Outline of Geology of Iceland

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by

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OUTLINE OF THE GEOLOGY OF ICELAND

1.1 Introduction

Iceland is located in the North Atlantic Ocean between Greenland and Norway at 63°23'N to 66°30'N. It is a landmass that is part of a much larger entity situated at the junction of two large submarine physiographic structures, the Mid-Atlantic Ridge and the Greenland-Iceland-Faeroe Ridge (Fig. 1.1). As such, Iceland is a part of the oceanic crust forming the floor of the Atlantic Ocean and is the subaerial part of the Iceland Basalt Plateau, which rises more than 3000 m above the surrounding sea floor and covers about 350000 km^2. About 30 per cent of the plateau (~103.000 km^2) is above sea level, the remainder forms the 50 – 200 km wide shelf around the island, sloping gently to depths of ~400 m before cascading into the abyss.

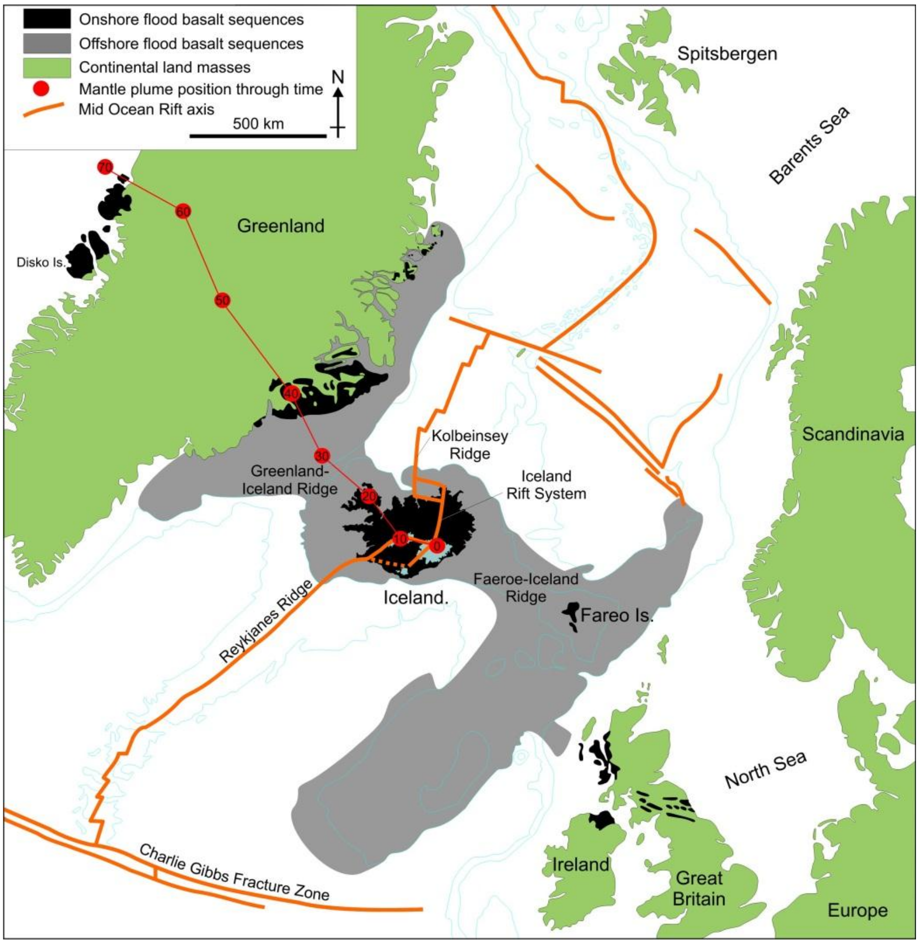

Fig. 1.1 Iceland is an elevated plateau in the middle of the North Atlantic, situated at the junction between the Reykjanes and Kolbeinsey Ridge segments. Also shown: the axis of the Mid-Atlantic Ridge (heavy solid line), the North Atlantic basalt plateau (black) and their submarine equivalents (grey). The line with the dots shows the position of the Iceland mantle plume from 65 million years to the present day.

Iceland is geologically very young and all of its rocks were formed within the last 25 million years. The stratigraphic succession of Iceland extends across two geological periods: the Tertiary and the Quaternary (Table 1.1). The construction of the Iceland is thought to have begun about 24 million years ago, but the oldest rocks exposed at the surface in Iceland are only 14-16 million years old. If we take the age of the Earth as one year, then Iceland was born less than two days ago. The first regional glaciers of the Ice Age appeared in Iceland about five hours ago and only a minute has passed since the Holocene warming removed this ice cover from Iceland.

The surface of Iceland has changed radically during its brief existence by construction (i.e. volcanism and sedimentation) and degredation (i.e. erosion). These forces of nature operate faster in Iceland than in most other places. The rocks are shattered by the frequent change of frost to thaw, and the sea, rivers and glaciers laboriously grind down the land. Erosion removes about a million cubic metres of land from Iceland each year, but volcanism and sedimentation more than counterbalance this loss as is evident in the landmass that now is Iceland.

Table 1.1 Geologic time table for Iceland showing the terminology used in this text for geologic periods, epochs and stages. Age is shown in thousands (ky) or millions (my) years.

Era	Period	Epoch	Age	Stage	Sub-Stage	Formations	Events
Cainozoic	Quaternary	Holocene	0 2.5ky	Late Bog Period (sub-Atlantic)		Upper Pleistocene Formation	
			5.0ky	Late Birch Period (sub Boreal)			
			7.2ky	Early Bog Period (Atlantic)			
			9.3ky	Early Birch Period (Boreal)			
			10ky	Pre-Boreal			
		Upper Pleistocene	11Ky	Weichselian	Younger Dryas		Ice Age glacier disappears
			12ky		Allerød		Fossvogur sediments accumulate
			20ky		Older Dryas		
			70ky				Last glacial stage
			130ky	Eemian			Elliðavogur sediments accumulate Last interglacial
			170ky	Saale			Second last glacial stage
			700ky				Svínafell sediments accumulate
		Lower Pleistocene	2.5my			Plio-Pleistocene Formation	Rauðsgjá tillite Breiðavík tillite and sediments Furuvík tillite formed Full scale glaciation
	Tertiary	Pliocene	3.3my				Tjörnes sediments stop accumulating Pacific Ocean fauna arrives in Iceland Bearing strait opens
			7my			The Tertiary Basalt Formation	Tjörnes sediments begin to form First sign of cooling climate
		Upper Miocene	12my.				Warm temperate climate
		Middle Miocene	18my				Oldest rock on land.
		Early Miocene	25my				Birth of Iceland

1.2 Geological setting: global perspective

The prologue to the formation of Iceland includes the continental break-up that separated Newfoundland and Greenland from Europe and the subsequent formation of the sea floor that now surrounds Iceland (Fig. 1.1). Around 400 million years ago the continents on either side of the North Atlantic Ocean had merged to form a continuous landmass, which remained intact for >300 million years. About 70 million years ago this landmass began to break up along a fracture zone extending from the latitudes of Newfoundland-British Isles northwards into the Arctic between Scandinavia and Greenland and a new divergent plate boundary was formed.

This plate boundary is the site of active spreading and plate growth via upwelling of mafic magma that has gradually constructed the ocean floor around Iceland. The spreading of the sea floor is a piecemeal process and in the North Atlantic the spreading rate is about 2 cm per year (i.e. 1 cm per year in each direction). The plate boundary is delineated by series of faults and volcanoes, which together form a distinguishing ridge-like structure in the middle of the ocean; i.e. the Mid-Atlantic Ridge, which is the suture where the American plate (to the west) and the Eurasian plate (to the east) that are actively being pulled apart by the forces of plate motions (Fig. 1.1).

Iceland is the only place on Earth where the mid-ocean ridge rises above sea level. More eruptions than usual occur on the plate boundary across Iceland because under the ridge is the Iceland mantle plume, which has been active for the last 65 million years. During this period it has brought unusual amounts of magma to the surface forming the North Atlantic Large Igneous Province that now stretch across the Atlantic from Scotland to Greenland. Iceland is the youngest part of the province and the only one that is still active (Fig. 1.1). The province is approximately 2000 km long and represents about 10 million cubic kilometres of magma that has emerged from the Iceland mantle plume through volcanic activity in 65 million years; a figure that is roughly 50 times the volume of Iceland.

1.3 Geological framework

Iceland is located at the junction between the Reykjanes Ridge in the south and the Kolbeinsey Ridge in the north, which are submarine segments of the mid-ocean ridge closest to Iceland. The surface expression of the plate boundary in Iceland is the narrow belts of active faulting and volcanism extending from Reykjanes in the southwest, which zigzag across Iceland before plunging back into the depths of the Arctic Ocean of Öxarfjörður in the north (Fig. 1.2). This plate boundary is the focus of active spreading and plate growth, and is Iceland's major geological showpiece because it is the only section of the Mid-Atlantic Ridge exposed above sea level. The spreading rate in Iceland is about 1.8 cm per year and the spreading directions are 105°E and 285°W.

