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SEISMICITY OF THE SVALBARD REGION: A PRELIMINARY REPORT ON THE MICROEARTHQUAKE ACTIVITY

by

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SUMMARY

A program for microearthquake surveillance of the Svalbard Archipelago was initiated by installation of seismic stations in Barentsburg, Pyramiden and Longyearbyen in December 1977. During the first 2½ months of operation these stations recorded 687 seismic events altogether. About 75% of these events were local earthquakes from the Svalbard area, thus indicating a high level of seismic activity in this region. While a significant amount of the recorded events are from the mid-oceanic ridge west of Svalbard, the dominating source area for the local events is around 77.7°N, 18.5°E on the east coast of West Spitsbergen in Storfjorden, a distance of about 40 km from Sveagruva. A seismic station which is now under installation in Svea is expected to contribute significantly in the further investigation of this seismic activity. For a more in-depth study of the Svalbard seismicity additional seismic stations in Kvalvågen, in Agarddalen and on Edgeøya will be required.

INTRODUCTION

Up until now, only very limited data have been available for the study of the seismic activity in and around Svalbard (see Fig. 1), and most of the studies so far have been based on teleseismic data (Hodgson et al, 1965; Sykes, 1965; Husebye et al, 1975; Bungum, 1977; Bungum et al, 1978). However, even if only about 1-2 intraplate earthquakes from Svalbard are reported every year from the teleseismic recordings, the large (M_s=5.9) event in the Storfjorden area on January 18, 1976, clearly showed that a certain seismic hazard is present. The fact that this event had a faulting mechanism atypical for intraplate earthquakes (Bungum, 1977) also emphasized the need for a closer investigation, which could be done only by installing seismic stations on the archipelago itself.

The first seismic station on Svalbard was in operation at Isfjord Radio (ISF) between 1958 and 1963. Even though no epicenter locations could be obtained, this station did reveal a significant local seismic activity (Sellevoll, 1960). Since 1967, a WWSSN station has been in operation at Kings Bay (KBS), from where three-component data were used by Austegard

