Chapter 1
A Brief Resumé of the Geology of Iceland

Jón Eiríksson and Leifur A. Símonarson

Abstract The current divergent plate boundary between North America and Eurasia across Iceland and the Iceland shelf is expressed by several segments between the submarine Reykjanes Ridge in the southwest and the Kolbeinsey Ridge in the north. Major elements of the present plate margin configuration were established at about 25 Ma, and Iceland occupies a complex plate boundary between the Reykjanes Ridge and the Kolbeinsey Ridge. Volcanic productivity is higher in Iceland than along the spreading axes to the south and north, indicating a mantle anomaly beneath the island, a hot spot. The area of the shelf around Iceland is larger than the subaerial island. Miocene lava sequences predominate in the far east and far west of Iceland, with Quaternary rocks occupying the central island. The geological structure is broadly symmetrical with gentle regional dips toward the volcanic spreading axes. Since the onset of the last Ice Age at about 2.6 Ma, Iceland has been periodically covered by an ice cap extending to the shelf. Today, Iceland is located directly in the path of high-altitude westerly jet streams. The climate is cold-temperate and maritime, and at present, c. 10% of the island's area of 103,000 km^2 is covered by glaciers.

Keywords Plate tectonics · Iceland · Quaternary · Ice age · Neogene · Marine sediments · Submarine ridges

1.1 Introduction

The geological structure of Iceland is controlled by plate boundary processes. Geographically, Iceland is located at the intersection of two oceanic ridges, the Mid-Atlantic Ridge separating the North American and the Eurasian lithospheric plates on one hand, and the series of ridges connecting Greenland and Iceland, Iceland and the Faroe Islands, and continuing to the United Kingdom. Volcanism within the North Atlantic igneous province was initiated at c. 61 Ma, with massive volcanic activity extending from northern Canada to Scotland between 61 and 56 Ma (Storey et al., 2007). Until c. 25 Ma, the active spreading between Greenland and Scandinavia

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took place along the Ægir Ridge (Fig. 1.1), which is now extinct. A segment of East Greenland was separated from the North American plate by a new, more westerly rift system and spreading axis, which has been active for the last 25 Ma. The Jan Mayen Ridge represents this isolated segment of continental crust between Iceland and Jan Mayen to the north. This westward jump of the plate boundary reflects the nonstationary nature of the rifting axis. Currently, the axis appears to be moving northwestward with respect to the mantle below. Features of the geological structure of Iceland indicate that this movement is still active, leading to repeated eastward shifts of the spreading axis across Iceland.

From east to west, the geological structure of Iceland is broadly symmetrical, with the youngest rocks in the central part (Fig. 1.2). Factors contributing to the