Above the plate boundary, the spreading rips apart the brittle crust and results in the formation of extensional cracks and faults perpendicular to the spreading direction. The spreading also results in the formation of vertical subsurface dykes and one out of four dykes becomes a pathway to the surface for the magma. Above ground, these rifts appear as swarms of linear volcanic fissures that are confined to narrow belts commonly referred to as volcanic zones (Fig. 1.2). The volcanic zones are connected by large transform faults known as fracture zones or when volcanically active as volcanic belts. Together, these structures cover about one third of Iceland (~30000 km^3) and the nomenclature used for these structural identities is given in Fig. 1.2.

The volcanic zones are 20-50 km-wide belts and their magma production does more than match the extension generated by the plate movements. Consequently, the magma that emerges at the surface through volcanic activity accumulates within the volcanic zones, more so towards the centre than to the margins. Thus, the volcanic successions in the centre of the rifts are buried rapidly and follow a steep path as they move away from the spreading centre (Fig. 1.3). On the other hand, the successions closer to the margins of the rift zones keep too much shallower paths as they travel away from the spreading axis. The excess load in the middle of the volcanic zones also causes downsagging of the crust, such that the successions closer to the margins are tilted, acquiring a shallow dip (5-10°) towards the spreading axis. This tilt remains with the rock pile as it drifts out of the volcanic zones and is accreted to the plates on either side. Thus, together, the spreading and the volcanism produce a shallow syncline, which explains why the regional dip of the flanking older successions, is generally towards the currently active volcanic zones (Figs 1.2 and 1.3).

The construction of Iceland resulted from interaction between a spreading plate boundary and a stationary mantle plume. The overall morphology and geological architecture of Iceland is a representation of this interaction and its development through time. The most obvious manifestation of the interaction is the elevation of Iceland over the surrounding sea floor. Here the buoyant mantle plume has pushed up the crust to form a large oval shaped bulge (Fig. 1.1). The submarine Faeroe-Iceland and Greenland-Iceland ridges on either side of Iceland are older traces of this bulge that have been displaced from their original position by seafloor spreading. The centre of the Icelandic mantle plume is below the northwestern part of Vatnajökull ice cap. It is modelled as a 200-300 km-wide cylindrical zone of highly viscous semi-solid material that is hot and buoyant, rising extremely slowly from depths of 400-700km. As it approaches the surface, parts of the plume melt and thus provide magma to the volcanoes. About 24 million years ago the centre of the mantle plume was positioned at the extrapolated intersection of the Reykjanes Ridge and the Kolbeinsey Ridge (Fig. 1.1).

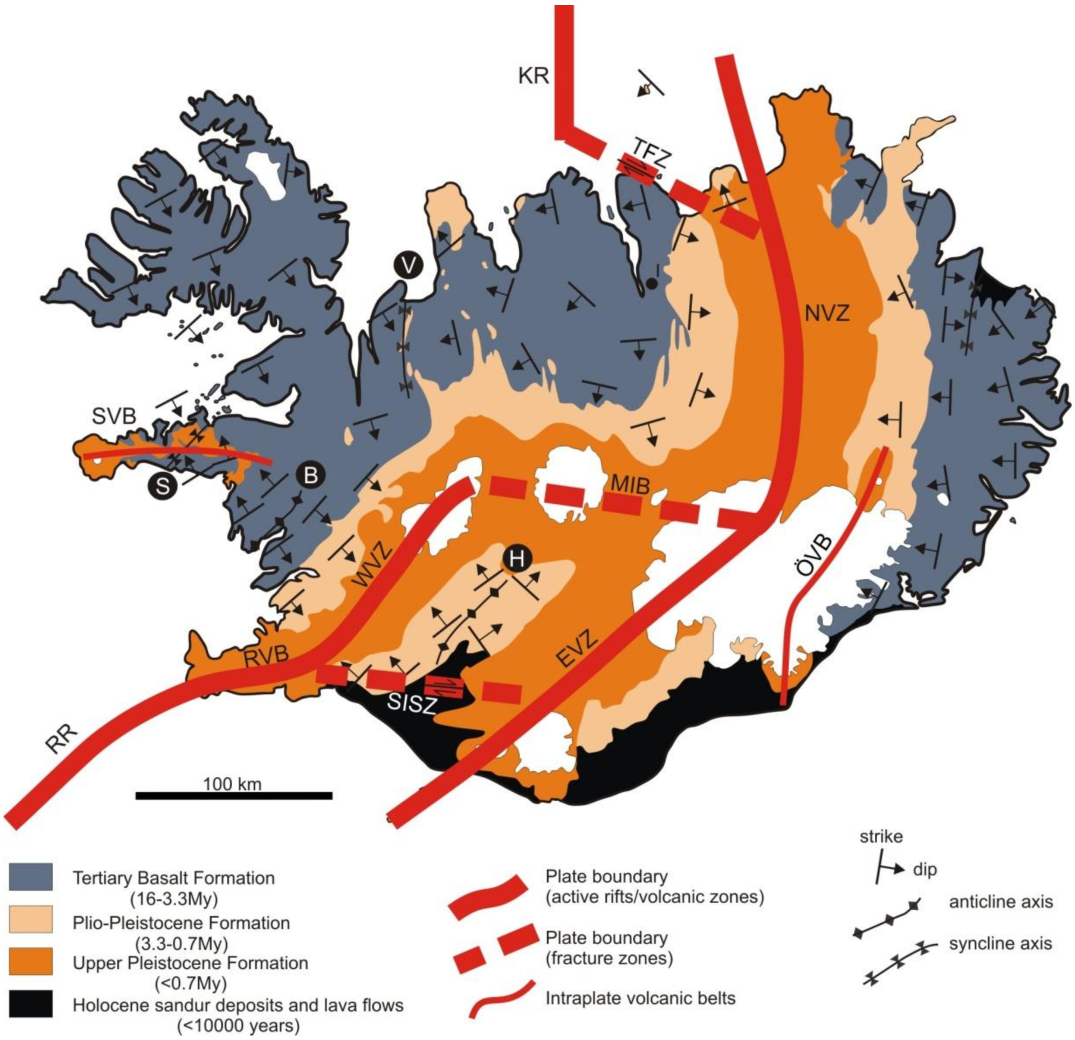

Fig. 1.2 The principal elements of the geology in Iceland, outlining the distribution of the major geological subdivisions, including the main fault structures and volcanic zones and belts. RR, Reykjanes Ridge; RVB, Reykjanes Volcanic Belt; WVZ, West Volcanic Zone; MIB, Mid-Iceland Belt; SISZ, South Iceland Seismic Zone; EVZ, East Volcanic Zone; NVZ, North Volcanic Zone; TFZ, Tjörnes Fracture Zone; KR, Kolbeinsey Ridge; ÖVB, Öræfi Volcanic Belt; and SVB, Snæfellsnes Volcanic Belt. Letters enclosed by filled black circles indicate axes of anticlines and synclunes refered to in the text, where B and H indicate the Borgarfjörður and Hreppar anticlines and S and H the Snæfellsnes and Víðidalur synclines.

Although the plate-tectonic model outlined above explains the gross features of the regional geology of Iceland, it does not fully conform to all established geological facts. Distinctive reversals in dip directions in Borgarfjörður and Hreppar areas indicate broad anticlines that follow the same axial trends as the rifts (Fig. 1.2). These anticlines are also associated with major unconformities and breakdown in the trends of isochrons (lines of equal age) across Iceland (Fig. 1.3). These discrepancies thought to occur because the relative positions of the spreading axis and the mantle plume have changed with time.

If we assume that the mantle plume is a stationary structure, then the position of the spreading axis must have changed by migrating towards the west-northwest at a rate of 0.3 cm/year. This movement is in addition to the actual spreading motion that separates the plates and occurs concurrently. As the active spreading axis moves away, the plume responds by re-adjusting the position of the axis and forming new rifts closer to its centre. The rifts further away gradually become inactive (Fig. 1.4). This process is called a rift jump. The key consequences of rift jumps are the trapping of older crust between the two rift segments and the overlap in activity on the established versus the developing rift segments with respect to time (Fig. 1.4). The accumulation of volcanic material within the rift zones results in tilting of the adjacent rock piles towards the volcanic zones. Consequently, the trapped crustal segment acquires the form of a broad anticline is formed (Fig. 1.3a). Thus, shifts in the position of the spreading axis explain the occurrence of synclines and anticlines in the geological succession of Iceland. According to this model, the currently active rifts are the West and North Volcanic Zones. The East Volcanic Zone is a rift in the making that eventually will take over from the West Volcanic Zone. Similarly, the precursor rift to the current West and North Volcanic Zones is a broad syncline that is exposed in the Tertiary succession of Snæfellsnes in west Iceland and Víðidalur in northern Iceland (Fig. 1.2).

