5 Earthquakes in Iceland

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Most of the seismicity of Iceland is related to the mid-Atlantic plate boundary that crosses the country. The boundary approaches Iceland from the southwest along the crest of the Reykjanes Ridge (Fig. 1) and from the north along the Kolbeinsey Ridge. In Iceland the plate boundary is displaced to the east by two major fracture zones, the South Iceland seismic zone in the south and the Tjörnes Fracture Zone in the north. Because of the lack of a clear topographic expression, both zones are defined primarily by their high seismicity, earthquake focal mechanisms and configuration with respect to the spreading axes. The largest earthquakes in Iceland occur within these zones and may exceed magnitude 7. Earthquakes also occur along the volcanic rift zones between the fracture zones, but they only rarely exceed magnitude 5. A large part of this seismicity appears to be related to central volcanoes.

Epicenters of earthquakes of the period 1962—77 large enough to be located by seismograph networks outside of Iceland are shown in Fig. 1. The map includes events down to magnitude 4, but is complete for magnitude 4.5 and larger events. Single event focal mechanism solutions available so far are also shown. This map shows many of the characteristics of the Icelandic seismicity, even though some of the locations are in error by as much as 40 km. Concentration of activity is seen in the Tjörnes Fracture Zone near the coast of N-Iceland, and in SW-Iceland on the Reykjanes Peninsula and in the South Iceland seismic zone. The focal mechanisms indicate strike-slip faulting. If the easterly striking nodal planes are taken as the fault planes, the sense of motion is right-lateral in N-Iceland and left-lateral in SW-Iceland, which is consistent with a transform fault interpretation of these zones. Outside of the fracture zones clusters of activity are seen in the Borgarfjördur area in W-Iceland, in the volcanic zone in Central Iceland, and near the volcanoes Katla in S-Iceland and Krafla in N-Iceland. Each of these zones will be considered separately.

Reykjanes Peninsula

The Reykjanes Peninsula is an area of high seismicity and recent volcanism that forms a transition between the Reykjanes Ridge to the west, and the western volcanic zone and the South Iceland seismic zone to the east (Fig. 2). The mid-Atlantic plate boundary as defined by the seismicity enters Iceland near the tip of Reykjanes and then runs along the peninsula in an easterly direction (Fig. 2). Detailed studies show that the seismic zone is less than 2 km wide in most places. The earthquakes are mostly at the depth of 1—5 km and are not located on a single fault. The seismicity seems to be caused by deformation of the brittle crust above a deeper seated and aseismic deformation zone. Small scale structures can be resolved in the seismicity within the zone. Several seismic lineations or faults can be identified, striking obliquely or even transversely to the main zone.

Focal mechanisms have been determined for a large number of small earthquakes, using data from dense, local networks, and for two earthquakes larger than magnitude 5 using teleseismic data. The minimum compressive stress is consistently oriented in a horizontal, NW direction. The maximum compressive stress rotates between the vertical direction, causing normal faulting on NE-striking faults, and the horizontal NE direction, causing strike-slip faulting on N or E striking faults. Thus the stress regime is characterized by the NW-trending minimum stress. The other principal stresses are probably nearly equal and may change directions according to local, or time dependent conditions. Dykes open up against the minimum stress and strike NE, in accordance with the eruptive fissures observed on the surface.

The mode of strain release changes systematically along the peninsula. Near the tip of Reykja-