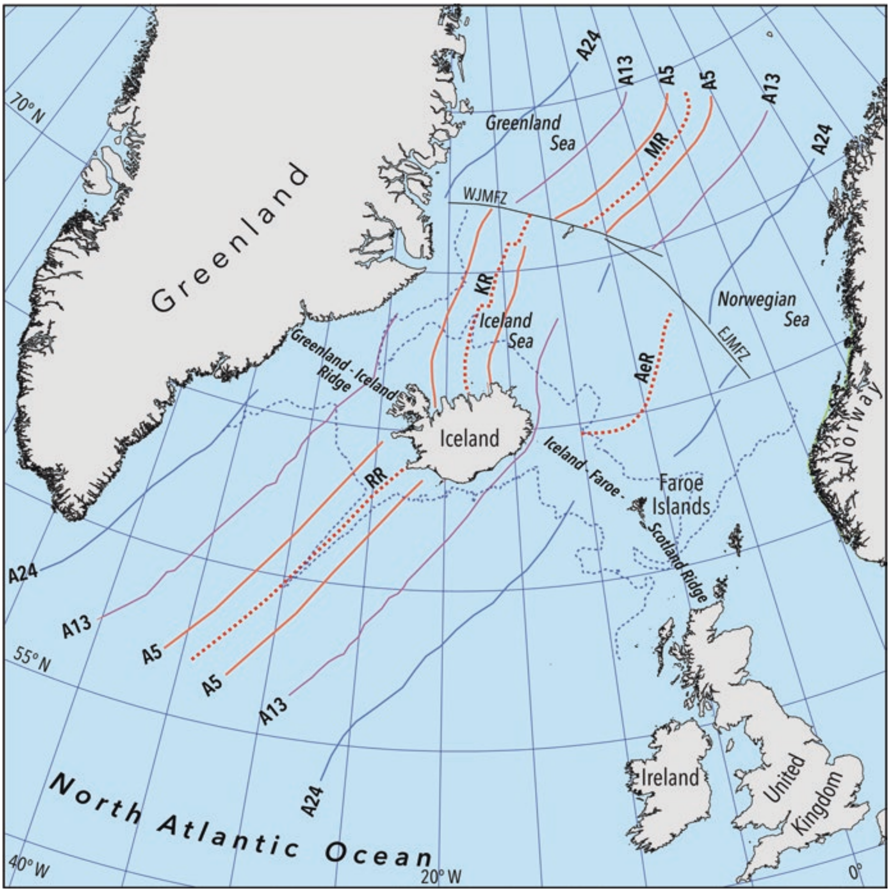

Fig. 1.1 Map of the northern North Atlantic showing the geographical location of Iceland and its relationship to major plate tectonic features including submarine ridges and magnetic anomalies, with age boundaries, on the seafloor. (Modified after Olesen et al. (2007). AeR Ægir Ridge, KR Kolbeinsey Ridge, MR Mohn's Ridge, RR Reykjanes Ridge, WJMFZ West Jan Mayen Fracture Zone, EJMFZ East Jan Mayen Fracture Zone)

