JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 93, NO. B11, PAGES 13,493-13,506, NOVEMBER 10, 1988

HENGILL TRIPLE JUNCTION, SW ICELAND
1. TECTONIC STRUCTURE AND THE SPATIAL AND TEMPORAL DISTRIBUTION OF LOCAL EARTHQUAKES

G. R. Foulger

Department of Geological Sciences, University of Durham, Science Laboratories, United Kingdom

Abstract. The Hengill area is an unstable ridge-ridge-transform triple junction in SW Iceland. It contains the active central volcano Hengill, associated with the present accretionary zone, and the extinct Grensdalur central volcano, associated with an accretionary zone that became inactive at about -0.7 m.y. when the locus of spreading migrated about 5 km W to the Hengill zone. The dominant tectonic trend of the area is N25°E, parallel to the accretionary zones, but transverse tectonic/topographic features have also developed in the neighborhood of the two central volcanoes. These result from local modification of the regional stress field associated with the spreading by radially symmetric stress fields associated with the volcanoes, and the migration of volcanism. A double-high temperature geothermal system mirrors the double volcanic system. The transform branch of the triple junction is represented by an EW striking zone of historic destructive earthquakes in the S of the area. A seismological study was conducted with the aims of studying the tectonic structure and evaluating the passive seismic method as a geothermal prospecting tool. The seismicity may be broadly divided into two groups. First, infrequent intense episodes of crustal movement occur that are associated with the release of tectonic stress along the plate boundary. Second, continuous small-magnitude activity occurs on a day to day basis. This activity is mostly associated with the extinct Grensdalur central volcano, not the present plate boundary. Statistically significant temporal variations in b accompanied a swarm in the transform zone. The continuous small-magnitude activity may be geothermal in origin, releasing thermal stress, and not associated with plate boundary tectonics.

1. Introduction

The Hengill ridge-ridge-transform triple junction is a highly complex portion of the plate boundary in Iceland, containing both high-temperature (>200°C in the upper 1000 m) and low-temperature (<150°C in the upper 1000 m) geothermal resources. It provided an ideal laboratory for a passive seismic study, since it displays the highest level of continuous earthquake activity of any area in Iceland, and also there is considerable interest in commercial exploitation. The aims of the Hengill seismological study were (1) to research the tectonic structure and the geothermal prospect using earthquake data augmented by explosions, and (2) to evaluate the utility of earthquake studies as a geothermal prospecting tool.

In recent years a number of passive seismic studies of geothermal areas have been reported [Foulger, 1982]. Activities have included the search for the "geothermal earthquake" [e.g., Peppin and Bufe, 1978] and the interpretation of the three-dimensional spatial pattern of activity in terms of reservoir properties [e.g., Eberhart-Phillips and Oppenheimer, 1984]. Much work has, however, been of the "pilot project" type, involving small numbers of stations deployed for short periods in unoptimized geometries. The Hengill study aimed at assessing the true utility of the method, by conducting a purpose-designed project.

During the period 1979-1980, all available earthquake data from the area were processed, and a number of temporary instruments were deployed from time to time. These studies revealed a remarkable stability in the spatial and temporal pattern of the continuous earthquake activity [Foulger and Einarsson, 1980], from which it was concluded that a seismometer network could be deployed in the area with very good prior knowledge of where and at what rate earthquakes would occur.

In 1981, a 23-station seismometer network was installed for 3 months; 2000 local earthquakes were located. The gross spatial and temporal distribution of the continuous activity was very similar to that which had been predicted, and this paper describes in detail those aspects of the data set. In addition a large number of well-constrained focal mechanism solutions were obtained, many of which were non-double couple in type. These data provided valuable information about processes within the high-temperature geothermal reservoir and have important implications for fracture mechanics at accretionary plate boundaries in general. That material is presented in a companion paper [Foulger, this issue].

2. Tectonics

Evolution of the Plate Boundary in Iceland

Iceland is the product of excessive volcanic activity associated with the large, ridge-centered Icelandic hotspot. This hotspot is migrating eastward with respect to the ridge at an average rate of approximately 1.6 cm yr^{-1} [Vogt, 1983] and has had a profound effect on the evolution, stability, and morphology of the accretionary plate boundary in Iceland.

The present position of the plate boundary in Iceland is indicated by the neovolcanic zones

Paper number 88JB03242.
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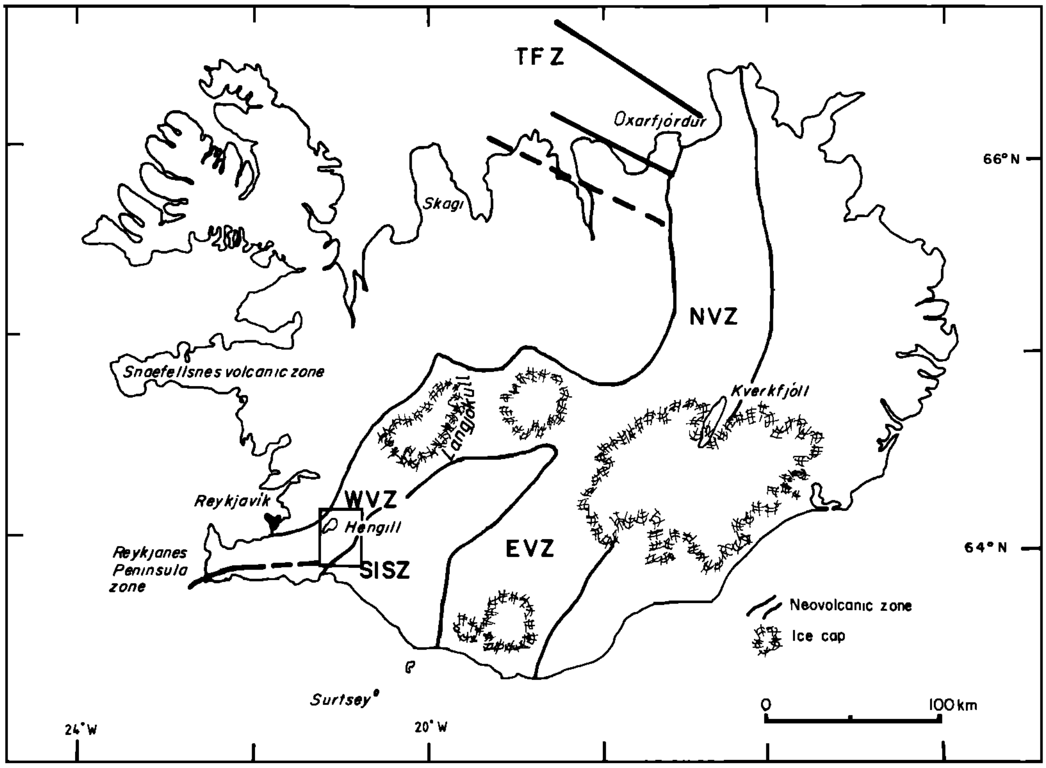

Fig. 1. Tectonic map of Iceland illustrating the neovolcanic zones where crustal accretion is taking place, and the transform zones. NVZ, Northern Volcanic Zone; EVZ, Eastern Volcanic Zone; WVZ, Western Volcanic Zone; TFZ, Tjornes Fracture Zone; SISZ, South Iceland Seismic Zone. The Hengill area is shown as a box.

(Figure 1), where postglacial eruptives occur [Saemundsson, 1978, 1979]. These zones typically exhibit en echelon fissure swarms, each containing a central volcano with acid and intermediate rocks and a high-temperature geothermal field, all indications of magma chambers in the crust. The central volcanoes mark the sites of maximum lava production. The mountain Hengill is such a central volcano. Geochemical evidence indicates that the hotspot is presently centered below Kverkfjoll [Sigvaldason et al., 1974]. Thus it may be concluded that the Langjokull-Kverkfjoll transverse zone represents the migration trajectory of the hotspot over the last 10 m.y.

Two seismic zones are recognized that are interpreted as complex transform faults [e.g., Einarsson and Bjornsson, 1979]. In the N of Iceland the Tjornes Fracture Zone (TFZ) connects the Northern Volcanic Zone (NVZ) to the Kolbeinsey Ridge, and in the S the southern ends of the Western and Eastern Volcanic Zones (WVZ, EVZ) are connected by the South Iceland Seismic Zone (SISZ). This zone is defined by a belt of severe ($M_s > 7$) historical earthquakes [e.g., Einarsson et al., 1981].

During the last 10 m.y. or so, the plate boundary crossing Iceland has progressively migrated E in response to the eastward migrating hotspot [Saemundsson, 1974; Johannesson, 1980; Helgason, 1985]. Ridge response south of the hotspot has lagged behind that of the north. The WVZ is still active but is becoming replaced by the EVZ. This zone is a southward propagating accretionary plate boundary that started forming at about -2 m.y. Its tip is thus propagating at an average rate of 5-10 cm yr^{-1}. It connects with the WVZ via the SISZ. That this "transform fault" has no surface topographic expression and that older surface breaks are observed N of its present position support the theory that it is unstable, and propagating S with the southern end of the EVZ [Einarsson and Eiriksson, 1982].

The eastward migration of the plate boundary north of the hotspot may have preceded that of the south because there the plate boundary is normal to the trajectory of the hotspot. Thus longitudinal flow northward from the hotspot ceased quickly after the hotspot migrated off axis. South of the hotspot, the WVZ is oblique to the hotspot trajectory, permitting longitudinal flow to be maintained for longer. The Snaefellsnes Volcanic Zone is kept active by lateral flow from the hotspot, enabled by its colinearity with the migration trail of the hotspot.

