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Seismicity and present-day tectonics of the Svalbard region

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SUMMARY

Data collected by temporary seismic networks and individual stations over a 7-yr period in the Svalbard Archipelago are integrated and used to study the seismicity and present-day tectonics of the archipelago and surrounding regions. Most of the continental seismic activity occurs in three concentrated zones, one in Heer Land near the eastern coast of the island of Spitsbergen and two, in close proximity to one another, on the island of Nordaustlandet. All three zones are in regions which have been devoid of major orogenic activity since the late Devonian. The Heer Land zone and at least one of the zones in Nordaustlandet define active faulting which has not been identified by surface mapping. The other zone in Nordaustlandet occurs in the region of a mapped system of faults, all branches of which are relatively minor. A number of smaller concentrations and individual earthquakes occur throughout much of the archipelago and surrounding continental shelves. Seismicity is currently low in the region of Tertiary orogenic activity in western Spitsbergen. A roughly linear pattern of minor activity in southern Spitsbergen occurs west of the Heer Land zone and extends at least 50 km southward. The major N–S faults in Spitsbergen which are thought to have accomodated large displacements in Devonian time are currently inactive, except perhaps at the southern termini of the Billefjorden and Lomfjorden fault zones, where they approach the Heer land seismic zone. Earthquakes located near the western continental margin of Spitsbergen may occur on segments of rifting and shearing which reflect the opening of the Greenland Sea during the Tertiary. The limited extent of the currently active zones of activity, their spatial stability over several years, and the lack of activity on the major faults of Svalbard argue against the existence of plate boundaries, along which motion is currently occurring, in the Svalbard region.

All fault-plane solutions on Svalbard are consistent with a stress field characterized by E–W compression, whereas previously published fault-plane solutions for the ridge system west of Svalbard indicate E–W extension. The magnitude of the compressive stress increases from small values near the ridge system to values sufficiently large to dominate the regional seismicity of Svalbard over distances of 200–300 km.

Key words: earthquakes, seismicity, Svalbard, tectonics.

INTRODUCTION

Svalbard is an archipelago located less than 150 km from segments of the Atlantic Ridge system to the west and less than 500 km from the Nansen (or Gakkel) Ridge to the north (Fig. 1). Its crustal thickness and seismic velocities are typical of continental regions (Chan & Mitchell 1982), as are those of most of the Barents shelf stretching southward to the European craton and eastward to Novaya Zemlya (Demenitskaya, Ivanov & Volk 1973; Chan & Mitchell 1985a). Except for a strip along the western coast, major tectonic activity in Svalbard has been absent since late Devonian time. Svalbard thus provides a unique opportunity to study earthquake activity and present-day tectonics in a relatively stable continental platform which lies in close proximity to actively spreading plate boundaries.

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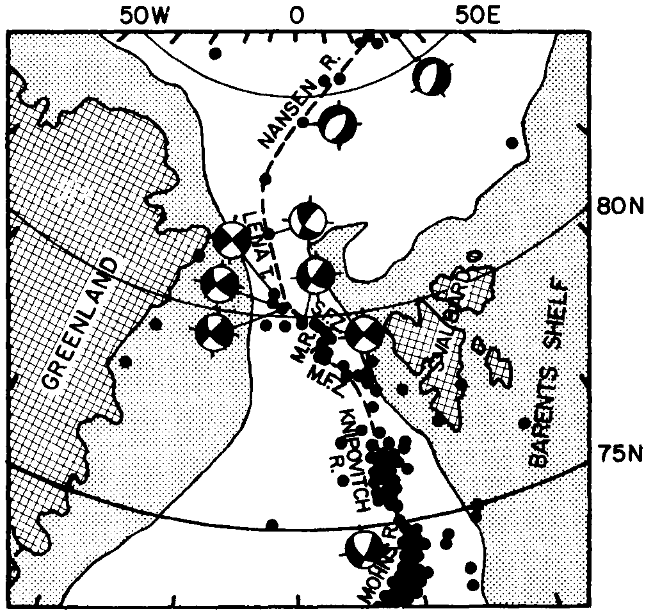

