# Seismic Activity Recorded In Surtsey During The Summer Of 1966

By

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## ABSTRACT

A tripartite array of short period seismometers was operated in Surtsey from June 1 to September 25, 1966 with a few interruptions. Most of the recorded seismicity appeared to be associated with the decrease and cessation of volcanic activity in Jólnir and subsequent beginning of the lava eruption in Surtsey. The earthquakes occurred mostly in swarms, each swarm emanating from relatively small source volume. The hypocenters that could be located were at depths of 0 to 5 km and seemed to follow the tectonic trend defined by the Jólnir-Surtsey-Syrtlingur-Surtla row of volcanic centers. A swarm of small, shallow earthquakes was recorded shortly before the beginning of the lava eruption in Surtsey on August 19. The lava eruption was accompanied by continuous volcanic tremor with predominant frequency of 3 Hz.

## INTRODUCTION

During the summer of 1966 an arry of short-period seismometers was operated in Surtsey. The purpose was to obtain a continuous record of the volcanic activity and to get information about the origin of the seismic activity.

Seismic activity near a volcano can be generated in a number of ways, for example:

1. Release of preexisting tectonic stress in the region.
2. Release of stress set up by intrusion of volcanic material under the volcano.
3. Release of stress generated by the additional loading of the crust and settling of the volcanic pile.
4. Movement of magma underground and in the crater.
5. Explosions in the crater.

This paper is a preliminary report on the analysis of seismological data obtained during the summer of 1966. The analysis of similar data recorded in 1967 and other seismological data obtained during the Surtsey eruption will be the subject of later papers.

When the seismic recording began in Surtsey on June 1, 1966 the crater of Jólnir was erupting, building up a small island off the south-western coast of Surtsey. Towards the end of July the intensity of this eruption diminished and after August 10 no activity was seen in Jólnir. There was a period of nine days with no visible volcanic activity in the Surtsey region. On August 19 a lava eruption began on a fissure in Surtsey itself. Similar shifts in the activity were observed at least six times during the entire Surtsey eruption.

This shift in the volcanic activity during the seismic recording in Surtsey offers an excellent opportunity to study the relationship between the volcanic activity and the seismicity. Indeed, it appears that most of the seismic activity during the summer of 1966 was in some way associated with this change in the volcanic activity.

## INSTRUMENTATION AND DATA ANALYSIS

The seismic array in Surtsey consisted of one central station in the northern part of the island where three components of motion were detected, one station in the southern part and one station in the western part of Surtsey where only one component of motion was detected. The seismometer signals were brought by cable to the

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research hut where they were amplified and recorded on magnetic tape. The recorder was a seven channel FM magnetic tape recorder. The recording speed was 15/160 i.p.s. and the center frequency 84.4 Hz, which allows 10 days of recording on one reel of tape. One track on the tape was used for continuous recording of a radio time signal as well as a chronometer time signal. The array was in operation from June 1 to September 25 with a few interruptions.

To demonstrate the experimental difficulties with seismic recordings in a harsh environment, a few entries in the log book of the seismometer will be cited: "The cable to geophone 1 had broken in a storm and was reconnected. The geophone was also moved a little because it had been buried by blowing sand and heated so that the mass sagged". "Cable on the east coast broken by an avalanche". "The lava flowed over the cable to geophone 6 and the geophone was removed about 14h".

The seismic records of interest were reproduced on paper with a time resolution of 25 mm/sec. When sufficient data were available the earthquake hypocenters were calculated using the relative arrival times of the P- and S-waves at the three stations. The method of analysis is described by Einarsson and Björnsson (paper in preparation) and Ward and Gregersen (1973), and will not be repeated here. The precision of the hypocentral locations is considered to be better than ± 1 km in horizontal dimension and ± 1.5 km in dept. It is encouraging to note that most of the locations of earthquakes within individual earthquake swarms cluster within volumes smaller than the error estimates of a single location.

Since only three seismic stations were in operation, only a minimum amount of data is available for the location of an earthquake. This lack of redundancy means that a misinterpretation of the data is not detectable and will result in a mislocated earthquake.

