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Characteristics of Earthquakes in the Heerland Seismic Zone of Eastern Spitsbergen*

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Abstract: A large number of earthquakes have been found to occur in the continental crust of eastern Spitsbergen (Heerland) and the adjoining Storfjorden region. These earthquakes are characterized by their continental type high-frequency wave forms and their concentrated occurrence in a relatively small zone. Available apparent velocity data suggest that the focal depths for the small Heerland earthquakes are concentrated in the upper crust. Surface wave amplitude spectra indicate that the two largest events in recent years occurred at depths of 3 and 5 km.

Zusammenfassung: In der kontinentalen Kruste Ostspitzbergens (Heerland) und im angrenzenden Storfjord-Gebiet treten Erdbeben in großer Zahl auf. Sie sind gekennzeichnet durch ihre bei kontinentalen Beben üblichen hochfrequenten Wellenzüge und ihr gehäuftes Auftreten in einer relativ schmalen Zone. Vorliegende Daten von Scheingeschwindigkeiten lassen vermuten, daß die Herdtiefen der schwachen Heerland-Erdbeben in der oberen Erdkruste konzentriert sind. Die Amplitudenspektren der Oberflächenwellen zeigen an, daß die beiden größten Beben der letzten Jahre in Tiefen von 3 und 5 km auftraten.

INTRODUCTION

The seismicity of Spitsbergen was first studied by a German expedition (TAMS, undated) in 1911—1912. Later studies were conducted by SELLEVOLL (1960) using a single vertical-component seismograph which was emplaced near the entrance of Isfjorden, and by AUSTEGARD (1976) who used the World Wide Standard station at Kings Bay (KBS). In both studies, many earthquakes were recorded which could be associated with the nearby mid-Atlantic Ridge system. In addition, amplitude measurements by AUSTEGARD (1976) revealed a substantial number of earthquakes which were located in a south-easterly direction from KBS. Although the precision of those locations was poor, he obtained several approximate epicenters in Storfjorden, off the eastern coast of Spitsbergen. MITCHELL et al. (1978) emplaced small temporary microearthquake networks to study earthquakes from that region during the summers of 1976 and 1977. The reliable locations indicated that the great majority of those earthquakes occurred in a small zone which extends through eastern Spitsbergen (Heerland) and into the western edge of Storfjorden (Fig. 1). If a single directional trend is present, it was found to be most likely oriented in an approximate east-west direction. This result was not expected, since most of the major mapped faults in Spitsbergen trend in a north-south direction. It is important to note that these earthquakes are intraplate in nature, even though they occur in a region not far from the mid-Atlantic ridge. They, therefore, provide a unique opportunity to study intra-plate earthquakes which occur near a major plate boundary.

BUNGUM et al. (1978) have also recently observed a concentration of earthquakes in the same region. Their station configuration did not, however, permit locations to be made accurately enough to delineate any directional trends.

Although several earthquakes in the Heerland region have been reliably located, only the earthquake of 18 January 1976 was large enough to yield a fault-plane solution (BUNGUM, 1977; MITCHELL et al., 1978). That solution indicated strike-slip motion along a nearly vertical fault. In order to be consistent with the observed seismicity

