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Recent Earthquakes in the Hengill-Hellisheidi Area in SW-Iceland

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Abstract. Epicenters of 106 earthquakes ($M_L \leqq 3.7$) have been located in the Hengill-Hellisheidi area during the first four years of operation of a short-period seismograph network in SW-Iceland. This area is part of the active zone of Iceland, and is located near the junction of three branches of this zone, the Reykjanes Peninsula, the Western Volcanic Zone and the South Iceland Seismic Zone, all of which have different tectonic characteristics. The epicenters delineate a NNE trending seismic zone that extends from the Hengill geothermal area about 30 km southwards along the eastern edge of the Hellisheidi highland. An additional, E–W trending seismic lineation is suggested by the distribution of epicenters in the lowland east of Hellisheidi at 63°57.5 N. The earthquake sequences in the Hengill-Hellisheidi area are of different types, ranging from mainshock-aftershock sequences to earthquake swarms. This variability probably reflects the complex tectonic position of the area.

Key words: Iceland – Hengill – Earthquakes – Tectonics.

Introduction

The mid-Atlantic plate boundary in SW-Iceland is expressed by a rather complex pattern of three tectonically active zones. The Reykjanes Peninsula is the direct landward continuation of the submarine Reykjanes Ridge, the Western Volcanic Zone is one of two parallel volcanic zones in the southern part of Iceland, and the South Iceland Seismic Zone is an E–W trending belt of destructive earthquakes that extends across the lowlands in South Iceland. The three active zones join in some kind of a triple point near 64° N and 21° W (Fig. 1). The seismicity near this junction is the subject of the present paper. After the installation of a short-period seismograph network in this part of Iceland in 1974 it was possible to study the seismicity in more detail than before. In the time interval August 1974 to November 1978, 106 locatable seismic events in this area were recorded. The epicentral distribution sheds some new light on the tectonics of the area in spite of the limited number of epicenters. More tectonic elements are expected to emerge when more data become available.

Tectonic Setting

The Reykjanes Peninsula is a zone of volcanism and high seismic activity. It has been interpreted as an obliquely spreading ridge or a transform fault with a component of opening (Tryggvason, 1968; Nakamura, 1970; Klein et al., 1973). The plate boundary as delineated by the seismically active zone has a trend of N70°E (Klein et al., 1973; 1977), and is therefore oblique to the assumed direction of relative plate motion in this region. The surface tectonics is characterized by swarms of normal faults, open and eruptive fissures arranged *en echelon* with respect to the seismic plate boundary. There is a gradual change in the mode of seismic energy release along the peninsula. Near the tip of the peninsula the earthquake sequences are mainly of the swarm type. Mainshock-aftershock sequences become more common towards the east (Tryggvason, 1973; Einarsson, 1979). The seismicity in the eastern part of the peninsula has been very low in the last 10 years. For this reason it has not been possible to trace the seismic plate boundary towards the junction with the Western Volcanic Zone and the South Iceland Seismic Zone.

The seismicity of the Western Volcanic Zone is low to moderate. The structure near the southern end of the zone is dominated by a swarm of fissures and normal faults with a NE strike. This swarm passes through the Hengill central volcano. The structural relationship is therefore somewhat similar to that of the presently active Krafla central volcano and the Krafla fault swarm in the volcanic zone of northern Iceland (Saemundsson, 1974, 1978;

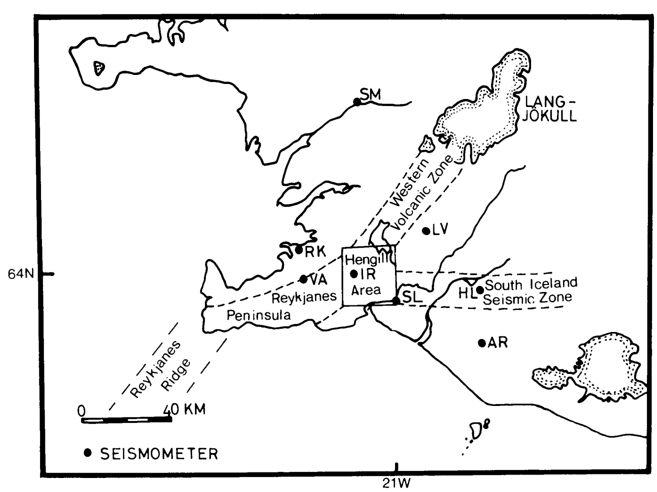

Fig. 1. Map showing the volcanic and seismic zones of southwest Iceland and the relationship of the Hengill area to these zones. The main ice caps are also shown (Jökull in Icelandic). *Rectangle* shows area of Fig. 2. *Black dots* show the main seismic stations