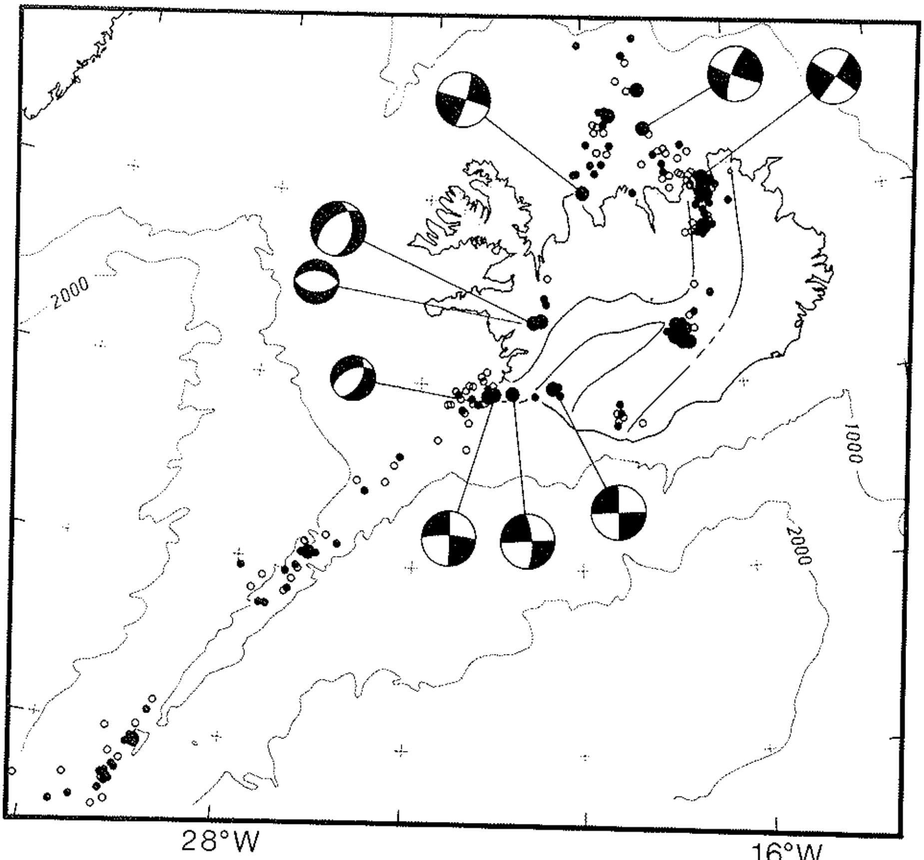

Fig. 1. Epicenters and focal mechanisms of earthquakes in Iceland and the northern part of the Reykjanes Ridge. Epicenters are taken from the PDE lists of USCGS, later NOAA and USGS, for the period 1962—1977. Open circles denote epicenters determined with fewer than ten P-wave readings or epicenters of earthquakes smaller than $m_b = 4.5$. Dots are epicenters of events of $m_b = 4.5$ and larger that are determined with ten or more readings. Large dots are epicenters of events of $m_b = 5.0$ and larger. The focal mechanisms are shown schematically as lower hemisphere equal area projections. The compressional quadrants (containing the least compressive stress axis) are shown black. The bathymetry is taken from a map by the Icelandic Hydrographic Service, Reykjavík, 1975. Depths are in meters. The volcanic rift zones of Iceland are shown.

nes, earthquakes occur in swarms, i.e. in sequences where no one event is much larger than the others. Normal faulting is the most common faulting mechanism. Towards east the earthquakes tend to occur more in mainshock-aftershock sequences and strike-slip faulting becomes more prominent. The plate boundary in the eastern part of the peninsula has not been mapped in detail because of the low seismic activity there in recent years.

South Iceland seismic zone

The South Iceland seismic zone bridges the gap between the two volcanic zones in South Iceland. Few instrumentally determined epicenters are available for this zone, but the destruction areas of some of the large, historic earthquakes are shown in Fig. 2. In spite of the clear E-W orientation of the seismic zone, there is no indication on the surface of a major E-W fault in this area. Many of the earthquakes, however, have been associated with surface faulting and the faults generally seem to be oriented N-S or NE-SW. The destruction zones are elongated in the N-S direction.

The surface faults formed during the 1912 earthquake, which is the most recent major earthquake in this zone, can still be observed in the districts Land and Rangárvellir. Most of the faults are arranged *en echelon* within a narrow, about 9 km long fault zone trending almost due N-S. The faulted zone was originally considerably longer, but has now been partly obliterated. The *en echelon* structure appears on many different scales, ranging from meters to a kilometer, and suggests right-lateral movement on a N-S striking fault. Surface faulting during earlier earthquakes seems to be of the same type. The sense of motion implies a least compressive stress in a horizontal NW-SE direction and a maximum compressive stress in a NE-SW direction.