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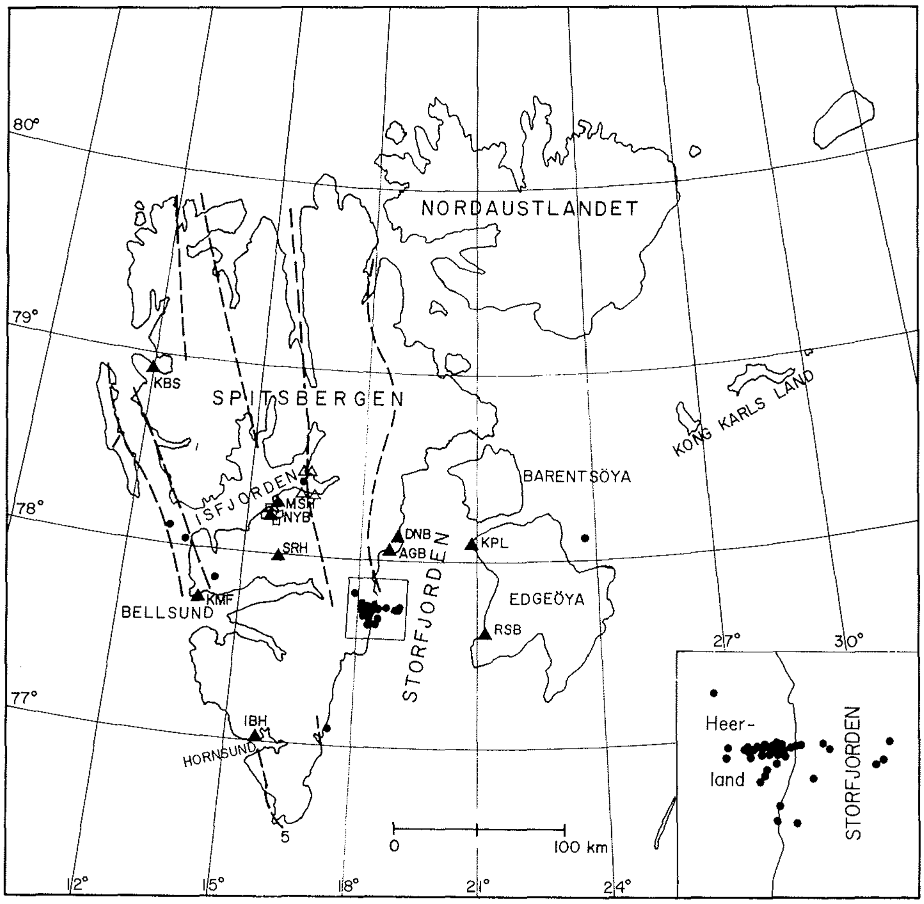

Fig. 1: Map of Spitsbergen showing major mapped faults (dashed lines, from HARLAND et al., 1974), earthquake epicenters located from 1977 field data (circles, from MITCHELL et al., 1978) and stations of the temporary Saint Louis University networks for the summers of 1976 (open triangles indicate the Billefjorden network and open squares indicate the Longyearbyen network), and 1977 (closed triangles). The inset at the lower right is an enlargement of the Heerland region.

Abb. 1: Karte von Spitzbergen mit den hauptsächlichen Störungszonen (gestrichelte Linien, nach HARLAND et al. 1974), den nach Feldarbeiten 1977 bestimmten Erdbeben-Epizentren (Kreise, nach MITCHELL et al. 1978) sowie den Stationen des temporären Beobachtungsnetzes der Saint Louis University während des Sommers 1976 (offene Dreiecke geben das Billefjorden-, offene Quadrate das Longyearbyen-Netz an) und 1977 (gefüllte Dreiecke). Die Nebenkarte unten rechts stellt einen vergrößerten Ausschnitt der Heerland-Region dar.

pattern, the fault motion would have to be sinistral and occur on a fault-plane which is oriented in an east-northeast west-southwest direction.

This study is intended to supplement that of MITCHELL et al. (1978). Using data collected during the field seasons of 1976 and 1977 we will be able to discuss the nature of the wave forms generated by the Heerland earthquakes and will speculate on the cause of features observed on the seismograms. In addition, focal depths for those earthquakes will be inferred from the velocities of regional phases, as well as from spectra of surface waves recorded on long-period instruments of the World-Wide Standard Seismograph Network (WWSSN).