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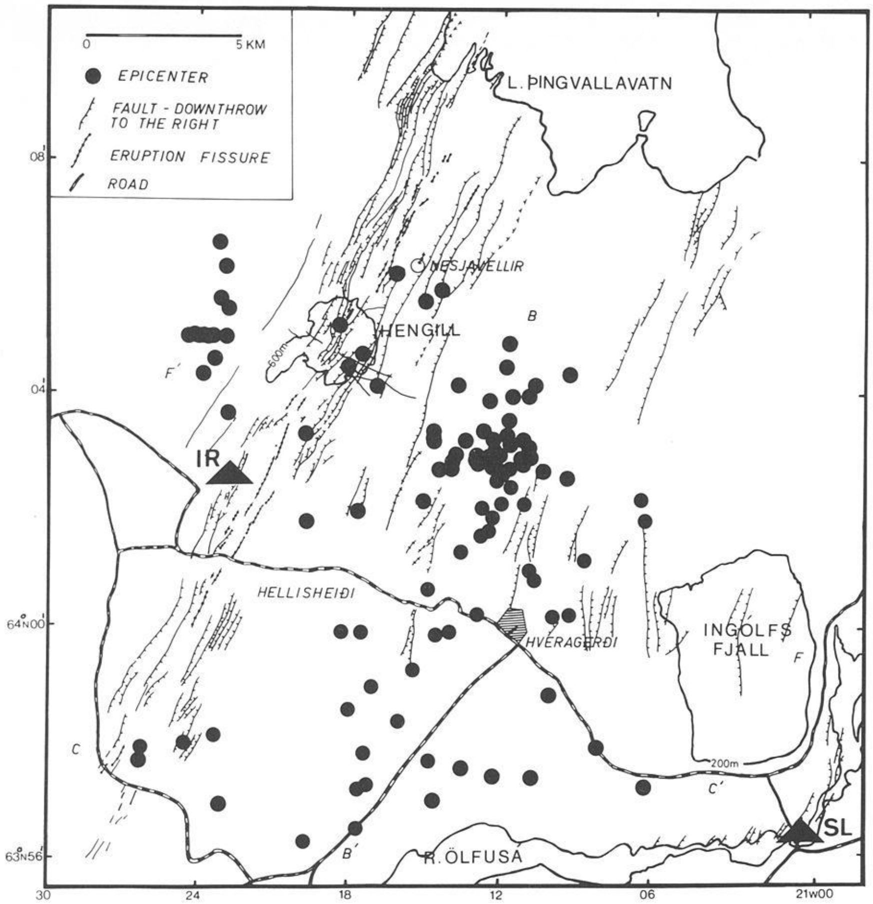

Fig. 2. Map showing the epicenters of 106 events that occurred between August 2, 1974 and November 19, 1978. Faults and fissures compiled from Saemundsson (1967), Eiríksson (1973), Árnason et al. (1969), Jónsson (1978). Seismic stations *IR* and *SL* are marked with *triangles*

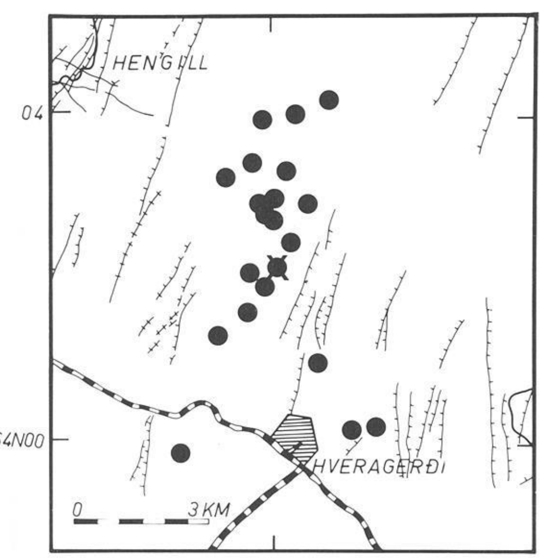

Fig. 3. Map showing the epicenters of 21 events occurring in sequence in February 1977. Symbols as in Fig. 2. Mainshock is marked with X

