INTRAPLATE EARTHQUAKES IN ICELAND

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ABSTRACT. Only a small proportion of Icelandic earthquakes is not directly associated with the mid-Atlantic plate boundary that crosses the island. These intraplate earthquakes fall mainly into two classes. In the first class are earthquakes occurring west of the main rift zone through Iceland, within the tongue of lithosphere that is bounded by the two transform zones in North and South Iceland. This seismicity is associated with internal deformation of the North American Plate. Best known are the Borgarfjörður events of 1974 in Central West Iceland, which were a prolonged series of earthquakes with maximum magnitude of 6. The epicentral area was at least 25 km long and the earthquakes were clearly not associated with displacement on a single fault. Most of the hypocenters were at a depth of 0 - 8 km but events did occur down to 10 km depth. Thus fracturing extended through most of the crust. Fault plane solutions show normal faulting, indicating horizontal extension. Areal extension of the lithospheric tongue is consistent with the westward divergence of the transform zones bounding it in the north and south. This phenomenon is most likely related to the exess production of the Iceland hot spot, although the exact mechanism is unclear. The extension could be achieved by underplating and intrusion of magma into the crust from the partially molten layer beneath it.

The second major class of Icelandic intraplate earthquakes consists of events originating on the insular shelf off Eastern and Southeastern Iceland. Most of them have epicenters very close to the shelf edge, which is thus shown to be a seismogenic structure. The shelf edge in this area probably represents a structural discontinuity formed after about 36 m.y.b.p., when the main discharge area of the Iceland hot spot shifted from the Iceland-Faroes Ridge to produce the present Iceland socle. The discontinuity is expressed in surface topography as well as in crustal and mantle structure. There probably also is an age jump of 15-25 m.y. and a resulting thermal discontinuity across the shelf edge. The present seismicity is thus interpreted as the result of differential lithospheric response to loading or different cooling rate on either side of the edge.

1. Introduction

The term intraplate earthquake has a somewhat more diffuse meaning in Iceland than in other surrounding areas, even if the adjacent sections of the Mid-Atlantic Ridge are included. The mid-Atlantic plate boundary branches into a complex series of rifts and transform zones as it crosses the country (Einarsson, 1986). Ridge jumps, propagating rifts and migrating transforms further complicate the picture, so it is not always easy to define what is an intraplate setting and what is not.

A large majority of Icelandic earthquakes are clearly related to the plate boundary, i.e. the volcanic rift zones and the two transform type zones that connect them to the submarine spreading centers on the Reykjanes and Kolbeinsey Ridges off the SW and N coasts. Some of the volcanoes of the volcanic flank zone in South Iceland (Sæmundsson, 1986) also exhibit significant seismicity. The remaining seismicity may be called truely intraplate, even though some of it may be indirectly related to the process of crustal generation. This particularly applies to activity in West Iceland. Earthquakes occur on the insular shelf off

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the east coast, that bear some resemblance to earthquakes at passive margins of the continents. A study of these events may provide some insight into the possible causes of their continental analogs.

In this paper an attempt is made to assemble all available information on intraplate earthquakes in Iceland, and speculate on their possible causes. But first, let us review the configuration of the plate boundary, and the current understanding of its development.

2. The Plate Boundary

The two transform zones of Iceland have a rather complex structure and lack the clear topographic expression typical of most oceanic transform faults. They are zones of high seismicity, and the largest earthquakes reach magnitude 7 (M_s). Fault plane solutions show strike-slip faulting, but the slip is distributed on a series of faults instead of being concentrated on one major fault as seems to be the case in the oceanic transforms. This is clearly seen in the seismicity map of Fig. 1, that contains epicenters of the period 1982-1985. The seismicity of the Tjörnes Fracture Zone in North Iceland is distributed over a

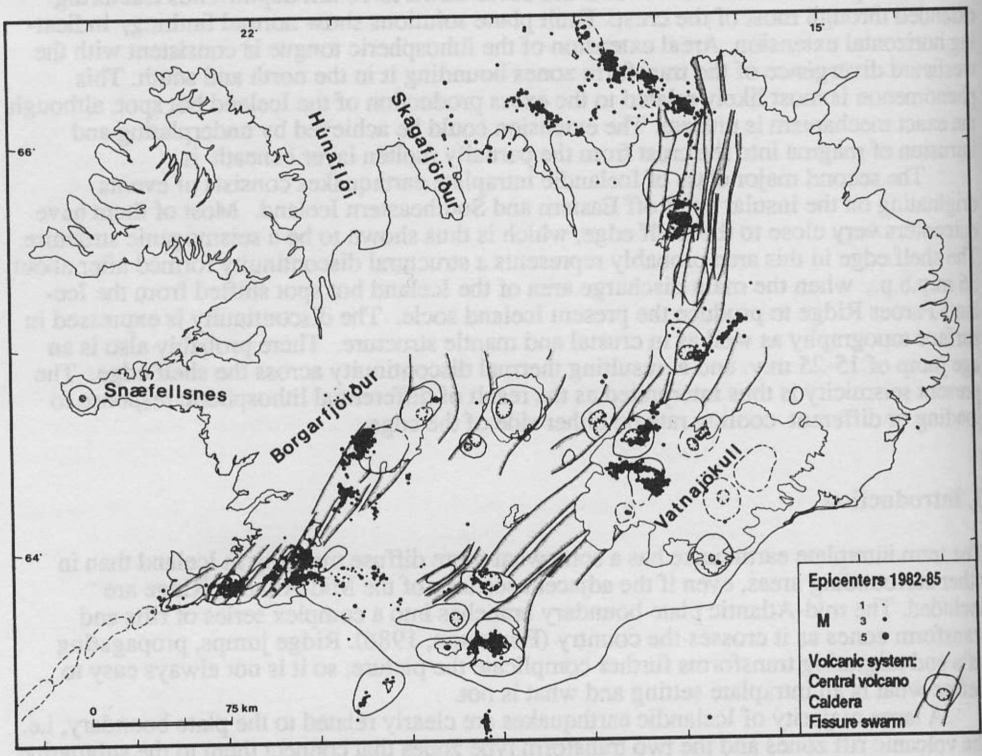

Fig.1. Epicenters of earthquakes in Iceland 1982-1985. Shown are all epicenters with location errors smaller than 5 km, almost all have errors smaller than 2 km. Active volcanic systems, with their central volcanoes, fissure swarms and calderas are also shown. From Einarsson and Björnsson (1987). The spreading centers are caracterized by fissure swarms.