It will be seen in the ensuing discussion of the Hengill triple junction, that many analogies can be drawn between the behavior of the plate boundary on gross and local scales.

Geology and Geophysics of the Hengill area

The area is dominated by the 803-m-high central volcano Hengill, which is dissected by a swarm of normal faults and open fissures striking at N 25°E (Figure 2).

Its geology has been described by Saemundsson

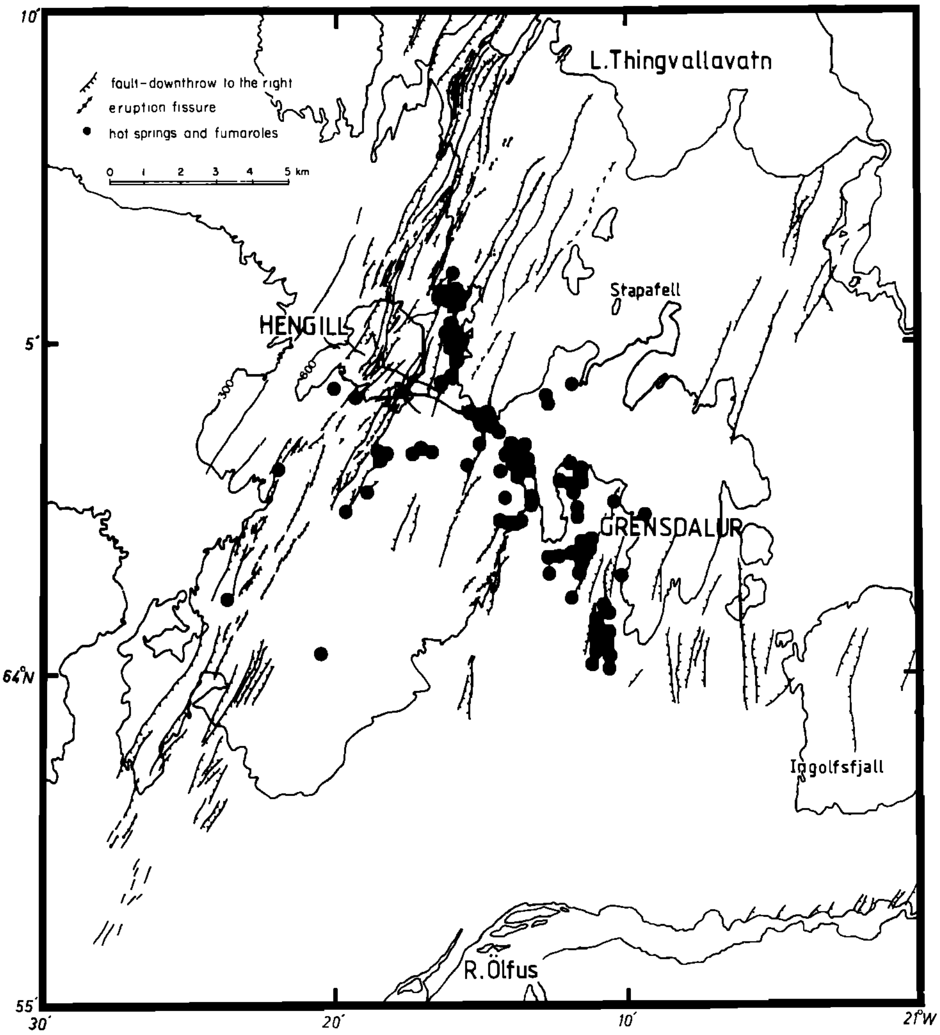

Fig. 2. Tectonic map of the Hengill area showing the 300- and 600-m contours, surface faulting, fissuring, hot springs, and fumaroles [from Saemundsson, 1967].

[1967, 1978], Saemundsson and Bjornsson [1970], Saemundsson and Arnorsson [1971], Torfason et al. [1983], and Hardadottir [1986]. The location of postglacial eruptive sites indicates the position of the currently active spreading plate boundary. A large majority of these are within the fissure swarm, and rocks exposed at the surface become progressively older with distance from it. Small amounts of intermediate and acid rocks are associated with Hengill, and Stapafell, NE of Hengill (Figure 2).

Geological observations in the fissure swarm indicate lateral extension in the lavas of about 0.5 cm yr^{-1} [Saemundsson, 1967], or 25% of that estimated for the Reykjanes Ridge [Talwani and Eldholm, 1977]. The subsidence rate is estimated at 5-8 mm yr^{-1} over the past 8000 years, whereas precision leveling over a 5-year period revealed subsidence at a rate of only 2.5 mm yr^{-1} [Tryggvason, 1974]. Rifting is thus probably episodic, with most of the movement occurring during short periods of high activity. Such an episode is known to have occurred in 1789, when rifting and 60 cm of subsidence were observed during an earthquake swarm [Thoroddsen, 1899].

Geomagnetic studies [Bjornsson, 1976; Hersir, 1980] indicate that the area has been volcanically active since the early Matuyama epoch, when an active volcano existed in the Grensdalur area. At some time during the early Bruhnes (-0.7 m.y. to present) that volcano became extinct, and a new one (Hengill) formed to the W of it. The old volcano was first buried by lavas and hyaloclastites but later eroded, and its roots are now exposed in the Grensdalur topographic depression. The acid and intermediate rocks associated with Hengill and Stapafell have probably originated from magma chambers associated with the Hengill and Grensdalur central volcanoes, respectively.

A large geothermal area (70 km^2) encompasses Hengill, and surface displays extend over a large area to the SE of the volcano (Figure 2). It is thus highly asymmetric with respect to the accretionary plate boundary.

A transverse tectonic/topographic structure strikes normal to the fissure swarm and runs from Hengill, ESE to the Grensdalur area (Figure 2). It is delineated by hyaloclastite ridges, fracture lines, a topographic ridge, changes of strike of faults, and the trend of hot springs.

The part of the research area that is S of

64°N and E of the fissure swarm is associated with transform faulting in the SISZ (Figure 2). It is a flat featureless plain exhibiting no morphological evidence for a large fault. This part of the area constrasts starkly with the rugged terrain to the N.

Much geophysical research targeting the geothermal prospect has been conducted in the area [Stefansson, 1973; 1975; Bjornsson et al., 1974; Hersir, 1980; Bjornsson and Hersir, 1981]. Resistivity studies indicate that a conductive layer <15 Ωm underlies the area. This layer is limited in the W by the western boundary of the fissure swarm. Beneath the site of the extinct Grensdalur volcano it occurs down to approximately 300 m, but beneath Hengill and the fissure swarm it extends below 500 m. It is interpreted as indicating the extent of the geothermal reservoir. S of 64°N, resistivity measurements and drilling indicate low-temperature geothermal resources.

Hydrology and borehole studies indicate that separate groundwater circulation systems are associated with the Hengill and Grensdalur areas [Arnason et al., 1969; Arnason, 1976]. Thus a double hydrological system mirrors the double volcanic system. Borehole temperature measurements up to 230°C are recorded in the Grensdalur area, and up to 380°C on the N perimeter of the Hengill system [Arnason et al., 1986; Steingrimsson and Stefansson, 1979; Stefansson et al., 1983; Ragnars et al., 1979; Xi-Xiang, 1980]. The geothermal reservoir thus extends beneath both volcanoes but is hottest beneath Hengill.

The concentrations of several gases in fumaroles are related to the temperature of the water from which the steam boiled off and thus indicates the temperature of the geothermal reservoir [e.g., Arnorsson and Gunnlaugsson, 1985]. The geochemistry of fumarole gases in the Hengill area indicates that separate deep reservoir temperature highs are associated with the Hengill and Grensdalur systems [Torfason et al., 1983].

Tectonic structure of the Hengill area

The early suggestion made by Saemundsson and Arnorsson [1971] on the basis of geological evidence, that the Hengill area contains both an active central volcano (Hengill) and an extinct one in the Grensdalur area, is consistent with the geophysics. Resistivity studies indicate that the geothermal area underlies both volcanoes but extends deeper beneath Hengill than the Grensdalur system. Hydrological studies indicate that the groundwater circulation system in the Grensdalur system is independent of that of the Hengill system. Borehole and geochemical studies indicate that the geothermal area is hotter beneath the Hengill system than the Grensdalur system, and that separate temperature maxima occur.

It is proposed here that prior to -0.7 m.y. the accretionary plate boundary passing through the area was the then active Grensdalur central volcano and an associated fissure swarm. Westward ridge migration of about 5 km then occurred, and the new Hengill central volcano/fissure swarm system developed. Crustal accretion was transferred to this zone and ceased along the Grensdalur volcanic zone. Continued crustal accretion along the Hengill zone has caused the Grensdalur system to be transported an additional 2.5 km further away from the presently active plate boundary. It will now be shown that this hypothesis can account for the gross tectonic morphology of the area.

The presence of a volcanic center on an accretionary plate boundary affects the morphology of the area locally in two ways. First, the linear stress field of the plate boundary is modified by the radial field of the volcanic center [Ode, 1957; Muller and Pollard, 1977]. Second, volcanic activity is enhanced in the vicinity of the center.

Figure 3 illustrates schematically the principal stress trajectories associated with (a) an accretionary plate boundary, (b) a central volcano, and (c) a combination of the two. Tensional features such as normal faults, fissures, and dykes will preferentially develop along these trajectories.