Björnsson et al., 1977). The geology of the Hengill area has been described in detail by Saemundsson (1967). The surface materials are mostly basaltic pillow lavas and hyaloclastites, erupted under ice. Both intermediate and acid rocks occur also. Several eruption fissures of post-glacial age exist. North of the central volcano the Hengill fault swarm has the structure of nested grabens. An inner graben of 4–5 km width is nested within an outer graben of 15–20 km width. Geological observations in this part of the graben, the Thingvellir graben, indicate that the inner graben has been subsiding at the average rate of 5–8 mm/a during the past 8,000 years. Precision levelling over a 5-year period revealed subsidence at a rate of only 2.5 mm/a (Tryggvason, 1974). The subsidence is hence probably episodic, with most of the movement occurring during short periods of high activity similar to the present activity of the Krafla area. In the volcanic zone of northern Iceland such rifting episodes occur at intervals of 100–150 years (Björnsson et al., 1977), and are intimately related to magmatic processes of central volcanoes. Similar events may have taken place in the Hengill area in the year 1789, when earthquake activity was accompanied by some 60 cm of subsidence in the Thingvellir graben (Thoroddsen, 1899).

The structure and mechanics of the South Iceland seismic zone is not well understood. Stefánsson (1967) described it as a zone of horizontal shear deformation and Ward et al. (1969) and Ward (1971) used the term fracture zone for this area. The epicenters of large, historic earthquakes are arranged within a fairly narrow, E-W trending zone near 64°N (Tryggvason, 1973; Björnsson, 1975), but there is no evidence for a major, E-W striking fault on the surface. Each earthquake appears to be associated with right-lateral movement on northerly striking faults, as evidenced by surface faulting (Tryggvason, 1973) and the shape of the destruction zones (Björnsson, 1975). Individual faults thus appear to be transverse to the epicentral belt of the large earthquakes.