zone, 150 km long and 90 km wide. Three parallel bands of seismicity can be discerned within the zone. These belts trend NW-SE and fault plane solutions indicate that right-lateral strike-slip motion is occurring along them (Einarsson, 1986). The transform motion is thus taken up by at least three belts of seismicity. Significant crustal deformation is also taking place between these belts as shown by scattered epicenters. Furthermore, graben and trough structures and evidence for recent volcanic activity within the area (Sæmundsson,1974, McMaster et al., 1977) indicate that crustal extension plays a significant role in the tectonics of the Tjörnes Fracture Zone.

The transform zone in SW Iceland is also complicated, but in a different way. The plate boundary of the Reykjanes Ridge is gradually deflected to the east as it approaches Iceland. On the Reykjanes Peninsula it has the appearance of a highly oblique ridge or a leaky transform. The plate boundary as defined by the seismic zone is 2-5 km wide, and is oriented N70°E. The faulted zone is, however, much wider. The fissure swarms trend NE-SW and are arranged en echelon along the boundary (Fig. 1). These are probably active mostly during magmatic episodes, which in this area appear to occur at intervals of several hundred years. At the present time the deformation is mostly along the seismic zone, with the largest events reaching magnitude 5.5-6.5.

Farther east, near 21°W, the transform zone changes caracter. This part of the zone, the South Iceland Seismic Zone, is 10-15 km wide and bridges the gap between the two parallel rift zones. Here the crustal deformation is purely seismic, with only minor magmatic component. The largest earthquakes reach magnitude 6-7 and occur in sequences with an average recurrence interval of 80-100 years (Einarsson et al., 1981). This zone is relatively quiet at the present time, but a major sequence of events is expected with high probability within the next two decades. In spite of the E-W orientation of the zone, the earthquakes are associated with slip on N-S striking faults (Einarsson and Eiríksson, 1982). The transform motion is thus taken up by slip on transverse faults, conjugate to the zone, and small counterclockwise rotation of the blocks between them. This peculiar behaviour led Einarsson and Eiríksson (1982) to suggest that the South Iceland Seismic Zone is a transient feature migrating sideways in response to the southwards propagation of the Eastern Volcanic Zone. A migration velocity of 3-5 cm/year was estimated by Einarsson (1988 a).

In contrast to the relatively narrow spreading centers of the submarine part of the ridge system the volcanic rift zones of Iceland are wide features, and consist of several parallel or en echelon fissure swarms (Fig. 1). Each fissure swarm has a central volcano associated with it, where the volcanic production is highest. They are often caracterized by a high temperature geothermal area, acidic rocks and a caldera structure. The seismicity of the rift zones is highly clustered in space, and large parts of the zones are completely aseismic at the present time. Most of the clusters are associated with central volcanoes, some of them are due to persistent activity and others are earthquake swarms. This seismicity is related to processes of the central volcanoes (Einarsson, 1985, 1987), such as inflation or deflation of magma chambers (Krafla, Grímsvötn, Bárðarbunga and Katla volcanoes), cooling of magma bodies (Hengill, Torfajökull), or eruptions (Krafla, Grímsvötn). Earthquakes associated with magma intrusion and rifting have also been identified (Einarsson and Brandsdóttir, 1980, Brandsdóttir and Einarsson,1979), but no such events are included in Fig.1.

The part of the Eastern Volcanic Zone that is south of 64°N has a peculiar setting. It is south of the junction with the South Iceland Seismic Zone, and is therefore strictly speaking not a plate boundary. Rifting structures are insignificant and the volcanic production rate is relatively low (Jakobsson, 1972, Sæmundsson, 1978), in spite of frequent eruptions. Two of the volcanoes in this zone, Torfajökull and Katla, are moderately seismically active. A few events also occur every now and then near Surtsey and

Heimaey, probably as the result of the eruptions there in 1963-67 and 1973. This seismicity is not grouped with the intraplate activity because of its obvious association with volcanic processes. Several events have also been recorded near the intraplate volcano Öræfajökull, near 64°N, 16.7°W. These events are similarily left out of the present discussion.

It has been suggested on the basis of petrologic and structural arguments (Meyer et al., 1985, Óskarsson et al., 1985, Einarsson and Eiríksson, 1982, Einarsson, 1988 a, b) that the southern end of the Eastern Volcanic Zone is the tip of a propagating rift. According to these ideas the rift started propagating about 3 million years ago from Central Iceland, near the center of the Iceland hot spot, gradually taking over the spreading from the Western Volcanic Zone. Similar ridge jumps have occurred earlier in the history of the present Icelandic land mass (Jóhannesson, 1980, Helgason, 1985). Thus the present Western Volcanic Zone and the rift zone in North Iceland have taken over from, or been active parallel to spreading centers farther west, which are now dead. These changes occurred after Anomaly 5 time (ca. 9 m.y.b.p.), leaving behind dead rift zones, fossil transforms and other structural complexities in Western Iceland, in the crustal tongue between the transform zones.