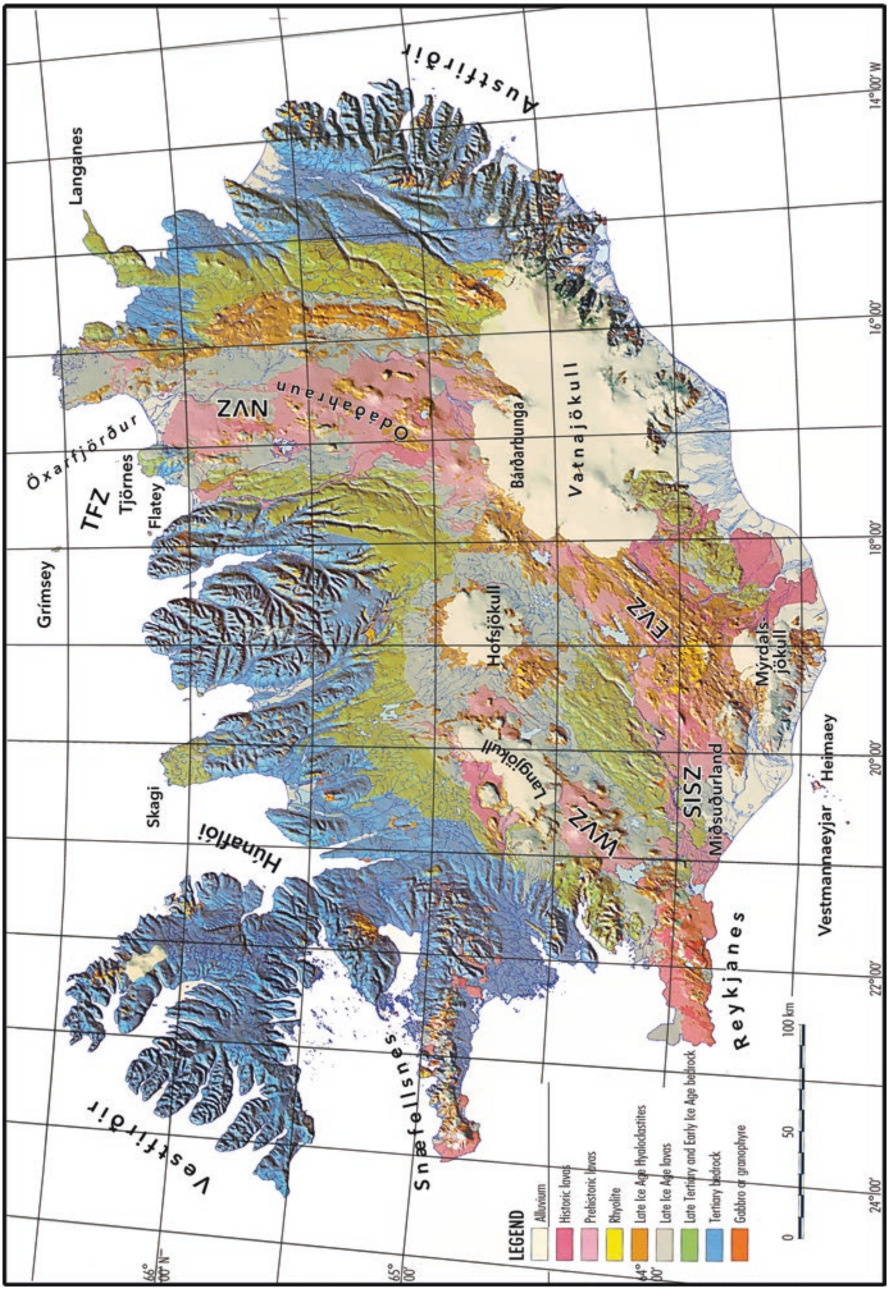

Fig. 1.2 Geological map of Iceland with major volcanic and seismic zones superimposed. WVZ Western Volcanic Zone, SISZ South Iceland Seismic Zone, EVZ Eastern Volcanic Zone, NVZ Northern Volcanic Zone, TFZ Tjörnes Fracture Zone. (Modified after Jóhannesson & Sæmundsson, 1998; Thordarson & Höskuldsson, 2002; Einarsson, 2008; Hardarson et al., 2008)

exceptionally thick Miocene, Pliocene, and Quaternary sequences in Iceland include the relatively constant extrusion of volcanics along the plate margin, coupled with subsidence and tilting of flanking rock units toward the axial zones of rifting and volcanism. These elements are significant for the preservation potential of the geological record because the resistant lava flows form a shield against subsequent erosion and weathering of any underlying sediment. When the plates move away from the rifting zones, erosion and weathering have led to the development of exposures of tilted rock sequences in distal fjords and valleys.

Today, Iceland is located within a sensitive climatic zone in the North Atlantic directly in the path of high-altitude westerly jet streams. The climate is cold-temperate and maritime, and c. 10% of the island's area of 103,000 km^2 is covered by glaciers. Any changes in the path of cyclones across the Northern Hemisphere, or changes in the ocean circulation and configuration of the water masses, are likely to express themselves rapidly in climatically controlled environmental conditions such as geomorphological processes, vegetation, the mass balance of glaciers, or ice sheets in Iceland. The late Cainozoic sections in Iceland comprise a substantial data archive on the variations in ice caps and glaciers in the North Atlantic area.

1.2 Plate Tectonic Setting

The topography of Iceland forms a large bulge on the North Atlantic Ocean floor (Fig. 1.3), which is generally considered to reflect an anomaly in the mantle below. This anomaly represents a stationary hot spot beneath Iceland, which was initiated at c. 61 Ma as a major temperature anomaly in the mantle, a mantle plume, with an

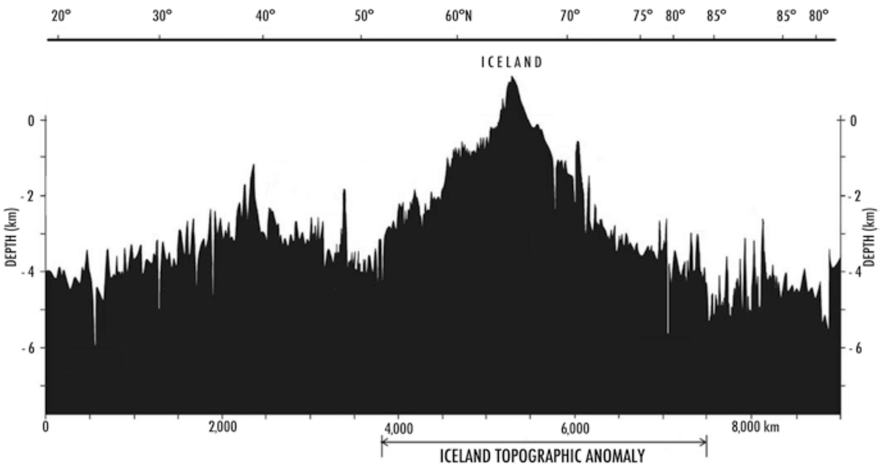

Fig. 1.3 Topographic profile along the axis of the Mid Atlantic Ridge (c. 20–80°N), across the Azores and Iceland highs and into the Arctic Basin. (Modified after Vogt & Jung, 2005). The topographic peak in Iceland coincides with the center of the assumed mantle plume beneath Iceland

initial radius of c. 1000 km (Richards et al., 1989). The current plume is seismically depicted as a c. 150 km wide anomaly (Bijwaard & Spakman, 1999; Wolfe et al., 1997), rooted at a depth of over 660 km under Iceland (Shen et al., 1998).