Figure 1. The NW portion of the Barents shelf, including Svalbard, and its relation to oceanic ridge system in the northern Atlantic and Arctic Oceans. The stippled pattern indicates continental shelves and cross-hatching indicates land areas. Teleseismically located earthquakes are shown for the period 1960–1983 (Espinosa & Michael 1984). Focal mechanism solutions are from Savostin & Karasik (1981) and Jensek *et al.* (1986). S.F.Z. denotes the Spitsbergen Fracture Zone, M. R. denotes the Molloy Ridge, and M. F. Z. denotes the Molloy Fracture Zone.

The present paper is a summary of the results of seismicity studies conducted in Svalbard since 1977. Because of the severe climate and difficulties in travel in this remote region, recording periods were often discontinuous and the distribution of seismic stations was often less than satisfactory. We will, however, present a seismicity map of Svalbard which, we believe, is representative of that region. In addition, some of the data allow us to determine fault-plane solutions and to infer stress patterns in that region. Those patterns, plus available geological information, provide information on the present day tectonics of Svalbard and surrounding regions.

TECTONIC SETTING

Svalbard lies in the NW corner of the Barents shelf (Fig. 1) and forms part of the continental structure of Eurasia. Because of its location and because of the variety of geological formations exposed there it has played a key role in unravelling the tectonic evolution of the Arctic.

The tectonic history of Svalbard has been described in several studies (e.g. Harland 1961, 1965, 1969; Sokolov, Krasiltchikov & Livshitz 1968; Kellogg 1975; Faleide, Gudlaugsson & Jacquart 1984). Two events dominate that history and both are related to the movement of Greenland along the western edge of the Barents shelf. The first of these events, the Svalbardian orogeny, occurred in late Devonian time and was a period of folding and faulting with sinistral movement across the entire archipelago. Harland *et al.* (1974) suggested that at least 200 km, and as much as 1000 km, of transcurrent displacement may have been accomodated by the Billifjorden Fault Zone, or have been distributed among two or more faults, at that time. The major faults, along which motion occurred, run predominatly N–S and form the boundaries of the main structural elements of the archipelago (Sokolov *et al.* 1968). Harland (1979) points out, however, that these faults are seldom observed directly because they pass through zones of poor exposure, or are covered by surficial deposits, ice, or water. Harland (1979) also states that there is a ubiquitous distribution of minor faults which are often well exposed and easy to identify and interpret.

The Svalbardian orogeny was followed by relatively stable conditions with minor uplift, warping, and igneous activity, but no major tectonism until the mid-Tertiary. At that time sea-floor spreading began in the Eurasian Basin and Greenland–Norwegian Sea along the Spitsbergen Fracture Zone and Knipovitch Ridge and caused dextral transpression between northern Greenland and Svalbard and causing the West Spitsbergen Orogeny. The effects of that orogen are restricted to a strip along west-central and SW Spitsbergen, the largest island of the archipelago, and smaller islands off the western coast. When Greenland became attached to the North American plate about 36 Myr ago, rifting was initiated and new oceanic crust accreted as an ocean basin formed between NE Greenland and Svalbard (Talwani & Eldholm 1977).

Dextral transcurrent movement along the Spitsbergen and Molloy Fracture Zones continue to separate Svalbard from Greenland and North America. Activity along those zones and along the spreading centres to the north and south of them, the Nansen Ridge and Knipovitch Ridge, respectively, dominate seismicity maps of the eastern Arctic obtained from teleseismic data (Fig. 1). The two northernmost fault-plane solutions in Fig. 1 are taken from Jensek *et al.* (1986) and the remainder from Savostin & Karasik (1981). They indicate that motion along the Knipovitch and Nansen ridges occurs as normal faulting, whereas that along the Spitsbergen fracture zone occurs as strike–slip faulting. All but one of the solutions are consistent with a stress field which is everywhere extensional along the active plate boundary. Because of the high level of seismicity along this boundary, major strains generated by plate tectonic movement are largely relieved at points well to the west of Svalbard. Intraplate seismic activity within Svalbard still occurs, however, especially in a few concentrated zones (Mitchell *et al.* 1979; Bungum, Mitchell & Kristoffersen 1982; Chan & Mitchell 1985b). This intraplate activity and its implications for the present-day tectonics of Svalbard form the main areas of emphasis in this paper.