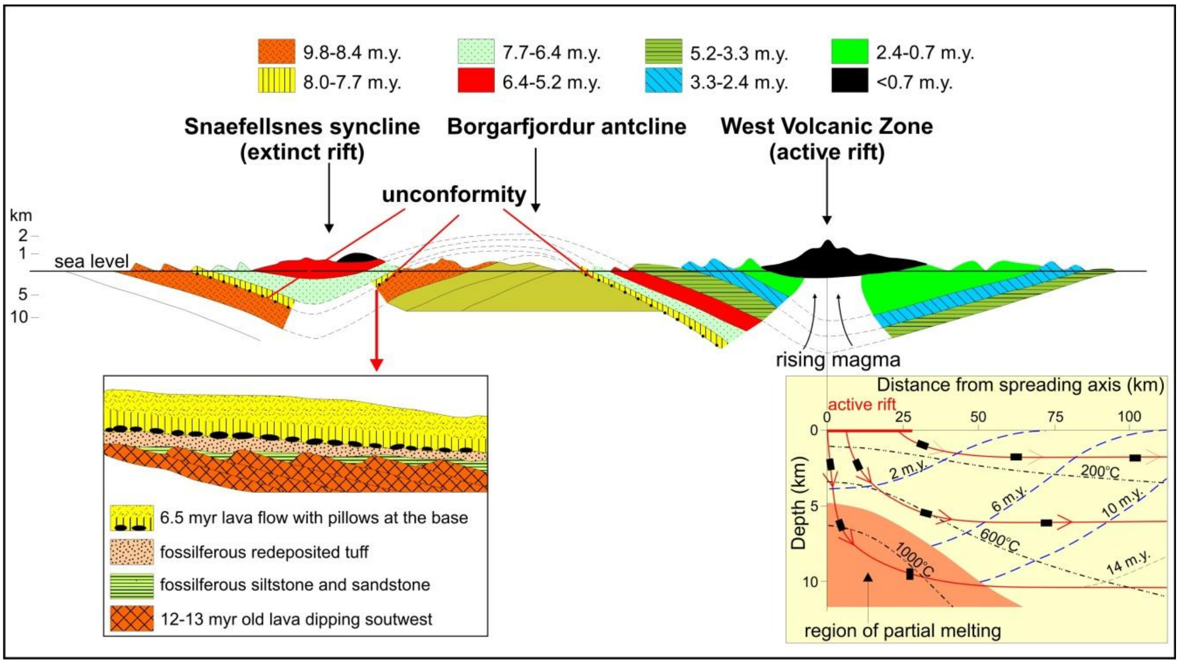

Fig. 1.3 A stylised cross section showing the general structure of the Icelandic crust from the Snæfellsnes peninsula across the West Volcanic Zone. Loading by volcanism tilts the strata towards the volcanic zones forming a shallow syncline centred on the spreading axes and a shallow anticline in the region between the volcanic zones. The lower right inset depicts the spreading paths for crustal elements (black squares) formed within different parts of an actively spreading volcanic zone. Rocks formed near the edge of the zone follow a shallow spreading path, whereas those formed close to the spreading axis follow a much steeper path.

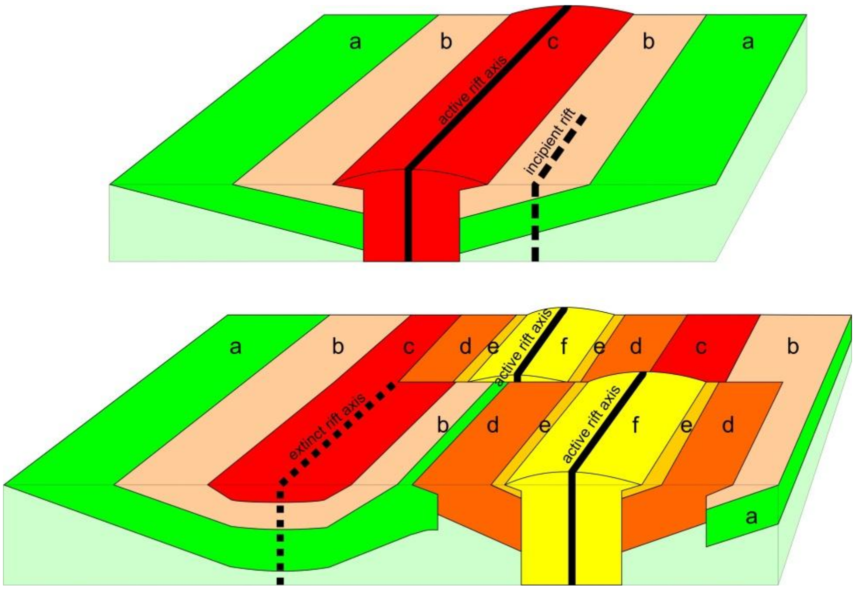

Fig. 1.4 Cartoon of structural developments on a regional scale as a result of rift jumps caused by westward migration of rift zones relative to stationary mantle plume.

There are two active intraplate volcanic belts in Iceland (Fig. 1.2) where young (<2 million years) volcanic rocks rest unconformably on older rock formations, indicating a significant time break in volcanic activity and the outpouring of magma. The first is the Öræfi Volcanic Belt situated to the east of the plume centre and the current plate margins. The second is the Snæfellsnes Volcanic Belt in west Iceland, which is on the mantle plume trail. The Snæfellsnes Volcanic Belt is in part superimposed on an extinct volcanic rift zone thought to be the precursor to the West Volcanic Zone.

The Öræfi Volcanic Belt most likely represents an embryonic rift. It is possible that the westward migration of the entire Iceland rift system is forcing the plume to establish a new volcanic zone by melting its way through the crust of eastern Iceland. Thus, the Öræfi Volcanic Belt may be yet another jump in the spreading axis across Iceland.

1.4 Volcanism

Iceland is well known for its volcanic activity and questions often asked by visitors are: How many eruptions have taken place in Iceland? What is the number of active volcanoes? One might anticipate a simple answer but unfortunately, it is not as straightforward as one might hope. The definitions of a volcano and an eruption encompass a wide range of phenomena that deviate significantly from the simple image of a conical mountain with smoke rising from its top.

It is not easy to say how many eruptions have occurred in Iceland throughout its geological history because it is not always obvious what part of the rock sequence represents a single eruption. However, recent volcanic activity in Iceland shows that on average there is an eruption every five years or ~200 eruptions in the last 1000 years. Using this frequency as a guide, the total number of eruptions that may have taken place since the birth of Iceland, 24 million years ago, is in the order of 5 million. Also, it is not clear how many of the volcanoes in Iceland should be considered active. Although it is easy to count the number of central volcanoes that have erupted time after time in the recent geological past (20 in total; Fig. 1.5), the difficulty arises when we try to assess the status of monogenetic volcanoes and fissures. By definition such volcanoes and fissures are extinct, but the region in which they are situated may still be volcanically active. To circumvent this problem the concept of a volcanic system has been introduced.