In the Hengill area the dominant trend of tensional features is N25°E, parallel to the accretionary zones. Transverse tectonic features occur in the neighborhood of the volcanic centers. In the W of the area these are recent tectonic features (fissures, eruptive ridges) associated with the active Hengill volcanic center, and in the E they are erosional features (valleys, lines of hot springs) associated with the extinct Grensdalur volcanic center. These features are reinforced by a thermal "migration trail," because central volcano migration occurred roughly colinearly. All these features therefore combine to form a single structure connecting and crossing the two central volcanoes.

While still active, the volcanic center will form a topographic high. After extinction it will erode down faster than the surrounding areas because of its greater elevation, and because its high temperature enables progressive fracturing by the action of groundwater fluids [Foulger, this issue]. This may result in a topographic depression forming over the old volcanic center, with erosional features mirroring the trends of faults, fissures, and dikes. This is observed in the Hengill area, the Hengill central volcano forming a topographic high, and the Grensdalur center a topographic depression.

In Figure 4 a schematic diagram of the double volcanic system and its associated transverse tectonic structure is proposed based on the locations of surface tectonic features and the geological and geophysical evidence available. A double geothermal system mirrors this double volcanic system.

3. Local Seismicity

Introduction

A considerable body of historic and regionally recorded seismic data from the Hengill area was analyzed prior to the detailed study described in this paper. The most remarkable feature of the seismicity was the constancy of the spatial and temporal distribution of the continuous activity (Figure 12).

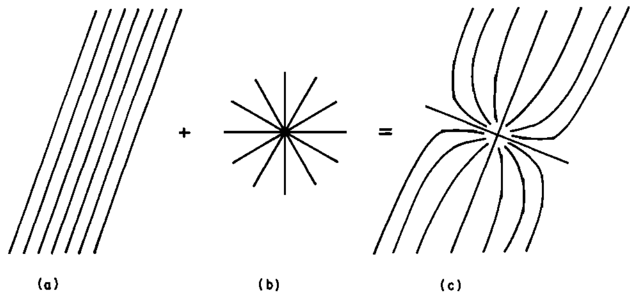

Fig. 3. Pattern of maximum principal stress trajectories caused by the addition of a linear stress system (a) such as that associated with an accretionary plate boundary, and a radial stress system (b) such as that associated with a central volcano. The resulting stress system is shown in Figure 3c.

On the basis of these results a dense seismometer network was deployed for 3 months in 1981 with good prior knowledge of where the activity would occur and at what rate. This stratagey was very succesful, and a vast data set was collected on a network with near-optimum geometry.

Data Set

The data may be divided into four groups.

1. Historic macroseismic data for the 288-year period 1700-1987. The data set contains three events and is complete for $M_s \geqslant 6.0$ [Einarsson et al., 1981].
2. Instrumental records for the 52-year period 1930-1981 from the regional station at Reykjavik (REY) (Figure 1). This data set contains 116 events and is complete for $M_{IL} \geqslant 3.0$ (Icelandic local magnitude; see below).
3. Data recorded on the permanent Icelandic regional seismograph network, intermittently augmented with temporary stations, for the 7-year period 1974-1981. Computer locations were calculated for these events and are accurate to 1-2 km. The data set is complete for $M_{IL} \geqslant 2.0$ and contains 1040 events.
4. Data recorded on a dense seismometer network deployed in the area for 3 months in 1981 (Figure 5). This network consisted of a radio-telemetered array of 23 Willmore Mk III vertical seismometers with natural period 1 s and recording on 14 channel analog tape recorders [Foulger, 1984]. It was supplemented by six paper and ink helical drum recorders. Computer locations for these events typically involve 10-

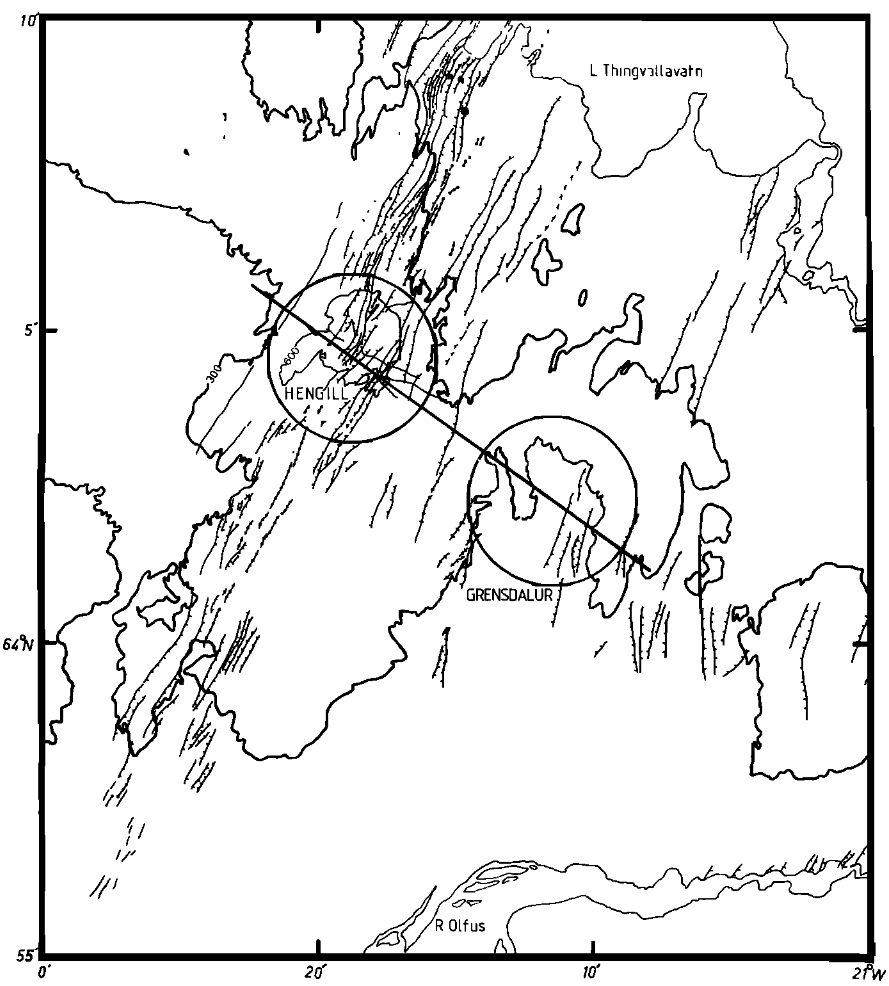

Fig. 4. Tectonic map of the Hengill area showing the proposed locations of the double volcanic system and the transverse structure.

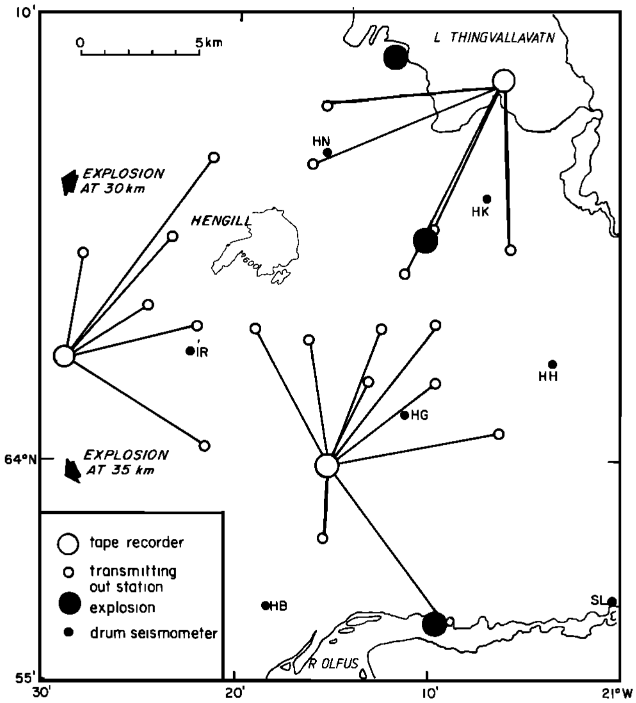

Fig. 5. Locations of stations of the temporary seismometer network deployed for 3 months in 1981, and explosions detonated while the network was recording. Radio transmission beams are shown. Seismometers were deployed at each tape recorder site and transmitting out station.

20 P wave arrival times. The data set contains 1918 events. Relocation of three explosions detonated within the network (Figure 5) indicate that earthquake epicenter mislocations are less than 400 m.

Data Processing

1. Locations and magnitudes for the historic events were taken from Einarsson et al. [1981].
2. Events recorded solely on the two component instrument at Reykjavik could not be located more accurately than to associate them with the Hengill area (station bulletins [Tryggvason, 1978a, b, 1979]).
3 and 4. Hypocentral locations were calculated using the program HYPOINVERSE [Klein, 1978].

Crustal Structure

The velocity structure used was obtained by modeling explosion data from S Iceland [Palmason, 1971; Angenheister et al., 1980] using the program TTGEN [Klein, 1978] (Figure 6, Table 1).

Subsequent to this work a tomographic study of the crustal structure of the Hengill area was conducted using local earthquakes [Toomey and Foulger, 1986; Foulger and Toomey, 1986]. This study revealed relatively minor local structural variation, and adjustments in the hypocentral parameters after relocation were mostly less than 400 m.