DATA ACQUISITION AND EARTHQUAKE LOCATIONS

Figure 2 shows the locations of the various seismic stations which operated in the Svalbard archipelago over the period 1977–1986. Some of those stations were deployed as networks intended to record earthquakes which occurred over much of Svalbard and surrounding regions, whereas others were deployed to study specific regions in detail. Periods of operation of the instruments are given in Table 1 and Fig. 2.

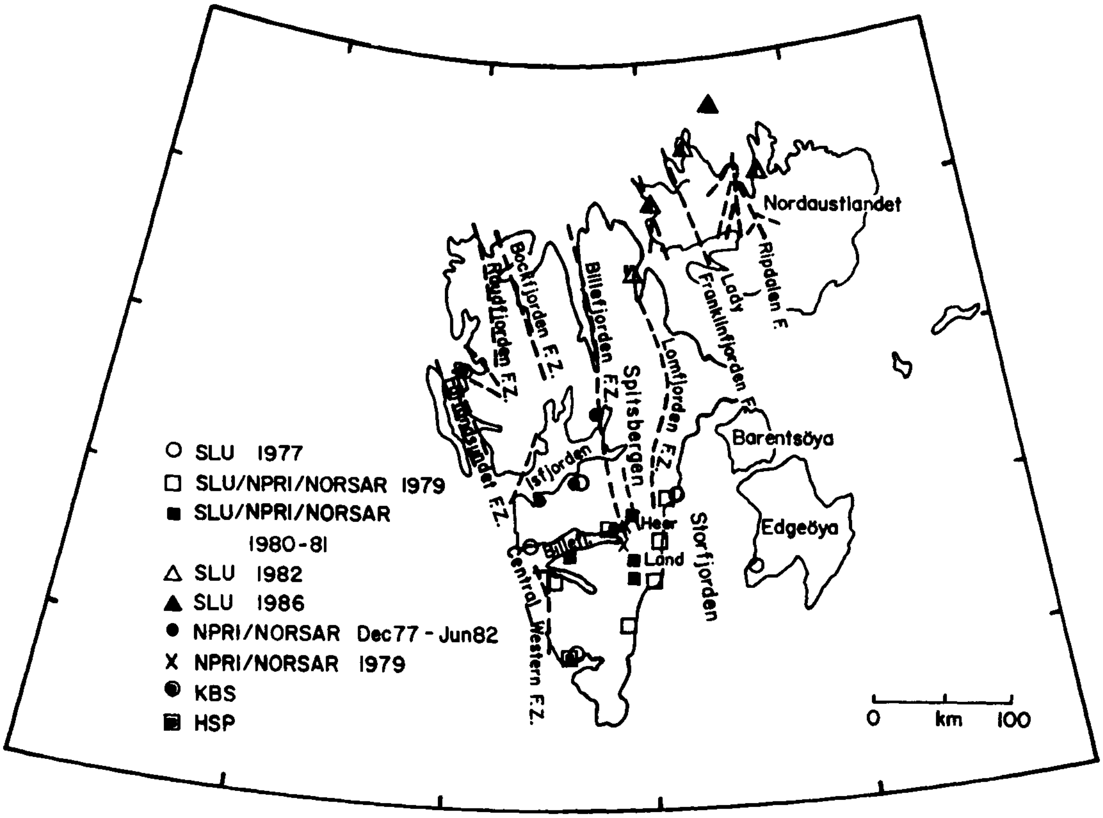

Figure 2. The major faults of Svalbard and seismograph stations which operated there over the period 1977–1986. Half-filled triangles in Nordaustlandet indicate stations that operated in both 1982 and 1986.

Table 1. Periods of recording.