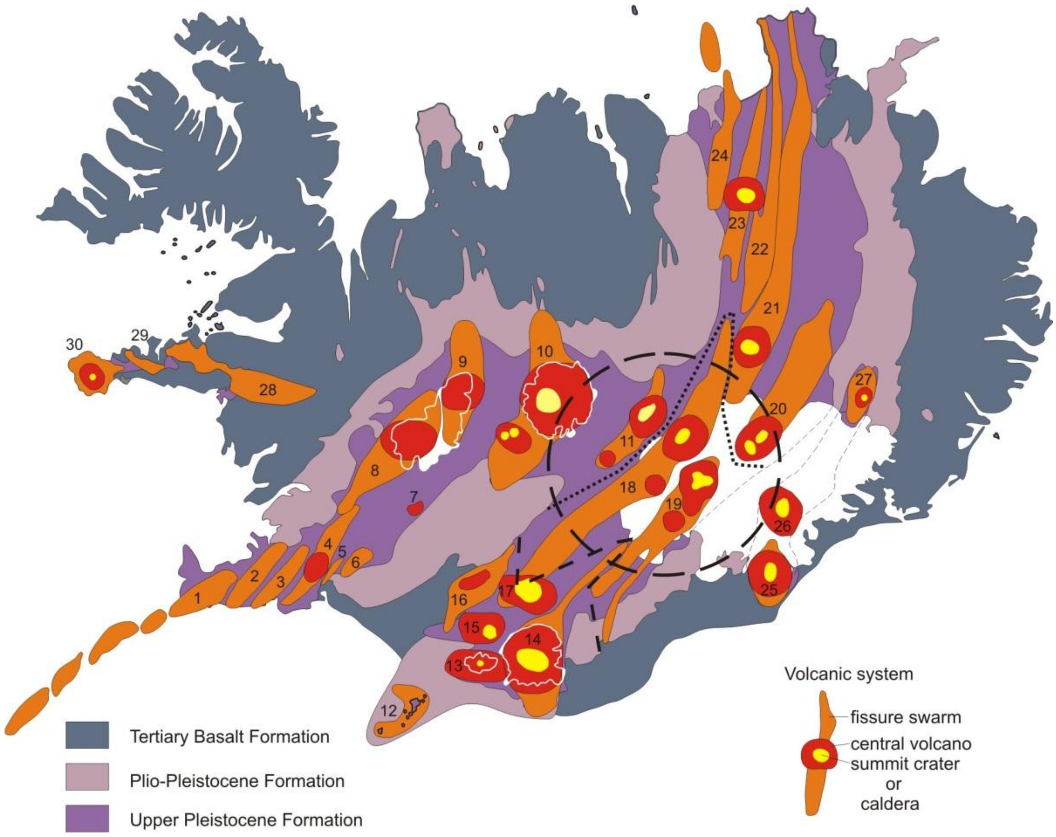

Fig. 1.5 Distribution of active volcanic systems among volcanic zones and belts in Iceland: 1. Reykjanes, 2. Krýsuvík, 3. Brennisteinsfjöll, 4. Hengill, 5. Hróðmundartindur, 6. Grímsnes, 7. Geysir, 8. Prestahnjúkur, 9. Hveravellir, 10. Hofsjökull, 11. Tungnafellsjökull, 12, Vestmannaeyjar, 13. Eyjafjallajökull, 14. Katla, 15. Tindfjöll, 16. Hekla-Vatnafjöll, 17. Torfajökull, 18. Bárðarbunga-Veiðivötn, 19. Grímsvötn, 20. Kverkfjöll, 21. Askja, 22. Fremrinámur, 23. Krafla, 24. Þeistareykir, 25. Öræfajökull, 26. Esjufjöll, 27. Snæfell, 28. Ljósufjöll, 29. Helgrindur, 30. Snæfellsjökull. The large open circle indicates the approximate centre of the Iceland mantle plume. Dotted line shows the northern limits of the East Volcanic Zone, whereas the hachured line indicates the boundary between the active and propagating rift segments of the zone.

A volcanic system is the principal geological structure in Iceland. It consists of a fissure swarm or a central volcano, or both, which are surface expressions of two different types of subsurface magma holding structures: the first a deep-seated magma reservoir, the second a shallower crustal magma chamber (Fig. 1.6). Each volcanic system is characterised by conspicuous tectonic architecture and distinct magma chemistry and typically has a lifetime between 0.5-1.5 million years. All together there are 30 active volcanic systems in Iceland (Fig. 1.5). The fissure swarms are narrow and elongated strips (5 to 20 km-wide and 50 to 100 km-long) of tensional cracks, normal faults and volcanic fissures (Fig. 1.6). They are the surface expressions of elongated magma reservoirs, which are situated at the base of the crust (>20km depth). These swarms are typically aligned subparallel to the axis of their host rift zone, illustrating that the fundamental force responsible for their formation is plate pull. Wide cracks indicative of pure crustal extension are usually the most conspicuous structures on the surface. Fault scarps and graben are also common and indicate vertical displacement and extension of crustal blocks. Young volcanic fissures typically appear as a row of small volcanic cones, whereas subglacial fissures occur as elongated 'móberg' ridges.

When present within a volcanic system, the central volcano is the focal point of eruptive activity. It is the surface manifestation of the crustal magma chambers 2-6 km below the surface. Usually, the central volcanoes are the largest volcanic edifice within each system and are often capped by a caldera (Fig. 1.6).

Events on the volcanic systems are intimately linked to the plate movements. The spreading and subsequent rifting of the crust that take place at the plate boundary are not continuous, in either time or space. They occur as distinct rifting episodes confined to a volcanic system at any one time. Normally the whole system is activated in these episodes, which typically last several years or decades. Recurring earthquake swarms and volcanic eruptions on the fissure swarm and within the central volcano characterise these rifting episodes and in Iceland such events are referred to as 'eldar' (fires).

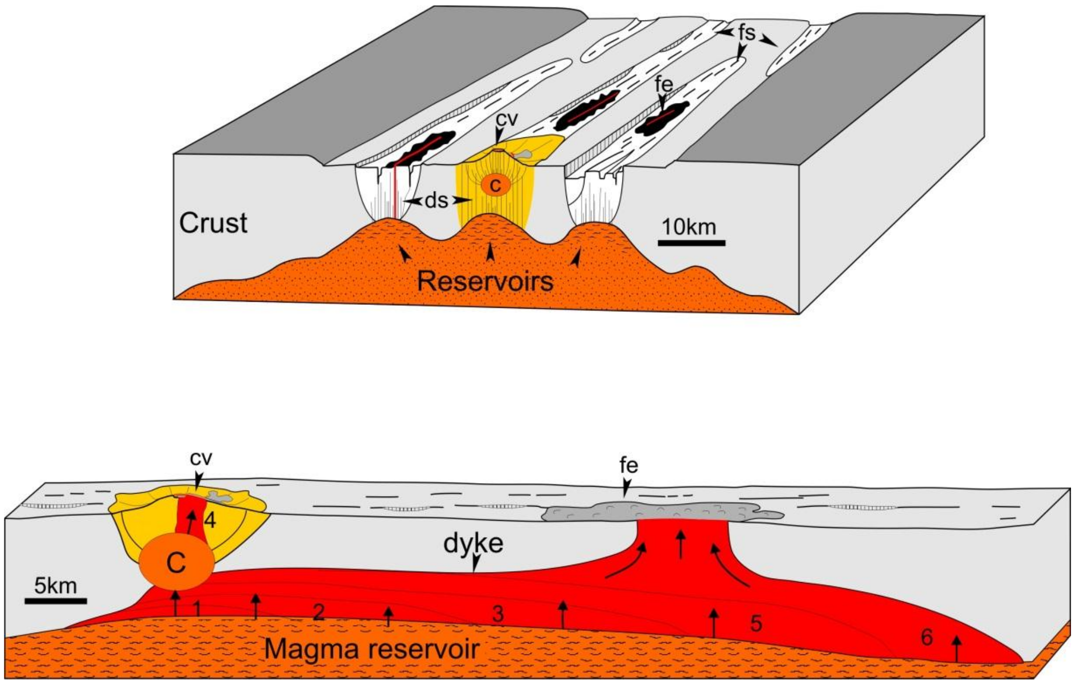

Fig. 6. (a) The main structural elements of a volcanic system. Abbreviations: c, crustal magma chamber; ds, dyke swarm; cv, central volcano; fs, fissure swarm; fe, fissure eruption. (b) Injection and growth of a dyke feeding an eruption during a rifting episode. The numbers indicate the growth sequence of the dyke rising through the crust in a major eruption episode.

1.4.1 Volcanic eruptions and their products

A volcanic eruption refers to expulsion of magma, gas and rocks, in any shape or form, onto the Earth's surface. Consequently, a volcanic eruption can be a single explosion that last only a few seconds or it can represent a continuous effusion of lava that lasts for years or even decades. An eruption can also feature a single style of activity, either purely explosive or effusive, or it can encompass both styles, because many eruptions that begin explosively transform into quiet effusion of lava over time. As a result, the definition of a volcanic eruption is not simple. It is customary among volcanologists to take any near-continuous expulsion of magma, gas and rocks, whether they are erupted in a single pulse or continually over period of time, to be a volcanic eruption.

In essence, there are two fundamental styles of eruptions, effusive and explosive **(**Fig. 1.7a and b). Effusive eruptions are characterised by a more quiet extrusion of magma, which flows away from the vent(s) as a coherent body of lava. In explosive eruptions the magma is disintegrated by the rapid expansion of gases or steam, producing rock fragments that are collectively referred to as tephra. Many eruptions feature both styles of activity, producing both tephra and lava, and are referred to as mixed eruptions (Fig. 1.7c).

a. b. c.

Fig. 1.7 (a) Effusive eruption, (b) explosive eruption, (c) mixed eruption.

1.5 Geothermal activity and hot springs

Geothermal energy is important for the economy in Iceland and is mainly used for domestic heating. Just over 80% of the population enjoy this facility. District schools have been deliberately located near geothermal areas to utilise this source of energy for heating and swimming pools.

Groundwater that percolates through cracks and voids in the top1-2 km of the crust is heated in accordance with the temperature gradient of any particular area. In areas such as Iceland, where the temperature increases sharply with depth (50-200° per 1000m), the groundwater is quickly heated to elevated temperatures (70°C or more) and rises to the surface through fractures in the bedrock as geothermal water. The outlet vents of the geothermal water at the surface are known as hot springs (hver in Icelandic) and the area in which hot springs occur are known as geothermal areas. Geothermal areas are traditionally categorised on the basis of their overall average temperature – low-temperature areas, where the water is below the boiling temperature, and high-temperature areas, where the water is above it. Low-temperature geothermal areas typically occur in the regions bordering active volcanic zones, whereas the high-temperature areas are usually confined to active volcanoes. In addition one can find cold or lukewarm carbonated springs, especially in the Snæfellsnes Volcanic Belt. These carbonated springs are one of the sources of mineral water.

