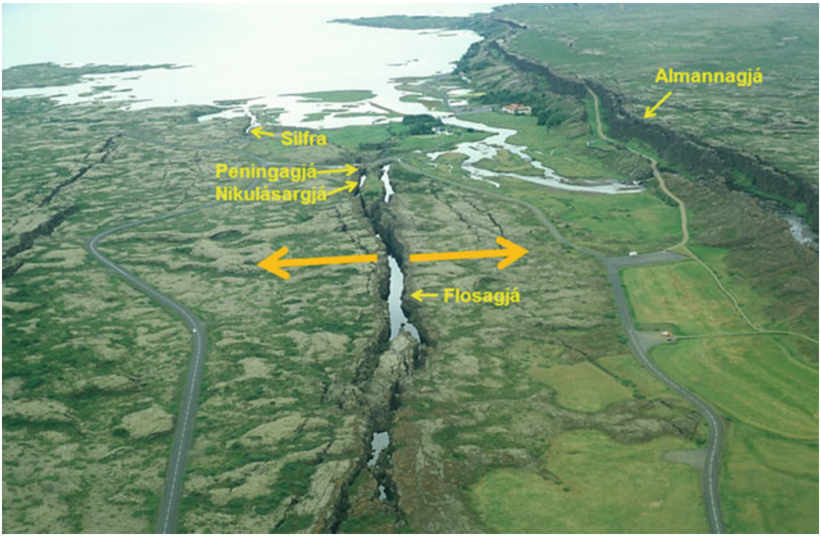

Fig. 5.11 Aerial view of the tension fractures Peningagja (Peningagjá), Nikulasargja (Nikulásargjá), Flosagja (Flosagjá), and Silfra, as well as the normal fault Almanngja (Almannagjá). View southwest, the plate-tectonic forces, indicated schematically by orange arrows at Flosagja, tear the crust apart, rupture it, and form tension fractures and normal faults. Close to the road, at the east (left) margin of the photographs are normal faults

Flosagja (**Flosagjá**). The latter, Flosagja, is the original name of the entire fissure, and Peningagja and Nikulararargja are just among its southernmost segments or parts (Fig. 5.11).

Peningagja and Nikulasargja are very impressive structures (Fig. 5.12). But in some ways the main fracture, Flosagja, is the most spectacular of them all (Fig. 5.13). Peningagja/Nikulasargja and Flosagja here count as the **seventh stop (7)** in two parts. Flosagja (Fig. 5.13) can be reached through walking from Peningagja/Nikularsargja. Alternatively, if you drive into the Thingvellir Graben along Road 36 and then take Road 52 to the south to the parking place close to the waterfall **Öxararfoss** (**Öxarárfoss**), seen in Fig. 5.3, and walk from there to the fracture. In Sect. 5.3 I explain how the fractures form, but first let us have a look at the water in the fractures.

The water is very clean and clear—it is a perfect example of high-quality **groundwater**. In fact, the lava fields of Thingvellir and its surroundings are among the largest groundwater aquifer systems in Iceland. The water originally comes from precipitation, either directly from the rain and snow that falls on the area or, more indirectly, from melting of the glaciers in the north—in the highlands of Iceland—particularly the Langjökull ice cap. The groundwater migrates from the highlands surrounding the Thingvellir Graben through the lava flows which act as a sieve or filter for cleaning the water. When the water reaches the fractures it migrates into them and finally into **Lake Thingvallavatn** (Figs. 5.1, 5.11 and 5.14). About 90% of all the water in the lake comes from groundwater springs, the rest being from surface water (rivers). And since much of the water comes from far away, from Langjökull and the surrounding highlands, it takes many years—even tens of years—for the water to migrate the distance of about 50 km from the ice cap to the lake.