Continuous recording

Stations	Recording period
KBS (WWSSN station)	Continuous over time period of study
NPI/NORSAR network) (four stations)	1977 December 8–1982 June 30
HSP (Hornsund Polish station)	Continuous since 1979 August 2

Recording during summer field seasons

Year	Stations	Recording period
1977	SLU (five portable stations)	1 July–19 August
1979	NPI (two portable stations)	24 July–20 August
	SLU (seven telemetered stations)	1 August–21 August
1980	SLU (four telemetered stations)	12 August–3 October
1981	SLU (four telemetered stations)	6 July–13 September
1982	SLU (four portable stations)	4 July–23 July
1986	SLU (four portable stations)	1 July–30 July

The first data using a seismic network in Svalbard were obtained during the summer of 1976 when a group from Saint Louis University established four stations near Isfjorden in close proximity to a segment of the Billefjorden fault system. Their purpose was to determine the level of activity on this fault which was once the site of major transcurrent movement (Harland *et al.* 1974). Only one small event occurred which could be associated with the Billefjorden fault, but numerous events were recorded which occurred in Heer Land, in a southeasterly direction from the network. Diffuse patterns of poorly located earthquake activity had been reported there earlier using teleseimic data (Husebye *et al.* 1975) and single-station data from the WWSSN station KBS at King's Bay (Austegard 1974).

The Saint Louis University group returned the following summer (1977) and established temporary seismic stations at points surrounding Heer Land (Mitchell *et al.* 1979). They recorded numerous events in that region, most of which occurred in a concentrated zone with an E–W trend. The earthquakes occurred along a fault or system of faults which has not yet been mapped and which is oriented in a direction approximately normal to the trend of most of the major faults in Svalbard.

The Norwegian Polar Research Institute (NPRI), in cooperation with the seismology group of the Royal Norweigan Council for Scientific and Industrial Research (NTNF/NORSAR), installed microearthquake seismographs in mines in the Norwegian towns of Longyearbyen and Svea and the Russian towns of Barentsberg and Pyramiden in December 1977. Those stations, in combination with the WWSSN station KBS, recorded numerous events in Svalbard and surrounding regions year-round over a period of $4\frac{1}{2}$ yr until June 1982. Large uncertainties were, however, associated with the locations of those events since the network aperture was quite large and because absolute timing was not available at the mine stations, a situation forcing the use of $S-P$ times for the locations.

In a cooperative project, Saint Louis University (SLU), NPRI, and NTNF/NORSAR installed a seven-station telemetered network surrounding the Heer Land zone in

July 1979. That network operated through the end of August 1979 at which time it ceased operation because of ice damage to the antennae at high-altitude stations. It operated again during the summer months of 1980 and 1981, but at new station sites forming a smaller network aperture. Three portable stations were also operated during the summer of 1979 by NPRI. The combined data from the telemetered network and the portable instruments were analysed and used to obtain relatively precise earthquake locations in Heer Land and approximate locations outside of the network area (Bungum *et al.* 1982). In addition to the concentrated earthquake zone in Heer Land, found by Mitchell *et al.* (1979), that study indicated another concentration of earthquakes, with an apparent E–W trend, in Nordaustlandet at a latitude of about 80°N. Since the stations were located 200 km and more from that activity, however, those earthquakes could not be located well.

During the summers of 1982 and 1986, Saint Louis University emplaced four portable seismographs around the concentration of earthquakes in Nordaustlandet. The data from 1982 revealed that what had been thought to be a linear E–W trend was really at least two concentrations of earthquakes oriented in approximate N–S directions and separated by several kilometres (Chan & Mitchell 1985b).

The Polish Academy of Sciences began to operate a group of seismographs (HSP) at their base at Hornsund in August 1979 and have reported arrival times from then until June 1985 (Gorski 1986). This period of operation overlaps portions of the operating intervals of the SLU and NPRI stations.