In locating the earthquakes it is assumed that the crust under Surtsey is made up of horizontal layers. Any deviation from this structure will cause systematic errors in the locations. It is desireable to set off explosions around a seismic array in order to detect any systematic errors. No such tests are available from Surtsey. It is therefore not possible to estimate to what extent the precision of the locations represents the true accuracy. This limitation should be born in mind when reading this paper.

## SEISMICITY

The seismic activity as recorded by the seismic array on Surtsey is summarized in Figure 1. From this figure it is obvious that the earthquakes do not occur randomly in time, but are concentrated into bursts of activity. Most of these bursts are earthquake swarms, i.e., a sequence of earthquakes occurring close together both in time and space and without an outstanding main shock. The most intense activity of the swarms usually lasted less than one hour.

The seismic activity in June and July was generally low. During this time the crater of Jólnir, SW of Surtsey, was erupting. Towards the end of July the eruption in Jólnir became intermittend and at the same time the seismic activity increased (Fig. 1), culminating on August 9 and 10 when the volcanic activity in Jólnir ceased. The bulk of the seismicity is thus seen to be associated with changes in the eruption, i.e., the decrease and cessation of activity in Jólnir. Unfortunately no records are available for the period August 11-18, but prior to the outbreak of the lava eruption in Surtsey on August 19 an earthquake swarm was recorded. After the beginning of that eruption the high tremor level in Surtsey prevented any further detection of earthquakes.

Because of uncertainty in the polarity of the seismic detectors no systematic study could be made of the first motion of P-waves. It can be said, however, that not all earthquakes had the same first motion on the same station. Therefore it can be concluded that if the source of the earthquakes is monopolar it is not always in the same sense, i.e., sometimes it is dilatational and other times it is compressional. Most likely the source is nonmonopolar, probably the result of a shear dislocation.

Hypocentral location could be determined for 76 earthquakes occurring in the time interval July 27 to August 18. The earthquakes originated east, south and west of Surtsey as well as under the island itself at the depths of 0-5 km (Fig. 2, 3, and 4). The events of individual earthquake swarms were tightly clustered in space as well as in time. The source areas of the different swarms are shown in Figures 2, 3, and 4.

The epicenters define an ellipse shaped zone with the major axis trending ENE. This trend is even more pronounced if earthquakes during shorter time intervals are considered, e.g. the time intervals July 31-August 2 (Fig. 2), August 8-18 (Fig. 4). The trend of the epicentral zone coincides with the trend of the row of volcanic