The surface elevation of the lake varies somewhat, but is at about 100 m above sea level on average (Fig. 5.14) and is at the same elevation as the water level in the fractures (Figs. 5.11, 5.12 and 5.13). This level is also the general elevation of the surface of the groundwater in the vicinity of the lake, so that the surface of the lake and the surface of water in the fractures close to the lake are at the same elevation (Figs. 5.1 and 5.11), named the **water table**. The lake itself exists because the valley or graben it occupies reaches below the water table—a common

Fig. 5.12 Peningagja, the water-filled fissure with numerous coins at its bottom, is a part of a tension fracture named Nikulasargja, most of which is seen here

Fig. 5.13 Peningagja and Nikulasargja (Fig. 5.11) are a part of a larger tension fracture named Flosagja, part of which is seen here. View northwest, the maximum opening or aperture ('width') of the fracture is about 15 m. Tension fractures form by pure opening, where the forces or stresses causing the opening are directly related to the plate-tectonic forces. Flosagja, as well as Nikulasargja and Peningagja, are seen from the air in Fig. 5.11

reason for the formation of lakes everywhere in the world. In fact, the lake is as deep as 114 m, so that its deepest parts reach below sea level (are at 14 m below sea level, to be accurate). The average or mean depth of the lake, however, is only 34 m. The lake covers an area of about 84 km^2, making it the largest natural lake in Iceland (Fig. 5.14).

The fractures (Figs. 5.11 and 5.12) were not in any way formed by the pressure of the water. All the fractures are formed directly by plate-tectonic forces or stresses (Fig. 5.11) and are just conduits for the groundwater. The groundwater moves or circulates very slowly through the rock before it meets the fractures that conduct the water into the lake. Groundwater has close to the same temperature throughout the year, a temperature which is similar to the average annual temperature in the area. In the fractures the water temperature is mostly 3–4 °C (Figs. 5.12 and 5.13). The water is thus very cold, yet warm enough so that it does not freeze. Thus, even in mid-winter, the water in the fractures does not become covered with ice.

The temperature of the lake (Fig. 5.14), however, changes over the year. It is lowest in the winter months and highest in the summer months. In the winter months of January to March the average temperature is less than 1 °C, but 9–10 °C in July and August. The average temperature of the surface water of the lake itself is somewhat higher than that of the water in the fractures. For the decades before the turn of the century, that is, before the year 2000, the water temperature in the lake was between 4 and 5 °C. In the present century, that is, after the year 2000, however, the temperature has so far been above 5 °C. This is, at least partly, related to the general warming in Iceland (and elsewhere) which has been most noticeable in the past two decades or so. Ice does form on the whole lake during the winter but