The frequent ridge jumps in the Iceland area are considered to be the result of the drift of the plate boundary as a whole over a fixed mantle plume (e.g. Sæmundsson, 1974, Vink, 1984). The Iceland hot spot is then taken as the expression of the plume activity. A new rift starts propagating from the center of the plume when the plate boundary has migrated some critical distance off it.

The Iceland hot spot is not only expressed in excessive volcanic production and topography. It is also seen in crustal and mantle structure. Anomalous seismic velocities in the Icelandic mantle have been detected down to the depth of 300 km (Tryggvason et al., 1983). The Icelandic crust has seismic velocities similar to the oceanic crust, but the thickness is greater by a factor of 2 to 3 (Pálmason, 1971, Gebrande et al., 1980), probably reflecting the higher magmatic productivity. Beneath the crust the Icelandic mantle is very different from that of the surrounding oceanic area. Instead of the typical sub-Moho velocities of 8 km/s the P-wave velocity beneath Iceland is about 7 km/s. The P- to S-wave velocty ratio is anomalously high, and S-waves are strongly attenuated (Angenheister et al., 1980, Gebrande et al., 1980), which indicates partial melting. This interpretation is supported by magnetotelluric measurements, that show a layer of low electrical conductivity at the depth of 8-20 km beneath large parts of Iceland (e.g. Beblo et al., 1983, Björnsson, 1985). A melt fraction as high as 23 % has been estimated by Schmeling (1985). In the context of the present paper it is important to note that the partially molten layer is not confined to the plate boundary regions, but appears to be present under most of Iceland. The Iceland hot spot may therefore be viewed as a ´weak spot´ in the lithosphere, with magmatism and crustal deformation occurring out to some distances from the plate boundary.

3. Intraplate Earthquakes

3.1. EARTHQUAKES 1930-1960

The source of information for this period is Tryggvason´s (1978 a, b, 1979) reports. Most of this time only one seismic station was in operation in Iceland. Epicentral locations are therefore largely based on felt reports. The best locations are plotted in Fig. 2. The only unequivocal cases of intraplate events are:

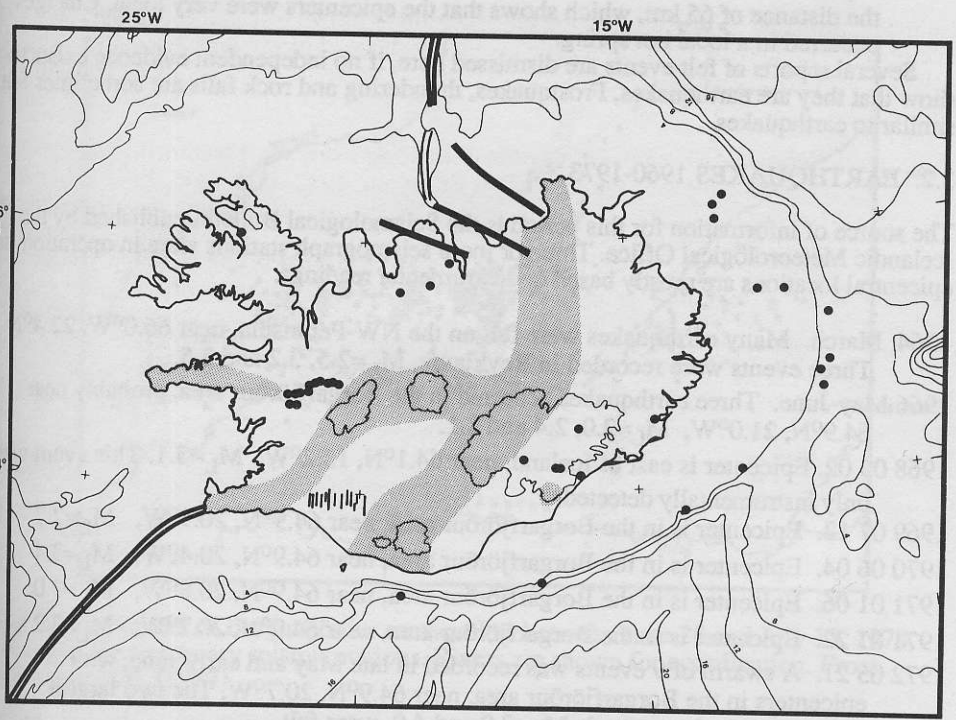

Fig. 2. Intraplate earthquakes and the plate boundaries in the Iceland area. Epicenters of swarms and single events are shown with dots. Neovolcanic zones on land are shaded, submarine spreading centers are marked with a double line, transforms of the Tjörnes Fracture Zone with a thick line. Thin lines show the main faults of the South Iceland Seismic Zone. Bathymetric contours are drawn every 400 m.

1931 10 28. Earthquakes were felt widely in West Iceland. Seven events were recorded in Reykjavík, the largest of M_L=4 1/2. Distance from Reykjavík was 70 km and the epicenter probably in the Borgarfjörður area.

1934 07 18. A swarm of 12 events was recorded in Reykjavík, the largest one of M_L= 4 1/4. The epicenters were probably in the same place as those of the 1931 events.

1935 March. Numerous earthquakes were felt in Borgarfjörður, near 64.8°N, 21.2°W. Seven events were recorded in Reykjavík, the largest of M_L=3 3/4.

1938 02 10. A large swarm of earthquakes occurred at the distance of 75-80 km from Reykjavík. About 40 events were recorded, the largest of M_L=5 1/4. The most likely source area is here considered to be on the Reykjanes Ridge, but some contradictory felt reports may indicate that the earthquakes originated in the eastern part of the Snæfellsnes Peninsula.