Some hot springs erupt by sending up a narrow column of water and steam (and occasionally rocks) high into the air. Such erupting hot springs are known as geysers, named so after the most famous of them, the Great Geysir in Haukadalur, south Iceland. This historical geyser has amused onlookers for centuries (since 1294) with its spectacular eruptions (Fig. 1.8). In the past two to three decades the Great Geysir was very quiet and appeared to have retired from its previous activities. However, in June 2000, earthquakes reactivated it. Other Icelandic hot springs such as Grýla in Hveragerði and Strokkur in Haukadalur have also entertained the visitors with their frequent eruptions.

Fig. 1.8 An erupting geyser, Strokkur, the most active gusher in the Geysir geothermal field.

1.6 Geological history: summary of the Tertiary, Quaternary and Holocene periods

The stratigraphic succession in Iceland records about 16 million years of geologic history (Table 1.1), which appears trivial when compared to the 4000 million years of its nearest neighbour, Greenland. However, a lot can happen in 16 million years, even on a geological time scale, especially in a dynamic place like Iceland. Traditionally the succession in Iceland is grouped into three major stratigraphic formations, the Tertiary Basalt (16-3.3 million years), the Plio-Pleistocene (3.3-0.7 million years) and the Upper Pleistocene Formation (< 0.7 million years). As we shall see below, this stratigraphic division is based on the most distinctive volcanic rock types formed during each time interval, which broadly correlate with the changes in the climate through time.

1.6.1 The old rocks – The Tertiary Basalt Formation

The Tertiary Basalt Formation is oldest stratigraphic formation in Iceland; it spans the time period from 16 to 3.3 million years. It mainly appears in two large regions on either side of the active rift zones, covering about a half of the country. In the east, the Tertiary Basalt Formation extends from Skaftafellsfjöll in the southeast across the eastern fjords to Bakkaflói in the northeast. In the west, it stretches from Hvalfjörður in the southwest across Snæfellsnes and the western fjords to Bárðardalur in North Iceland (Fig. 1.2). The cumulative thickness of the Tertiary Basalt Formation is close to 10000 m. However, the true thickness of the succession at any location does not exceed 3000 m, because the vertical accumulation of volcanic and sedimentary rocks is coupled with outward spreading of the pile.

The original Tertiary landscape, which is not readily visible today, featured scattered 300 to more than 1000 m-high central volcanoes towering over broad and flat-lying lava plains. These plains were spotted with wetlands and dissected by the occasional gorge or river valley. Today we have an excellent cross-sectional view through the Tertiary succession, because of the extensive erosion by the Ice Age glacier; a scene rarely available within the active volcanic zones. The most distinctive outcrop feature of the Tertiary rocks is its ‘apparent’ layer-cake stratigraphy, where one basaltic lava flow is stacked onto another, forming gently dipping successions hundred to thousand meters thick. However, a closer inspection will show that there is more to it than this.

The Tertiary Basalt Formation consists largely of volcanic rocks (> 85%) and was constructed by similar volcanotectonic processes operating in the currently active volcanic belts. Consequently, it features the same geological elements as the active volcanic zones, with the exception of subglacial landforms, which are rare because the climate was considerably warmer. Thick basalt lava series form 10-30 km-wide and 50-100 km-long lenticular bodies that represent volcanic systems (Fig. 1.9a). These lava piles are cut by many thin (1-10 m wide) dykes that strike parallel to the long axis of the systems. The density of these dykes is such that they often make up 3-15% of the rock outcrop, and the dykes define distinctive swarms that transect the strata (Fig. 1.9b). In essence, the dyke swarms are the subsurface component of the fissure swarms in active volcanic systems shown on Figure 1.5. These dyke swarms are typically closely associated with clusters of andesite-rhyolite lava and tephra formations marking the location of extinct central volcanoes (Fig. 1.9a). Alltogether, 40 extinct volcanic systems have been identified in the Tertiary succession.

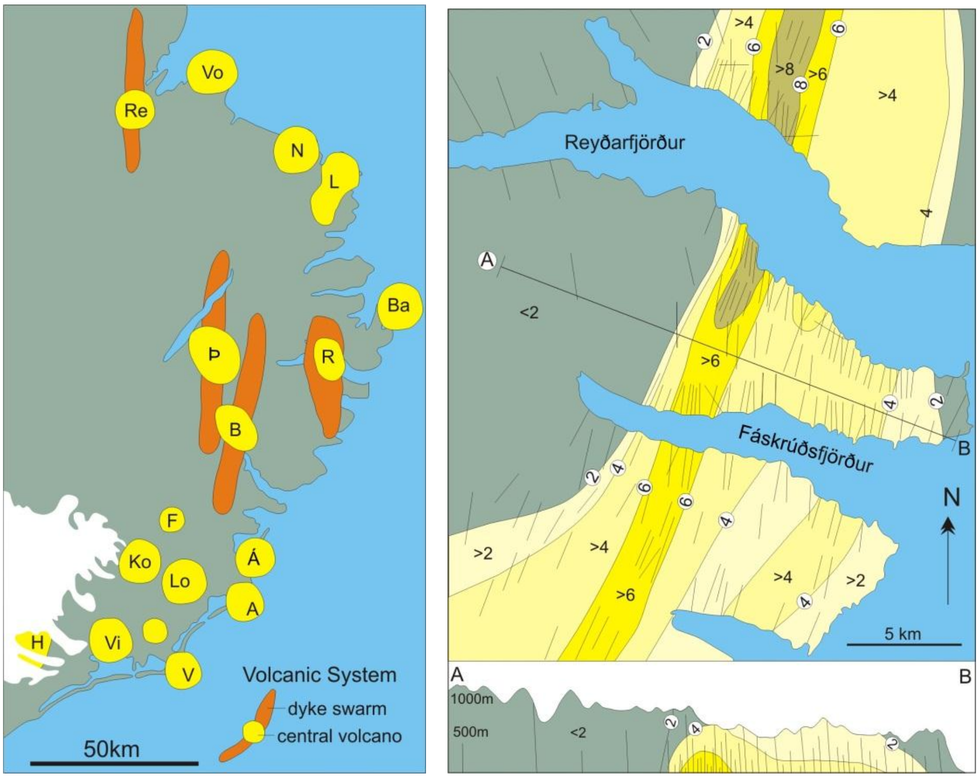

Fig. 1.9 (a) Extinct volcanic systems in the Tertiary succession in East Iceland. (b) Map showing the variation in intrusion densities within the Reyðarfjörður dyke swarm.

Although sedimentary rocks make up only about 10-15 per cent of the Tertiary succession, they are an important component because they best preserve information about the environment and the climate at the time. The most conspicuous are the ‘red interbeds’, named so because of their distinctive rusty-red colour. Other types of sediments, such as finely bedded lacustrine siltstone and fluvial gravels, occur sporadically throughout the succession.

The red interbeds are ancient soils that were stained red by chemical weathering in warm and humid climate of the Tertiary. Fossilised plant remains are often found in these ancient soils, which also contain fossil-rich lignite seams (i.e. primitive coal). About 50 genera of plant fossils have been identified and the collection includes leaf imprints, fruit, seeds, pollen grains and tree moulds. The oldest flora, which includes trees such as swamp cypress, dawn redwood, vine and magnolia, indicates warm temperate climate conditions in Iceland during the Miocene, similar to that of North Carolina or Portugal. The younger Pliocene flora is characterised by conifers and broadleaf trees such as pine, spruce, alder and birch, indicating temperate climate conditions and signifying the onset of the cooling that eventually led to the Quaternary Ice Age.

1.6.2 The middle aged rocks – the Plio-Pleistocene Formation

The Plio-Pleistocene Formation spans the time period of 3.3-0.7 million years ago (Table 1.1). It occupies a broad region on either side of the active rift zones and covers about a quarter the surface of Iceland. On the east side it extends from Skaftártunga in the south to Langanes in the northeast. On the west side, it stretches from the Mt. Esja region in the southwest to Skjálfandi in the north (Fig. 1.2). The cumulative thickness of the Plio-Pleistocene Formation is ~2000 m.