The E-W epicentral belt may be interpreted as the expression of a deep seated deformation zone. The sense of motion conforms with a transform fault interpretation of the zone. The brittle crust responds to this motion with right-lateral strike-slip on northerly striking surface faults.

The strain in the South Iceland seismic zone is released in sequences of large earthquakes with a recurrence time of 50—100 years. The sequence often starts with a magnitude 7—7½ shock in the eastern part of the zone which is followed by slightly smaller shocks in the western part. This propagation of activity is documented in the sequences of 1732—34, 1784 and 1896 (Fig. 2).

Tjörnes Fracture Zone

The Tjörnes Fracture Zone is a broad zone of faulting and seismicity that connects the southern end of the submarine Kolbeinsey Ridge and the volcanic zone in North Iceland. The seismicity is too diffuse to be associated with a single fault or a simple plate boundary. The epicentral locations shown in Fig. 1 are based on teleseismic data and

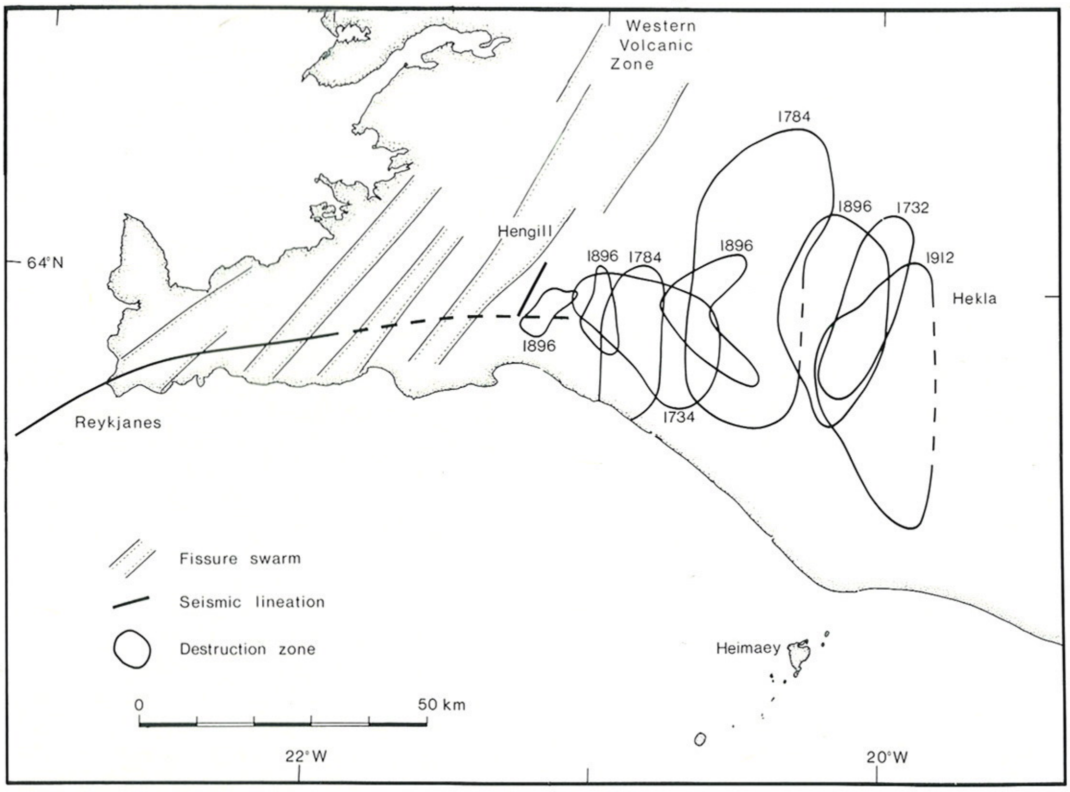

Fig. 2. Map of the seismic zones of SW-Iceland, showing some of the tectonic features of the Reykjanes Peninsula and the South Iceland seismic zone. The seismic lineaments are taken from Klein et al. (1973 and 1977) and Foulger and Einarsson (1979). The destruction zones of the historic earthquakes of 1732—34, 1784, 1896 and 1912 are shown. Within these zones more than 50% of houses at each farm were ruined. Corresponding intensity is MM VIII—IX.