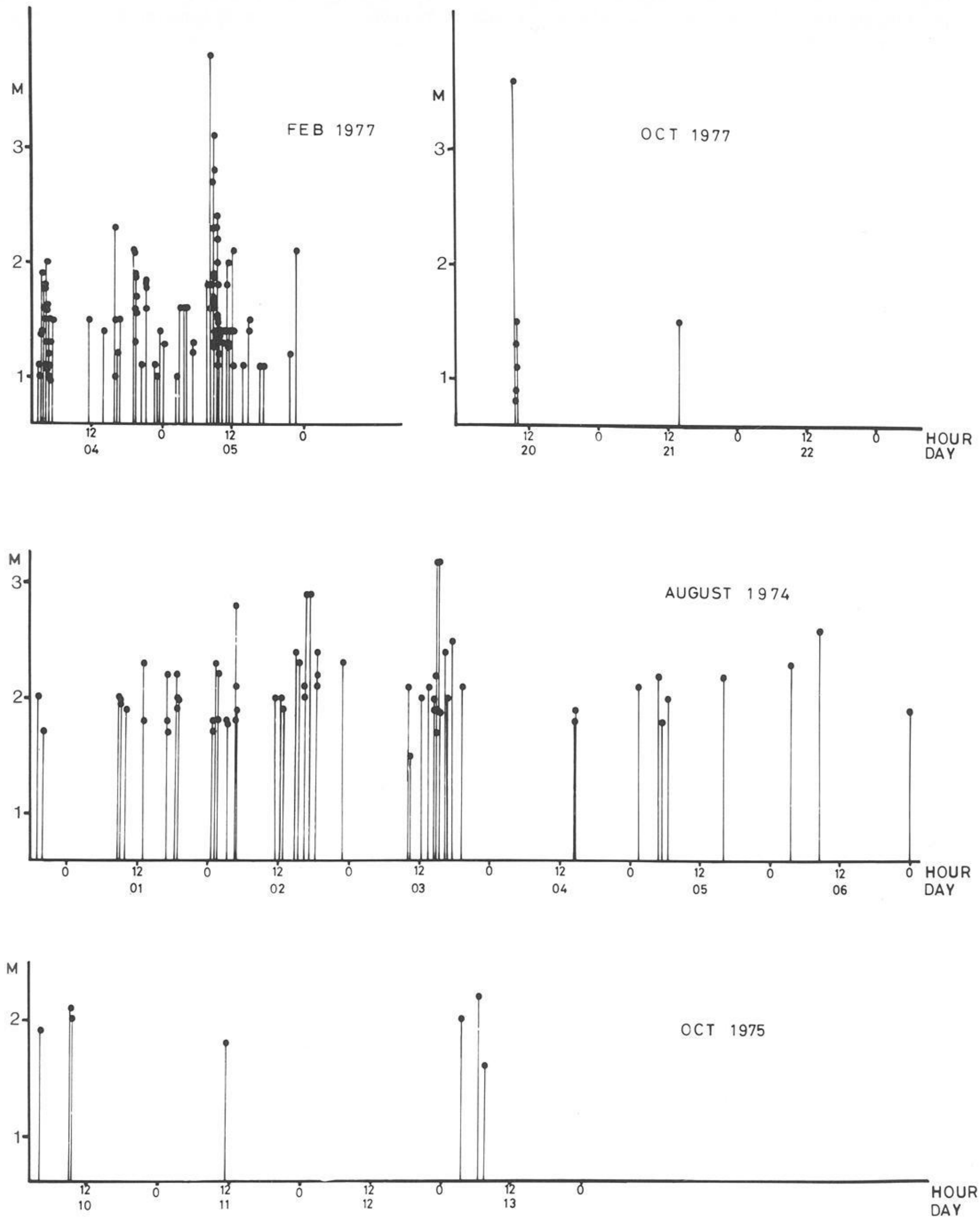

Fig. 4. Magnitudes of all events detected, plotted against time for the earthquake sequences of February 1977, October 1977, August 1974, and October 1975. The magnitude of each event was obtained using both the maximum trace amplitude and the time duration of the event on the seismograms at all calibrated stations which detected the event

Data Collection and Analysis

Seismological data were collected from a network of permanent, short-period seismographs in SW-Iceland (Fig. 1). For a large part of the time, 8 stations were in operation within 80 km of the Hengill-Hellisheidi area. Most of the records are in the form of revolving drum paper records inscribed with pen and ink. Radio time is recorded at all stations, eliminating the necessity for clock corrections. Time resolution is of the order of 0.1 s.

The hypocenters were located using the computer programs HYPO71 (Lee and Lahr, 1972), HYPOELLIPSE (Lahr and Ward, in preparation.) and HYPOINVERSE (Klein, 1978) by minimizing the root mean square of the difference between the calculated and observed travel times. The crustal velocity structure used is an average structure based on seismic refraction data from Pálmason (1971). The hypocentral locations are based mostly on P-wave arrival times, but S-waves were used whenever possible.

Earthquake magnitudes used in this paper are obtained by averaging time duration magnitudes at AR, SL, and VA, and maximum amplitude magnitudes at AR and RK. The duration magnitude scales were found by comparison with the maximum amplitude magnitudes at RK. The comparison was made in the magnitude range 1.8–3.7. The duration magnitude scale was then extrapolated to smaller magnitudes. This procedure is similar to that used by Klein et al. (1977) for earthquakes on the Reykjanes peninsula and was found to provide a reliable estimate of magnitude. The detection threshold for earthquakes in the Hengill-Hellisheidi area is near magnitude 1.0, and the set of locatable events is complete above magnitude 2.0.

Spatial Distribution of Seismic Events

All epicenters that could be located with horizontal standard error less than 2.5 km are plotted on the map of Fig. 2. The hypocentral depths appear to be smaller than 10 km, but the error of the depth determinations is large because of the lack of seismic stations in the immediate epicentral area of most of the earthquakes. No evidence has been found for seismic activity deeper than 10 km.

Many of the epicenters are located within a relatively small area about 5 km N of the town Hveragerdi. This cluster of epicenters is elongated in a SSW-NNE direction. This trend is even more pronounced if shorter time intervals are considered. The earthquake sequence of February 1977 (Fig. 3), for example, occurred within the cluster. The mainshock ($M_L=3.7$) was located near the cluster. The aftershocks then migrated to the NNE and SSW, suggesting bilateral rupture on a NNE striking fault. A total zone length of 8 km was activated during this sequence. The seismic zone defined by the cluster can be traced by the distribution of epicenters farther to the SSW This zone (BB' in Fig. 2) is 30 km long and extends along the eastern border of the Hellisheidi highland.

The alignment of epicenters in Fig. 3 is not an artifact of the location program. The horizontal standard error of the locations is smaller than 2.5 km but for most of the events the error is smaller than 1 km. The error ellipsoid for most of the solutions is nearly spherical.

One further seismic belt is suggested by epicenters in the lowland of the Ölfus district. This is an E-W trending zone at 63°57.5 N (CC' in Fig. 2). This zone is not as well defined as the first one, but its trend suggests that it may be related to the zone of large earthquakes in south Iceland.

The cluster of epicenters west of Hengill belongs to one earthquake swarm that occurred in August 1974 (Fig. 4). This isolated cluster demonstrates how variable the seismicity is, both in space and time. A recording time of 3–4 years is not long enough to reveal all the seismically active elements, even where the activity is high such as in the Hengill-Hellisheidi area. It is noticeable, for example that very few earthquakes occurred in the central part of the Hengill fault swarm, which is the most heavily faulted part of the area.