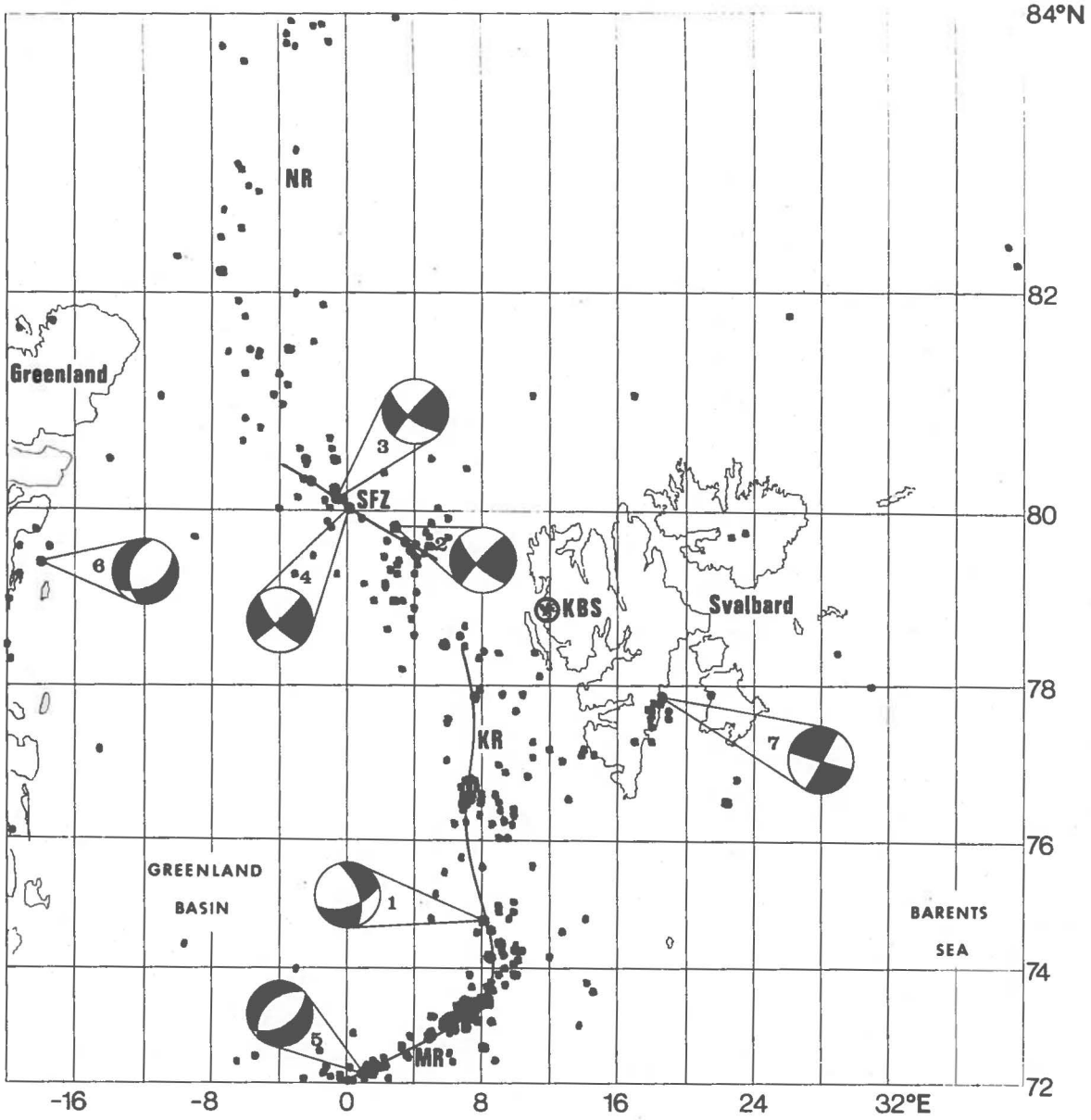

Fig. 1 Earthquake occurrence in the Greenland/Svalbard region, as taken from Sykes (1965) for 1957-60, from PDE (Preliminary Determination of Epicenters, U.S. Geological Survey) for 1961-63, and from ISC (International Seismological Centre, Edinburgh) and PDE for 1964-75, with priority for ISC. Only epicentral solutions based on at least 6 stations are used, and the larger symbols indicate a magnitude of at least 5.0. For the focal mechanism solutions, black and white areas indicate areas of compression and dilatation, respectively. The locations of Mohns Ridge (MR), Knipovich Ridge (KR), Spitsbergen Fracture Zone (SFZ) and the Nansen Ridge (NR) are also given, as well as the location of station KBS. (From Bungum et al, 1978.)

(1976) to show that the seismically active area in Storfjorden (Husebye et al, 1975) also was associated with a rather intense microearthquake activity. However, the locations were not precise enough for a closer delineation of this zone.

During the summer of 1976 and 1977, scientists from St. Louis University Missouri, USA, operated a number of portable microearthquake stations at various sites in Svalbard. During a field season of 9 weeks in 1977, this team (Mitchell et al, 1977) recorded about 500 local events and located about 50, resulting in the delineation of a relatively small but seismically very active area on the west side of Storfjorden at about 77.7°N.

The proximity of the intraplate seismicity in western Spitsbergen to present and future industrial activity suggest that studies of the contemporary tectonic situation may be very valuable. Norsk Polarinstitutt has therefore in cooperation with NTNF/NORSAR (Norwegian Seismic Array), the Russian mining trust Arktikugol and Store Norske Spitsbergen Kullkompani initiated a project for mapping of the seismic activity in Spitsbergen. As Phase I, a pilot project with 6 months' recording by a network of 3-4 microearthquake stations will be undertaken to provide the basis for recommendations for future work.

In this report we present the first scientific results of this project based on data from the first 2½ months of operation of the seismograph network, from December 8, 1977, to February 25, 1978.

DATA ANALYSIS AND RESULTS

Three microearthquake instruments of the type Sprengnether MEQ-800 were installed in December 1977 in the mining towns of Barentsburg (BBG), Longyearbyen (LYR) and Pyramiden (PRD), in cooperation between the Russian mining trust 'Arktikugol', Store Norske Spitsbergen Kullkompani, Norsk Polarinstitutt and NTNF/NORSAR. The coordinates of these stations (including KBS) are given in Table 1, where also the recording time (up-time in per cent) is given for each station. From the latter figures we see that the operation during the first few weeks was quite unstable;

this was due to various technical problems, most of them instabilities related to installation in sub-zero temperatures. For this reason, reliable time corrections were not available for the data analyzed in this report. We consequently had to develop an event location procedure which only used the relative arrival times of the P and S waves at each station. This method takes advantage of the fact that there normally is a constant ratio between P and S velocities in the crust, which makes (for short distances) the epicentral distance Δ approximately linearly dependent upon the P-S time:

$$\Delta \simeq k \cdot t(P-S) \tag{1}$$

With two stations, this gives two possible epicenters, an ambiguity which can be solved by adding observations from a third station. This P-S location method is well known and much used especially because it is ideal for a rapid graphical solution: What we have done here is to develop the method into a maximum likelihood procedure which also uses all available information about the various errors involved.