The preceding paragraphs describe a diverse set of instrumental recordings of earthquakes on Svalbard and surrounding regions. Limited portions of the data have been reported and interpreted in previous papers; however, it has not been possible until recently to combine all of the data in an integrated study. The present report is an attempt to do that and to interpret those data in terms of the present-day tectonics of the Svalbard region. Some data, such as that collected by Saint Louis University during the summers of 1980, 1981, and 1986, will be reported for the first time. For the period of recording 1977–1981, we have, whenever possible, combined data collected by Saint Louis University, NPRI, KBS, and HPS. In many instances this has led to locations which are much improved over those obtained by using data obtained by any of those groups separately.

Locations in previous seismicity studies on Svalbard employed a variety of methods, depending on whether the events occurred within or outside the network and whether or not uniform timing was available for all stations (Bungum *et al.* 1982). In the present study, we apply the same location method for all events. It is a modification of the program FASTHYPO (Herrmann 1979) which employs Geiger's method for locating local and regional earthquakes using P-wave and S-wave times. The modification allows $S-P$ times to be used as well as either P-wave times or S-wave times in any combination. Thus $S-P$ times can be used for seismograms where timing is uncertain and absolute P times and/or S times can be used for seismograms on which time is well determined. The velocity model used for the locations is the model of Chan & Mitchell (1982) for central Spitsbergen. It consists of four crustal layers having thicknesses of 4.1, 10.0, 7.4, and 5.8 km and compressional wave velocities of 4.65, 6.21, 6.30, 6.65, and 7.90 km s^{-1} with increasing depth, overlying an upper mantle velocity of 8.15 km s^{-1}. Shear wave velocities are assumed to be related to compressional wave velocities by a Poisson's ratio value of 0.25.

Figure 3 shows a seismogram recorded by a portable instrument on Edgeoya over a 24-hr period in July 1977 and Fig. 4 shows a seismogram from a telemetered station recorded over a 24-hr period in August 1980. These seismograms indicate the relatively high rate of occurrence of small earthquakes in this region, a situation which has allowed us to map seismicity patterns accurately even though recording periods may be of limited duration. Note also the relatively low noise levels even though the gain settings for the instruments are about 500 000. These high signal/noise levels lead to sharp, well-determined first breaks of seismic phases, even for small events. Stations at remote sites away from the mining towns on Svalbard are all characterized by similarly low noise levels, except during periods of high wind. At those times the magnifications were reduced to values as low as about 20 000.

SEISMICITY PATTERNS

Several hundred earthquakes in Svalbard and surrounding regions were detected over the period 1977–1986, but a much smaller number were locatable. Those earthquakes which were located with an uncertainty of 30 km or less appear in Fig. 5. The most conspicuous feature of the map is the concentration of earthquakes which extends through Heer Land and across the coast into the western part of Storfjorden. Two concentrations occur side by side in Nordaustlandet, both with an apparently NNW orientation. Numerous other small earthquakes occur throughout Spitsbergen, Edgeoya, Nordaustlandet, Storfjorden, and water-covered shelf areas near the western and northern coasts of Spitsbergen. It is interesting that no earthquakes, except perhaps a few near the Heer Land concentration, appear to have occurred on any of the major N–S faults on the island of Spitsbergen. Several of the oceanic earthquakes appear to be associated with the Knipovitch Ridge, the Molloy Fracture Zone, and the Molloy Ridge. Others are not associated with those features, but lie clearly outside the 500 m contour, and must be oceanic intraplate earthquakes.

Several epicentres lie 30 km or less from the continental margin west of Svalbard. Given the large uncertainties in those locations it is possible that many or most of those earthquakes actually lie on the margin. The located earthquakes in this region occur diffusely throughout much of the near-margin parts of the shelf. This pattern contrasts with the seismicity within continental Svalbard which is largely concentrated in three small zones. Recent work by Eldholm, Faleide & Myhre (1987) and Myhre & Eldholm (1988) indicates that the margin consists of rift and shear segments reflecting the stepwise opening of the Greenland Sea. The offshore seismicity mapped in the present study supports the hypothesis of those workers that the western Svalbard margin is fault-related.