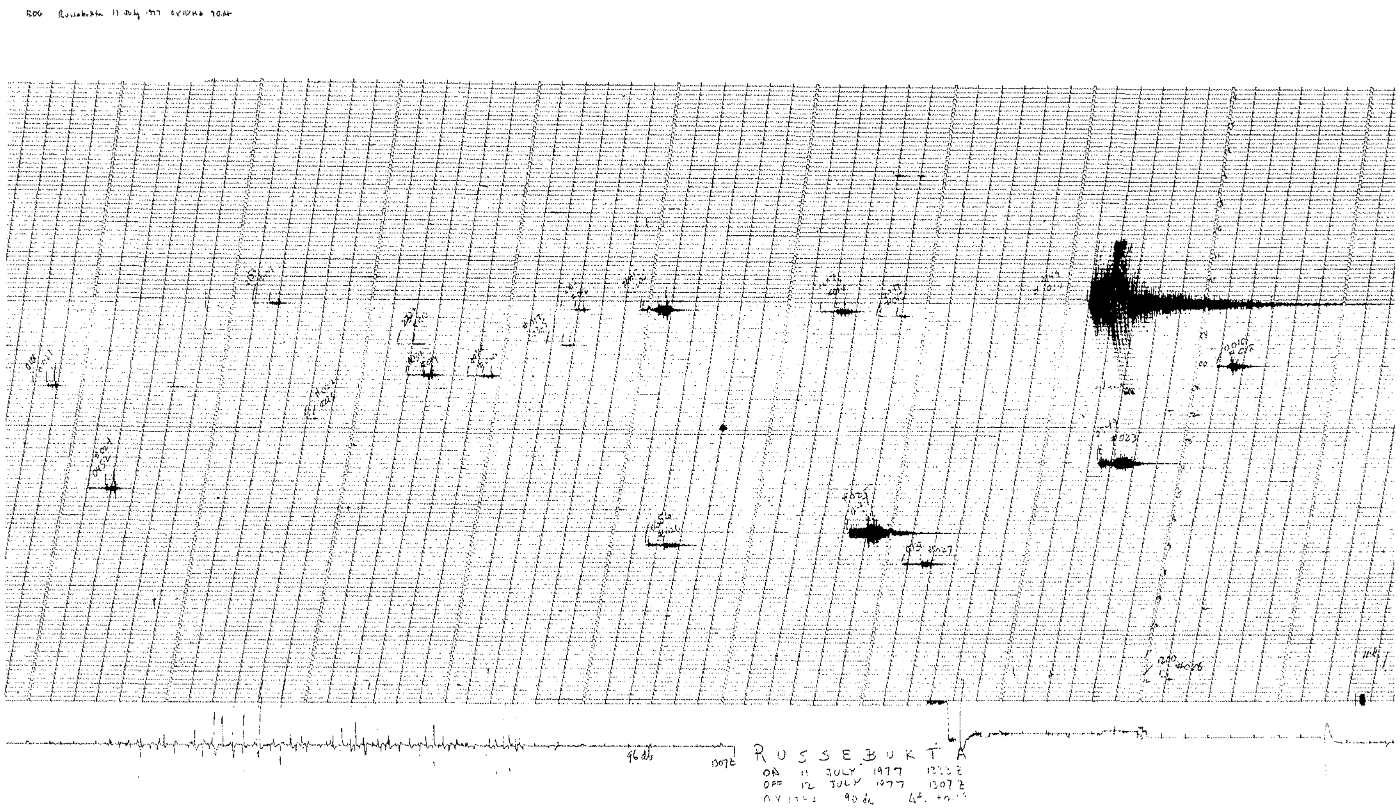

Fig. 2: Example seismogram for a one-day recording period at station RSB (see Fig. 1).

Abb. 2: Beispiel einer Seismogrammregistrierung eines Tages an der Station RSB (vgl. Abb. 1).

REGIONAL PHASES

The seismogram in Fig. 2, from one of our network stations (RSB) which was emplaced on Edgeöya during the 1977 field season, illustrates the prevalence of small earthquakes from the Heerland region. It was not uncommon for our more sensitive stations to record that many events, or more, in a single 24 hour period.