Spatial Distribution

Three events of M_s = 6-6.5 have occurred in the area since the year 1700. They are all associated with the transform zone south of the 64° line of latitude (Figure 4). An intense seismotectonic episode occurred in the Hengill fissure swarm in 1789, causing subsidence over at least 20 km of the fissure swarm. This picture of episodic large-magnitude activity associated with the plate boundary contrasts with that of the continuous small-magnitude activity described in this paper (Figure 12).

The two computed data sets (3 and 4) are

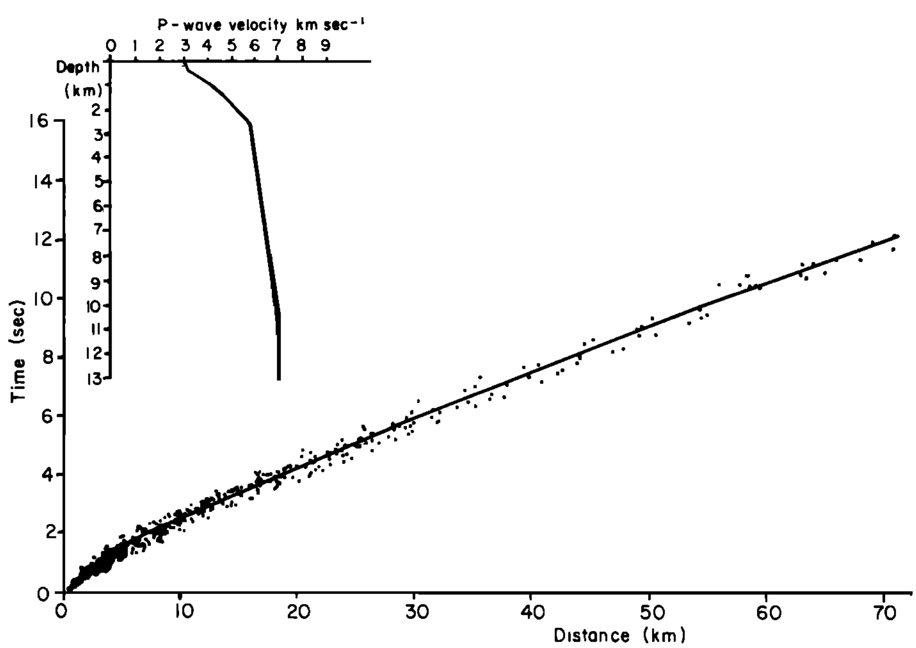

Fig. 6. Travel times of explosions shot in S Iceland by Palmason [1971]. Line is a travel time plot for the Hengill-South Iceland crustal model which was used to locate the Hengill events. Inset is a velocity-depth profile for this model.

TABLE 1. Hengill, South Iceland, Crustal Model Parameters

Layer	Velocity, km s^{-1}	Depth, km
1	3.0	0.0
2	3.3	0.4
3	4.5	1.2
4	5.8	2.5
5	7.0	10.8

treated separately here because of their contrasting time periods and magnitude ranges. Their epicentral distributions are shown in Figures 7 and 8. The accuracy constraints imposed are given in Table 2. Two striking features may be noted.

1. Broad similarity is observed in the epicentral distributions.
2. There is a strong negative correlation with surface faulting. In particular, the presently active accretionary plate boundary that would intuitively be expected to be most active is almost seismically quiescent.

Much of the activity is associated with the Grensdalur volcanic center, and the regional network data set (Figure 7) exhibits two trends, one striking NW and colinear with the transverse tectonic structure (cf. Figure 4) and the other striking NE and parallel to the dominant tectonic trend of the area. In the temporary network data set (Figure 8) the activity in this part of the area forms several clusters, some of which occurred as single swarms, and others as continuous activity. The Klambragil (K, Figure 8) cluster, the largest of these, contains 80 events that occurred uniformly on a daily basis.

NE of Hengill, a linear group of events occupies a deep subsidence valley in the fissure swarm. These events comprise the majority of the very few that were located within the fissure swarm during the period 1974-1981. A cluster of activity also occurs NW of Hengill, and in this area both surface faulting and geothermal displays are absent.

Over the 8-year period depicted in Figures 7 and 8, a broad scatter of events also occurred S of 64°N, within the transform branch of this triple junction. Additionally an unprecedentedly large swarm occurred in the E part of this zone (Ki, Figure 8) during a 3-day period in 1981, and over 700 events in the range $M_{IL} \leqslant 2.2$ were located.

Very few events were located close to 64°N, and earthquake sequences tended to be confined

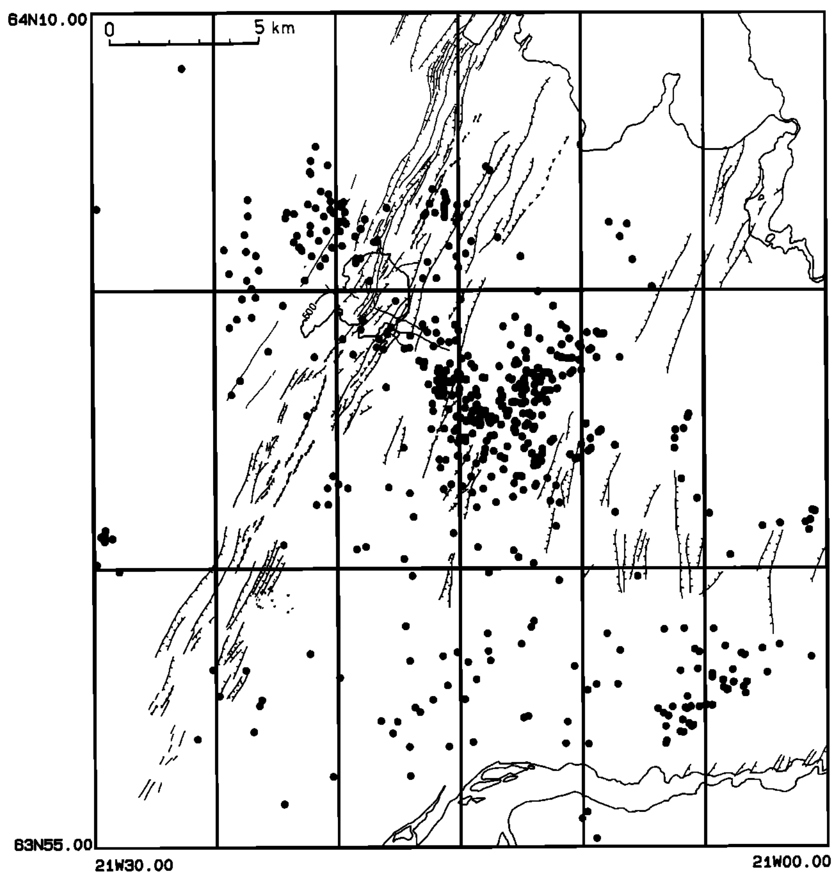

Fig. 7. Epicenters of permanent regional drum seismograph data set. Events occurred in the 7-year period 1974-1981. All epicenters lie within the network; 514 events are plotted. See Table 2 for plotting constraints. These events occupy the magnitude range $0 \leqslant M_{IL} \leqslant 4.2$.

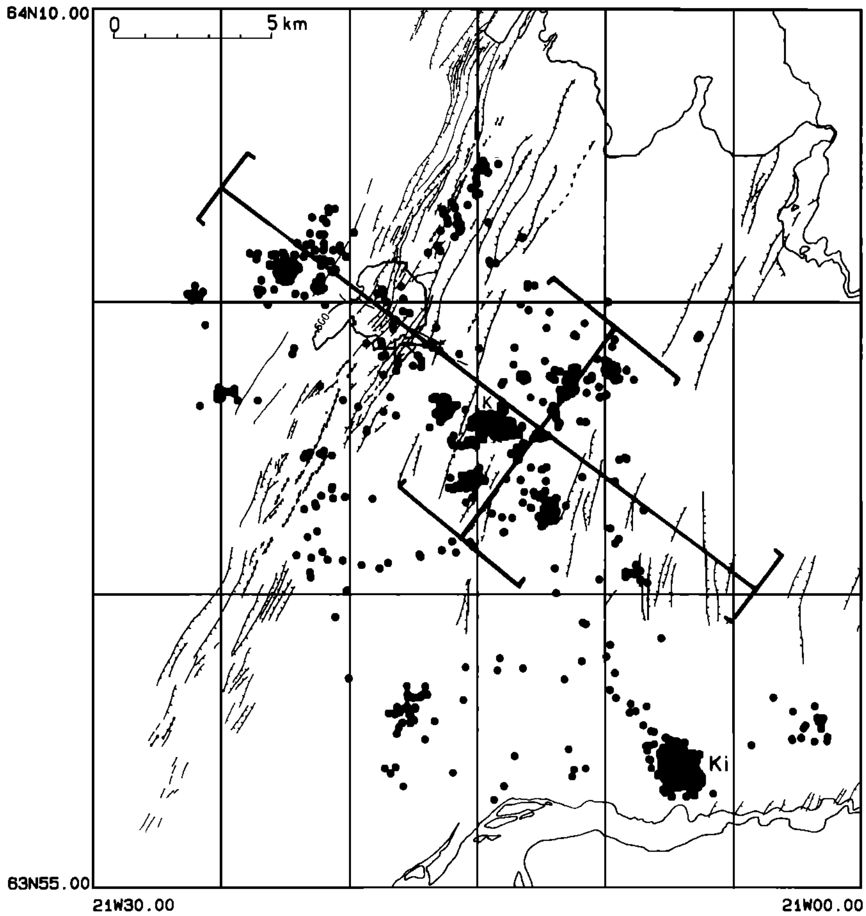

Fig. 8. Epicenters of temporary local seismometer network data set, events occuring in the 3-month period of July-September 1981. All epicenters lie within the network (Figure 5); 843 events are plotted. See Table 2 for plotting constraints. Lines of cross sections shown in Figures 10 and 11 are indicated. These events occupy the magnitude range $-3 \leq M_{IL} \leq 2.2$.

either to the N of 64° N, or to the S; epicentral zones did not cross this "barrier" (see also Figure 9).