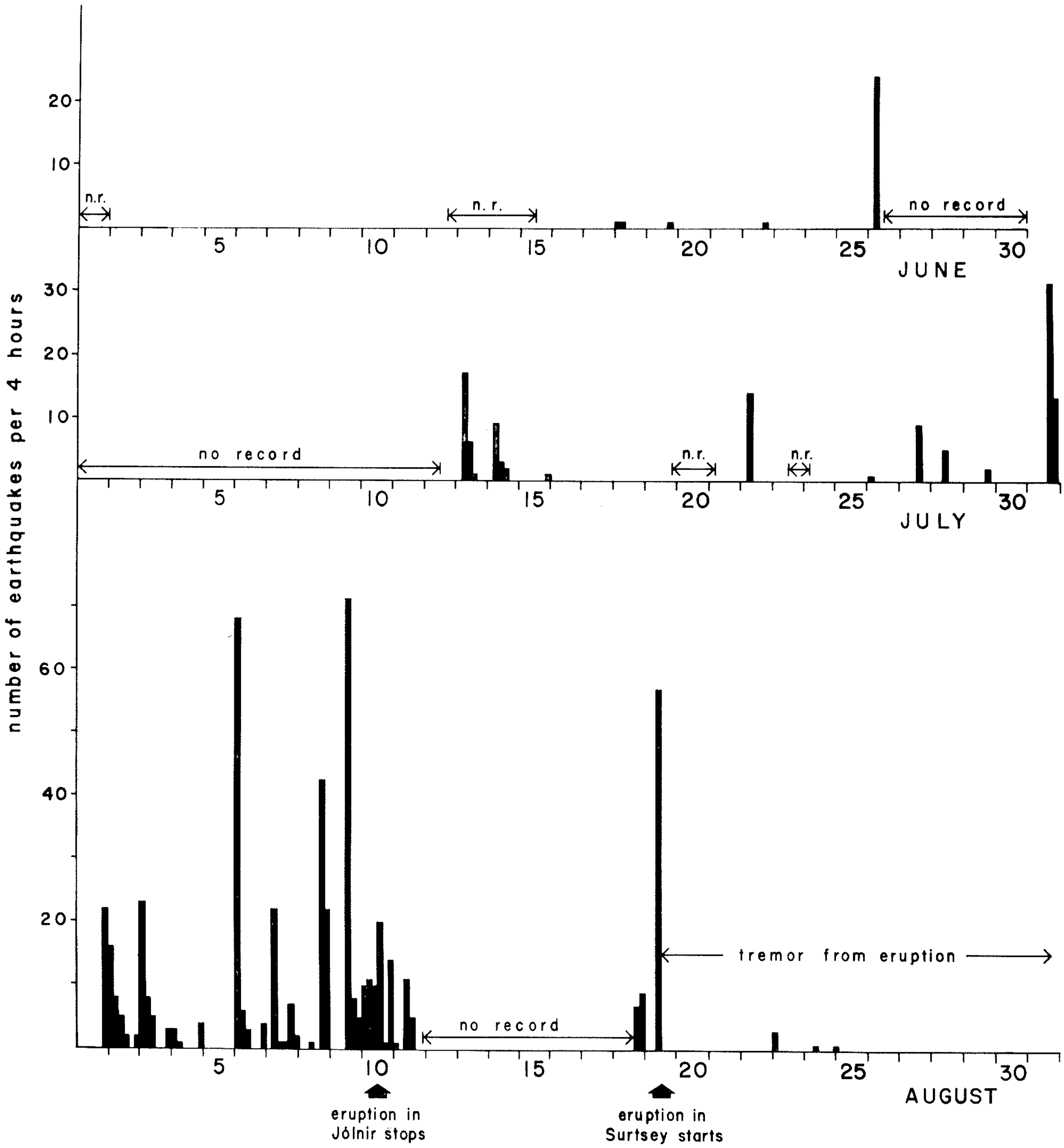


Fig. 1. Earthquake rates for June, July and August 1966 as recorded by the seismometers in Surtsey. Each bar represents counts for four hours. An earthquake was counted if it was recorded by two or more stations. After August 19 only very few earthquakes could be recognized on the records because of the intense volcanic tremors accompanying the lava eruption that started on August 19 in Surtsey itself.

vents Jólnir-Surtsey-Syrtlingur-Surtla. Individual eruptive fissures within this row, however, have a more northerly trend, as was pointed out by Thórarinsson (1966) and Jakobsson (1968). The eruptive fissure active in November 1966 had a trend of N 35° E (Thórarinsson, 1965), the Jólnir fissure had a trend of N 25° E (Thórarinsson, 1967) and the fissure that opened on August 19, 1966 in Surtsey had a trend of N 10°E (Thórarinsson, 1967). This en echelon arrangement of the eruptive fissures suggests a component of left-lateral strike-slip motion along an elongated zone with an ENE trend. It should be noted, however, that the motion does not need to be of a pure strike-slip nature. A component of opening perpendicular to the zone may also be present. In the case of the Reykjanes Peninsula oblique spreading motion was demonstrated along an ENE trending zone (Klein et al. 1973). Volcanic fissures are arranged en echelon with