Although most of the earthquakes in the seismogram of Fig. 2 occurred in the Heerland region, events which occurred on the mid-Atlantic Ridge were also recorded. It is

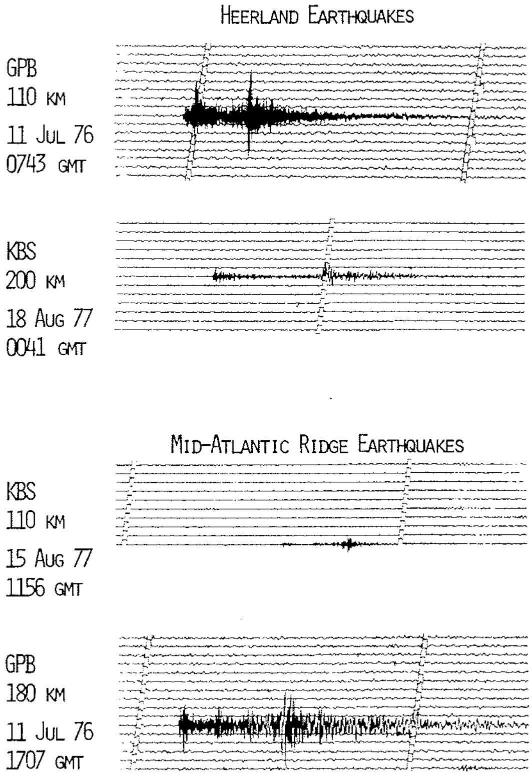

Fig. 3: Wave forms for selected events on the mid-Atlantic Ridge and in Heerland as recorded at our temporary stations at Kings Bay (KBS) and at station GPB of our Billefjorden network (see Fig. 1).

Abb. 3: Wellenzüge von ausgewählten Ereignissen auf dem Mittelatlantischen Rücken und in Heerland, wie sie an der temporären Station bei Kings Bay (KBS) und der Station GPB des Billefjord-Netzes aufgezeichnet wurden (vgl. Abb. 1).

interesting to compare the frequency content of events which occur in the different regions. Fig. 3 presents seismograms for events in Heerland and along the mid-Atlantic ridge for similar distances. Although the amplitudes are small, the KBS seismogram of the mid-Atlantic ridge event ($\triangle$ = 110 km) clearly lacks the high frequencies which occur on the GPD recording of a Heerland event ($\triangle$ = 110 km). The same observation, that wave forms from Heerland earthquakes have a higher dominant frequency than events from the Mid-Atlantic ridge for the same epicentral distance, can be made for the other seismograms of Fig. 3. AUSTEGARD (1976) first observed this difference in frequency content for the two regions on recordings of the WWSSN short-period instruments at Kings Bay (KBS) which have a peak response at 1 Hz. Our observations, using instruments with a peak response at 10 Hz, extend this conclusion to higher frequencies.

The reason for the difference in frequency content between Heerland and Mid-Atlantic ridge events can be explained by the difference in the anelastic properties of the crust along the different travel paths. Paths between the Heerland events and our stations are continental in character (RYGG, 1970), whereas paths from the Mid-Atlantic ridge events contain a substantial portion of oceanic crust. MITCHELL et al. (1977) have shown that the oceanic crust, especially in the vicinity of spreading centers, is characterized by much greater attenuation (or lower Q values) than is continental crust. Consequently, higher frequencies will be attenuated more rapidly along oceanic paths than along continental paths.

It is also notable that regional seismograms of Heerland earthquakes are characterized by two compressional wave arrivals and sometimes also by two shear wave arrivals. AUSTEGARD (1976) described the arrival of two compressional wave phases and interpreted them as P_n (a wave which travels through the uppermost mantle) and P_g (a wave which travels through the upper crust). As noted by AUSTEGARD, the first arrival is much smaller than the second. Fig. 4 exhibits the wave form for one of the larger Heerland earthquakes. Note the very small dilatational arrival which precedes a much larger arrival a second or two later. The initial arrival is so small that it would probably be missed for the smaller Heerland events. Our observations of the apparent velocities, described in the following section, for the two compressional wave arrivals (at distances of 120 km and less) indicate that the first arrival is P_g and later arrivals are either P_n or additional crustal phases.