Event location procedure

Knowing the epicentral distance from two stations, we may usually compute two epicenters symmetrically located about the line connecting the stations. Having a distance observation from one or more additional stations located non-symmetrically relative to the former ones, we will generally be able to choose the proper solution, however, in this case the final location should be based on a sort of 'averaging process' since the 'distance circles' will normally not intersect each other in one single point, due to the distance errors involved.

The location procedure outlined below is based on the maximum likelihood principle from statistical theory. Assuming that the error in the 'observed' epicentral distance Δ_i for a given station i is normally distributed with zero mean and standard deviation σ_i, we may locally (close to the epicenter) approximate the 'distance circle' by a straight line and express the associated probability density function as a 'Gaussian ridge' distributed about this line (see Fig. 2):

$$p_i(x,y) = \frac{1}{\sqrt{2\pi}\,\sigma_i} \, e^{-\frac{1}{2}\left(\frac{a_i x + b_i y + c_i}{\sigma_i}\right)^2} \tag{2}$$

Site	Code	Lat	Long	Up-time (%)	Operated by
Barentsburg	BBG	78.073	14.240	89.5	Norsk Polar-institutt & NTNF/NORSAR
Pyramiden	PRD	78.659	16.303	58.7	
Longyearbyen	LYR	78.189	15.578	63.8	
Kings Bay	KBS	78.918	11.924	30.4	Univ. Bergen

Table 1. Names and coordinates of the seismic stations used in this study. In the last column is given the percentage of the time between December 8, 1977, and February 24, 1978, during which each of the stations has been in operation (or data available in case of KBS).

	BBG	PRD	LYR	KBS	Total
Detected events, total	448	303	482	57	687
- Average per day	6.3	6.5	9.6	2.4	
Detected events, local	337	199	377	31	515
- Average per day	4.8	4.3	7.5	1.3	
Located events, local	205	175	196	7	234
- Average per day	2.9	3.8	3.9	0.3	

Table 2. Detectability statistics for the four stations used in this study. Data for the stations BBG, PRD and LYR cover the time period between December 8, 1977, and February 24, 1978, whereas data from KBS have been available only for December 1977. The daily averages have been corrected for station down-time.

No. of Stations	Detected Events	(%)	Located Events	(%)
1	282	41.0	0	
2	211	30.7	119	50.9
3	190	27.7	115	49.1
4	4	0.6	0	

Table 3. Number of events which have been detected at, and located using, 1, 2, 3 and 4 stations, respectively. The events plotted in Fig. 3 have all been taken from the base of 115 events which are located using 3 stations (BBG, PRD and LYR).