A linear pattern of earthquakes occurs to the north of the Knipovitch Ridge and appears to be continuous with it. This pattern may indicate that the Knipovitch Ridge should extend northward beyond the northern terminus mapped by

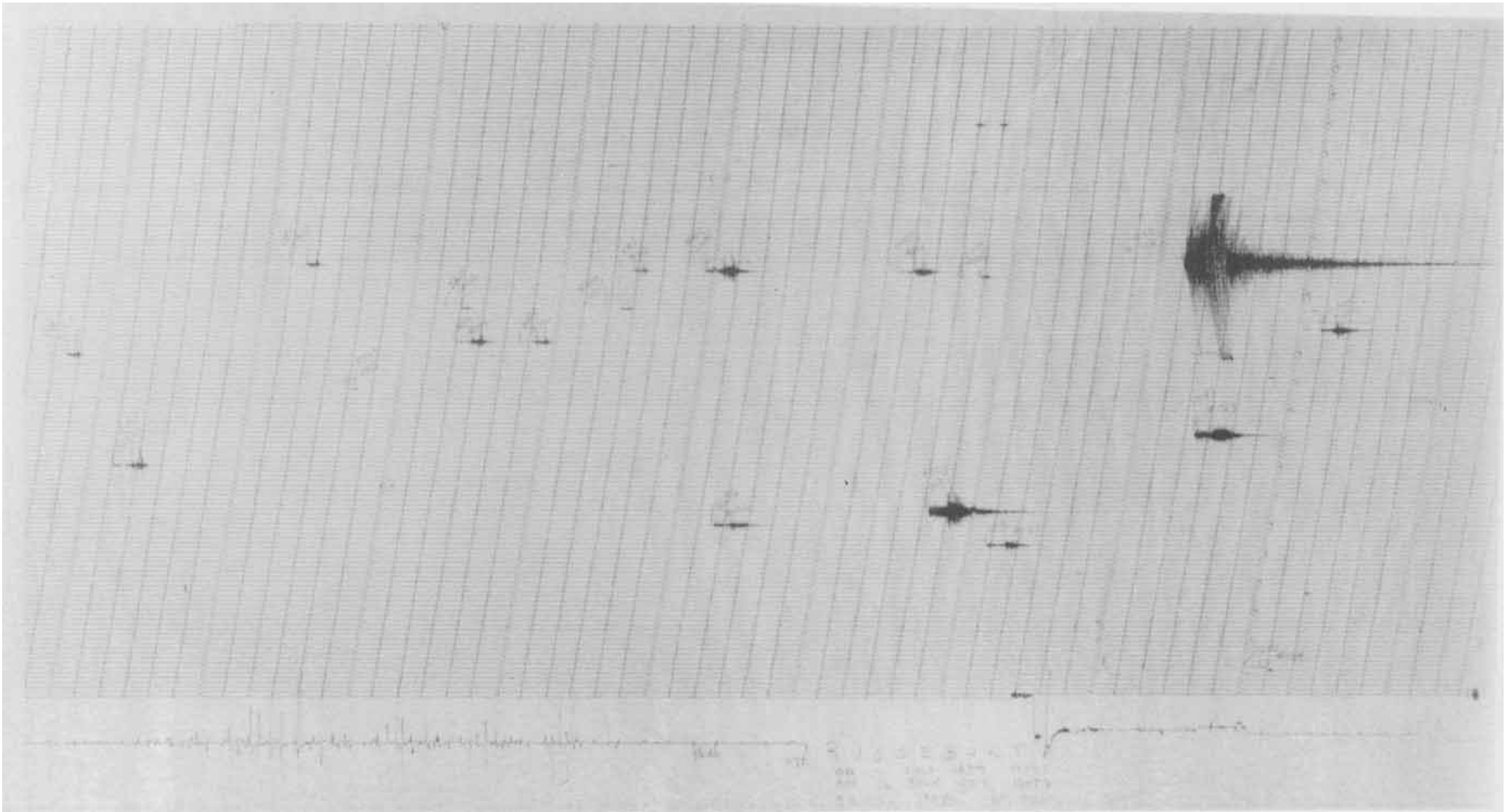

Figure 3. Example seismogram from a temporary portable instrument at a station on Edgeoya for a 24-hr period over 1977 July 11–12.