A large slice of the Plio-Pleistocene Formation, locally known as the Hreppar Formation, occupies the region between the active West and East volcanic zones in south Iceland. The Formation also has two outliers, one at the Snæfellsnes Peninsula in west Iceland and another at Skagi in north Iceland (Fig. 1.2). In both of the outliers, the Plio-Pleistocene volcanic products rest on glacial marine deposits, which in turn rest on much older rocks of the Tertiary Basalt Formation. The upper surface of the Tertiary succession is heavily eroded, indicating that a significant amount of time passed before the sediments covered it. Thus, here the boundary between the Tertiary and the Plio-Pleistocene formations is an unconformity, because there is a gap in the stratigraphic record across it. As in the Tertiary, volcanic rocks of basaltic composition are the most widespread rock type in the Plio-Pleistocene succession. Basalt lava flows make up a significant portion of the basalt strata, but alternate with subglacial formations such as pillow lavas, móberg breccias and tuffs. As before, andesite and rhyolite lavas and tephras are found in significant proportions in association with extinct central volcanoes.

Towards the end of the Tertiary Period (about 7 million years ago), the global climate had begun to deteriorate and the cooling trend that eventually led to the Quaternary Ice Age had truly set in. About 3.3 million years ago when the first rocks of the Plio-Pleistocene Formation were forming, the 'autumn' that preceded the frigid Ice Age 'winter' had arrived in Iceland. Glaciers began to nucleate in the highlands and the rivers grew larger due to increase in precipitation. A progressive cooling resulted in incremental north- and westward growth of the Quaternary ice sheet from its nucleus in southeast Iceland. By 2.5 million years it had covered more than half of the country and around 2.2 millon years the whole of Iceland was covered by glaciers for the first time (Fig. 1.10). The Ice Age glaciation had arrived in full force.

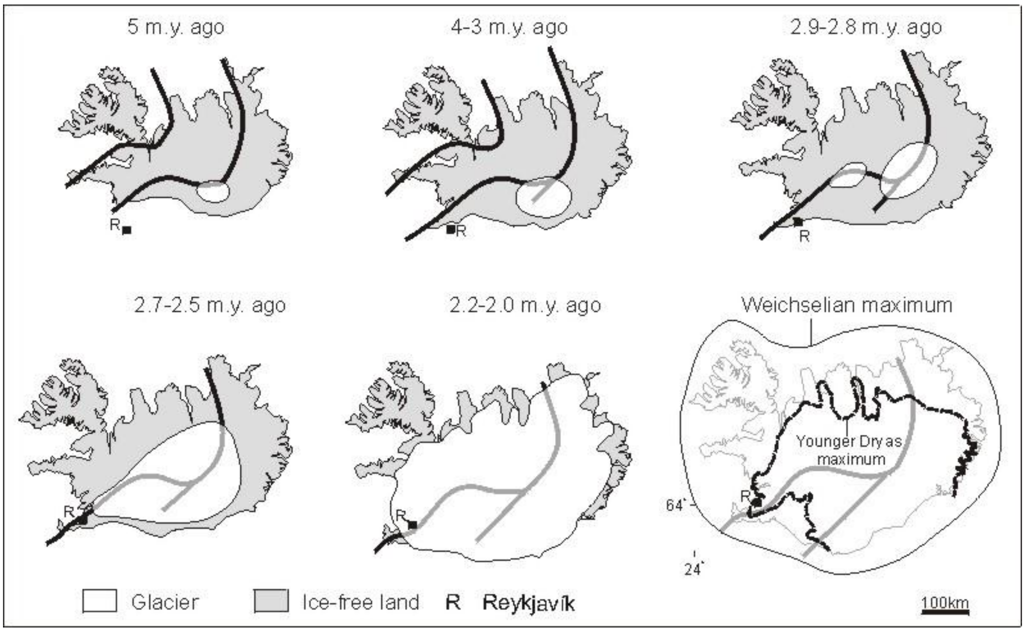

Fig. 1.10. The growth of the Quaternary ice sheet in Iceland over the last 5 million years Also shown is the evolution of the Iceland rift system over the same period and the present geographic position of Reykjavík.

However, this overall cooling trend was not a uniform one, but were characterised by frequent fluctuations between colder and warmer intervals. By 2.2 million years ago this fluctuation had developed into distinctive alternation between glacial stages, characterised by island-wide glaciation, and interglacial stages, when most of the land was free of ice. Total of nine glacial and interglacial stages are identified in the Plio-Pleistocene Formation, indicating that each glacial-interglacial cycle lasted for 200.000 years.

The changing climate had a marked effect on the landscape. Although the mechanism of rifting and volcanism proceeded along the same general lines as in the Tertiary, the face of volcanic activity changed markedly. As the glaciers grew in size, subglacial eruptions became a more frequent occurrence. Móberg ridges and table mountains were formed in ever-increasing volume. Likewise, while rivers and the glaciers grew bigger, their erosive might increased, forming deeper and broader valleys. Consequently, the Plio-Pleistocene landscape was typified by irregular topography where jagged ridges and mountains towered over steep-sided valleys. The transformation of the climate during the Plio-Pleistocene is literally written in stone because it resulted in the formation of new rock types not found in the Tertiary Basalt Formation.

During interglacial stages, when the land was mostly ice free, the nature of the volcanic activity remained much as it did during the Tertiary, forming widespread lava flows and tephra deposits. On the other hand, during the cold spells, the glaciers put down various types of till and other glacial deposits whilst subglacial eruptions produced vast amount of pillow lavas, volcaniclastic breccias and tuffs. There is a noticeable increase in the proportion of clastic and volcaniclastic sediments up through the Plio-Pleistocene Formation. In the lower part, such deposits make up between 15-30 per cent of the succession, increasing to 50-60 per cent in the upper part. As the climate cooled the red interbeds/soils become less conspicuous while the expanding river systems were carrying forth more debris. The rivers dispersed the debris to the lowlands and to the sea where it settled out to form fluvial, lacustrine or marine sediments in ever increasing proportion.

1.6.3 The young rocks – the Upper Pleistocene Formation

The Upper Pleistocene Formation consists of rocks that are younger than 0.7 million years old, the distribution of which is for the most part confined to the active volcanic zones (Fig. 1.2). The climate behaved much in the same way as during the latter half of the Plio-Pleistocene, with frequent alternations between colder glacial and warmer interglacial stages. Consequently, the Upper Pleistocene succession is typified by paired rock sequences, one formed under a thick glacier and the other on ice-free land.

The most prominent topographic features of the volcanic zones are from this period. This includes the central volcanoes, such as Katla and Askja, and the móberg ridges and table mountains that jut through the Holocene lava cover. The most youthful looking structures were formed during the Weichselian (most recent) glaciation, whereas more scrappy-looking structures that have suffered substantial glacial erosion date from previous the glacial or interglacial stages. The younger table mountains constitute most impressive morphological structures (e.g. Herðubreið in northern Iceland) and can be used to estimate the ice thickness of the Weichselian glacier (Fig. 1.11).

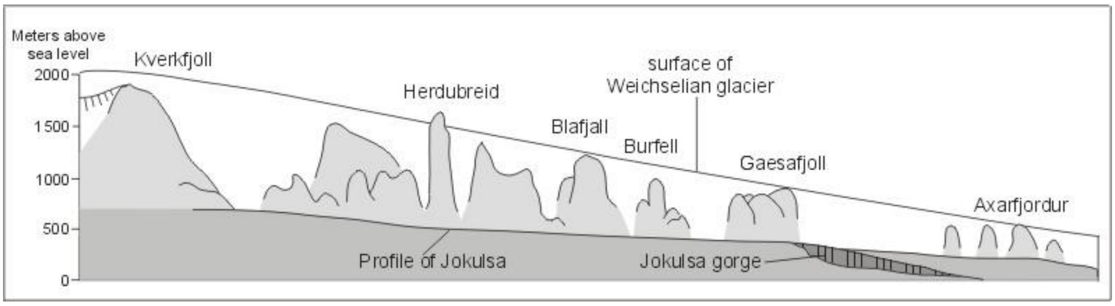

Fig. 1.11 Profile from the Kverkfjöll volcano to the northern coast at Öxarfjörður, showing the elevation of subglacial móberg ridges and table mountains in the North Volcanic Zone and how it is used to reconstruct the thickness of the Weichselian glacier.

Five glacial periods have been identified in the last 0.7 million years, indicating 120000-140000 years for the duration of each glacial-interglacial cycles. The Ice Age glacier reached its greatest extent at the maximum of the most recent glaciation, the Weichselian stage that lasted from 120000-10000 years ago (Fig. 1.10). Today's glacial landscape is largely the work of this last countrywide ice sheet. At the maximum of the Weichselian glaciation, about 25-30000 years ago, more than a kilometre of ice blanketed large part of North America and Eurasia. The global sea level was 100-150 m lower than today, because large quantities of the Earth's water was locked up as glacial ice. In Iceland, the ice sheet extended well beyond the present shores and covered the coastal shelf up to a distance of 130 km. About 18000 years ago the bitter cold of the last glacial period was on the decline. The global climate became milder and the Weichselian glacier began to melt. This melting released large quantities of water, and sea level began to rise. As the glacier retreated, the sea followed in its path inundating the land. However, this improvement in the climate was not without setbacks and we know of at least two periods when the cooling was great enough to see the glaciers recuperate and re-advance. These cold spells set in about 12000 and 11000 years ago and are known as the Older and Younger Dryas stages. The warm spell between them is the Allerød stage, a time when large parts of the lowlands in Iceland where at the bottom of the sea.