1953 06 21. Two small earthquakes were felt in Borgarfjörður, the larger one was recorded in Reykjavík (M_L=2.6). Epicenters are most likely near 64.8°N, 21.2°W.

1957 05 31. Numerous small earthquakes were felt in Borgarfjörður this day and the next, near 64.7°N, 21.2°W. The events were too small to be recorded in Reykjavík at the distance of 65 km, which shows that the epicenters were very local. Changes occurred in a local hot spring.

Several reports of felt events are dismissed here, if no independent evidence exists to show that they are earthquakes. Frostquakes, thundering and rock falls are sometimes felt similar to earthquakes.

3.2. EARTHQUAKES 1960-1973

The source of information for this period is the Seismological Bulletin published by the Icelandic Meteorological Office. Three or more seismograph stations were in operation, so epicentral locations are mostly based on instrumental readings.

1964 March. Many earthquakes were felt on the NW-Peninsula, near 66.0^{o}W, 22.4^{o}N. Three events were recorded in Reykjavík, M_L=2.5, 3.2 and 3.5.

1966 May-June. Three earthquakes occurred in the Borgarfjörður area, probably near 64.9^{o}N, 21.0^{o}W, M_L=2.0, 2.4 and 2.1.

1968 03 02. Epicenter is east of Iceland, near 64.1^{o}N, 13.2^{o}W, M_L=3.1. This event was only instrumentally detected.

1969 07 12. Epicenter is in the Borgarfjörður area, near 64.9^{o}N, 20.9^{o}W, M_L=2.7

1970 06 04. Epicenter is in the Borgarfjörður area, near 64.9^{o}N, 20.4^{o}W, M_L=3.4

1971 01 06. Epicenter is in the Borgarfjörður area, near 64.9^{o}N, 20.8^{o}W, M_L=3.0

1971 01 22. Epicenter is in the Borgarfjörður area, near 64.9^{o}N, 20.7^{o}W, M_L=3.2

1972 05 21. A swarm of 9 events was recorded in late May and early June, with epicenters in the Borgarfjörður area, near 64.9^{o}N, 20.7^{o}W. The two largest earthquakes, of magnitude M_L=3.9 and 4.0, were felt.

1972 10 28. A swarm of earthquakes begins in the Borgarfjörður area, near 64.8^{o}N, 21.4^{o}W. The largest event was of magnitude M_L=3.2, and 37 were recorded in the following 11 days. Many events were felt locally. Three more events occurred on Oct. 23, and one on Nov. 4.

1973 11 27. A swarm begins in the Borgarfjörður area, near 64.9^{o}N, 20.7^{o}W. During the next 4 days 49 events were recorded, the largest of M_L=3.7. Further 14 events originated in this area on Dec. 5-19, the largest of magnitude M_L=3.5.

3.3. THE BORGARFJÖRÐUR EARTHQUAKES OF 1974

The increased seismic activity of the Borgarfjörður area in 1972-73 turned out to be the prelude to a major earthquake sequence, that culminated in June 1974 with an earthquake of M_L=6.3 (m_b=5.5). This sequence was studied in some detail by Einarsson et al.(1977), who operated 9 portable seismographs in the epicentral area and determined a teleseismic fault plane solution for the main event. No single fault could be identified as the source of the earthquakes. Instead, the epicenters were distributed within two intersecting, elongate zones (Fig. 3). The more prominent zone was 25 km long and 4 km wide, and had an E-W trend. The other zone trended NE-SW and intersected the first one in the middle. The mainshock was inferred to have originated near the intersection and its fault plane solution showed normal faulting. The hypocenters were found to span the depth range 0 to 8 km, i.e. the whole brittle crust. Several fault plane solutions were obtained for small events in the western part of the epicentral zone (Fig.4). They all indicated normal faulting, which is

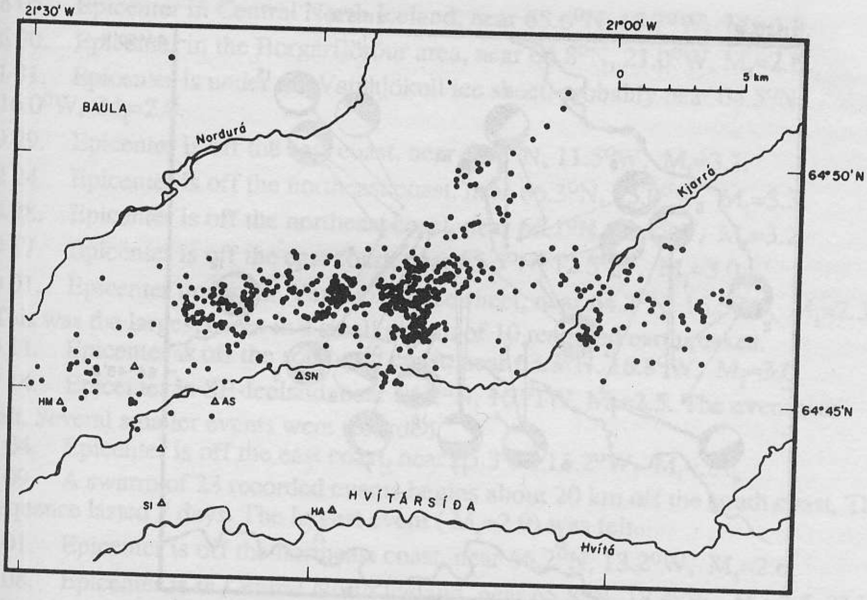

Fig. 3. Epicenters of Borgarfjörður earthquakes between June 28 and July 15, 1974. Triangles are temporary seismic stations. Rivers are shown for coordination. From Einarsson et al. (1977).

consistent with surface ruptures in the area. Dip-slip displacements of several cm to a few tens of cm were found on four faults, all of which had an E-W strike. Secondary surface effects such as slumping, mudslides, rock falls, changes in springs, and damage to buildings were also documented. Overturned rocks indicated that the acceleration had approached 1 g near the fault trace during the main event.