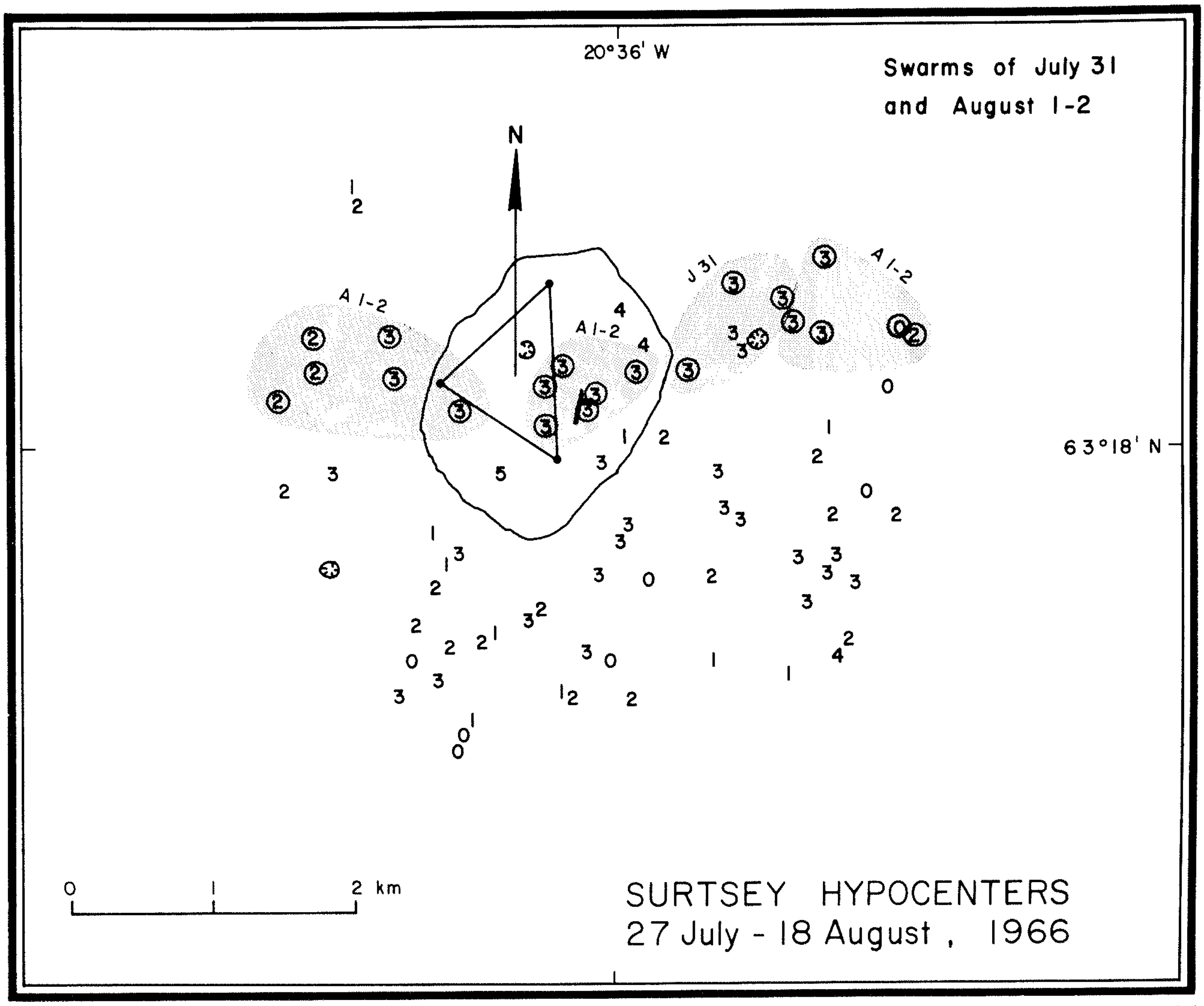


Fig. 2. Epicenters of all earthquakes between July 27 and August 18 large enough to be located are shown in Figures 2, 3, and 4. An epicenter is marked with a number that gives the depth of the hypocenter to the nearest km. A shaded area groups together all events belonging to the same swarm of earthquakes. The events belonging to the swarm are marked with a circle or a square. The date of the particular swarm is indicated near the edge of the shaded area. The craters of Syrtlingur, Surtur II and Jólnir as well as the eruptive fissure of August 19, 1966 are shown for reference. The outlines of Surtsey are those of August 1966. The seismometers were at the corner points of the triangle.

respect to the volcanic zone and the seismic belt on the Reykjanes Peninsula. Focal mechanism solutions for earthquakes in that seismic belt show that the minimum compressive stress is consistently horizontal and has a NW trend, perpendicular to the tensional structures on the surface. By analogy we infer that the minimum compressive stress in the Surtsey region is horizontal and has a WNW trend.

*Course of Events*

June 26: A swarm of earthquakes clustered under the south and south-west coast of Surtsey, depth about 3 km.

July 13: A swarm of very small earthquakes recorded.

July 14: An earthquake recorded with a few fore- and aftershocks.

July 27: A swarm of earthquakes, one of which was located under Surtsey at 4 km depth.