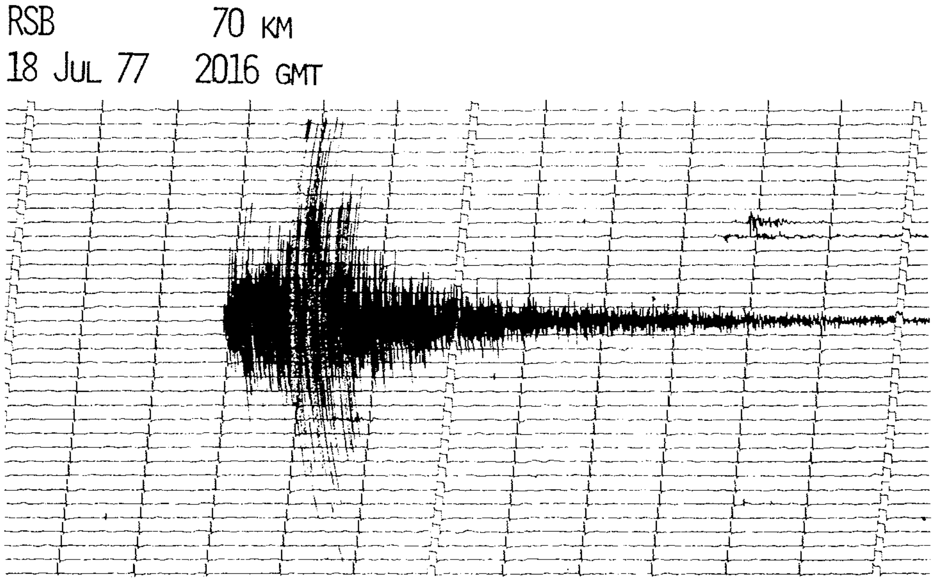

Fig. 4: A seismogram of a larger Heerland event as recorded at RSB in 1977.

Abb. 4: Seismogramm eines größeren Heerland-Bebens, das 1977 bei RSB aufgezeichnet wurde.

EARTHQUAKE FOCAL DEPTHS

The most widely used method for determining earthquake focal depths is to measure the time interval between the initial compressional wave arrival (P) and the surface reflection near the source (pP) as recorded on seismographs at teleseismic distances. This method, however, cannot always be used, since the onsets of P or pP often cannot be read accurately. The earthquake may be too small to generate sufficient compressional wave energy to be recorded at teleseismic distances, or if the earthquake is shallow, the onset of pP may be obscured by the P wave. It will be useful, therefore, to use other methods to estimate the depth of focus of the Heerland earthquakes.

Approximate depth information can be obtained from the apparent velocities of regional phases. Apparent velocities, observed across a network of stations, can be no smaller in value than the velocity of the rock at the depth at which the earthquake occurs (assuming a plane-layered earth model with velocities increasing as a function of depth). For instance, if an earthquake would occur in the upper mantle, the observed apparent velocity would have a minimum value corresponding to upper mantle velocity values ($\sim$ 7.8 km/s or more). We have used the networks of our 1976 field season to obtain apparent velocities from the Heerland events. The apparent velocities of the slowest phases will place limits on the maximum depth at which the events occurred. Before applying the method, it is necessary to know the approximate velocity structure for the region. RYGG (1970) has obtained a velocity model for the Barents shelf (Table 1)

Layer Thickness (km)	Compression Velocity (km/sec)	Shear Velocity (km/sec)	Density (gm/cm^3)
0.5	1.52	0.00	1.03
2.0	3.60	2.12	2.40
12.0	6.00	3.55	2.70
14.0	6.65	3.80	3.00
	8.20	4.65	3.35

Tab. 1: Crustal model (from RYGG, 1972).

Tab. 1: Krustenmodell der Geschwindigkeiten (nach RYGG 1972).

which we have used as a guide to interpret the observed apparent velocities in terms of the corresponding earthquake focal depth. Note that the compressional wave velocities in the upper crust are 6.00 km/s or less, whereas in the lower crust they are about 6.65 km/s. These values have been found to be fairly typical for upper and lower crustal compressional wave velocities in continental regions of the world. Corresponding shear wave velocities in the upper crust are 3.55 km/s or less and 3.80 km/s, respectively. The observed apparent velocities were obtained by solving for apparent velocity and azimuth of approach of plane waves across the networks of the 1976 field season (see Fig. 1). The values which were obtained appear in Table 2. We have restricted our