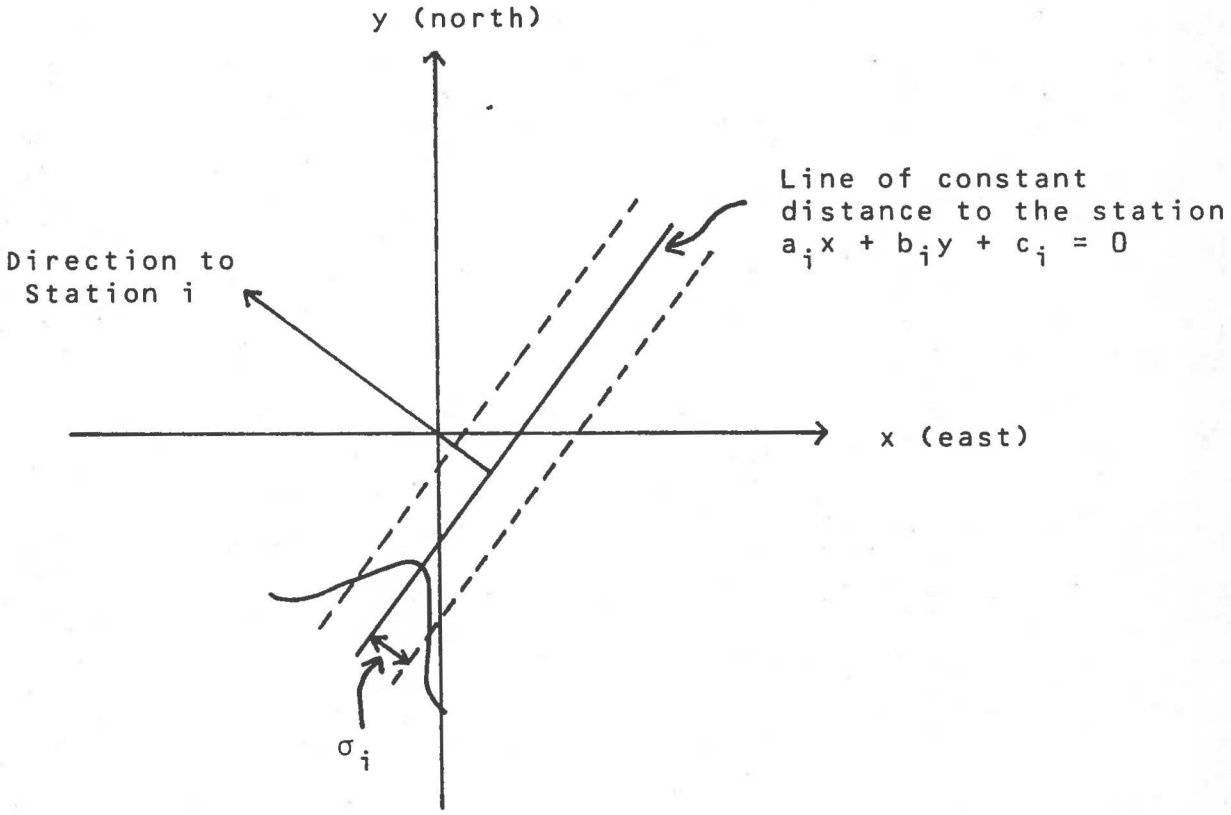

Fig. 2 Error distribution of the 'distance line' from each station, calculated from the P-S times.

Here, x and y are rectangular coordinates centered in a point in the vicinity of the true epicenter, and a_i, b_i and c_i are parameters defining the 'distance line' in this coordinate system .

Having chosen the origin of this system, e.g., in the intersection point between two arbitrarily chosen distance circles, the parameters, a_i, b_i and c_i may be easily computed from the station coordinates and the 'observed' value of the distance Δ_i.

When an expression like (2) has been found for N stations, we may compute the joint probability density of the epicenter by forming the product

$$p(x,y) = \prod_{i=1}^{N} p_i(x,y) \qquad (3)$$

and locate the epicenter in the point corresponding to the maximum value of p(x,y) which can be shown to represent a binormal distribution for $N \geq 2$. In addition to the location of the maximum point (point of maximum likelihood), we can analytically find the axes and orientation of the confidence ellipses of the resulting distribution.

Detection and location results

Seismograms have been available and read from the three microearthquake stations for various time intervals between December 8, 1977, and February 24, 1978, and from KBS for December 1977. The basic detectability results are given in Table 2, where it is seen that a total of 687 earthquakes have been detected at one or more of the stations. 515 of these (or 75%) are local events, being classified as such when at least one S wave is found and/or at least one of the P waves have a frequency above 2 Hz. When comparing the different stations we see from Table 2 that the best station is LYR, where an average of 9.6 events per day (corrected for down times) have been detected, 7.5 of which were local according to our own definition. The poorest station in this respect is the WWSSN station KBS, where the same numbers are 2.4 and 1.3 events per day, respectively. The station PRD is the one for which we can expect the greatest improvements in detectability; this station seems to have the

best seismic noise conditions (being farthest away from the coast), while the performance so far has been reduced by a severe cultural noise problem which now has been solved.