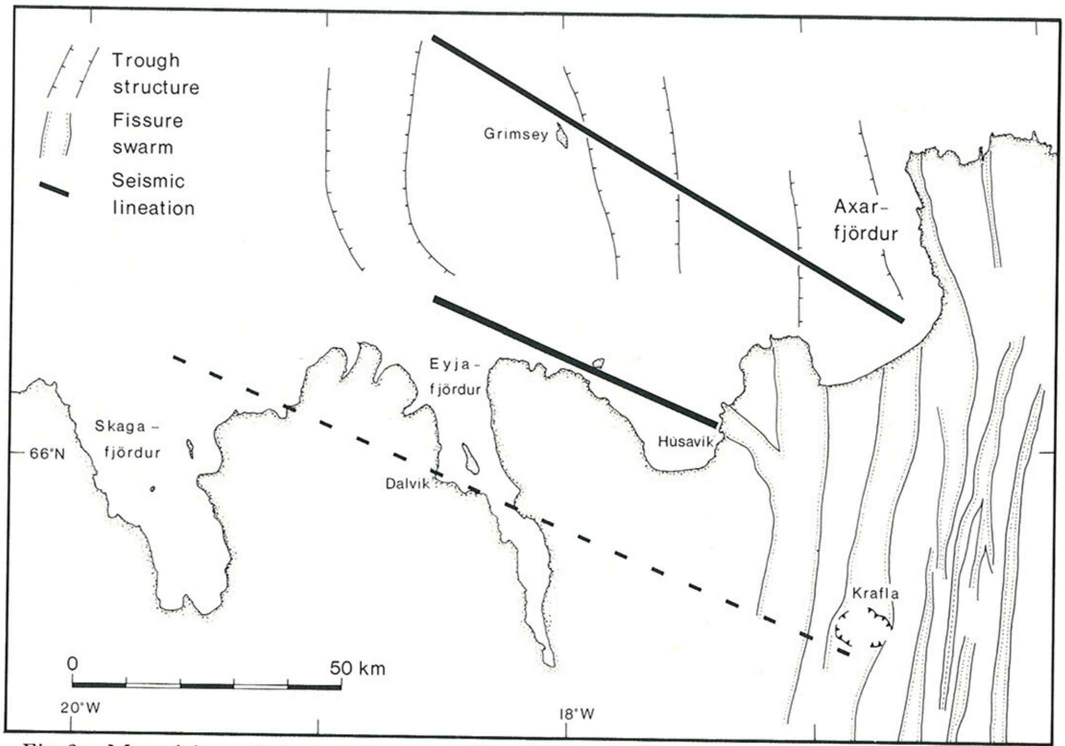

Fig. 3. Map of the main tectonic features of North Iceland. The fissure swarms in the volcanic zone are taken from a map by Saemundsson in Björnsson et al. (1977). The trough structures are based on McMaster et al. (1977), and the seismic lineaments are based on Einarsson (1976) and later data.

are not accurate enough for detailed tectonic interpretation. Detailed studies have shown that a considerable part of the seismicity is associated with a WNW trending line that runs slightly north of the island Grímsey and joins the Krafla fissure swarm in the Axarfjördur Bay (Fig. 3). The sense of motion along this seismic line is right-lateral strike-slip as evidenced by two focal mechanism solutions. The Grímsey seismic line has no clear expression in the topography. Instead, the surface structure in this area is characterized by northerly trending troughs and ridges that are arranged *en echelon* with respect to the fracture zone and the seismic line. In some respects this structural relationship resembles that in SW-Iceland, where the epicentral belts also lack a surface expression.