3.4. EARTHQUAKES OF 1975-1987

The number of seismograph stations increased greatly in the period 1973-77 (Einarsson and Björnsson, 1987). After 1975 there have been more than 20 stations in operation, and by 1985 the number had risen to 40. Most of the stations are located within or in the immediate vicinity of the active zones along the plate boundary, but the coverage of activity in the intraplate areas is also quite good. The coverage of the area off the east coast, in particular, improved greatly in 1977, when three stations were installed in Eastern Iceland. The source of information for this period is ´Skjálftabréf´ (Bulletin of events), published by the Science Institute, University of Iceland, and the Icelandic Meteorological Office. A good part of the seismograms were read by the author. The uncertainty of the locations of epicenters within the seismic network is mostly smaller than 2 km, but for the off-shore areas the uncertainty is larger, of the order of 10 km. M_t is a magnitude based on the time duration of the earthquakes on the seismogram. Intraplate events of this period were:

1975 07 17. A small event in the Borgarfjörður area, probably near 64.8°N, 21.1°W.
1975 08 09. A small event occurred in Húnaflói in Western North Iceland.
1975 Nov. A small swarm occurred in the Borgarfjörður area, near 64.8°N, 21.1°W. Nine events were recorded, the largest one M_t=2.7. One event was felt.

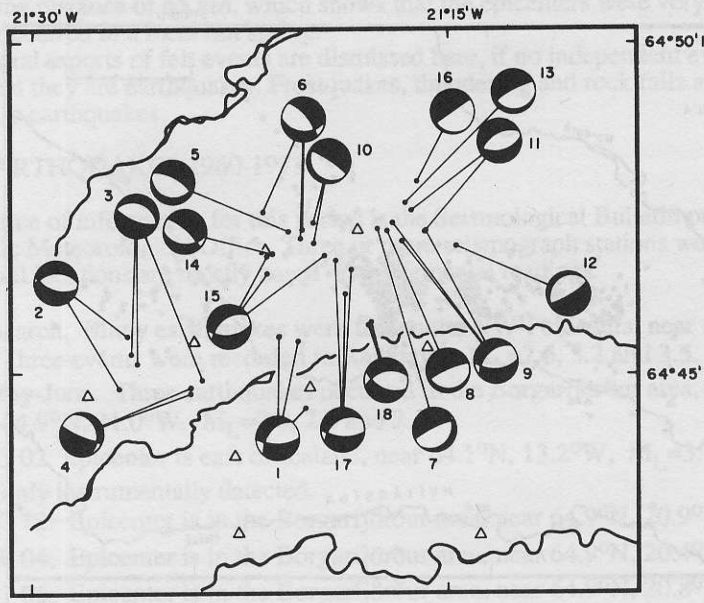

Fig. 4. Fault plane solutions of earthquakes in the Borgarfjörður swarm of 1974. Upper hemisphere first motion patterns are shown schematically along with the epicenters used for the solutions. The compressional quadrants are shown in black, the dilatational quadrant in white. All solutions indicate normal faulting. From Einarsson et al. (1977).

1975 12 15. An earthquake swarm occurred in Borgarfjörður, near 64.7°N, 21.3°W. The largest event was of M_t=2.3, and 16 events were recorded. Several events were felt locally.

1976 11 29. A small swarm occurred under the Vatnajökull ice sheet, probably near 64.2°N, 16.4°W.

1977 04 30. An earthquake swarm occurred in Skagafjörður in North Iceland, near 65.6°N, 19.3°W. The largest of the 5 recorded events was M_L=3.4, and was felt.

1977 10 21. Epicenter is off the east coast, near 64.9°N, 11.3°W.

1977 12 30. A swarm of small events occurred under the Vatnajökull ice sheet, near 64.3°N, 17.1°W. 60 events were recorded.

1978 02 07. Epicenter is off the east coast, near 65.5°N, 12.0°W.

1978 10 28. A small earthquake occurred in Eastern Iceland, near 64.6°N, 14.7°W.

1980 03 25. Epicenter is off the southeast coast, near 63.8°N, 14.2°W, M_t=2.5.

1980 10 02. A swarm of small earthquakes occurred in the Borgarfjörður area, near 64.7°N, 21.3°W. About 110 events were recorded in three days, all smaller than magnitude 2.

1981 03 13. Epicenter in Skagafjörður, near 65.9°N, 19.6°W, M_t=2.0.

1981 April. Two events occurred in the Borgarfjörður area, near 64.8°N, 20.9°W, M_t=2.2 and 2.0.

1981 08 05. Epicenter in Central North Iceland, near 65.6°N, 18.7°W, M_t=1.8.

1982 06 30. Epicenter in the Borgarfjörður area, near 64.8°N, 21.0°W, M_t=2.6.

1983 01 31. Epicenter is under the Vatnajökull ice sheet, probably near 64.5°N, 16.0°W, M_t=2.0.

1983 09 29. Epicenter is off the east coast, near 64.8°N, 11.5°W, M_t=3.1.

1983 12 24 Epicenter is off the northeast coast, near 66.3°N, 13.0°W, M_t=3.3.

1984 04 28. Epicenter is off the northeast coast, near 66.1°N, 13.2°W, M_t=3.2.

1984 09 17. Epicenter is off the east coast, near 65.5°N, 12.5°W, M_t=3.0.

1984 10 01. Epicenter under the Vatnajökull ice sheet, near 64.2°N, 16.5°W, M_t=2.3. This was the largest event in a small swarm of 10 recorded earthquakes.