Compressional waves (km/sec)		Shear waves (km/sec)	
6.48	± 0.38	3.46	± 0.01
6.29	0.19		
6.48	0.38		
4.30	0.32	3.49	0.02
5.29	0.56	2.13	0.47
4.64	0.23		
5.82	0.02	3.51	0.09
5.06	0.30	3.05	0.03
5.74	0.64		
4.74	0.29		
6.92	0.67		
5.23	0.71		
4.29	0.33		
4.74	0.29	3.57	0.39
5.23	0.71		

Tab. 2: Apparent wave velocities.

Tab. 2: Wellen-Scheingeschwindigkeiten.

analysis to include only those values which were obtained using four or more stations, and for which the standard deviation of the direction of approach was less than 5°. Only one value (including both columns) is large enough to indicate a focal depth in the lower crust, and that value has a very large standard deviation associated with it. We conclude that the great majority, and perhaps all, off the small earthquakes in Heerland occur in the upper crust.

There have been two Heerland earthquakes in recent years which have been large enough to generate surface waves which were recorded at distances of several hundred km from the source region. Those are the earthquakes of 18 January 1976 ($m_b = 5.6$) and 17 July 1977 ($m_b = 4.5$). TSAI & AKI (1970) developed a method for determining earthquake focal depths from the amplitude spectrum of fundamental-mode surface waves. In order to apply the method, the earthquake fault-plane solution and a velocity model for the propagation path should be known, and the attenuation coefficients corresponding to the travel paths should be approximately known. We have used the fault-plane solution of MITCHELL et al. (1978) for the 1976 event and assumed that it pertains to both the 1976 and 1977 earthquakes. Attenuation coefficients were calcu-

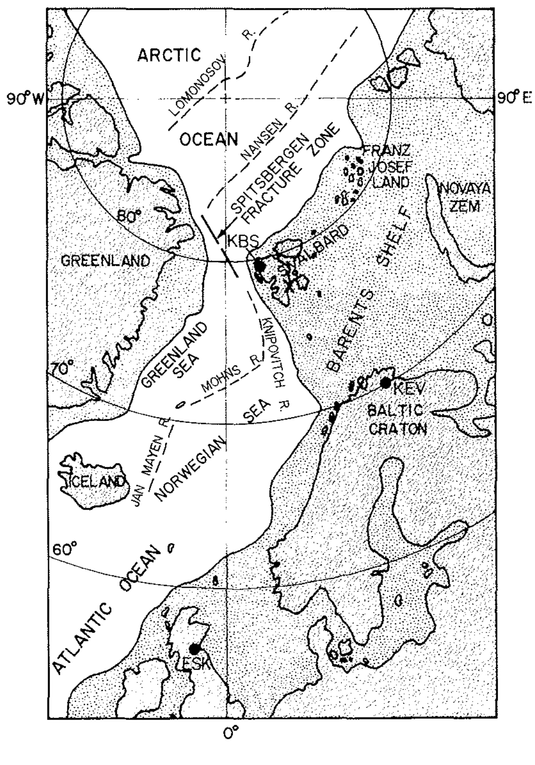

Fig. 5: Map of the North Atlantic and Arctic regions indicating the epicentral region (X) and WWSSN stations (KBS, KEV, and ESK) used for obtaining Rayleigh wave amplitude spectra for local depth determinations.

Abb. 5: Karte des Nordatlantik und des arktischen Gebietes mit Epizentrengebiet (X) und WWSSN-Stationen (KBS, KEV und ESK), die zur Bestimmung lokaler Herdtiefen mittels Amplitudenspektren der Rayleigh-Wellen herangezogen wurden.

lated for the velocity model of RYGG (1970) and a Q model appropriate for a continental crust with a relatively low Q upper crust (shear wave Q = 100) and high Q values (shear wave Q = 1000) in the lower crust (MITCHELL, 1975).