Even though the Grímsey seismic line has been responsible for the majority of earthquakes in this area for the last decade, it is not the only seismically active line. The Húsavík faults form a distinctive fault swarm exposed on the Tjörnes Peninsula. The faults can be traced from the shore near the town Húsavík east-south-eastwards into the volcanic rift zone (Fig. 3). Off shore the fault can be traced as a topographic offset of the Grímsey shoal and a strong, negative anomaly in the free air gravity field. Earthquake locations in recent years have shown that significant earthquake activity occurs on the Húsavík faults, and large, historic earthquakes have been accompanied by surface faulting near Húsavík.

In addition to the Grímsey and the Húsavík faults a third major WNW-striking earthquake fault near the town Dalvík has been suggested (Fig. 3). The main evidence for the existence of this fault is the earthquake (M=6¼) that caused extensive damage in Dalvík in 1934, the topography on the east side of Eyjafjördur and the alignment of low temperature geothermal springs between Eyjafjördur and Skagafjördur. The 1963 earthquake (M=7) in the mouth of Skagafjördur possibly occurred on this fault. The fault plane solution of that earthquake would imply right-lateral strike-slip along the fault. The seismicity of this region has been very low in recent years, and the fault remains to be confirmed by geological mapping. Its existence should therefore be considered speculative.

One can conclude that a large part of the seismicity of the Tjörnes Fracture Zone can be attributed to the activity along two and possibly three WNW-striking faults. The existence of further seismic zones can certainly not be excluded. The transform motion is thus taken up by at least two parallel faults within a broad deformation zone.

Volcanic zones

Earthquakes in the volcanic zones are generally smaller than in the fracture zones. Volcanic eruptions are usually accompanied by earthquakes, but between eruptions most parts of the volcanic zones are seismically quiet. A few areas of persistent seismic activity are found, the most prominent ones in Central Iceland and near the subglacial volcano Katla in South Iceland (Fig. 1).

The seismic area in Central Iceland is largely covered by the ice cap Vatnajökull, and the tectonic structure is poorly known. Recent studies of ERTS images of this area seem to indicate that the structure is dominated by a group of central volcanoes and it is tempting to relate the earthquakes to volcanic processes. The seismic activity of this area has been unusually high in recent years. Six earthquakes of magnitude 5 and larger occurred in the period 1974—79, but before 1974 no such large events were known.

The Katla volcano is located near the southern end of the eastern volcanic zone, south of its junction with the South Iceland seismic zone. The structure of this part of the zone is characterized by several central volcanoes, rifting structures are less significant. Historic eruptions of Katla have been preceeded by felt earthquakes, and because of the potential danger of future eruptions the seismicity at Katla is monitored by a relatively dense seismograph network. The epicenters located so far delineate two active areas. One is under the SE-part of the Mýrdalsjökull ice cap and coincides with the eruption sites in the latest Katla eruptions. The other area is under the SW-part of Mýrdalsjökull, about 15 km W of the first one. The depths of hypocenters in both areas are in the range 0—30 km. The hypocenters thus delineate two chimney-like features that penetrate the crust and extend well into the anomalous upper mantle.

The seismic activity in the Mýrdalsjökull area shows a pronounced annual cycle. The probability of an earthquake occuring within a given time interval is several times higher in the second half of the year than in the first half. This annual cycle was first noted by E. Tryggvason (1973) for the years 1952—58 and has been confirmed by later data.

The Heimaey eruption in 1973 was preceeded by an intensive swarm of small earthquakes that started 30 hours before the eruption. Earthquakes also accompanied the eruption, but the seismicity declined as the lava production diminished. No shock reached magnitude 4. The earthquakes during the eruption occurred at the depth of 15—25 km and occupied a spherical volume centered under Heimaey. It seems likely that the erupted magma either was stored or formed within this volume.

The depth of the Heimaey and Katla earthquakes is much larger than observed elsewhere in Iceland. In these areas the upper boundary of the anomalous mantle underlying Iceland is at the depth of 12—15 km. Earthquakes at the depth of 20—30 km may be taken to imply brittle failure in the mantle where creep or ductile behaviour is normally assumed. In these volcanic regions it is possible, however, that high strain rates associated with magmatic processes may cause brittle failure in material that would be ductile at lower strain rates.