The distribution of detected events with the number of detecting stations is given in Table 3, where it is seen that as many as 41% of the earthquakes are picked up only by one station. It should be emphasized that this number is primarily an effect of non-overlapping recording times, and should therefore not be interpreted as being caused by a variation in detectability. The periods of operation (the average numbers in Table 2 are computed on the basis of a more detailed statistics) are shown in the upper part of Fig. 2, which also shows the number of detected (and located) events for each day. The peak on December 12 is due to a small earthquake swarm from Storfjorden, the same applies to the peak on January 17-18, whereas the large number of events on January 20-21 are caused by a swarm from the mid-oceanic ridge west of Svalbard.

In Fig. 3 we also see the number of located events for each day. Based on the analysis by Mitchell et al (1978) on events from Storfjorden, distances have been computed using a value of k=0.0758 deg/sec in equation (1), with a standard deviation of 0.0040 deg/sec. We have furthermore assumed an uncertainty in picking the P and S arrival times of 0.15 and 0.30 sec, respectively. These values result in a distance uncertainty of about 6 km at a distance of about 100 km It is evident from our results that the assigned value of k is reasonably valid only up to distances of about 120 km from the Storfjorden epicenters; for that reason PS times from KBS have been used in locations when only one other station has reported the event. Using this method of analysis and the uncertainty estimates just described, we find that the location uncertainty axes (95% confidence ellipse) for Storfjorden events located using the 3 microearthquake stations are about 30 and 10 km respectively, the main axis being in the NE-SW direction.

The total number of located events is 234 (Table 2). About one half of the events are located using 2 stations and the other half with 3 stations (Table 3). The locations of the latter ones are shown as an epicenter map in Fig. 4, where a great cluster of events at the west side of Storfjorden appears as the dominating feature. The precisions of the

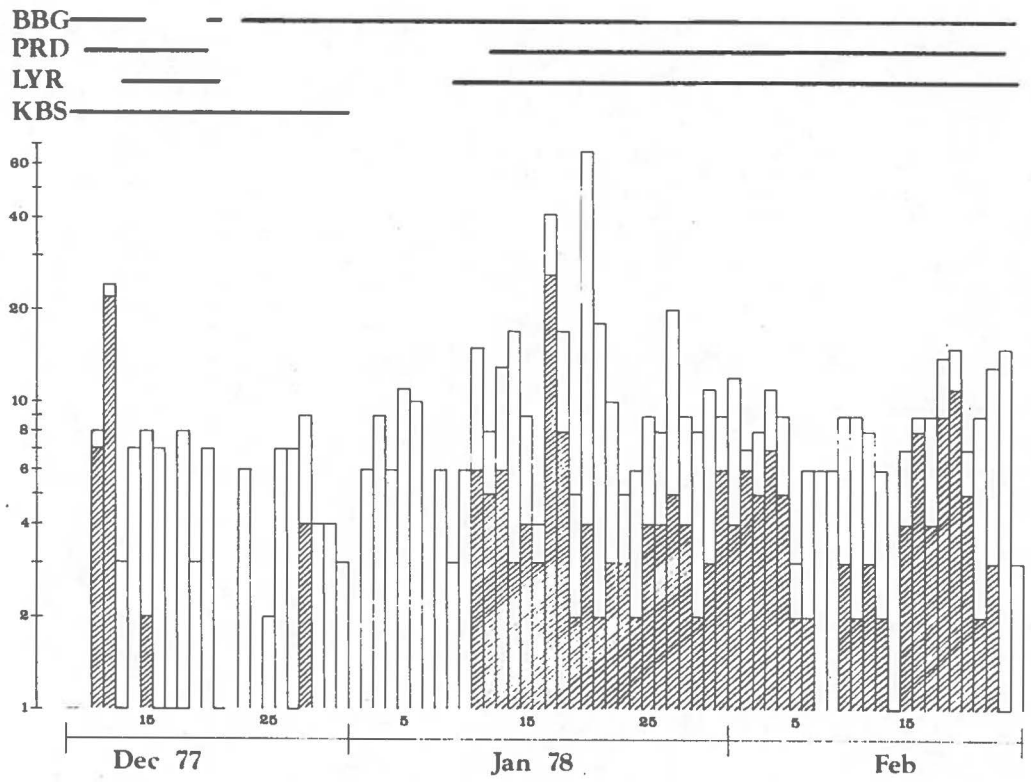

Fig. 3 Number of detected and located (hatched areas) earthquakes for each day between December 8, 1977, and February 24, 1978. For each station the periods of operation are also indicated (top of figure).