Data for the 1977 earthquake were available from two WWSSN stations, KBS in northwestern Spitsbergen and KEV in northern Finland (see Fig. 5). The long-period vertical component records were digitized and the amplitude spectra for Rayleigh waves

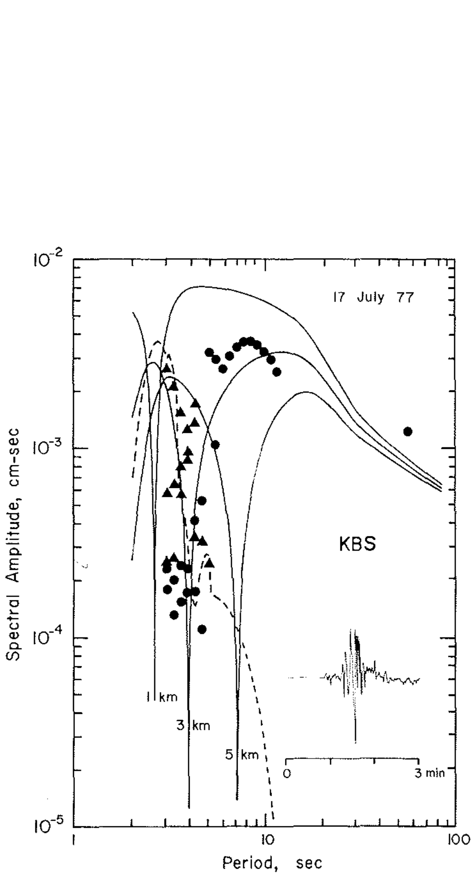

Fig. 6: Observed amplitude spectrum for the fundamental Rayleigh mode (circles) and higher mode Rayleigh waves (triangles) as recorded at KBS for the earthquake of 17 July 1977. These are compared with theoretical fundamental-mode spectra for earthquake focal depths of 1, 3, and 5 km (solid lines). The dashed line denotes the theoretical higher-mode spectrum for a focal depth of 3 km.

Abb. 6: Beobachtete Amplitudenspektren der Grundmoden (Kreise) und höheren Moden (Dreiecke) der Rayleigh-Wellen nach Registrierungen des Erdbebens vom 17. Juli 1977 an der Station KSB. Vergleich dieser Spektren mit theoretisch berechneten Grundmoden für Herdtiefen von 1,3 und 5 km (ausgezogene Linie). Die gestrichelte Linie zeigt das theoretische Spektrum höherer Moden für eine Herdtiefe von 3 km an.

were plotted. Fig. 6 presents the spectral amplitude values for station KBS along with theoretical values calculated for the source and model described above. Theoretical fundamental-mode spectra were calculated for 3 depths (1 km, 3 km, and 5 km). The important feature of these spectra is the minimum which occurs at larger and larger periods when the focal depth becomes greater. It is clear that these spectra indicate that the focal depth for the 17 July 1977 earthquake is about 3 km. The dashed line in Fig. 6 is the theoretical spectrum for the phase Lg (a superposition of several higher Rayleigh modes) for a focal depth of 3 km. Our observed Lg amplitudes are also consistent with the calculated values.

The KEV spectral amplitude data appear in Fig. 7. We have plotted only those theoretical values which correspond to the best fitting focal depth of 5 km. This value is 2 km greater than the depth obtained from the data at KBS described above. In view of the approximations and estimates made for the velocity and Q models, we consider that the degree of agreement between the two stations is good. We favor the shallower depth obtained at KBS as being more accurate, since the Rayleigh wave path is shorter and more likely to be uniform than is the path to KEV. The value of 3 km can be compared to the USGS value of 10 km, the depth at which the earthquake was constrained for location purposes.

Since the 1976 earthquake was much larger than the 1977 event, it was off scale at most of the nearby seismographs. We found that it was well-recorded, however, on the long-period vertical WWSSN station ESK, in Scotland. The theoretical and observed spectra appear in Fig. 8. A focal depth of 5 km provides the best fit to the data. The USGS had previously constrained the depth of this event at 33 km when it was located.