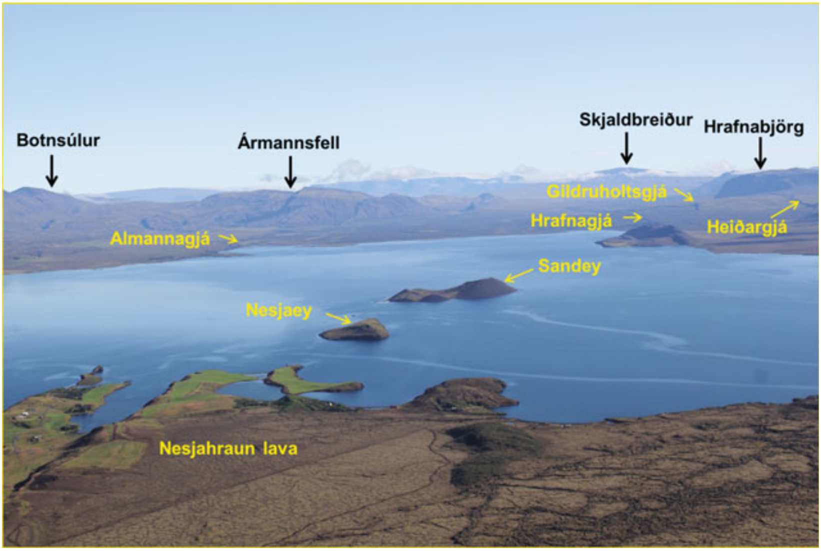

Fig. 5.14 The greater part of Lake Thingvallavatn. This aerial photograph shows the lake from the southwest. Most of the water in the lake originates in groundwater springs. The surface elevation of the lake is about 100 m above sea level, whereas its deepest part reaches a depth of 114 m, so that it extends below sea level. Lake Thingvallavatn, with an area of 84 km^2, is the largest natural lake in Iceland. For discussion of the mountains north of the lake (Armannsfell, Skjaldbreidur, and Hrafnabjörg) see Chap. 6 and for Botnsulur see Chap. 4. The largest faults at Thingvellir are indicated (Almannagja, Hrafnagja, Gildruholtsgja, and Heidargja) and discussed in Chaps. 5 and 6. The lava flow Nesjahraun 2-thousand year-old lava flow Nesjahraun on the south shore of the lake and the island Sandey formed about 2-thousand years ago and are discussed in Chap. 12

the number of days with ice cover has been declining considerably in the past two decades. In fact, in some of the years during the past decade there were no days when the entire lake surface was frozen.

5.3 How Do the Fractures Form?

Coming back to water-filled fractures (Figs. 5.11 and 5.12), how do they form? The general answer is that they form when the tectonic plates on either side of the Thingvellir Valley are being separated or pulled apart, resulting in spreading (Fig. 4.5). As we discussed above, Iceland is being pulled apart across the volcanic rift zones. In Thingvellir the rate of pulling apart, or spreading, is on average over thousands of years, about 1 cm per year. Far away from the volcanic zones (Fig. 2.2), in particular Thingvellir itself, the spreading is continuous, but its effects as regards fracture formation within the Thingvellir Graben is episodic. This means that centuries may pass between major **rifting events** with fracture formation or widening in Thingvellir. Recall that the last main rifting event in Thingvellir was in 1789, so more than two centuries ago.

So why does the rifting or rupture occur in separate events? Why is it not continuous like the spreading or plate movements themselves? The answer to both questions is that the plate-tectonic forces have to build up stress in the crust that is high enough to rupture the crustal rocks, to break the rocks. Gradually, as the forces move the plates apart, the Thingvellir Graben is stretched and its rocks become subject to higher and higher stress. As you know from tearing a sheet of paper, an existing rupture—a 'fracture'—makes it easier to tear the paper asunder. That is because the stress becomes raised or magnified at the rupture ends or tips, and these then propagate to the edges of the paper during the tearing. Similarly, the existing fractures (Figs. 5.11, 5.12 and 5.13) raise or concentrate the plate-tectonic stress at their lateral ends or tips, so that a particular fracture is most likely to lengthen, become longer, when the stress is high enough for a rifting event to take place. Thus, during rifting events, existing fractures become larger, that is, become longer and also deeper (Fig. 5.11). As rifting events continue, small offset fractures propagate and link up into larger fractures (Figs. 5.15 and 5.16).

Flosagja (and Nikulasargja and Peningagja) are clearly different from Almannagja in that the fracture walls in Flosagja on either side of the fracture are at the same elevation (Figs. 5.11, 5.12 and 5.13). By contrast, the eastern wall of Almannagja has subsided by as much as 40 m relative to the western wall (Figs. 5.1, 5.2, 5.7, 5.8 and 5.9). In geological terms, Almannagja is a **fault**, and more specifically a **normal fault**, whereas Flosagja (and Nikulasargja and