July 28: An earthquake recorded with a few fore -and aftershocks. One aftershock was located 2 km SE of Surtsey at 4 km depth.

July 29: Two small earthquakes, one was located under Surtsey at 5 km depth.

July 30: "No eruption in Jólnir 05:45-06:05 GMT" (seismometer log book).

July 31: A swarm of earthquakes located under Syrtlingur at 3 km depth (Fig. 2).

August 1: A swarm of earthquakes begins, located mostly under Surtsey at 3 km depth. Earthquakes felt in Surtsey. "The eruption in Jólnir

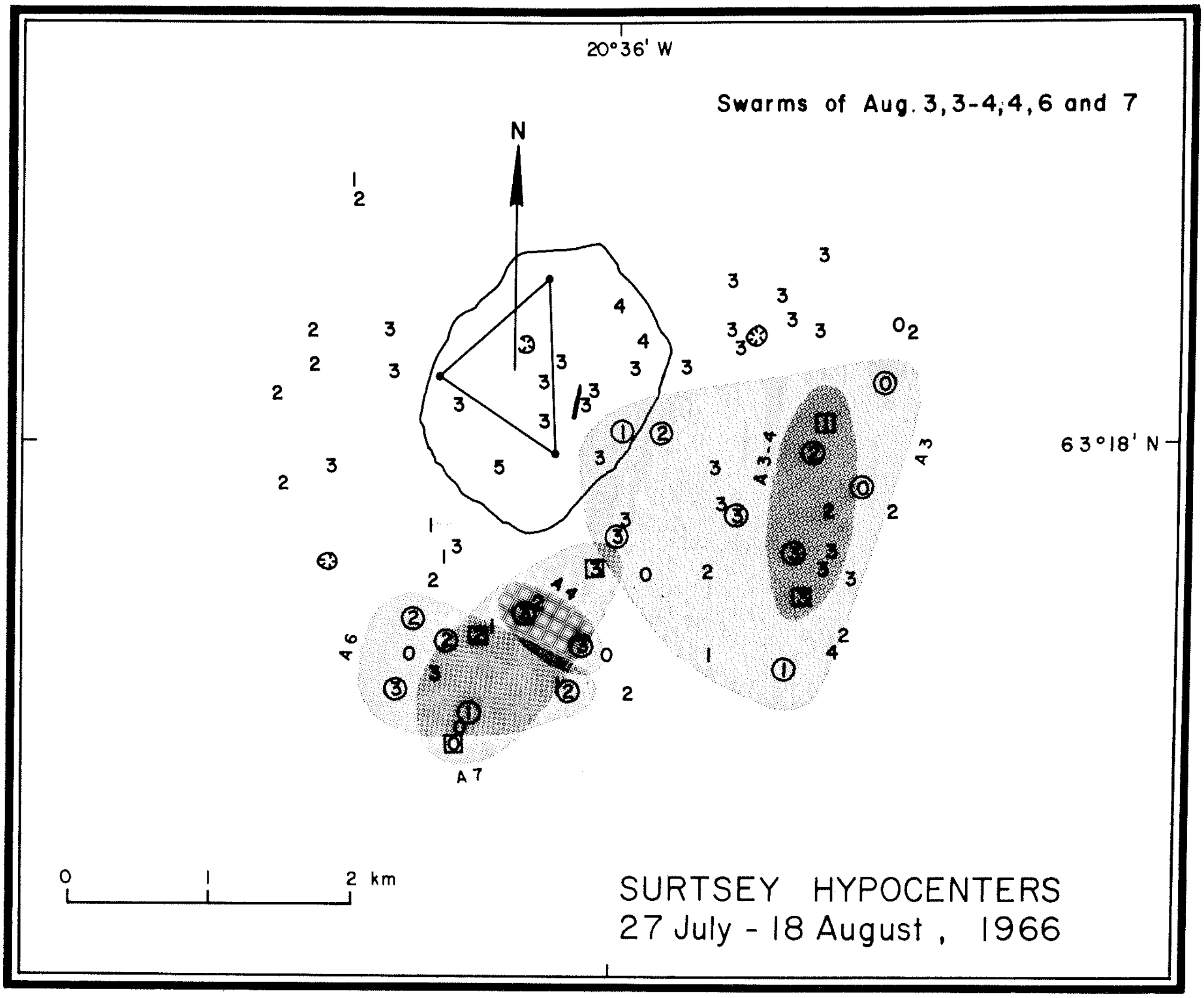


Fig. 3. Earthquake swarms of August 3-7. Symbols as in Figure 2.

very small with long intermissions between 13:15 and 14:00 GMT" (seismometer log book).