CONCLUSIONS

Earthquakes in the Heerland region of eastern Spitsbergen are characterized by high-frequency wave forms and the appearance of two or more compressional and shear wave

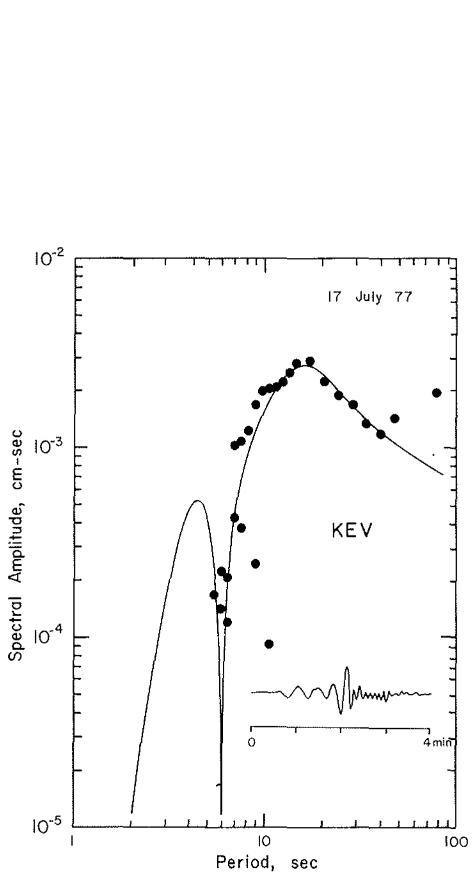

Fig. 7: Observed amplitude spectrum for the fundamental Rayleigh mode (circles) as recorded at KEV for the earthquake of 17 July 1977. This is compared with a theoretical spectrum for an earthquake with a focal depth of 5 km.

Abb. 7: Beobachtetes Amplitudenspektrum der Grundmode der Rayleigh-Wellen (Kreise) für das Erdbeben vom 17. Juli 1977, registriert an der Station KEV. Dieses wird mit dem theoretisch berechneten Spektrum eines Bebens mit einer Herdtiefe von 5 km verglichen.

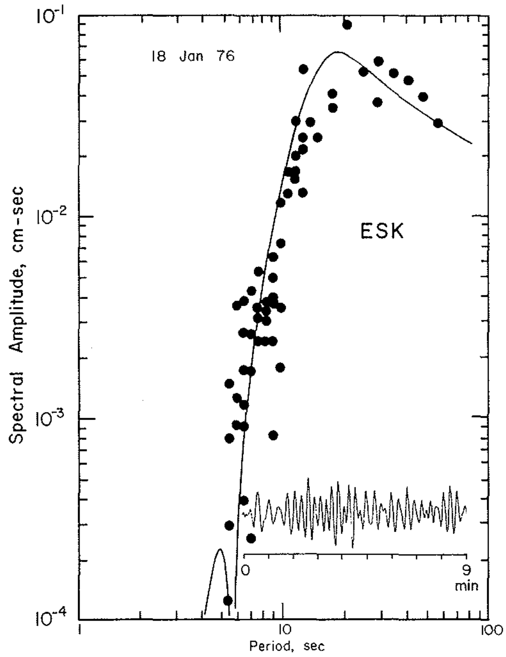

Fig. 8: Observed amplitude spectrum for the fundamental Rayleigh mode (circles) as recorded at ESK for the earthquake of 18 January 1977. This is compared with a theoretical spectrum for an earthquake with a focal depth of 5 km.

Abb. 8: Beobachtetes Amplitudenspektrum der Grundmode der Rayleigh-Wellen (Kreise) für das Erdbeben vom 18. Januar 1977, registriert an der Station ESK. Dieses wird mit dem theoretisch berechneten Spektrum eines Bebens mit einer Herdtiefe von 5 km verglichen.

phases when recorded at regional distances. These effects are produced by continental-type crust with low attenuating properties.

Apparent velocities determined for several small Heerland events indicate that the great majority, and perhaps all, of the earthquakes occur in the upper crust. Surface wave amplitude spectra yield depth values of 3 and 5 km for the two largest events in 1976 and 1977.

ACKNOWLEDGEMENT

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