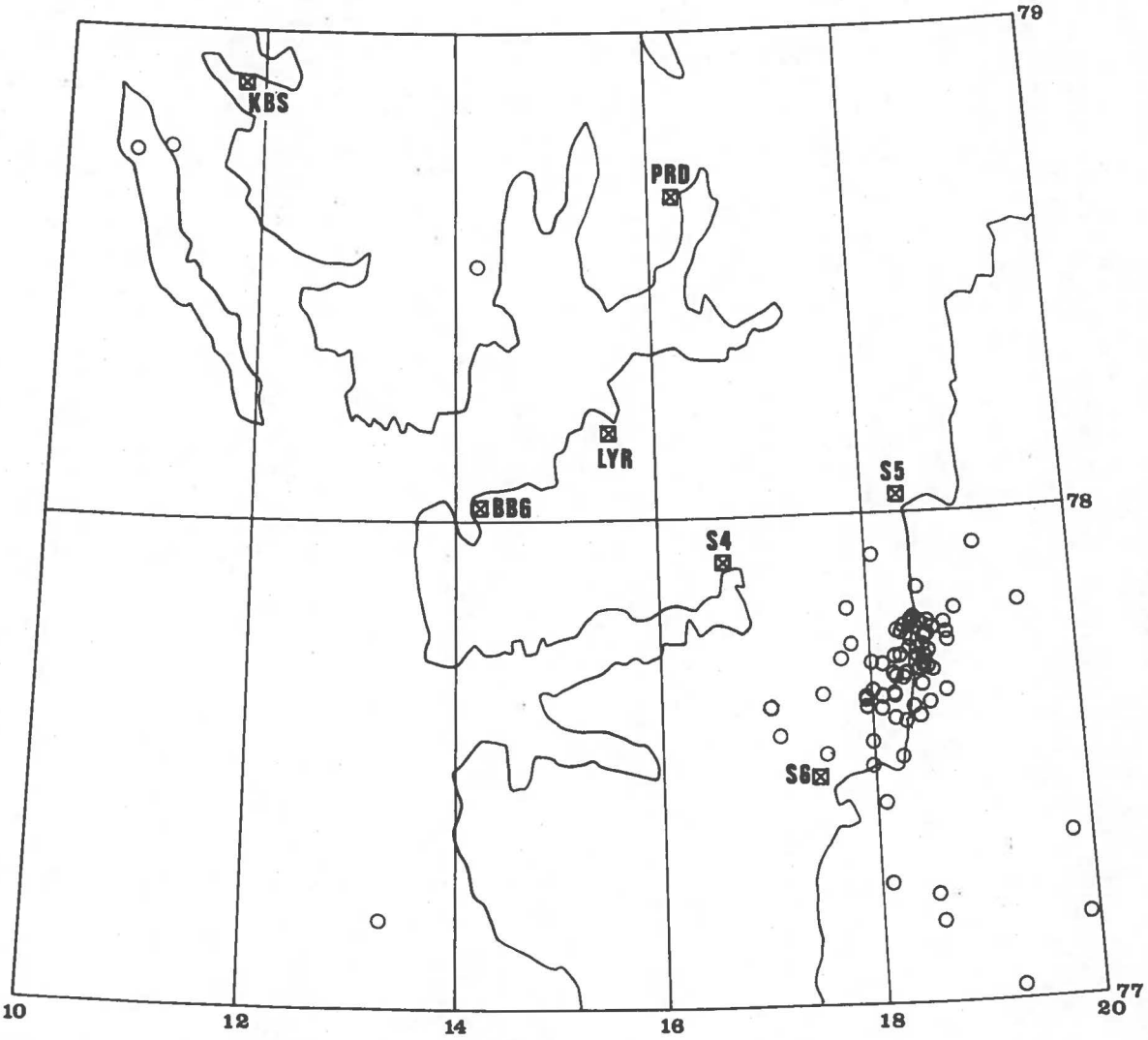

Fig. 4 Epicenter map of earthquakes located on the basis of the three stations BBG, PRD and LYR. The future station in Sveagruva is also indicated (S4), as well as two possible sites on the west side of Storfjorden (S5 and S6), that if available would greatly improve the array configuration.

locations are so far not good enough for a closer delineation of this highly active earthquake zone, since the size of the cluster is not much larger than the computed uncertainty ellipse for each event. The ways and means by which this can be improved are discussed below.