The start of the Holocene is usually set at the time when the global climate became as it is today and in Iceland this occurred when the glacier of the Younger Dryas stage retreated from its end moraines about 9700 years ago (Fig. 1.9). The retreat of the Younger Dryas ice sheet was very rapid and most of it was removed by melting in only a few hundred years. The land now responded by rising extremely rapidly. Basically, it sprang up like a cork that has been pushed under water and then released. We know that in Iceland all of these events happened in a geological instant (i.e. < 1200 years), because about 8500 years ago the Great Þjórsá lava flowed across ice-free and dry land from its vents at Veiðivötn to the sea at Eyrabakki. The Icelandic landscape we have before us today in Iceland was almost full developed at the beginning of the Holocene. The exceptions are the river courses and canyons, which were formed after the melting of the glacier, and the active volcanic zones, which have been subjected to continuous modification by volcanic activity. Large parts of the sandur plains, which currently cover about 5 per cent of the land surface (5000 km^2), were formed somewhat earlier by rivers emerging from the retreating glacier during the climatic transition. These plains have been modified and enlarged by the run-off from the present day ice caps.

The pattern of volcanism during the Holocene has been similar to that of the Weichselian glaciation although its habit changed significantly. All of the currently active volcanic systems have produced eruptions in the last 10000 years. Most of the magma has been erupted as lava, which today cover about 12000 km^3 of the land surface. However, a significant amount (~10%) of the basalt magma came up in explosive eruptions, as everyone can see from the many black and grey tephra layers in the soil cover. Many of these tephra layers are formed by subglacial eruptions, which have frequently been accompanied by catastrophic floods known as jökulhlaup. The brown and light coloured tephra layers in the soils are andesite and rhyolite fall deposits dispersed by explosive eruptions at the central volcanoes.

Volcanism in post-glacial times has not been evenly distributed in space or time. The most productive area has been the East Volcanic Zone in south Iceland, which has the highest eruption frequency and has produced the largest eruptions. Many of the large lava shields (e.g. Skjaldbreiður and Trölladyngja) and flood lavas (e.g. Þjórsá and Bárðardalur lavas) where formed during early Holocene times 8000-9500 years ago, showing that magma production was considerably greater than today.

The disappearing Weichselian glacier left behind barren and debris-covered land and aeolian reworking provided the raw material for soil formation. Plants began to spread out from ice-free areas in north Iceland. Birds and oceanic currents also introduced new species. Grasses, sedges and willow were the first to appear and were followed by birch. By the time the first Norseman arrived in Iceland in the ninth century the birch forest covered about 25 percent of the country. Vegetation changed dramatically with the arrival of man. Not only did it result in introduction of new species, mainly weeds, but also in sudden expansion of grasses and sedges at the expense of birch and willow. A few centuries after the arrival of the first settlers, the woodlands had been reduced to a fraction of what they used to be. Today woodland and scrubs cover 1 per cent of the country. This sudden and severe reduction in woodlands was mainly caused by cultivation and domestication of the land, although aggregated by gradual climate cooling.

SOUTHWEST ICELAND

General overview

The geology of southwest Iceland spans the last 3.2 million years, from the very last stages of the Pliocene through the Quaternary to the present day. The oldest rocks outcrop in and around Mt. Esja in the north, and the succession becoming progressively younger to the south. The youngest rocks outcrop along the axis of the Reykjanes Volcanic Belt, which connects the submarine Reykjanes Ridge and the West Volcanic Zone (Fig. 1. 12). The belt consists of four volcanic systems, which are from east to west; the Hengill, Brennisteinsfjöll, Trölladyngja, and Reykjanes systems. The systems have a northeasterly strike and extend across the peninsula.

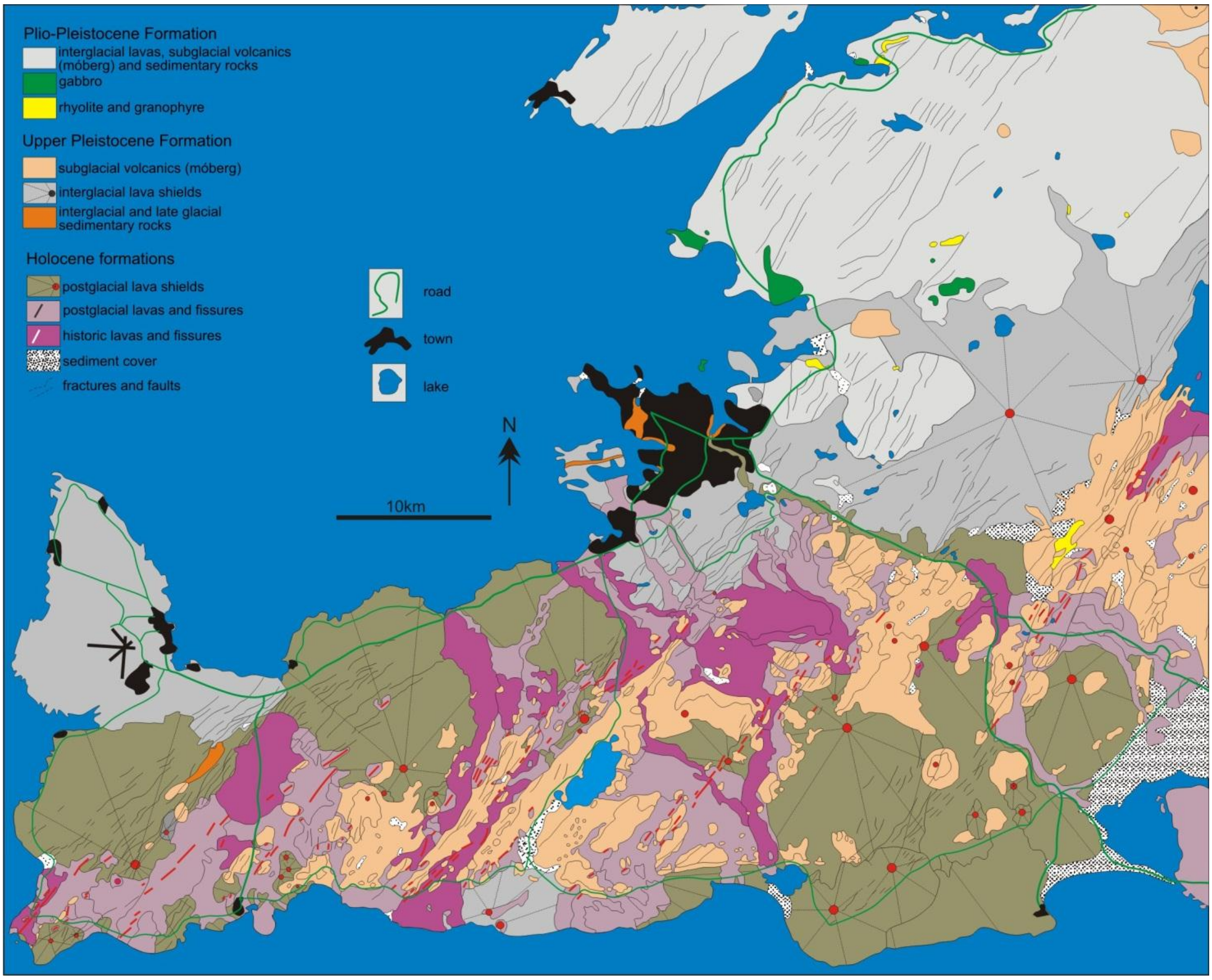

Fig. 1.12. The main geological features of the Reykjanes Peninsula.

Greater Reykjavík: a city on the margins of a mid-ocean rift

Situated on rather featureless rolling hills at the bottom of Faxaflói Bay, greater Reykjavík may not appear to offer much excitement to geology enthusiasts. However, there is more to it than catches the eye, at least enough to kill a day or two, if one prefers rocks to shops. Situated on the outer fringes of the Reykjanes Volcanic Belt (Fig. 1.12), it features many examples of the contrasting forces that have shaped and moulded the country in its recent geological past. These include glacial features as well as rift-zone volcanics and tectonics. Some outcrops are within walking distance from the city centre; others are within a short driving distance or can be reached by city bus, plus a hike of a few kilometres.

Reykjavík, "Smoky Bay", was named so by the first settler, Ingólfur Arnarsson, around 874 because of the columns of steam rising from geothermal springs in the present day Laugardalur. In the first decade of the twentieth century, these springs were used as washing pools, but they disappeared shortly after 1930 when their water was utilised for geothermal heating by the city of Reykjavík. The Laugardalur swimming pool, of course heated by geothermal water, is the only reminder of there past existence.