1984 10 11. Epicenter is off the southeast coast, near 63.3°N, 16.8°W, M_t=3.0.

1984 12 14. Epicenter in SE-Iceland, near 64.1°N, 16.°1W, M_t=2.5. The event was felt. Several smaller events were recorded.

1985 02 04. Epicenter is off the east coast, near 65.3°N, 11.2°W, M_t=3.1.

1985 07 09. A swarm of 23 recorded events begins about 20 km off the south coast. The sequence lasted 7 days. The largest event (M_t=2.9) was felt.

1985 12 01. Epicenter is off the northeast coast, near 66.2°N, 13.2°W, M_t=2.6.

1986 01 08. Epicenter is in Central North Iceland, near 65.8°N, 18.4°W, M_t=2.5. This event was felt.

1987 05 24. Epicenter is off the east coast, near 64.7°N, 11.5°W, M_t=3.2.

1987 07 25. Two events occurred in the Borgarfjörður area, near 64.9°N, 20.5°W, M_t=2.3 and 2.4. A third event occurred on Aug. 1 (M_t=2.2).

4. Discussion of the Results

From the epicentral map in Fig.2 two main classes of intraplate earthquakes can be identified. In the first class are earthquakes in Central Northern and Western Iceland, west of the rift zones and between the transform zones. This part of Iceland has a relatively complex geological history. It consists of dead rift zones and blocks caught between rift zones during ridge jumps. It also contains the trace of the Iceland hot spot as it has migrated eastwards with respect to the plate system. It is therefore perhaps not surprising to find intraplate deformation in this area. Seismically the Borgarfjörður area is by far the most active part, but epicenters are also scattered up through Skagafjörður. In a general way this area coincides with areas of considerable geothermal activity of the low temperature type. Faulting and low level volcanism has occurred here in the Quaternary period (Jóhannesson, 1988).

The Borgarfjörður earthquakes are clearly intraplate events. They occur within the North American Plate, in crust that is more than 2 million years old. They are associated with fracturing and horizontal extension of the crust. The cause of this extension remains conjectural. Einarsson et al.(1977) suggested that the extension may be related to rifting on zones radiating away from the Iceland mantle plume, or caused by thermal contraction of the lithosphere as it moves away from the accreting plate boundary. It may further be pointed out, that Borgarfjörður is an area of unusually high geothermal activity. This activity has been considered to be fed by the general heat flow and the flow of ground water from the highlands towards the coast (Tr. Einarsson, 1942, Árnason, 1976, Georgsson et al.,1984). Böðvarsson (1982), however, evaluated the energy balance and the rock-water contact areas required to maintain thermal systems of the type found in Borgarfjörður, and concluded that the thermal activity must be of transient nature and not a steady-state phenomenon. Arnórsson and Ólafsson (1986) reviewed recent studies of the thermal areas and came to the conclusion that the geothermal systems are driven by local convection and not by the regional heat flow. In their model they assume magmatic heat sources beneath the geothermal areas in this region. They pointed out that Quaternary volcanics are found unconformably on top of older rocks west of the Western Volcanic Zone. Parts of the magma may have been left behind in the crust and act as heat sources for the geothermal activity. It is tempting to develop these ideas a bit further, and combine them with the results of the earthquake study and the concept of the partially molten layer beneath the crust. Three scenarios can be envisaged, that will provide a transient magmatic source for the geothermal activity in Borgarfjörður:

1. The crust was fractured down to its base during the Borgarfjörður earthquakes, possibly all the way into the partially molten layer. The crustal extension was accompanied by some passive magma intrusion into the base of the crust.
2. Magma pressure in the layer may also have played a more active role in triggering the fracturing and the earthquakes by lowering the fracturing strength at the base of the crust. Increasing pore fluid pressure in the layer leads to intrusion of vertical dikes into the crust. Scenarios 1 and 2 require an external source of the crustal stress.
3. Furthermore, the crustal extension may have been the result of uplift and stretching caused by horizontal sheet intrusion at the base of the crust by magma from the layer. The crustal stress is caused by the magma and no external source is needed.

As can be seen in Fig. 1, there is a westwards divergence between the transform zones in North and South Iceland. In other words, the lithospheric tongue between the transform zones becomes wider with age. The transforms of the Tjörnes Fracture Zone trend WNW, and the South Iceland Seismic Zone and the Reykjanes Peninsula trend nearly E-W. There are all indications that the plate motion is locally parallel to these zones, and yet the trend of the regional plate motion vector is intermediate between them. This requires some N-S extension and generation of new crust within the tongue. Be it by rifting, dike intrusion or sheet intrusion and underplating, we might just have witnessed this process in action during the Borgarfjörður earthquakes of 1974. The intraplate Snæfellsnes Volcanic Zone in Central West Iceland is probably also an expression of this process.

The second main class of intraplate events contains earthquakes in the insular shelf area east of Iceland. Majority of the events are located on or very near the shelf edge, which is thus shown to be a seismogenic structure. Epicenters off the northeast coast are located somewhat landwards of the edge. With the exception of the swarm of July 1985 off the south coast, the earthquakes are single events, without aftershocks. The recorded wave trains usually contain quite high frequencies, and S-waves are clear and distinct. These are usual characteristics of intraplate earthquakes. They can also be taken as indication that the events are not due to surface processes such as slumping or explosions.