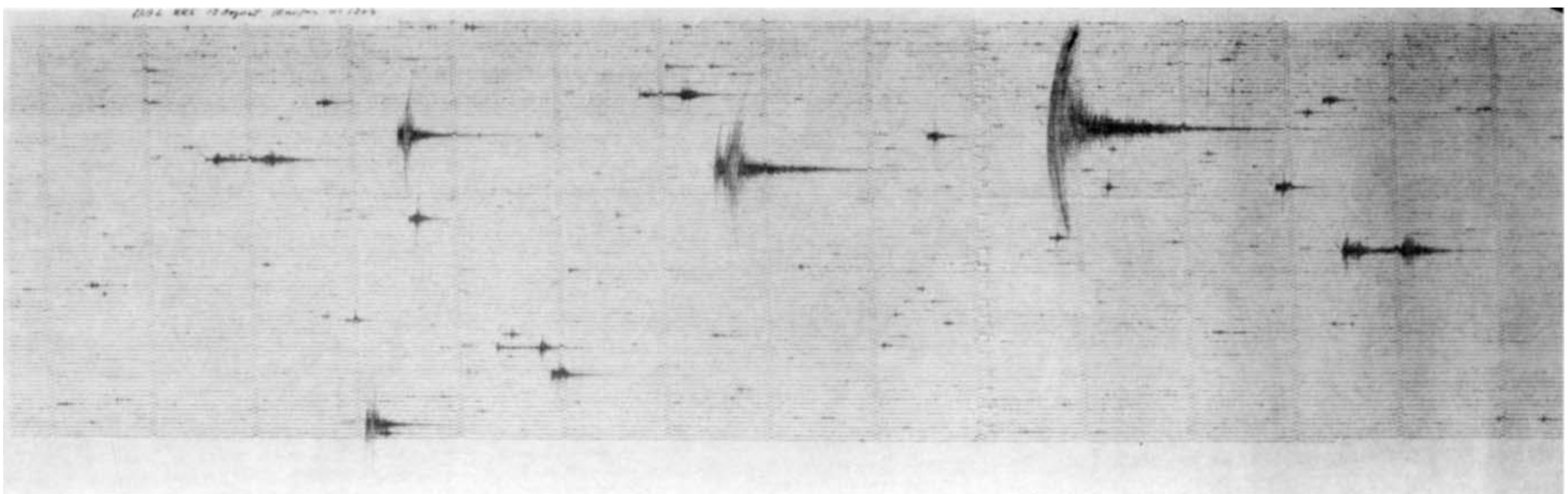

Figure 4. Example seismogram from a telemetered instrument at a station in southern Spitsbergen for a 24-hr period over 1980 August 13–14.