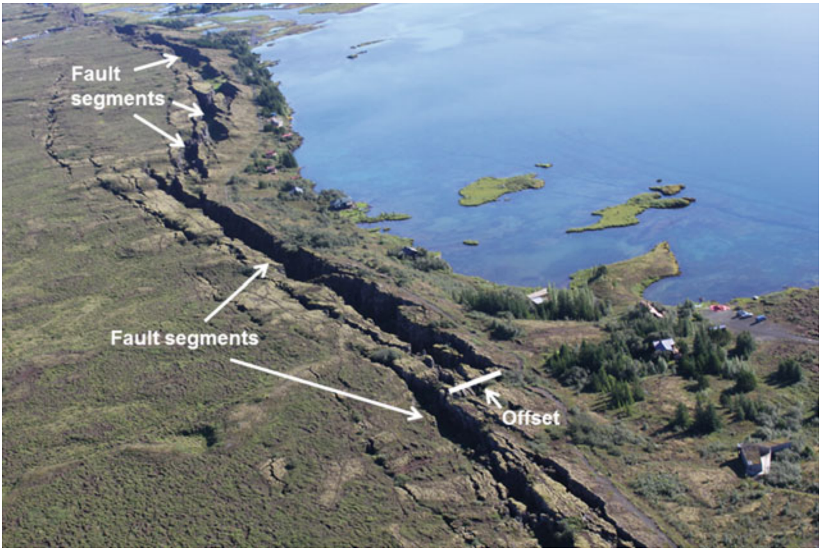

Fig. 5.15 The southwestern part of Almannagja is highly segmented, that is, divided into many smaller fractures. This is partly because the old fault beneath the surface lava flow and which controls where the surface fractures occur is no longer perpendicular to the main plate-tectonic force (as shown in Fig. 5.14). On a local scale, as here, the direction of the plate-tectonic force or spreading vector fluctuates ('wobbles' somewhat) so that a fracture that was initially oriented at right angle to the spreading vector or force may not be so for a while. The length of the offset indicates how much the fault shifts laterally when passing from one segment to another

Peningagja) is a **tension fracture**. In a fault, much of the movement of the rock on either side of the fracture is parallel with the plane of the fracture, either up or down (vertical) the fault plane, or sideways (horizontal). Most **earthquakes** are related to sudden movements of the walls or slip on faults, and all large earthquakes are generated by such movements. On a tension fracture, by contrast, the movement is simple opening, pulling the fracture walls apart (Fig. 5.11). There is thus no fracture-parallel movement during tension-fracture formation, and therefore no friction between the fracture walls (Fig. 5.9). For tension fracture opening, the earthquakes that occur, if any, are normally small.

So how much stress must build up before we will have a new rifting event in Thingvellir? That is easy to calculate and turns out to be about 3 million pascals (3 mega-pascals). Now this may sound as something very great. However, the unit pascal (Pa), which measures stress or pressure as force over area—force per unit area (newtons per square metre)—is tiny. One pascal is equal to the fluid pressure of a film or layer of water that is about 0.1 or one-tenth of a millimetre thick. At the bottom of a 2-m deep swimming pool the pressure due to the water is about 20 thousand pascal. At the bottom of Lake Thingvallavatn, at 114 m, the pressure due to the water is about million pascal. Thus, the stress needed to form Flosagja and other tension fractures at Thingvellir (and in general in rift zones and at ocean ridges worldwide) is of the same magnitude as the pressure at the depth of about 300 m in a lake or the sea. Alternatively, it is of the same magnitude as the pressure or vertical compressive stress (due to the weight of the rocks) at the depth of 120–130 m in the Thingvellir lava flow, the one seen in Almannagja (Fig. 5.5). I say the same magnitude because pressure or compressive stress seeks to compress an object, whereas tension or tensile stress (which may be of the same magnitude as the compressive stress or pressure, but with an opposite sign), responsible for the fracture formation, seeks to expand or extend the object—here the rocks at the

Fig. 5.16 Close to its southernmost end, just as it enters into Lake Thingvallavatn, Almannagja changes into a set of tension fractures. View southwest, this set is seen here. The opening of the fracture to the right (west) of the white car is 12 m. The step-like oblique arrangement of the fractures seen here is known in geology by the French term én echelon

surface of Thingvellir. As regards sign, in geology the sign of tensile stress is normally minus (−) and that of compressive stress plus (+), whereas in physics and engineering the sign convention is exactly the opposite.

The tensile stress needed to form the tension fractures is thus high, but not very high in comparison with the compressive stresses that generally exist in the crust. The compressive stress increases with depth in the crust. For example, in the roofs of many shallow magma chambers in Iceland (Chap. 4), at depths of one to three kilometres, the vertical stress is between about 24 million and 80 million pascal. The magnitude of the vertical stress in the roofs of shallow chambers is thus 8–27 times larger than the tensile stress needed to rupture the crust and form tension fractures at Thingvellir.