The swarm of July 1985 was recorded by numerous stations in South and Southeast Iceland. In spite of that, it turned out to be very difficult to locate. The P-waves had a very high apparent velocity across the net, which required an unusually large hypocentral depth. Even assuming this relatively large depth it was impossible to fit calculated travel times to very early arrivals at the two easternmost stations in SE-Iceland. Leaving them out of the calculations, satisfactory hypocentral solutions were obtained. One must conclude that the earthquake swarm originated at 20-30 km depth, a little seaward of the shelf edge. Furthermore, one is left with the unsolved problem of the early arrivals in SE-Iceland, which requires further research. Earthquakes at this large depth have only once before been identified with certainty in Iceland. These were earthquakes that occurred during the Heimaey eruption in 1973, 60 km to the WNW. They were considered to be related to rapid withdrawal of magma at 15-25 km depth from the partially molten layer beneath Heimaey (Einarsson and Björnsson, 1979). This layer deforms aseismically at the normal strain rates associated with plate tectonics, so much higher strain rates are required to cause brittle failure of this material. Similar arguments must apply in the case of the July 1985 swarm, if it was in fact located in the Icelandic anomalous mantle. The swarm was then probably associated with rapid magma movements at depth. The time history of the swarm (Fig.5) is in some respects similar to other swarms of probable magmatic origin. The other possibility is that it was located in the oceanic lithosphere, i.e. seaward of the structural boundary between Iceland and the oceanic area. The age of the lithosphere corresponds to magnetic anomalies 6-7, or about 20 million years, and brittle behavior may be encountered to the depth of 20 km at normal strain rates (Bergman and Solomon, 1984, Wiens and Stein, 1983).

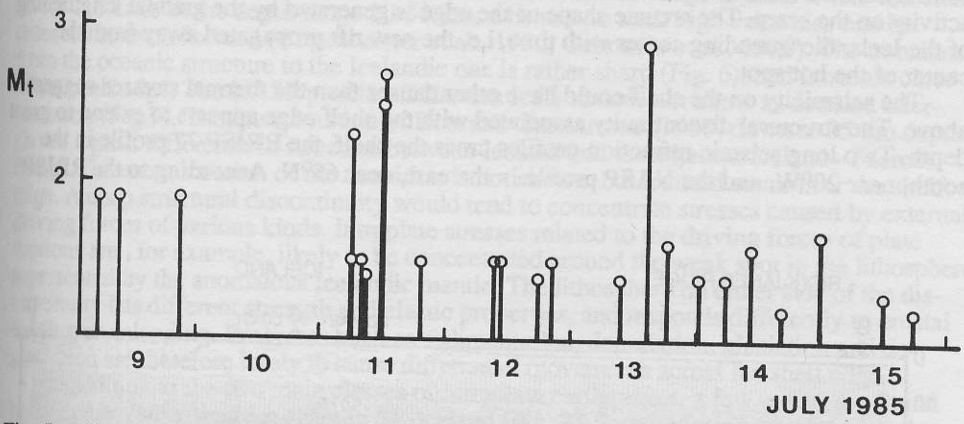

Fig. 5. Time history of the July 1985 earthquake swarm off the south coast of Iceland. Duration magnitude is plotted against time.

The insular shelf around Iceland is bounded by a relatively well defined edge at the depth of 200-400 m (Fig. 2). The edge is indistinct where the Reykjanes and Kolbeinsey Ridges enter the shelf area, but in most other places it forms a distinct scarp of up to 1000 m height and slope of up to 15° (Pálmason, 1974, Kristjánsson, 1976, 1979). The edge is particularly well developed off the southeast an east coasts. Geophysical surveys in this area have shown that the shelf basement is made of basaltic material overlain by thin sediments. The basement scarp is located 5-14 km inside the bathymetric shelf break. Thus the shelf edge has been built outwards by accumulation of sediments since its formation by igneous processes.

The shelf edge has been a subject of considerable discussion, as its existance is not predicted by any conventional, steady-state models of crustal generation. It is clearly the physiographic boundary that separates the Iceland mass from the surrounding sea floor. Its formation must therefore be closely linked to the existance of Iceland itself. It is therefore likely that processes such as enhanced magma productivity of the Iceland hot spot and shifts in the plate boundary are responsible.

Magnetic anomalies on the shelf are very subdued (Kristjánsson, 1976), so age determination is difficult. By extrapolating eastwards the age determined for the easternmost part of Iceland, one can estimate the age of the basement near the shelf edge. Using the $^{40}Ar/^{39}Ar$ date of 13 million years (Ross and Musset, 1976) for Eastern Iceland and a half spreading rate of 1 cm per year, an age of 22 million years is obtained for the shelf break. Off the shelf edge, however, the basement age is probably close to 37-47 million years, as determined from magnetic anomalies and the reconstruction of the spreading history of the North Atlantic (Nunns, 1981, Vink, 1984). Thus an age gap of 15-25 million years is probable across the shelf edge. This age gap was produced when spreading began on the Kolbeinsey Ridge and in the region of the present Iceland, taking over from the Aegir Ridge in the Norwegian Sea. Using the relationship between bathymetric depth and age derived by Parsons and Sclater (1977) one obtains a depth difference of 490-720 m across the age gap. A good part of the scarp height can therefore be explained by the different thermal structure of the lithosphere on either side of the shelf edge, which is the result of the age difference. A corollary to this is, that the thermal contraction rate is different across the edge, leading to differential movement and seismic activity on the scarp. The arcuate shape of the edge is generated by the gradual lengthening of the Icelandic spreading center with time, i.e. the new rift propagated away from the center of the hot spot.