Magnitudes

There are two commonly used ways of computing magnitudes of local events, namely, either from the largest amplitude or from the signal duration. For the purpose of this preliminary study we have used the following formulae, adopted by the US Geological Survey (Lee and Lahr, 1975):

$$M_a = \log(\frac{A}{R_f}) - \alpha_1 + \alpha_2 \log \Delta + C_a \qquad (4)$$

where

A = maximum peak-to-peak amplitude in mm, measured with a frequency f.

R_f = System amplification at frequency f.

α_1 = 0.15, α_2 = 1.60 $\quad 1 \leq \Delta \leq 200$ km

α_1 = 3.38, α_2 = 3.0 $\quad 200 \leq \Delta \leq 600$ km

Δ = epicentral distance in km

C_a = magnitude correction.

$$M_d = \beta_1 + \beta_2 \log D + \beta_3 \cdot \Delta + C_d \qquad (5)$$

where

β_1 = -0.87

β_2 = 2.0

β_3 = 0.0035

D = signal duration, measured as the time between the first P arrival and that where the peak-to-peak amplitude of the seismic trace drops below 1 cm.

Δ = epicentral distance in km.

C_d = magnitude correction.

Using the above formulae, and with the station corrections equal to zero in both cases ($C_a = C_d = 0$), we have computed 'amplitude magnitude' for 231 events, and 'duration magnitude' for 22 events. The small number in the latter case is due to the high threshold in determining the end of the signal; this is necessary in order to avoid having the measurements contaminated by noise, but makes the 'duration' formulae inapplicable for the large number of smaller earthquakes.

Fig. 5 shows the incremental and the cumulative frequency-magnitude distribution for the 231 M_a-calculations, where each of them is an average of individual station magnitudes in cases when the event is detected at more than one station. This distribution usually follows the relationship

$$\log N = a - b \cdot M \qquad (6)$$

where the slope b usually is around 1.0, as indicated in Fig. 5. We see that the incremental distribution peaks at around M=1 and then tapers off down to M=0; that is about what one should expect for a good micro-earthquake network, and it shows that our initial parameter values in equation (4) are not unreasonable. The next step will be to develop independently the attenuation parameters α_1 and α_2 for Svalbard, as well as to consider a non-zero value of the magnitude correction C_a.

The 'duration' magnitudes M_d measured by equation (5) are on the average of the same size as the M_a-values. However, the scatter on the M_a-M_d diagram is quite large, and more data are required for a closer investigation of that problem.