5.4 How Deep Are the Fractures?

Now that we know the stresses required to form the impressive tension fractures (and similar stresses are needed for the large faults such as Almannagja), the next question is how deep are the fractures? These are really two questions. One question is: what is the visible depth of the fractures, that is, the part mostly filled with groundwater? The other question is: what is the depth of the fracture as a narrow crack in the crust? As for the first question, Flosagja reaches a maximum visible depth of some 25 m (Figs. 5.11 and 5.13). There are other tension fractures nearby that reach even greater visible depths. The best known is **Silfra**, whose maximum visible depth is around 60 m. Silfra is on the north shore of, and extends into, Lake Thingvallavatn, a few hundred meters to the south of Peningagja (Fig. 5.11). Silfra is very popular for diving.

The second question is to what depths in the crust do the tension fractures reach? Here I mean the depth not as the widely open fractures seen at the surface, or with the openings that people can dive into, but rather the depths to which the fractures continue as narrow cracks down into the crust. You might ask how it is possible to find this depth. The answer is that all large tension fractures, such as Flosagja, Nikulasargja, Peningagja, and Silfra can only reach a certain maximum depth. If (say during a rifting event) they attempt to exceed this maximum depth, they will automatically change into normal faults. That is, one of the fracture walls will then subside relative to the other wall—just like at Almannagja and the other normal faults at Thingvellir. Using this information, and general knowledge of how fractures form (a specific scientific field named **fracture mechanics**), it is possible to calculate the maximum depths of tension fractures such as Flosagja and Silfra as being between 300 and 400 m. They are thus most likely entirely within the thick pahoehoe lava flow that occupies the uppermost part of the Thingvellir Graben—namely the Thingvellir lava flow.

And then, of course, the next question would be: how deep is Almannagja? The answer is that there are no simple methods for calculating accurately the depths of large normal faults such as Almannagja. If Almannagja were highly active seismically—with numerous small earthquakes—then their depths would indicate the depth of the fault. But Almannagja has very little seismic activity. One crude indication of the depth of a fracture, including faults such as Almannagja, is its length at the surface: longer fractures tend to be deeper than shorter fractures.

Almannagja is the longest continuous fracture of the Thingvellir Graben. By continuous fracture I mean that all the fracture segments or parts are physically connected or linked together—there is no strip of land in-between their nearby ends. Its total length as a continuous fracture is about 7.7 km. For comparison the shortest tectonic fracture in the Thingvellir Graben is about 60 m and the average or mean length of all the fractures about 620 m. The longer fractures are generally normal faults and generate earthquakes when they slip, whereas the shorter fractures tend to be tension fractures with little earthquake activity when they grow.

But Almannagja, like all the larger fractures, is composed of parts or segments, many of which, even if comparatively close to each other, are not physically connected—they are disconnected and offset (Figs. 5.8, 5.15 and 5.16). We know that in earthquakes segmented and disconnected faults commonly act as single faults, and the same would apply to all the segments of Almannagja during moderate to strong earthquakes (Almannagja cannot generate really major earthquakes of magnitude 7 or greater). And if all the segments of Almannagja are counted, then its length within Thingvellir is at least 15 km. Similar segments continue into the hyaloclastite mountains north of Thingvellir (Armannsfell, Ármannsfell, Chap. 6), as well as to the southwest along Lake Thingvallavatn and towards the Hengill Volcano (Chap. 12). If all these segments are regarded as parts of Almannagja, then its total length is easily 30–40 km. Similar lengths would be obtained for some other large faults in the area; their lengths may reach several tens of kilometres when all the segments, also in the older rocks, are considered parts of the same faults.

Then we come back to the question: how deep into the crust do Almannagja and the other large faults at Thingvellir extend. The answer is at least 10 km, and more likely about 20 km. Why not more than 20 km? Because at approximately that depth there is magma beneath the West Volcanic Zone (Fig. 2.2), of which the Thingvellir Graben is a part. The large faults of the Thingvellir Graben, and their extensions to the southwest and northeast along the West Volcanic Zone, most likely reach to the bottom of the crust, into the roofs of deep-seated and very large magma reservoirs (Fig. 5.17).