The hypocentral distribution of the data recorded on the dense network is illustrated in the N-S cross section of Figure 9. All the hypocenters lie in the range 1-8 km, and most in the range 2-6 km. It may be seen from the inset velocity-depth profile that this corresponds to the velocity range 3-6.5 km s^{-1}.

Figure 10 is a cross section colinear with the transverse tectonic structure passing through the Hengill and Grensdalur volcanic systems (Figure 8). Doming of the seismically active zone beneath the Grensdalur central volcano is apparent. Activity is greatest beneath the NW border of the Grensdalur system, at the location of the Klambragil (K) cluster. Figure 11 is a cross section perpendicular to that of Figure 10 (Figure 8). There is a slight suggestion in the data for a seismic zone with a SW dip in the depth range 3-6 km. This zone may be an aquifer allowing the rise of geothermal fluids from depth to feed the geothermal displays above (Figure 2). A proposed location for this aquifer is shown as a dashed line.

Temporal Distribution

The temporal distribution of the seismicity of the Hengill area is remarkable because of its continuous day to day nature. In this respect it contrasts with all neighboring seismic areas, both along boundary and intraplate, which are quiescent on a day to day basis. A whole spectrum of sequence types (swarms and mainshock sequences) is observed superimposed on a continuum of single shocks. On a smaller scale a few local areas are exceptionally active, e.g., Klambragil (K, Figure 8). No spatial pattern in the occurrence of different types of sequence has been observed. The temporal distribution of the activity recorded on the dense temporary network is shown in Figure 12.

All the magnitude data available from the area are combined in Figure 13, which spans seven magnitude units. The b values and associated errors (95% confidence limits) were calculated using the maximum likelihood method [Aki, 1965; Page, 1968]. Instrumental magnitudes quoted as M_{IL} are duration magnitudes at local stations calibrated against the instrument at Reykjavik (REY) [Tryggvason, 1968, 1973].

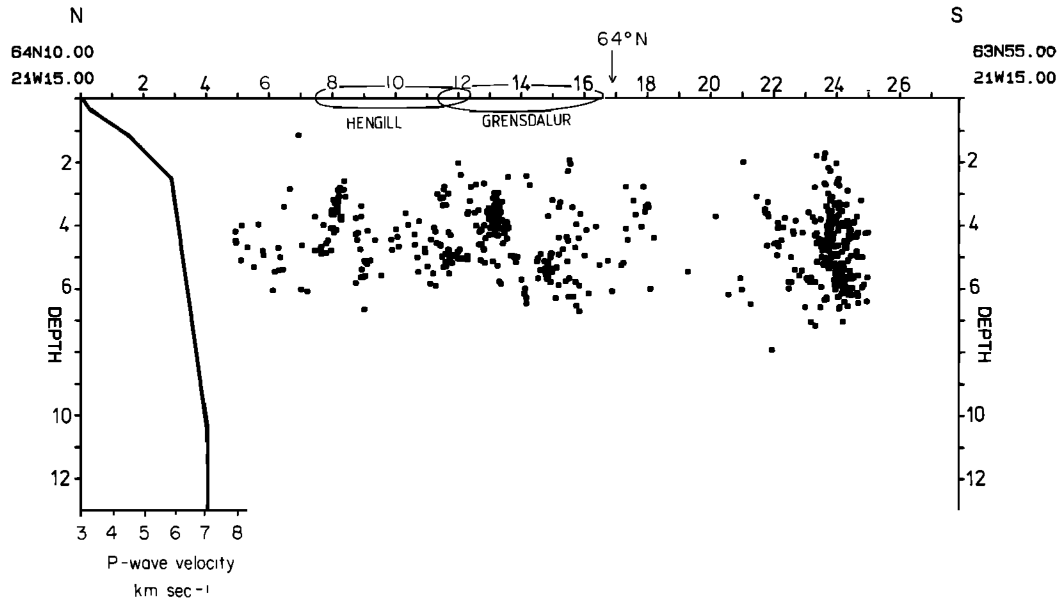

Fig. 9. NS cross section of hypocenters of the temporary local seismometer network data set. Projections of the Hengill and the Grensdalur volcanoes are indicated. A velocity depth profile is inset. See Table 2 for plotting constraints.

The average seismic rate of the area over the last 53 years has been approximately one event M_{IL} = 3.5 per year, and over a 7-year period, one event M_{IL} = 0 per day (Figure 13). No statistical evidence was found for a high-magnitude asymptote in the data, such as is observed elsewhere [Yegulalp and Kuo, 1974], which may be because the sample time (53 years) is too short. However, historic records indicate that the maximum magnitude of events occurring in the area is M_s = 6-6.5.

The b values of 0.68 ± 0.13, 0.72 ± 0.04, and 0.76 ± 0.05 were calculated for the three instrumental data sets (Figure 13). A value of b of approximately 0.74 for the Hengill area in the range $-0.9 \leqslant M_{IL} \leqslant 5.5$ is thus constrained by a large body of data. This b value is roughly comparable with b values of 1.33 and 0.65 calculated for the ridge and fracture zone portions of the Mid-Atlantic Ridge, respectively, using M_s [Francis, 1968a, b]. It has been suggested that b may be inversely related to stress [Scholz, 1968; Wyss, 1973]. In that case the crust of the Hengill area may be more highly stressed than the ridge portions of the MAR, though not as highly stressed as the fracture zone portions. The continuous seismicity in the Hengill area may therefore be occurring in response to uncharacteristically high stress levels for a spreading plate boundary.

The data collected on the temporary network were used to investigate spatial variations in b (Figure 14). The b values calculated for the majority of nine spatial subdivisions were

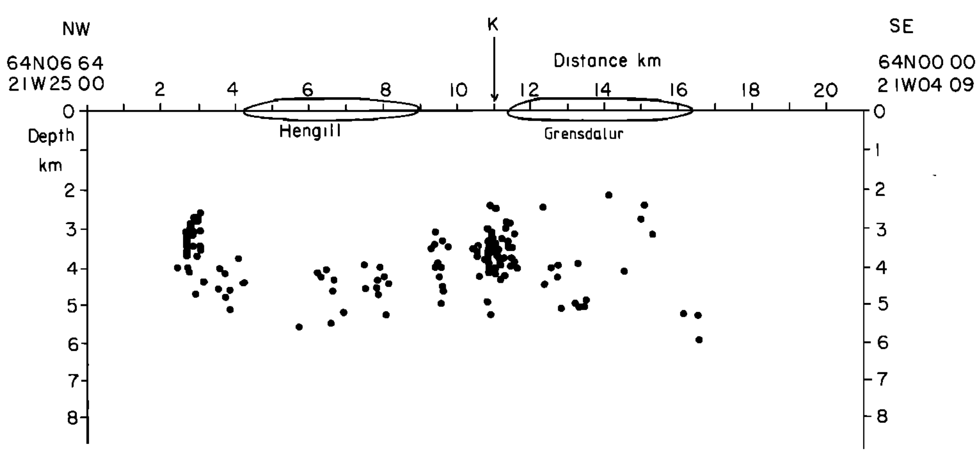

Fig. 10. NW-SE cross section colinear with the transverse tectonic structure (see Figure 8). Hypocenters of the temporary local network data set are plotted. Projections of the Hengill and Grensdalur central volcanoes are indicated. K, Klambragil cluster.

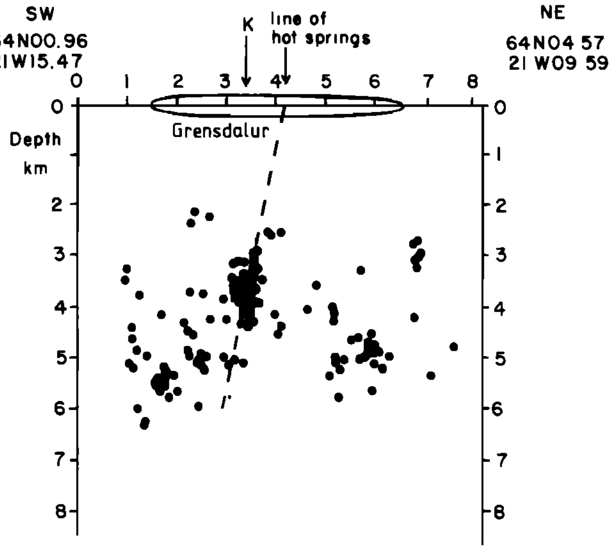

Fig. 11. SW-NE cross section at right angles to the transverse tectonic structure (see Figure 8). Hypocenters of the temporary local network data set are plotted. A projection of the Grensdalur central volcano is indicated. The suggested position of an aquifer with a SW dip of 75° is indicated by a dashed line. K, Klambragil cluster.

statistically the same. If one accepts that the b value is influenced by the stress state in the source volume, then one must conclude that stress in those parts of the Hengill area is similar. A b value of 1.0 ± 0.18 was obtained for the area W of the fissure swarm (Figure 14). This is significantly higher than that obtained for the entire area, which may indicate lower stress than over the rest of the Hengill area. This b value contrasts especially with a value of 0.68 ± 0.14 obtained for the fissure swarm immediately adjacent.