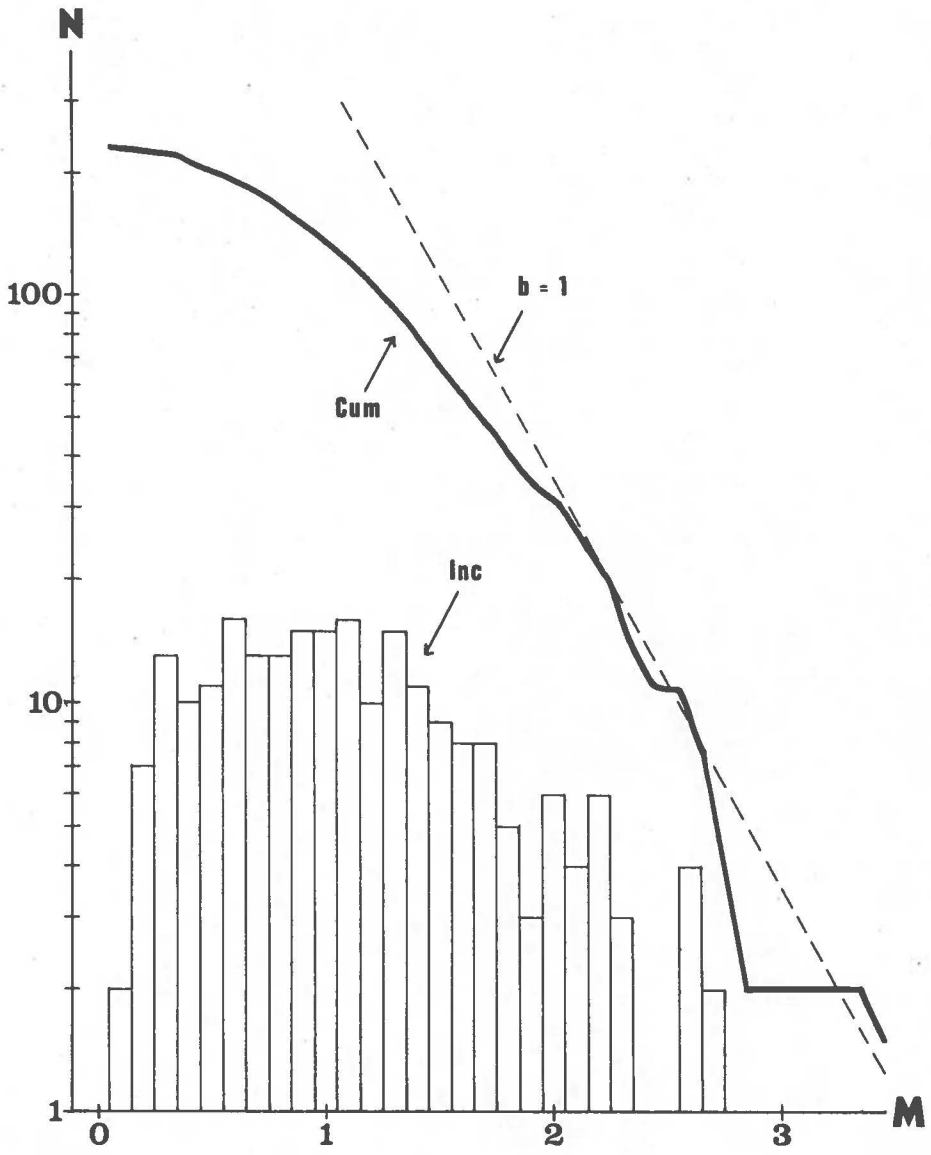

Fig. 5 Incremental and cumulative frequency-magnitude distribution for all earthquakes with magnitude calculated from amplitudes (equation (2)). The dashed line indicates a slope of b=1 in equation (6).

DISCUSSION

The event locations for the data presented in this report can and will be improved by improving the crustal model. From our data and also from the data presented by Austegard (1976) and Mitchell et al (1978) it is evident that equation (1) is not valid for all the epicenter/station combinations covered by these data. We therefore plan to introduce in the location program a crustal model from which P-S times can be calculated for any distance, possibly also allowing for azimuthal variations between interplate ridge events from the west and intraplate events from southeast. Furthermore, we plan to conduct a refraction survey in which timed explosions are fired especially in the Statfjord area, and recorded at the seismic stations, possibly supplemented by sonobuoys.

All the earthquake locations presented in this report are computed exclusively on the basis of the P-S times. When reliable absolute times are made available, this will greatly improve the quality of the locations (for future data, that is). We have seen above that for the Storfjorden events, using the present stations, the greatest uncertainty has been in the NE-SW direction. In knowing the relative times between stations we will first of all reduce this azimuthal variation, while less improvements can be expected in the computed distances.

The ideal configuration of a microearthquake network is such that the epicenter area is surrounded by stations. It is evident from Fig. 4 that this is not the case for the present configuration at Svalbard. However a station now under installation in Sveagruva (labelled S4 in Fig. 4) will improve the situation significantly. A real breakthrough with regard to the investigation of the Storfjorden epicenter area would be possible if additional stations were available in Agarddalen (S5) in Kvalvågen (S6) and on Edgeøya (not on map).

So far as the local Svalbard magnitudes are concerned, an improvement would first of all be dependent on developing local values for the attenuation parameters α_1 and α_2 in equation (4). This can be done as soon as sufficiently precise epicenter estimates are available, however, we may find also in this case that there are significant azimuthal variations.

A second problem is the determination of the absolute level for the magnitudes, for this purpose we need some teleseismically recorded local events from Svalbard.

The most interesting aspect of this investigation of the microearthquake activity of Svalbard is of course the geotectonic interpretation of the data, in particular the Storfjorden earthquakes. This is interesting from a purely geophysical point of view, but it has also obvious practical implications because it has to do with the seismic risk in the Svalbard mines, in particular that of Sveagruva which is only about 40 km away from the Storfjorden epicenter area. Because the data presented in this report are so limited, and also because data with better quality soon will be available, we have deliberately refrained from such interpretation and only concentrated on presenting the seismic bulletin data (detections and locations). The interpretation problem will be addressed in future reports.

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