Time Distribution of Seismic Events

The seismic energy release in the Hengill-Hellisheidi area occurs both in single events and in sequences of events that are related in space and time. Time-magnitude plots of all the largest distinct sequences appear in Fig. 4. It is immediately clear that great variation is displayed in the form of these sequences. Mogi (1963) considers the variation of earthquake sequences in relation to three sequence types, i.e., the mainshock-aftershock (Type 1), foreshock-mainshock-aftershock (Type 2) and the swarm type (Type 3). Complete gradation between all types is found in nature. The form of any sequence is considered to be dependent upon, amongst other things, the tectonic, magmatic and hydrothermal state of the crust (Sykes, 1970). A summary of some suggested associations is given in Table 1 These associations are not exclusive, however, and exceptions are known. Thus, for example, earthquake swarms are known in transform fault zones (Tatham and Savino, 1974; Einarsson, 1976) and normal faulting may occur in a mainshock-aftershock sequence as in the case of the mainshock of the Borgarfjördur earthquakes in West Iceland in 1974 (Einarsson et al., 1977).

Table 1. Physical associations of earthquake sequences

Swarm sequences	Mainshock-aftershock sequences
Inhomogeneity of crust	Homogeneity of crust
Inhomogeneity of stress	Homogeneity of stress
High fluid pressure	Low fluid pressure
Normal faulting	Strike-slip faulting
Short, shallow faults	Long, deep faults
Spreading ridge crest	Transform faults
Areas of recent volcanism	Tectonic earthquakes
Geothermal areas	

Illustrated in Fig. 4 are both typical swarm sequences and mainshock-aftershock sequences. The swarms of August 1974 and October 1975 occurred to the west of Hengill and SW of Hveragerdi respectively. The sequence of February 1977 occurred mostly to the N and W of Hveragerdi and is a foreshock-mainshock-aftershock sequence. The mainshock-aftershock sequence of October 1977 occurred immediately W of Hveragerdi. Thus all three types of sequences occur on the NNE trending epicentral belt (BB') in close proximity to each other. In addition to these larger sequences a continuous background of single events and short sequences is distributed over most of the active area. The wide variety of sequence types may be taken as evidence for large variations in the state of the crust in the Hengill-Hellisheidi area. When more data accumulate it may be possible to use the sequence types as an indicator of the variations in the hydrothermal and tectonic state of the crust on a fine scale.

Discussion

Ward and Björnsson (1971) analyzed seismic data from a small tripartite array, that they operated near Hveragerdi for 11 weeks in 1968. Their epicentral map is in some ways similar to the map presented in this paper. Their map is dominated by the cluster N of Hveragerdi, probably because of the proximity of the array, but the linear trends of epicenters are not clear except that the E-W trend is indicated in the Ölfus lowland. The difference between the results is most likely caused by our longer recording time and the use of a larger seismograph network that encompasses the whole study area. This way the detection capability of the network is more uniform over the area, and the background microearthquake activity that is often found to be associated with high temperature geothermal areas (Ward and Björnsson, 1971) is not as dominating on the epicentral map.

The fault pattern shown in Fig. 2 changes systematically from W to E. In the west the pattern is dominated by the Hengill fault swarm that has a NE-SW trend, but in the southeast part of the area the strike of the faults gradually becomes more northerly. Björnsson et al. (1974) suggested that the faults east of Hengill belonged to the fault swarm of another and older central volcanic complex. It is also possible that the change in strike represents the change in the stress field from the primarily extensional tectonic regime of the Western Volcanic Zone in the west to the strike-slip tectonics of the South Iceland Seismic Zone in the east. This question may be resolved with a focal mechanism study of the earthquakes, which has not yet been possible because of the poor depth resolution of the hypocentral locations obtained so far.

The hydrothermal circulation of the Hengill geothermal area is likely to be affected by the tectonics. The crust in the seismic belts probably has higher permeability and may thus allow water to percolate more freely than the surrounding crust. The concentrations of chlorine, tritium and deuterium in the thermal water indicate that the Hengill area is fed by two deep groundwater systems (Árnason et al., 1969; Árnason, 1976). The water from drill holes near Nesjavellir (Fig. 2) is believed to originate near the Langjökull glacier and this system may extend southerly along the entire length of the Hengill fault swarm. Around Hveragerdi, on the other hand, the deep water has a different deuterium content and may originate about 35 km to the NE. It is noteworthy that the NNE trending epicentral belt separates the Heragerdi system from the other systems. Perhaps the epicentral belt provides a flow channel for one of the deep circulation systems, and then most likely the Hveragerdi system.

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