A significant variation in b value with time was detected accompanying the swarm that occurred in the S of the area (Ki) that was recorded on the temporary local network (Figure 15). The b values were calculated for samples of 100 events, progressively incremented by 30. Prior to the swarm, the b value was normal compared with the rest of the Hengill area (0.85 ± 0.17), but with the onset of the swarm it rapidly decreased to 0.43 ± 0.08. It then increased to a high value (1.15 ± 0.22), and by the end of the swarm returned to a "normal" value for the area (0.81 ± 0.16).

Interpreted in terms of variation in stress within the source region, these results indicate that the onset of the swarm accompanied an increase in stress in the source region, which was quickly released during the early part of the

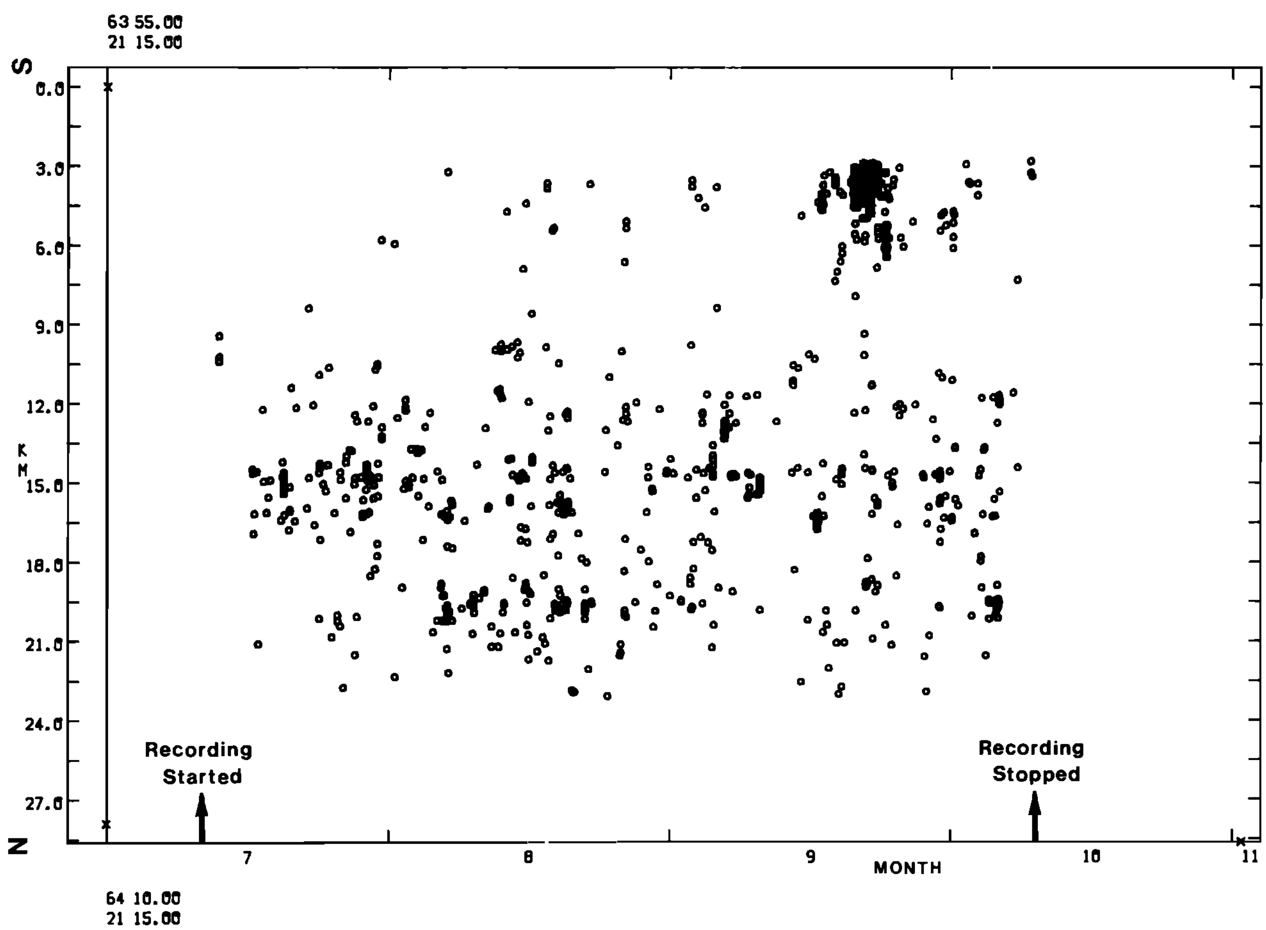

Fig. 12. Plot of latitude: time, showing the temporal distribution of events located in the 3-month deployment period of the temporary seismometer network. Apart from the swarm in the S of the area in late September, the activity was evenly distributed throughout the recording period.

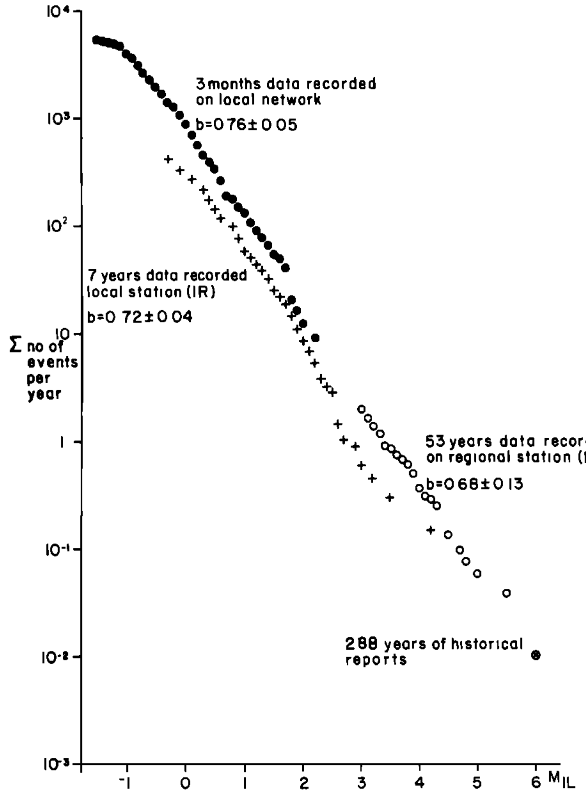

Fig. 13. Composite cumulative frequency-magnitude plot of events occurring in the Hengill area. Four data sets are plotted on a normalized frequency scale.

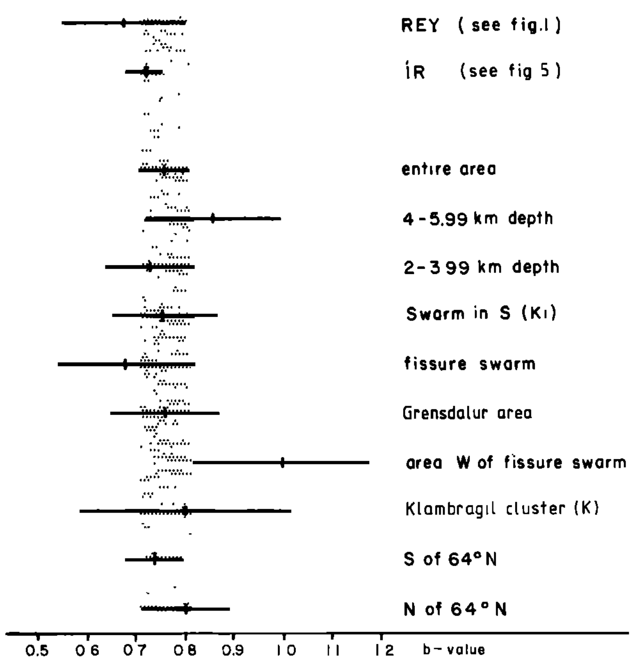

Fig. 14. The b values calculated for subdivisions of the Hengill area. Horizontal lines indicate the 95% confidence ranges. Shaded column indicates the 95% confidence range for the entire data set. REY, data collected on the regional station at Reykjavik; IR, data collected on the close station IR. Other values refer to subsets of the temporary local network data set (see Figure 8).

Table 2. Accuracy Constraints used to Select Events for Plotting.

Epicentral Plots	Permanent Regional Network Data (Figure 7)	Temporary Local Network Data (Figure 8)
GAP	⩽180°	⩽180°
ERH	⩽2.5 km	⩽1.0 km
RMS	⩽0.15 s	⩽0.10 s
ERZ	⩽99.0 km	⩽99.0 km
Hypocentral Plots		**Temporary Local Network Data (Figures 9-11)**
GAP		⩽180°
ERH		⩽1.0 km
RMS		⩽0.10 s
ERZ		⩽2.0 km
Arrival times used in location		⩾12
Distance/depth		⩽2.0

Abbreviations as used by HYPOINVERSE [Klein, 1978]. GAP, azimuthal gap; ERH, horizontal error; ERZ, vertical error. Distance/depth is ratio of horizontal distance to the nearest station to hypocentral depth. Constraining this ratio in the case of hypocentral plots ensured good depth constraint.

swarm. By the end of the swarm, stress had returned to its former level. These changes in b value are in a similar style to others reported for earthquake sequences [Rikitake, 1976] and are what would be expected if the source volume experienced a stress pulse accompanied by seismic activity.