August 2: The earthquake swarm continues. The activity appears to migrate east of Syrtlingur, later also towards the west. Together with the swarm of July 31 this activity defines a narrow zone, trending nearly E-W (Fig. 2).

August 3-7: Several earthquake swarms and isolated events located east and south of Surtsey at the depth of 0-3 km (Fig. 3). One earthquake on August 4, located about 2 km south of Surtsey at the depth of 3 km, was followed by a burst of volcanic tremors lasting for about 7 minutes. The predominant frequency of these tremors was about 3 Hz.

August 8: A relatively large swarm of earthquakes located south of Surtsey at the depth of 0-3 km, mostly around 1 km depth (Fig. 4).

August 9: An earthquake swarm started at 15:00 GMT, the most intense activity lasted about one hour and was located under the east coast of Surtsey at 3-4 km depth. Seismic activity continued at a fairly constant level until about 16h on August 10. This activity was mostly located in two groups, one under Syrtlingur at 3 km depth, the other about 2 km SE of Surtsey at the depth of 3 km (Fig. 4).

August 10: Eruptive activity last seen in Jólnir. A small earthquake swarm, one event located near Jólnir.

August 11: A small earthquake swarm, located near Jólnir (Fig. 4).

August 11-18: Seismic array not in operation.

August 18: Some seismic activity, two events were located SSE of Surtsey, 0-2 km deep (Fig. 4).

August 19: Between 00h and 09:30 no earthquakes recorded. A swarm of small earthquakes started at 09:30, the last earthquake occurred 10:29 (Fig. 5). No earthquake could be located, but the swarm is probably shallow and near the northernmost and the southernmost stations. This conclusion is based on the observation that