SOUTH ICELAND

General overview

South Iceland is bounded on either side by the active West Volcanic Zone and East Volcanic Zones (Fig. 1.13). The South Iceland Seismic Zone transects the lowlands from the Hekla volcanic system in the east to the Brennisteinsfjöll volcanic system in the west (Fig 1.2). It is the source of some of the largest earthquakes in Iceland, with events between 6 and 8 on the Richter scale occurring periodically every hundred years or so. At the time of writing, most recent major event occurred in the summer of the year 2000. At the surface, the South Iceland Seismic Zone is characterised by north-south trending strike-slip faults, but is thought to represent a major east-west trending transform fault zone linking the two volcanic zones.

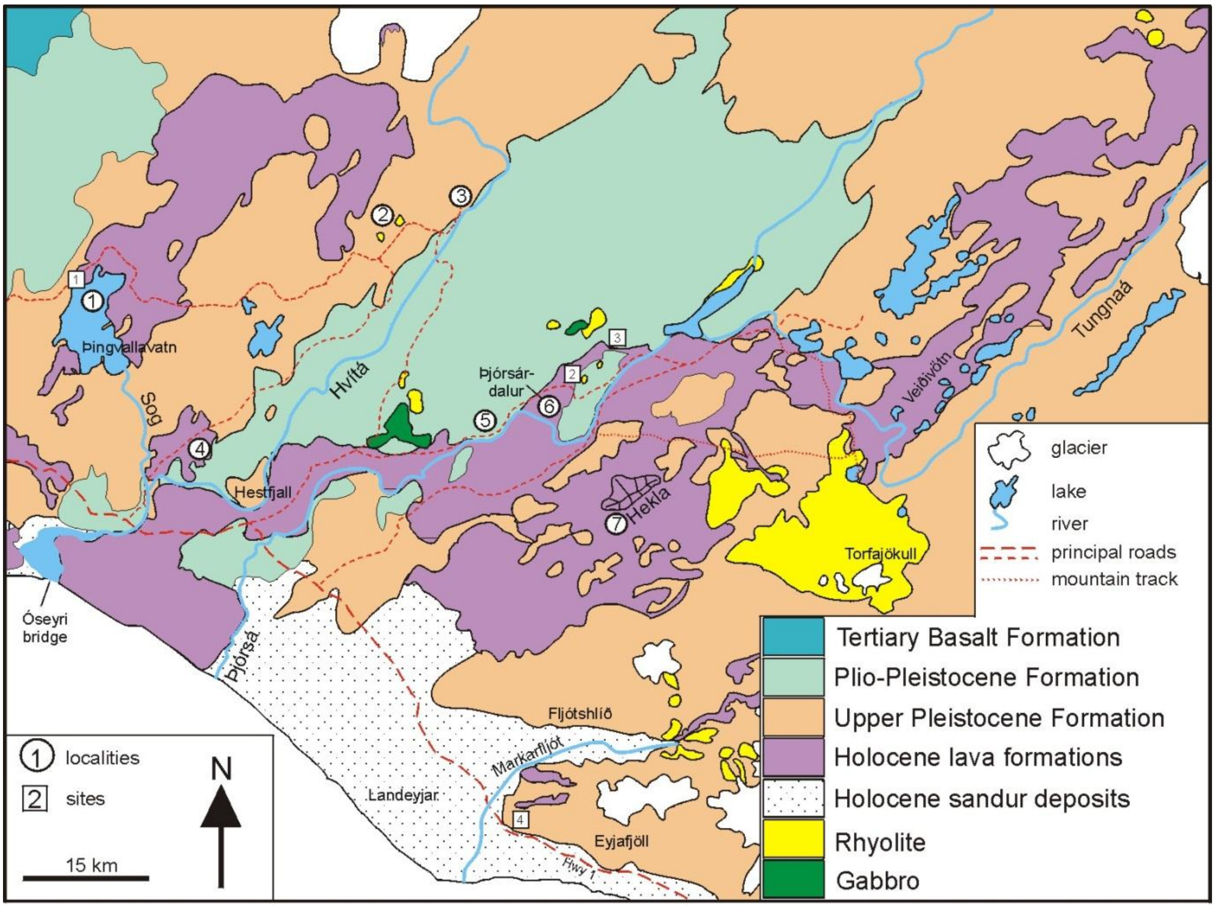

Fig. 1.13. The main geological features of South Iceland.

South Iceland is characterised by contrasting topography, where the foreground is the vast flat-lying southern lowlands that are surrounded on the periphery by rugged mountains that rise sharply up to 1000-1500m. During glacial times the weight of the ice pushed the land down so that in places it was well below seal level. When the Ice Age (Weichselian) glacier retreated from south Iceland about 10000 years ago, the lowlands were temporarily inundated by the sea and became the bottom of the then vast South Iceland Bay (Fig. 1.14). During the early Holocene the land gradually emerged from of the sea as it rebounded from the weight loss coupled by construction of vast sandur plains through accumulation of fluvial deposits carried off the highlands by the rivers. The Great Þjórsá lava flow that now covers the area between the Þjórsá and Hvítá-Ölfusá River made a significant contribution to this process some 8500 years ago (Fig. 1.13).

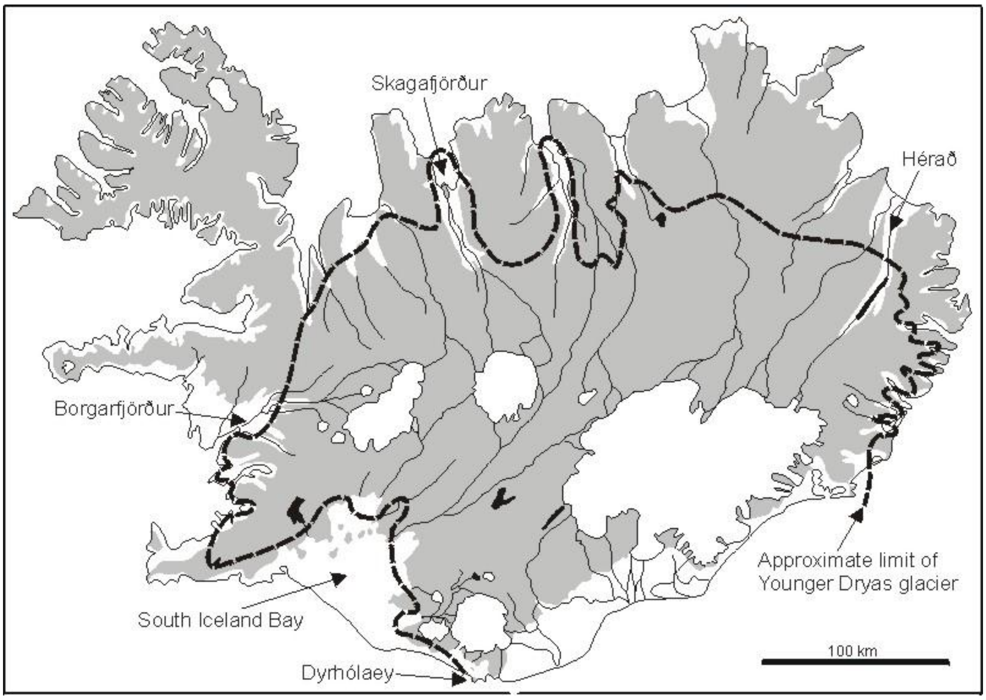

Fig. 1.14. Distribution of lowland areas invaded by the sea towards the very end of the Weichselian glaciation.

The Great Þjórsá lava is the oldest flow of the Tungnaár lavas; a series off eight lava flows that emanated from fissures within the Veiðivötn volcanic system to the north of Landmannalaugarduring the Holocene and flowed to the southwest across the highlands and onto the Southern Lowlands. It is the largest of many voluminous fissure-fed basalt lava flows, that were erupted in Iceland at the beginning of Holocene, with a volume of 22 km^3. The largest lava shield volcanoes are of similar size (e.g. Skjaldbreiður, 17 km^3). The occurrence of these large volume lava formations indicates that the production rate of basaltic magma at the beginning of the Holocene exceeds the present day production by a factor of 30-40. This high production rate coincides with rapid crustal rebound after removal of the glacier, up to 2000 m thick, of the most recent glaciation.

The mountains on the periphery of the region are either currently active central volcanoes or volcanic landforms formed by subglacial eruptions during the Pleistocene. On a good day the view from Óseyrarbrú (the Óseyri bridge) is one of the most breathtaking sights in Iceland, revealing a chain of towering central volcanoes from south to north, Eyjafjallajökull, Mýrdalsjökull, TindfjöllTorfajökull and Hekla. In the background further to the north one might get a glimpse of Langjökull and Hofsjökull, the second and third largest glaciers in Iceland. The latter is also the largest active volcano in the country.