4. Discussion

The geology and geophysics of the Hengill area are consistent with a 5-km westward ridge migration having occurred in the last 0.7 m.y. This is a small-scale example of a phenomenon that is observed on a gross scale in Iceland [Saemundsson, 1974; Johannesson, 1980; Helgason, 1985]. A transverse tectonic structure marks the trail of central volcano migration, and is broadly analogous to the Langjokull-Kverkfjoll Volcanic Zone that marks the migration trajectory of the Iceland hotspot.

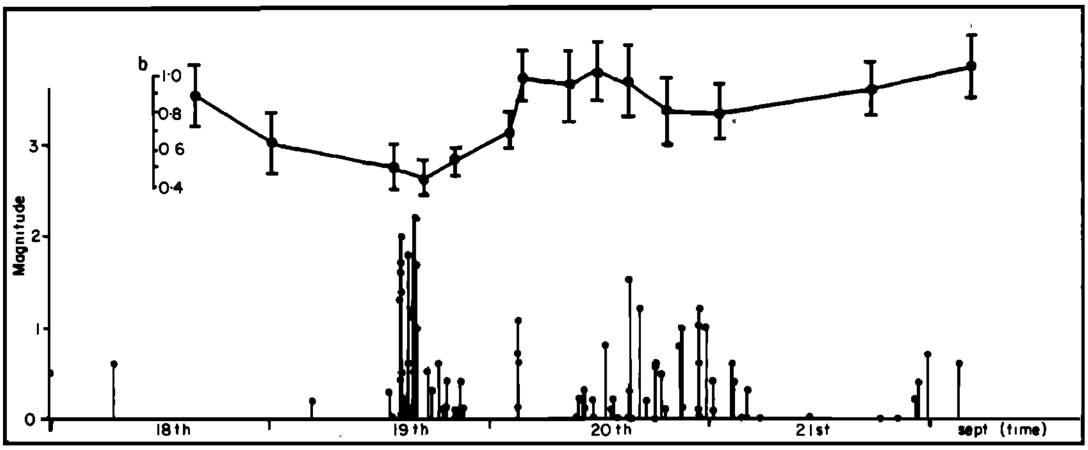

Fig. 15. Magnitudes (M_{LL}) of events in September 1981 swarm in the S of the area (Ki, Figure 8) and associated b values. The b values plotted were calculated for the preceding 100 events in the seismic volume. Bars indicate 95% confidence limits.

Although a broad scatter of occasional single shocks and swarms occurs in the accretionary and transform zones within the Hengill area, the highest level of continuous activity is associated with the extinct Grensdalur volcano, where also extensive geothermal resources occur. The presently active Hengill volcano and its much hotter geothermal field is much less seismically active.

The plate boundary in Iceland is generally quiescent on a daily basis except in geothermal areas [Ward et al., 1969; Ward and Bjornsson, 1971; P. Einarsson, personal communication, 1988]. These factors suggest that the continuous small-magnitude activity in the Hengill area, and perhaps the other geothermal areas of Iceland, may not be tectonic plate boundary seismicity, but related instead to the geothermal resources. A focal mechanism study of the Hengill events verified this and showed the mechanism by which they are generated [Foulger, this issue]. In that case the high stress implied by the low b value calculated for these events would be thermal in origin. Other examples of this phenomenon are to be found outside Iceland, e.g., the Geysers geothermal area [Eberhart-Phillips and Oppenheimer, 1984]. For the Geysers, the maximum magnitude event is approximately M_L = 4.0. By analogy, the maximum magnitude event for the high-temperature area N of 64°N may be less than M_s = 6.0, which would be consistent with historical data.

Where microearthquake studies have been conducted on the submarine ridge, a low level of activity is generally observed [e.g., Francis et al., 1978; Toomey et al., 1985]. The results from the Hengill area imply that these studies may have little relevance to the pattern of large-magnitude teleseismic activity from the same areas, and may also be unrelated to tectonic processes directly associated with spreading.

5. Conclusions

1. The Hengill area contains two central volcano/fissure swarm systems: the extinct Grensdalur system, and the presently active Hengill system. Crustal accretion was centered on the Grensdalur volcano and an associated NE striking fissure swarm prior to -0.7 m.y., after which westward ridge migration of 5 km occurred, the Hengill system developed and the Grensdalur system become extinct. This hypothesis can account for the gross geology, geophysics, and tectonics of the area.
2. Twin geothermal systems mirror this double volcanic system.
3. The seismic activity of the area is broadly separable into two groups. Infrequent intense seismic episodes occur along the accretionary plate boundary and the transform zone. These release tectonic stress accumulated along the boundary by plate movements. Continuous small-magnitude earthquake activity that has a relatively low b value releases thermal stress from the geothermal area.
4. Spatial and temporal variations in b value within the Hengill area have been observed, which may be stress related. The monitoring of this parameter is potentially useful for studying the transform zone where destructive earthquakes are expected, and the high temperature geothermal area, where exploitation is commencing.

Acknowledgments. This research was financed by the Geophysics Division, University of Iceland, the National Energy Authority, Iceland, and the Reykjavik Municipal District Heating Service. It was conducted while the author was employed by the Science Institute, University of Iceland. The seismometer network deployed in 1981 was lent by the NERC, United Kingdom. Some of the seismographs of the regional network were built with the support of the NATO Research Grants Program (grant 715). In a scientific context I sincerely thank Axel Bjornsson, Sveinbjorn Bjornsson, Pall Einarsson, and Roger Long. The parts of this paper concerning the tectonics of Iceland and the Hengill area benefited profoundly from discussions with many individuals, and the author is particularly grateful for the guidance of Kristjan Saemundsson.

References

Aki, K., Maximum likelihood estimate of b in the formula log N = a - bM and its confidence limits, Bull. Earthquake Res. Inst., Univ. Tokyo, 43, 237-239, 1965.

Angenheister, G., S. Bjornsson, P. Einarsson, H. Gebrande, P. Goldflam, W. R. Jacoby, I. V. Litvinenko, B. Loncarevic, H. Miller, G. Palmason, N. I. Pavlenkova, S. Richard, S. C. Solomon, W. Weigel, and S. M. Zverev, Reykjanes Ridge Seismic Experiment (RRISP 77), J. Geophys., 47, 228-238, 1980.

Arnason, B., Groundwater systems in Iceland traced by deuterium, Soc. Sci. Islandica, 42, 236 pp., 1976.

Arnason, B., P. Theodorsson, S. Bjornsson, and K. Saemundsson, Hengill, a high temperature thermal area in Iceland, Bull. Volcanol., 33, 245-260, 1969.

Arnason, K., G. I. Haraldsson, G. V. Johnsen, G. Thorbergsson, G. P. Hersir, K. Saemundsson, L. S. Georgsson, and S. P. Snorrason, Nesjavellir: Jardfraedi- og jardedlisfraedileg konnun 1985 (Nesjavellir: Geological and geophysical overview 1985), Rep. OS-86014/JHD-02, 125 pp., Natl. Energy Auth., Reykjavik, Iceland, 1986.

Arnorsson, S., and E. Gunnlaugsson, New gas geothermometers for geothermal exploration-calibration and application, Geochim. Cosmochim. Acta, 49, 1307-1325, 1985.

Bjornsson, A., Hengilssvaedi-flugsegulkort (Aeromagnetic map of the Hengill area), Map 14320, Natl. Energy Auth., Reykjavik, Iceland, 1976.

Bjornsson, A., and G. P. Hersir, Geophysical reconnaissance study of the Hengill high-temperature area, SW-Iceland, Trans. Geotherm. Resour. Counc., 5, 55-58, 1981.

Bjornsson, A., J. Tomasson, and K. Saemundsson, Hengilssvaedid: Stada jardhitarannsokna vorid 1974 (The Hengill area, the state of geothermal research in spring 1974), Rep. OS JHD 74 15, 11 pp., Natl., Energy Auth., Reykjavik, Iceland, 1974.

Eberhart-Phillips, D., and D. H. Oppenheimer, Induced seismicity in the Geysers geothermal area, California, J. Geophys. Res., 89, 1191-1207, 1984.

Einarsson, P., and S. Bjornsson, Earthquakes in Iceland, Joekull, 29, 37-43, 1979.

Einarsson, P., and J. Eiriksson, Earthquake fractures in the districts Land and Rangarvellir in the South Iceland Seismic Zone, Joekull, 32, 113-120, 1982.

Einarsson, P., S. Bjornsson, G. Foulger, R. Stefansson, and T. Skaftadottir, Seismicity pattern in the South Iceland Seismic Zone, in Earthquake Prediction: An International Review, Maurice Ewing Ser. 4, edited by D. W. Simpson and P.G. Richards, pp. 141-151, AGU, Washington, D. C., 1981.

Foulger, G., Geothermal exploration and reservoir monitoring using earthquakes and the passive seismic method, Geothermics, 11, 259-268, 1982.

Foulger, G. R., Seismological studies at the Hengill geothermal area, SW Iceland, Ph.D. thesis, 313 pp., Univ. of Durham, United Kingdom, 1984.

Foulger, G. R., Hengill triple junction, SW Iceland 2, Anomalous earthquake focal mechanisms and implications for process within the geothermal reservoir and at accretionary plate boundaries, J. Geophys. Res., this issue.

Foulger, G., and P. Einarsson, Recent earthquakes in the Hengill-Hellisheidi area in SW Iceland, J. Geophys., 47, 171-175, 1980.