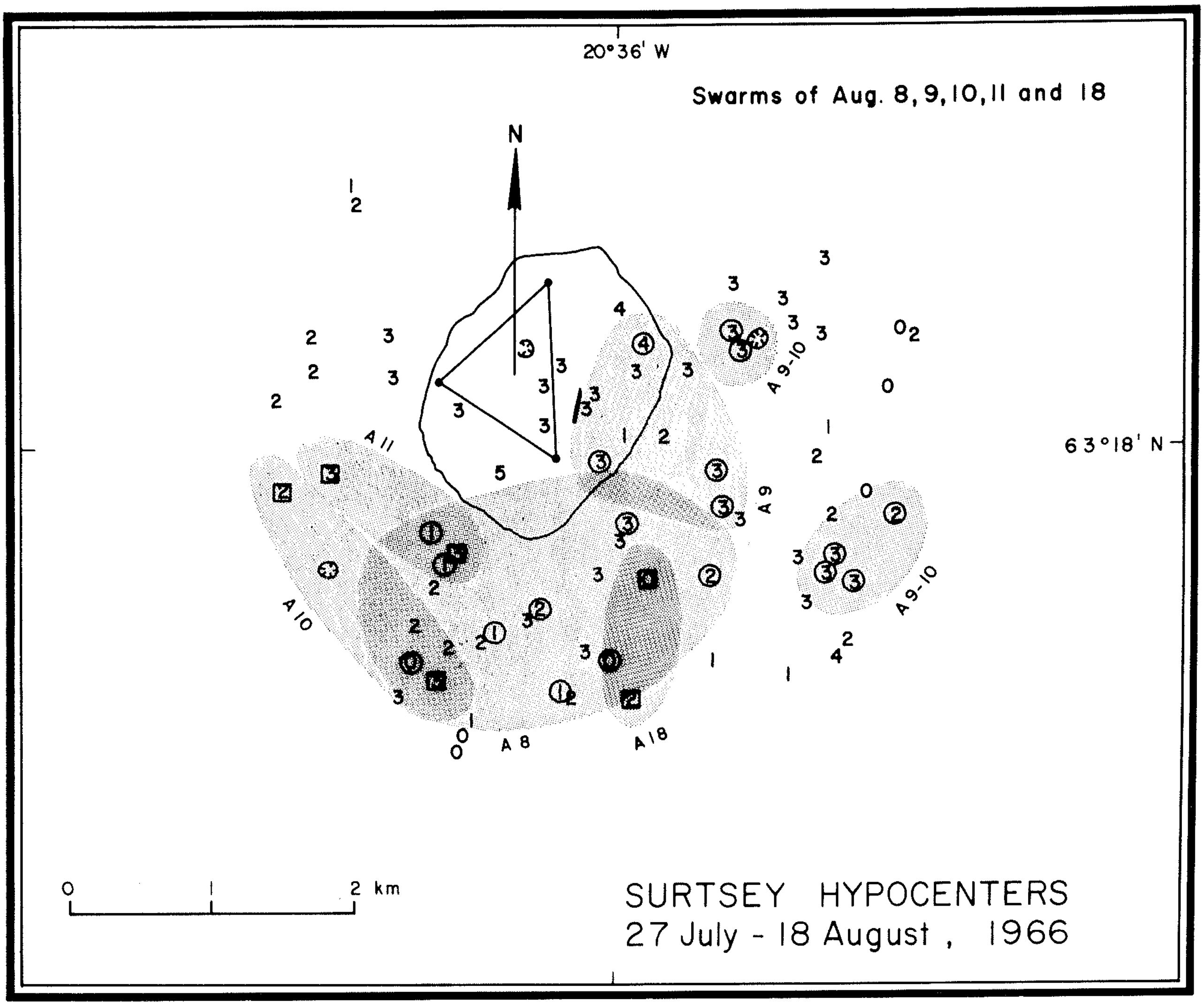


Fig. 4. Earthquake swarms of August 8-11 and August 18. Symbols as in Figure 2.

some of the earthquakes appear on the southern station only, while some earthquakes appear on the northern station only (Fig. 5). After 10:30 GMT volcanic tremors became visible on the seismic records, their amplitude increasing threefold in the next twenty minutes. The predominant frequency of these tremors was about 3 Hz. At 10:50 GMT the tremor amplitude increased suddenly (Fig. 5). After that time very few earthquakes could be identified on the records because of the high level of tremors. The continuous tremors were frequently felt in Surtsey.

The new lava eruption in Surtsey was first seen about 13h and by then lava had already spread 150-200 m from the fissure. It is natural to conclude that the lava eruption started about 10:50 GMT when the amplitude of the tremors increased suddenly. Note that the lava eruption was previously assumed to have started at 07h (Thórarinsson, 1967) which is inconsistent with the seismic records.

## CONCLUSIONS AND DISCUSSION

The conclusions of this data analysis can be summarized as follows:

1. The bulk of the seismic activity near Surtsey in the summer of 1966 was associated with the changes in the volcanic eruption when the activity in Jólnir diminished and ceased and the lava eruption in Surtsey started.
2. The earthquakes occurred mostly in swarms, tightly clustered in space and time.
3. The earthquakes appear to have a shear dislocation source.
4. The earthquakes that could be located were of shallow origin, between 0 and 5 km deep.
5. The epicenters appear to follow the tectonic trend defined by the Jólnir-Surtsey-Syrtlingur-Surtla row of eruptive centers.