The relatively well-defined divergent plate margin along the North Atlantic breaks up into a series of segments on crossing the Iceland platform leading to the formation of independently moving blocks, as well as two-direction conservative transform zones offsetting the main divergence boundary eastward relative to the offshore Reykjanes and Kolbeinsey submarine spreading ridge segments (cf. Einarsson, 2008). These transform zones, the Tjörnes Fracture Zone in the north and the South Iceland Seismic Zone in the south (Fig. 1.2), connect the North Atlantic submarine spreading ridges to the main spreading axis across Iceland.

This complex configuration of plate and microplate boundaries in Iceland is most probably related to the mantle anomaly beneath the Iceland platform, and the northwestward movement of the spreading system across the hot spot. This movement amounts to c. 0.3 cm/year and is independent of the divergence at the plate margin in the northern North Atlantic, which amounts to c. 2 cm/year (1 cm/year in each direction, see overview in Thordarson & Höskuldsson, 2002). In response to the movement of the plate boundary away from the hot spot, readjustment tends to take place and a new spreading axis develops above it.

Plate margins are defined on the basis of seismic and volcanic activity, and in Iceland, there are several zones of crustal deformation and volcanic activity. There is no general consensus on naming these deformation segments, but the main north–south trending spreading axis across the Iceland hot spot is generally called NVZ, the Northern Volcanic Zone (Fig. 1.2). It appears to be propagating in both directions (Einarsson, 2008), and the southern continuation, which extends to the South Iceland shelf is commonly called the EVZ (Eastern Volcanic Zone). This zone is parallel to the WVZ (Western Volcanic Zone), which is located in Southwest Iceland and forms an oblique continuation of the Reykjanes Ridge spreading axis. The accumulation of volcanic material within the rift zones results in sagging of the crust, and in tilting the adjacent rock units toward the main, active volcanic zones. In South Iceland, the crust between the WVZ and the EVZ assumes an anticlinal form.

In addition to the major volcanic zones, there are two active intraplate volcanic zones or belts in Iceland where young (< 2 million years old) volcanic rocks rest unconformably on older bedrock, indicating renewed magma extrusion after a significant interval of quiescence (Thordarson & Höskuldsson, 2002). These are the Öræfi Volcanic Belt to the east of the plume center and the current plate margin (EVZ), and the Snæfellsnes Volcanic Belt in West Iceland, which is situated on the mantle plume trail and is in part superimposed on an extinct volcanic zone, precursor to the WVZ (Thordarson & Höskuldsson, 2002). 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 East Iceland. Thus the Öræfi Volcanic Belt may indicate an embryonic eastward shift in the location of the spreading axis across Iceland (Thordarson & Höskuldsson, 2002).

1.3 Geological History

1.3.1 Accumulation of Volcanics and Sediments at a Terrestrial Divergent Plate Margin

The geological structure of Iceland is broadly symmetrical, with the youngest rocks in the central part (Fig. 1.2). Key elements in retaining the Miocene as well as the exceptionally thick Pliocene and Quaternary sequences in Iceland are the relatively constant extrusion of volcanics along the plate margins, coupled with subsidence and tilting of flanking rock units toward the axial zones of rifting and volcanism. The average rate of subsidence is of the order of 1 mm/year (Pálmason, 1973). These elements are significant for the preservation potential of the geological record because the resistant lava flows provide a shield against subsequent erosion and weathering of any underlying sediment. When the plates move away from the rifting zones, erosion and weathering supersede the constructive processes and thick, tilted rock sequences are exposed in mountainous sections in distal fjords and valleys.

In general terms, the geological units become younger toward the center of the island. But, as the rift zones in Iceland continually become inactive and new rift zones are formed closer to the mantle plume, older successions are broken up, tilted, eroded, and separated by younger geological units and unconformities. Such readjustments of the spreading axis across Iceland are considered to be manifested in the Neogene and Quaternary lava sequences, which display gentle, linear synclines reflecting former positions of the spreading axes and associated subsidence. The main episodes of this geological story were summarized by Denk et al. (2011). At 24–15 Ma, the main spreading activity on land was located in the so-called Northwest Iceland Rift Zone, now presumed to be located submarine on the shelf off the Vestfirðir coast, and around 15 Ma a new rift zone, the Snæfellsnes-Húnaflói Rift Zone, evolved to the east (Hardarson et al., 1997, 2008). At 7–6 Ma, the southern part of the Snæfellsnes-Húnaflói Rift Zone became extinct and the presently active Western Volcanic Zone (also known as the Western Rift Zone) developed. Then, at about 3–2 Ma, the northern part of the Snæfellsnes-Húnaflói Rift Zone also became extinct and the presently active Northern Volcanic Zone was formed (Jóhannesson, 1980). The repeated rift relocations have had an important effect on the geology of Iceland. Denk et al. (2011), among others, have suggested that they caused massive erosion and deposition, forming extensive sedimentary formations, often containing plant and, in some rare cases, animal fossils.