Foulger, G. R. and D. R. Toomey, 3-D crustal structure of the Hengill-Grensdalur central volcano complex, Iceland, from seismic tomography (abstract), Eos Trans. AGU, 67, 1110, 1986.

Francis, T. J. G., The detailed seismicity of mid-ocean ridges, Earth Planet. Sci. Lett., 4, 39-46, 1968a.

Francis, T. J. G., Seismicity of mid-ocean ridges and its relation to properties of the upper mantle and crust, Nature, 220, 899-901, 1968b.

Francis, T. J. G., I. T. Porter, and R. C. Lillwall, Microearthquakes near the eastern end of St. Pauls fracture zone, Geophys. J. R. Astron. Soc., 53, 210-217, 1978.

Hardardottir, V., The petrology of the Maelifell picrite basalt, southern Iceland, Joekull, 36, 31-40, 1986.

Helgason, J., Shifts of the plate boundary in Iceland: Some aspects of Tertiary volcanism, J. Geophys. Res., 90, 10,084-10,093, 1985.

Hersir, G. P. Electrical and electromagnetic measurements across the mid-Atlantic Ridge in SW Iceland, with special reference to the high temperature area of Hengill, Specialearbejde Report, 165 pp., Lab. for Geofys., Aarhus Univ., Denmark, 1980.

Johannesson, H., Evolution of rift zones in western Iceland (in Icelandic with English summary), Natturufraedingurinn, 50, 13-31, 1980.

Klein, F. W. Hypocenter location program HYPOINVERSE, U.S. Geol. Surv. Open File Rep., 78-694, 1978.

Muller, O. H. and D. D. Pollard, The stress state near Spanish Peaks, Colorado determined from a dike pattern, Pure Appl. Geophys., 115, 69-86, 1977.

Ode, H., Mechanical analysis of the dyke pattern of the Spanish Peaks area, Colorado, Bull. Geol. Soc. Am., 68, 567-576, 1957.

Page, R., Aftershocks and microaftershocks of the great Alaska earthquake of 1964, Bull. Seismol. Soc. Am., 58, 1131-1168, 1968.

Palmason, G., Crustal structure of Iceland from explosion seismology, Soc. Sci. Islandica, 40, 187 pp., 1971.

Peppin, W., and C. G. Bufe, Induced (?) versus natural earthquakes: Search for a seismic discriminant, Earthquake Notes, 49, 65, 1978.

Ragnars, K., H. Armannsson, and B. Steingrimsson, Olfusdalur, maelingar i borholum G3, G6 og G7 (Well logs of boreholes G3, G6 and G7, Olfusdalur), Rep. OS79053/JHD25, 51 pp., Natl. Energy Auth., Reykjavik, Iceland, 1979.

Rikitake, T., Earthquake Prediction, 357 pp., Elsevier, New York, 1976.

Saemundsson, K., Vulkanismus und Tektonik des Hengill - Gebietes in Sudwest-Island. (Volcanology and tectonics of the Hengill area in SW Iceland). Acta Natur. Island., 2(7), 109 pp., 1967.

Saemundsson, K., Evolution of the axial rifting zone in Northern Iceland and the Tjornes fracture zone, Geol. Soc. Am. Bull., 85, 495-504, 1974.

Saemundsson, K., Fissure swarms and central volcanoes of the neovolcanic zones of Iceland, Geol. J. Spec. Issue, 10, 415-432, 1978.

Saemundsson, K., Outline of the geology of Iceland, Joekull, 29, 7-28, 1979.

Saemundsson, K., and S. Arnorsson, Greinagerd um borholu Asi 1 hja Olfusborgum i Olfusi (On borehole Asi 1 in Olfus), Rep. Natl. Energy Auth., Reykjavik, Iceland, Dec. 1971.

Saemundsson, K., and S. Bjornsson, Umsogn um hahitasvaedi i Hengli og Krisuvik med tilliti til virkjunar fyrir hitaveitu hofudborgarsvaedisins, (Evaluation of the high temperature areas of Hengill and Krisuvik, with regard to exploitation for hot water for the Reykjavik area), Rep. OSJHD, 202, 16 pp., Natl. Energy Auth., Reykjavik, Iceland, 1970.

Scholz, C., The frequency-magnitude relation of microfracturing in rock and its relation to earthquakes, Bull. Seismol. Soc. Am., 58, 399-415, 1968.

Sigvaldason, G. E., S. Steinthorsson, N. Oskarsson, and P. Imsland, Compositional variation in recent Icelandic tholeiites and the Kverkfjoll hot spot, Nature, 251, 579-582, 1974.

Stefansson, V., Rafleidnimaelingar i Olfusi og Floa 1973 (Conductivity measurements in Olfus and Floi 1973), Rep. OS-JHD, Natl. Energy Auth., Reykjavik, Iceland, 1973.

Stefansson, V., Rafleidnimaelingar vid Thorlakshofn (Conductivity measurements near Thorlakshofn), Rep. OS-JHD-7519, Natl. Energy Auth., Reykjavik, Iceland, 1975.

Stefansson, V., J. Tomasson, E. Gunnlaugsson, H. Sigvaldason, H. Franzson, and O. Sigurdsson, Nesjavellir - hola NG-6, borun, rannsoknir og vinnslueiginleikar (Nesjavellir well NG-6, drilling, research and production characteristics), Rep. OS83023/JHD4, Natl. Energy Auth., Reykjavik, Iceland, 1983.

Steingrimsson, B., and V. Stefansson, Nesjavellir, hitastig og thrystingur i jardhitasvaedinu (Nesjavellir, temperature and pressure in the geothermal area), Rep. OS79032/JHD15, 31 pp., Natl. Energy Auth., Reykjavik, Iceland, 1979.

Talwani, M., and O. Eldholm, Evolution of the Norwegian-Greenland sea, Bull. Geol. Soc. Am., 88, 969-999, 1977.

Thoroddsen, T., Jardskjalftar a Sudurlandi (Earthquakes of Southern Iceland), Hid Islenzka Bokmenntafelag, Copenhagen, 199 pp., 1899.

Toomey, D. R., and G. R. Foulger, A tomographic inversion of local earthquake data: Hengill-Grensdalur central volcano, Iceland (abstract), Eos Trans. AGU, 67, 1110, 1986.

Toomey, D. R., S. C. Solomon, G. M. Purdy, and M. H. Murray, Microearthquakes beneath the median valley of the Mid-Atlantic Ridge near 23°N: Hypocenters and focal mechanisms, J. Geophys. Res., 90, 5443-5458, 1985.

Torfason, H., G. P. Hersir, K. Saemundsson, G. V. Johnsen, and E. Gunnlaugsson, Vestur-Hengill: Yfirbordsrannsokn jardhitasvaedisins (West Hengill: Surface research of the geothermal area), Rep. OS-83119/JHD-22, 133 pp., Natl. Energy Auth., Reykjavik, Iceland, 1983.

Tryggvason, E., Measurement of surface deformation in Iceland by precision levelling, J. Geophys. Res., 73, 7039-7050, 1968.

Tryggvason, E., Seismicity, earthquake swarms and plate boundaries in the Iceland region, Bull. Seismol. Soc. Am., 63, 1327-1348, 1973.

Tryggvason, E., Vertical crustal movements in Iceland, in Geodynamics of Iceland and the North Atlantic Area, edited by L. Kristjansson, pp. 241-262, D. Reidel, Hingham, Mass., 1974.

Tryggvason, E., Jardskjalftar a Islandi 1930-1939 (Earthquakes in Iceland 1930-1939), Rep. RH-78-21, 92 pp., Sci. Inst., Univ. of Iceland, Reykjavik, 1978a.

Tryggvason, E., Jardskjalftar a Islandi 1940-1949 (Earthquakes in Iceland 1940-1949), Rep. RH-78-22, 51 pp., Sci. Inst., Univ. of Iceland, Reykjavik, 1978b.

Tryggvason, E., Jardskjalftar a Islandi 1950-1959 (Earthquakes in Iceland 1950-1959), Rep. RH-79-06, 90 pp., Sci. Inst., Univ. of Iceland, Reykjavik, 1979.

Vogt, P. R. The Iceland mantle plume: status of the hypothesis after a decade of new work, in Structure and Development of the Greenland-Scotland Ridge, edited by M.H.P. Bott et al., pp. 191-216, Plenum, New York, 1983.

Ward, P. L. and S. Bjornsson, Microearthquakes, swarms and the geothermal areas of Iceland, J. Geophys. Res., 76, 3953-3982, 1971.

Ward, P. L., G. Palmason, and C. C. Drake, Microearthquakes and the Mid-Atlantic Ridge in Iceland, J. Geophys. Res., 74, 665-684, 1969.

Wyss, M., Towards a physical understanding of the earthquake frequency distribution, Geophys. J. R. Astron. Soc., 31, 341-359, 1973.

Xi-Xiang, Z., Interpretation of subsurface temperature measurements in the Mosfellssveit and Olfusdalur geothermal areas, SW-Iceland, Rep. 1980-7, UNU Geotherm. Training Programme, Iceland, 1980.

Yegulalp, T. M., and J. T. Kuo, Statistical prediction of the occurrence of maximum magnitude earthquakes, Bull. Seismol. Soc. Am., 64, 393-414, 1974.

G. R. Foulger, Department of Geological Sciences, University of Durham, Science Laboratories, South Road, Durham DH1 3LE, United Kingdom.

(Received September 29, 1987;
revised July 12, 1988;
accepted June 9, 1988.)