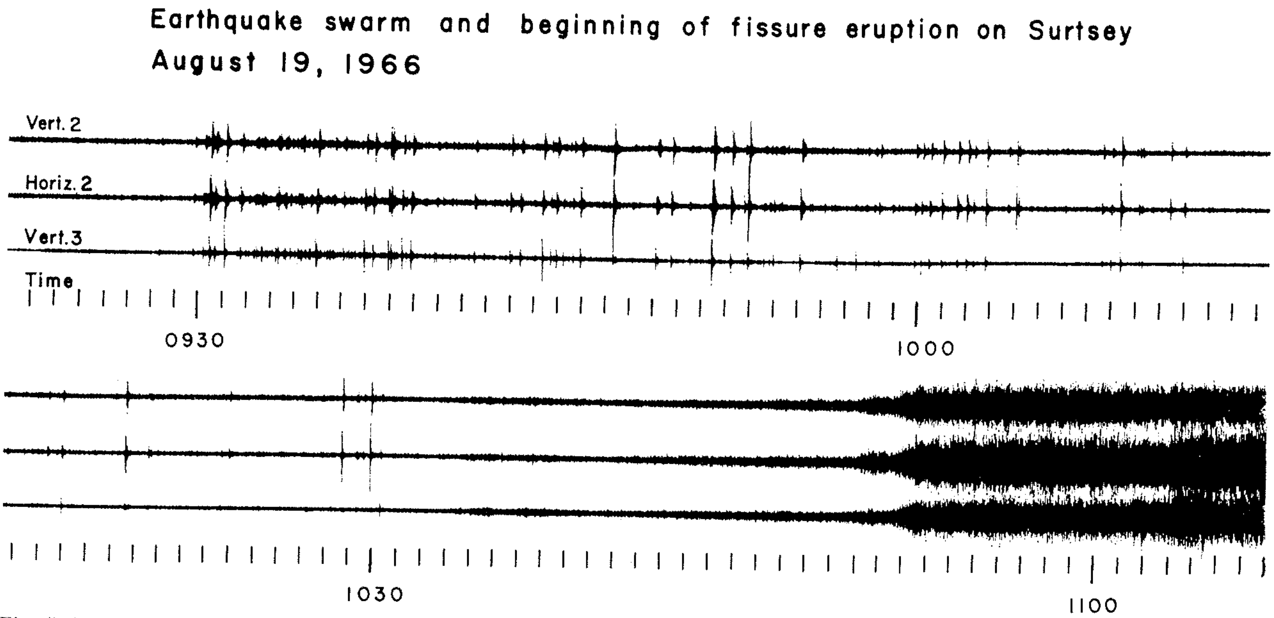

Fig. 5. The seismograms of August 19, 1966 showing the seismic activity associated with the beginning of a lava eruption on Surtsey. Shown are the seismograms of the vertical and one horizontal component of the northernmost seismic station and a vertical component of the southernmost station which was situated about 400 m from the fissure where the eruption broke out. The time is GMT.

A similar correlation between the increase in seismicity and changes in the eruption was found to hold during the Hekla eruption in 1970 (Einarsson and Björnsson, paper in preparation). This observation may be of some value when trying to predict the behavior of an eruption already in progress. An increase in seismicity implies higher probability for a change in the behavior of the eruption. The type of change, of course, cannot be determined with this empirical relationship.

The physical significance of the observation that most of the earthquakes occur in swarms as opposed to foreshock-mainshock-aftershock sequences is not clear. Earthquake swarms are frequently associated with volcanic regions (see e.g. Sykes, 1970) and are possibly related to the heterogeneity of the material or stress concentrations. The observation that the hypocentral domain is a volume rather than a plane (fault) may also be significant in this relation.

The depth of the Surtsey earthquakes is comparable to the depth of earthquakes on the Reykjanes Peninsula (Klein et al. 1973), which tend to occur in swarms but are clearly of tectonic origin. Earthquakes recorded during the Heimaey eruption 1973, however, occurred at depths of 20-30 km (Björnsson and Einarsson, paper in preparation), but appeared to be related to the rate of extrusion of lava at the surface. Such deep earthquakes produce complex seismograms at the surface above, which are difficult to interprete with limited amount of data available. Therefore, if small deep earthquakes occurred during the Surtsey eruption, they would have been missed in the data analysis.

It appears likely that the Surtsey earthquakes were of tectonic origin and occurred in response to some stress change. The earthquakes were related in space to the tectonic structure and in time to the changes in the eruption at the surface. At least two hypotheses can account for these relationships:

1. The earthquakes were caused by the regional stress being concentrated around the magma conduit. The tectonic displacements associated with the earthquakes blocked the Jólnir crater and the magma found another escape route to the surface.

2. The earthquakes were caused by a stress field produced by a decrease of the pressure in the magma conduit, resulting in a partial collapse. When the pressure increased again the easiest escape was no longer through the Jólnir crater.

The first hypothesis assumes that the pressure of the magma remains constant whereas in the second hypothesis the pressure fluctuates. The observation that the intensity of the Jólnir eruption diminished considerably before the seismicity increased would favor the second hypothesis.

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