However, it is doubtful whether the present state of geological mapping and the available scale of geological maps of Iceland does allow us to resolve the nature of the sedimentary horizons in the Neogene and Quaternary successions, and it has to be considered an open question whether the sedimentary horizons were formed across major structural and erosional unconformities or in active spreading systems with developing subsiding basins.

1.3.2 Climatic Conditions in Iceland

The modern climate of Iceland is cold-temperate and oceanic, and characterized by the geographic location in the northern North Atlantic (Einarsson, 1984). The Irminger Current branch of the Gulf Stream flows clockwise around Iceland and separates the region from the Arctic realm (cf. Símonarson et al., 2020). The boundary, however, is unstable and fluctuations have, in the geological past, repeatedly transferred Iceland to and from arctic climate conditions. An overview of the climate history of Iceland, based on vegetation record preserved in 11 sedimentary horizons in the volcanic succession has recently been published by Denk et al. (2011). From 15 to 12 Ma, the climate was subtropical, warm, and humid with no dry seasons and relatively hot summers, becoming somewhat cooler from 12 to 10 Ma, with disappearance of many warmth-loving plant species. No major changes are seen from 10 to 8 Ma, but a gradual cooling is indicated between 8 Ma and 5.5 Ma. A climate shift to cooler climate was suggested between c. 5.5 and 4.4 Ma, but relatively warm conditions are indicated between 4.4 Ma and 3.6 Ma. Another shift, and now toward the present cool to cold conditions, occurred between 3.6 Ma and 2.4 Ma.

1.3.3 Glaciation History of Iceland

Recent overviews of the glaciation record of Iceland show that a long record of repeated glacial-interglacial cycles has been preserved (Einarsson & Albertsson, 1988; Eiríksson, 2008; Geirsdóttir, 2011). Reconnaissance studies of the geology of Iceland at the turn of the nineteenth century showed that glacial processes began to affect the rock facies during the Pliocene before the onset of the so-called Glacial Period, and that the Ice Age glaciations were repeatedly separated by interglacials (Pjetursson, 1905; Thoroddsen, 1906).

The introduction of paleomagnetic techniques in the mapping of rock sequences in Iceland during the 1950s and 1960s and an increasing number of absolute radiometric dates for lava flows and intrusions have led to the accumulation of considerable data on the initiation and frequency of glaciations in Iceland. The first phase of this research started in the 1960s and dealt mainly with isolated sections. A second phase of the research history began in the 1970s with regional mapping of Pliocene and Pleistocene areas coupled with K/Ar dating. The results have been reviewed by Sæmundsson (1979) and by Einarsson and Albertsson (1988). Based on this mapping effort, a widespread late Pliocene onset of glaciation in Iceland was suggested at just over 3 Ma ago. The origin of many of the diamictites and volcaniclastic breccias was a controversial issue in the geological literature for most of the twentieth century, but the application of detailed sedimentological studies and facies analyses to these deposits in the last three decades has led to a new appraisal of the nature and regional extent of glaciation events in Iceland (Eiríksson & Geirsdóttir, 1991; Geirsdóttir, 1991; Geirsdóttir & Eiríksson, 1994).

1.3.4 Terrestrial Sedimentary Basins and Sequences

The great majority of Pliocene and Pleistocene rock sequences in terrestrial Iceland are exposed along the flanks of the presently active volcanic zones in Iceland, broadly outlined by the distribution of Late Ice Age lavas and hyaloclastites (Fig. 1.2). Most of the sections have been carved into the gently dipping volcanic successions by glacial and fluvial valley erosion or coastal abrasion. Quite continuous sequences have become available by combined symmetrical tilting due to subsidence in the volcanic zones leading to a synclinal structure and the gradual movement of newly created crust transversely away from these zones. However, the sections within the volcanic zones, which contain the Brunhes glacial record from the last 0.8 Ma or so, remain poorly exposed and the rocks are largely hidden by young volcanics.