The seismicity on the shelf could have other causes than the thermal stresses suggested above. The structural discontinuity associated with the shelf edge appears to extend to great depth. Two long seismic refraction profiles cross the shelf, the RRISP 77 profile in the south, near 20°W, and the NASP profile in the east, near 65°N. According to the RRISP

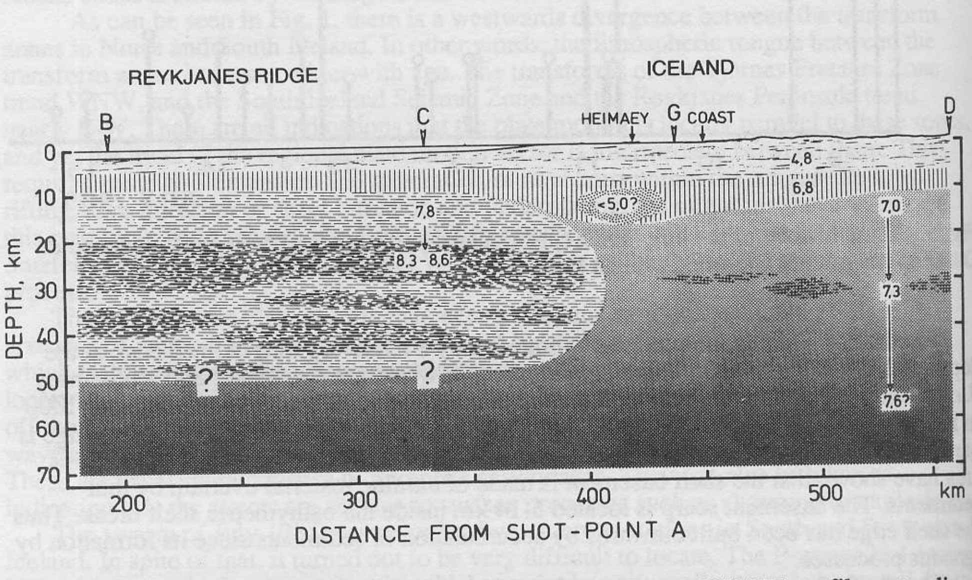

Fig. 6. Generalized crustal and upper mantle structure along a SW-NE profile, extending from the E-flank of the Reykjanes Ridge across the shelf and coast of Iceland. Shot points are indicated with letters, numbers give P-wave velocities in km/s. Crustal layers are continuous across the transition from the ocean to Iceland, whereas there is a drastic change in the upper mantle structure close to the shelf edge, where a well developed oceanic lithosphere beneath the ocean abuts on anomalous mantle in the state of partial fusion. From Angenheister et al. (1980).

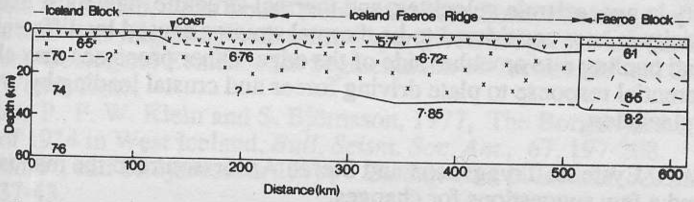

Fig. 7. Crustal and upper mantle structure along the NASP-profile crossing the coast and shelf of Eastern Iceland. This E-W profile shows the relationship of the structure of the Iceland-Faeroes Ridge to that of the adjacent Iceland and Faeroes blocks. From Bott and Gunnarsson (1980).

profile the oceanic lithosphere on the flank of the Reykjanes Ridge to the SW has velocities of 7.8-8.6 km/s in the depth range 10-50 km, whereas no such high velocities can be detected beneath Iceland (Angenheister et al., 1980, Gebrande et al., 1980). The transition from the oceanic structure to the Icelandic one is rather sharp (Fig. 6), and it occurs close to the shelf edge. The NASP profile off Eastern Iceland does not allow as detailed interpretation (Fig.7). The interpretation of Bott and Gunnarsson (1980) down to 35 km depth shows a great difference in structure between Iceland and the adjacent Iceland - Faeroes Ridge. The exact location of the transition is not shown, but it could occur near the shelf edge. A deep structural discontinuity would tend to concentrate stresses caused by external driving forces of various kinds. Intraplate stresses related to the driving forces of plate motions are , for example, likely to be concentrated around the weak spot in the lithosphere represented by the anomalous Icelandic mantle. The lithosphere on either side of the discontinuity has different strength and elastic properties, and responds differently to crustal loading or deloading. Processes such as sedimentation, denudation, glaciation and deglaciation are therefore likely to cause differential movements across the shelf edge.

In addition to the two main classes of intraplate earthquakes, a few events are found beneath the Vatnajökull ice sheet in SE-Iceland (Fig. 2). Some of these may be related to volcanic processes in subglacial central volcanoes that have so far not been recognized as being active. Two small swarms in 1976 and 1984 occurred in the Esjufjöll complex, and an event in 1983 originated near Breiðabunga. Both areas were suggested by Sæmundsson (1986) as potential active volcanoes, although neither one has had a confirmed eruption in historical times.

5. Conclusions

1. Two main classes of intraplate seismicity in Iceland are identified, i.e. earthquakes in the western part of the country, and earthquakes in the insular shelf area off the east coast.
2. The earthquakes in West Iceland occur in the tongue of lithosphere that is bounded by the rift zones in the east and the two transform zones in the north and south. A detailed study of the Borgarfjörður earthquakes of 1974 shows that this area is undergoing horizontal areal extension. The crust is possibly being extended by magmatic intrusions from the partially molten layer beneath the crust. This mechanism can explain the widespread geothermal activity in this part of Iceland and the westward divergence of the transform zones.
3. A majority of the eastern shelf earthquakes occur on the shelf edge, which is thus shown to be a seismogenic structure. The shelf edge is the expression of a deep litho-

spheric discontinuity in age, seismic velocities, and thermal structure. The most likely source of the seismicity is here considered to be thermal stresses caused by different thermal structure and cooling rate on either side of the edge. Other processes may also play a role, such as differential response to plate driving forces and crustal loading by sedimentation and glaciation.

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