A major rifting episode has been in progress since 1975 in the volcanic rift zone in NE-Iceland. The activity has been confined to the Krafla central volcano and its associated fissure swarm (Fig. 3), and provides a demonstration of a process that seems to play an important role in Icelandic tectonics. The activity is characterized by repeated cycles of relatively slow inflation and rapid deflation of the volcano. Magma apparently accumulates at a constant rate under the volcano during the inflation periods and during the deflation events the magma escapes from the reservoir area. Each cycle of activity is accompanied by a characteristic pattern of seismic activity. Continuous volcanic tremor starts in the caldera region at about the same time as the deflation. Small earthquakes also occur in the caldera, but the epicentral area is soon extended along the Krafla fissure swarm to the north or to the south. The rate of propagation of the seismic activity is highest during the first few hours, typically 0.5 m/sec., but the speed decreases as the deflation rate decreases and the epicentral zone is extended. The earthquake activity culminates after the maximum in tremor and deflation rate is reached. The largest earthquakes are located within a well defined, but each time different section of the fissure swarm. The magnitude only rarely exceeds 4.5. The depth of hypocenters is in the range 0—6 km. Extensive fault movements, both normal faulting and fissuring, occur in the area of maximum earthquake activity. The propagating seismic activity suggests that the magma escaping from the Krafla reservoir is injected laterally into the fissure swarm to form a dyke. The dykes may be as long as 40—60 km.

The first and the most violent deflation event started on Dec. 20, 1975. The deflation of the caldera exceeded 2 m and the accompanying earthquake swarm lasted about 8 weeks. Most of the epicenters that appear in the northern part of the volcanic zone in Fig. 1 belong to this swarm. The largest earthquakes were confined to two separate areas. One area was within the caldera and the earthquakes were apparently associated with faulting above the magma reservoir. Depth of most hypocenters was 0—4 km. The largest earthquakes reached magnitude 5. The other epicentral area was near the junction between the Krafla fissure swarm and the Grímsey fault (Fig. 3). The largest earthquake was of magnitude 6 and the focal mechanism shows right-lateral strike-slip along the Grímsey fault. This earthquake sequence demonstrates well the relationship between rifting along the diverging plate boundary and transform faulting in the fracture zone. The present Krafla events are assumed to be the result of interaction between magma pressure under the Krafla volcano and rifting of the plate boundary. The rifting is triggered by increasing magma pressure in the reservoir and a fluid filled extensional crack propagates horizontally along the Krafla fault swarm. The driving force of this process is the tectonic stress at the plate boundary, but the mode of strain release is modified by the presence of fluid.

Intraplate earthquakes

Earthquakes are rare outside of the volcanic zones and the seismic zones in South and North Iceland. Intraplate earthquakes are known in the Iceland region, however, for example near the insular shelf margin east of Iceland. A very significant sequence of intraplate earthquakes occurred in Borgarfjördur in West Iceland in 1974. The sequence lasted more than two months and culminated with a shock of $m_b = 5.5$. The epicenters were located in two intersecting linear zones. The main epicentral zone was about 25 km long and had an E-W trend. The second zone had a NE-SW trend and intersected the first one in the middle. The depth of the hypocenters was 0—8 km. Focal mechanism was determined for the main shock and several small shocks in the western part of the epicentral zone. All the obtained solutions show normal faulting, consistent with observed surface faults. The Borgarfjördur area seems to be undergoing horizontal extension. The direction of the least compressive stress rotates from the WNW in the center of the epicentral zone to N-S or even NNE in the western part. Here the epicentral zone is spatially related to the Snaefellsnes volcanic zone, where the tectonic structure is characterized by block faulting on WNW striking faults and volcanism on WNW trending lines. This structure also implies horizontal extension in the NNE-SSW direction. The crustal extension in West Iceland may be caused by subcrustal flow radially away from a mantle plume under Central Iceland, but could also be the result of gravitational stresses induced by the regional topographic high of Iceland.

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