A compilation of glacial events in Iceland shows that glaciation of high relief mountainous areas and volcanic centers had already started at 7 Ma (Albertsson, 1981; Geirsdóttir, 2011). The frequency of preserved glacial events after the first regional expansion of local highland glaciers close to the Gauss/Matuyama Chron boundary exceeds one event per 100,000 years. These events amounted to massive glacial events covering most of Iceland. Each event was separated by ice-free conditions.

1.3.5 Sedimentary Basins Offshore

The topographic anomaly created by Iceland is considerably larger than indicated by the present coastline of the island. In fact, the submarine shelf around Iceland covers an area larger than the terrestrial part (Fig. 1.4). Data on the geology of the shelf are rather limited. Outside the submarine plate tectonic Reykjanes and Kolbeinsey spreading ridges, which are characterized by volcanism, there are two deep drillings available, i.e., on the islands of Heimaey, South Iceland, and Flatey, North Iceland (Fig. 1.2). Both these boreholes indicate the presence of thick sediments on the shelf. A major gravity anomaly on the North Iceland shelf has been interpreted as reflecting a sedimentary basin with up to 4 km thick sediments within the Tjörnes Fracture Zone (Pálmason, 1974; Flóvenz & Gunnarsson, 1991). The Flatey borehole is located within this gravity anomaly, and the Pliocene and Pleistocene sediments exposed on the uplifted Tjörnes horst reflect shallow marine and coastal sedimentation (Albertsson & Eiríksson, 1989; Eiríksson et al., 1990; Ólafsson et al., 1992). Another uplifted segment of shallow marine sediments is exposed on Snæfellsnes peninsula in West Iceland (Fig. 1.2), and the borehole on Heimaey, South Iceland, as well as numerous fossiliferous xenoliths in volcanoes in the coastal and offshore South Iceland indicate shallow marine sedimentation on the shelf in that region (Áskelsson, 1960; Símonarson, 1979). Sedimentary basins in a shelf setting have thus formed along the Tjörnes Fracture Zone and the South

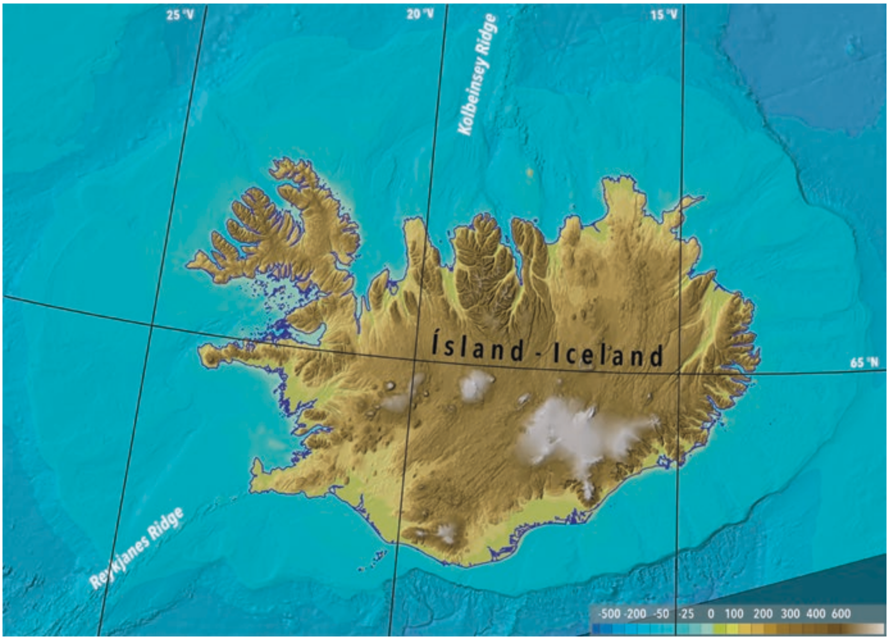

Fig. 1.4 Bathymetric map delineating the Icelandic shelf. (Modified after Jakobsson et al., 2012)

Iceland Seismic Zone which currently offset the spreading axis across Iceland. The uplifted Snæfellsnes marine sediments, as well as an isolated occurrence of marine fossiliferous sediments in Southeast Iceland (Akhmetiev et al., 1978) indicate that sediments may form a substantial part of the shelf around Iceland, and the age estimates of these deposits indicate that the shelf sedimentary basins were active during the Pleistocene and the Pliocene, at least.

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