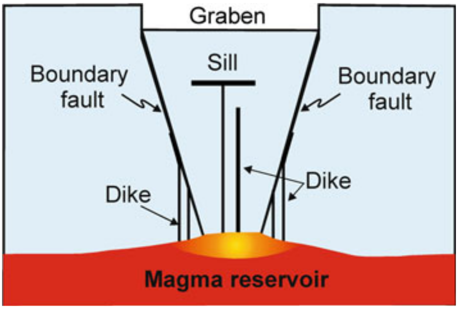

Fig. 5.17 Grabens are common in volcanic rift zones, such as in Iceland. Grabens can often act, temporarily at least, as barriers to dike propagation to the surface, and thus to fissure eruptions. Graben acts as a barrier to vertical dikes when the boundary faults deflect or stop or arrest the dikes and also when temporary compression inside the graben wedge stops or arrests dikes or deflects them into sills. When the graben wedge subsides, it enters into a narrower 'gap', so to speak, and may then become subject to horizontal compression for a while. Horizontal compression arrests vertical dikes or deflects them into sills; in both cases stopping the dike from reaching the surface to erupt

If so, why does the magma then not come up along the faults? The reason is their inclination and the unfavourable stresses generated temporarily in the graben following earthquake slip (Fig. 5.17). In a volcanic rift zone such as Thingvellir, the magma almost always travels to the surface through vertical magma-filled fractures, that is, **dikes** (Chap. 11). The magma very rarely uses existing inclined fractures, such as normal faults, for the simple reason that it requires much more energy to push the inclined fracture walls aside to make room for the magma, the dike, than to use the numerous vertical cooling fractures, columnar joints (Figs. 5.5, 5.6 and 5.10) to generate its own path to the surface. This follows because the plate movements are horizontal, so that it is easier for the magma to push the crust horizontally than in an inclined manner. Additionally, when the Thingvellir graben subsides along the main faults, Almannagja and Hrafnagja (Hrafnagja is discussed in Chap. 6), the effect is to hinder magma movement to the surface. When the wedge-shaped crustal block of the graben subsides, it is forced into a gradually narrower 'gap' in the crust (Figs. 4.14 and 5.17), so that the effect is mechanically similar to pressing a cork into a bottleneck, namely temporary horizontal compression. This compression generates compressive stresses which tend to prevent vertical dike propagation; the dikes either become deflected into horizontal sills or stop altogether (Fig. 5.17). In either case the dike is unable to reach the surface to erupt.

5.5 When Will the Next Eruption Occur?

When can we then expect the next volcanic eruption in the Thingvellir area? The last eruption in the area was not in Thingvellir Graben, but rather at the south end of the lake (Fig. 5.14), close to the volcano Hengill (Fig. 5.2; Chap. 12). This eruption occurred about 2 thousand years ago, during which a lava flow formed as well as the island of Sandey (Fig. 5.14; Chap. 12). Since that time there has not been any eruption in this part of the volcanic zone. The next eruption is in fact more likely to occur in the Hengill Volcano (Chap. 12) than in the Thingvellir Graben. This follows from pure statistics. As we discussed in Chap. 4, outside the main central volcanoes (such as Hengill) there is, at any given locality (such as Thingvellir), one new lava flow erupted every several thousand years—and occasionally there are tens of thousands of years between successive lava flows.

Given that the main lava flow in Thingvellir Graben is about 9 thousand year old (from Skjaldbreidur, Chap. 6), however, we might expect a new flow to come in the geologically near future. In active areas such as Thingvellir, however, the 'near future' commonly means tens or hundreds, even thousands, of years from now. Whether that eruption occurs inside the valley itself, or, as in the eruptions that formed the current lava flows in the graben, outside the graben, we do not know. But when the eruption occurs, it is likely to be much larger than the recent small eruptions in central volcanoes such Grimsvötn (Grímsvötn), Hekla, and Eyjafjallajökull (Chap. 14). In fact, an eruption in the Thingvellir area, when it occurs, is not unlikely to be of the order of several cubic kilometres.

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