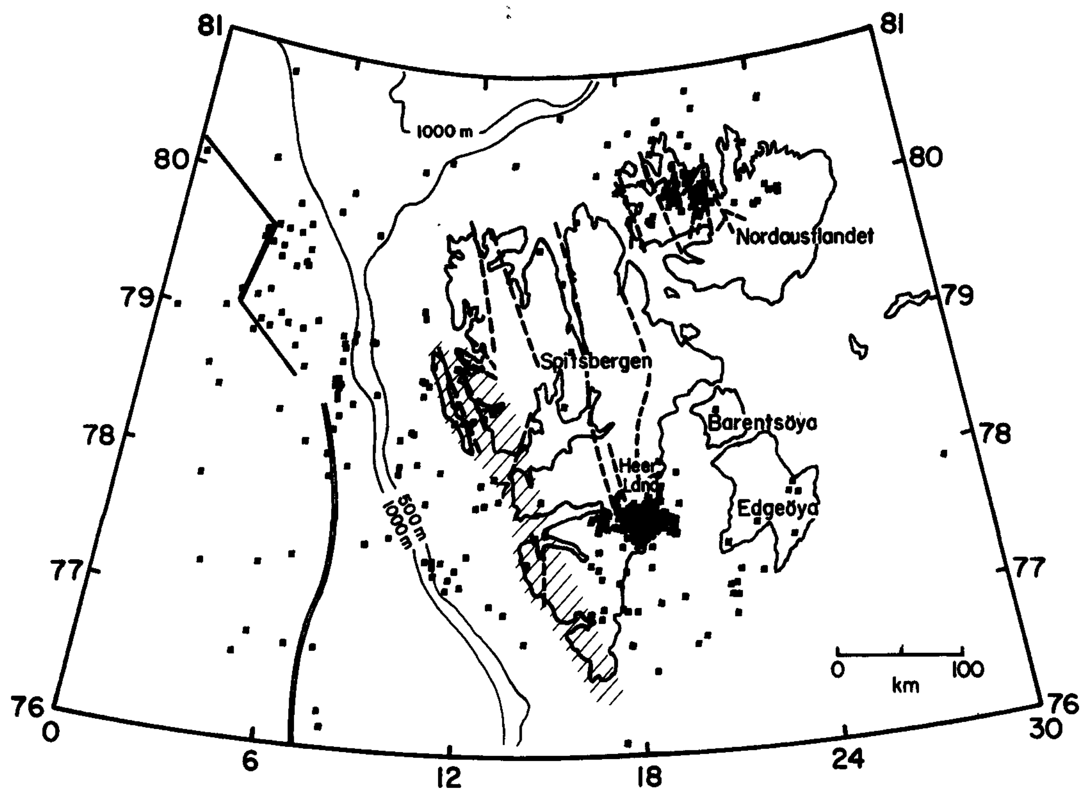

Figure 5. Earthquakes in Svalbard and surrounding regions over the period 1977–86 which were located with an uncertainty of 30 km or less by regional instruments. Cross-hatching marks the region affected by the West Spitsbergen orogeny of Tertiary age. Heavy dashed lines denote segments of the oceanic ridge system identified in Fig. 1 and the faults identified in Fig. 2.

Sundvor & Eldholm (1979) from magnetic data as shown in Fig. 5. Those earthquakes may, however, be systematically mislocated since the velocity model used for the locations is a continental model which differs considerably from the structure in oceanic regions. Even in continental regions many of the earthquakes outside Heer Land and Nordaustlandet could not be located well enough to be associated with specific tectonic features.

The frequency of earthquakes in Heer Land and Nordaustlandet appears to be much higher than that along the oceanic ridge system. This comparison is, however, misleading because networks were emplaced in Heer Land and Nordaustlandet for extended periods of time and earthquakes of smaller magnitude could be detected, whereas the spreading zone earthquakes occurred at large distances from the recording stations and only the larger earthquakes could be detected there.

Far fewer earthquakes can be located with an uncertainty of 5 km or less (Fig. 6), and almost all of these are in Heer Land or Nordaustlandet. A few apparently well-located earthquakes occur in water-covered areas of the shelf and two are near the Spitsbergen fracture zone, but those locations are likely to be biased by large systematic errors which do not show up in the formal solution. The concentrated zones occur as diffuse patterns with linear trends which are indicative of active faults. Those zones are discussed in detail in the following paragraphs.

Previous teleseismic data sets (Husebye *et al.* 1975) and single-station data from KBS (Austegard 1976) indicated a diffuse pattern of earthquakes near the Heer Land zone shown in Fig 6. The first indication that those earthquakes occur in a very concentrated zone, with most epicentres forming an E–W, roughly linear, pattern was obtained by a temporary network deployed in the summer of 1977 (Mitchell *et al.* 1979). Because of the relatively high level of seismicity in this region, Mitchell & Chan (1978) designated it the Heer Land seismic zone. The NPRI network which operated from December 1977 to June 1982 (Bungum *et al.* 1978; Bungum & Kristofferson 1980) recorded an average of several earthquakes a day from that region, the level of activity for any time period being, however, highly variable.

Mitchell & Chan (1978), using surface waves, found that the depths of the two largest earthquakes to have occurred in that zone in recent years were 5 and 3 km. In addition, they found that first arriving *P*-waves had apparent velocities corresponding to lateral travel through the upper crust, a result indicative of shallow focal depths. For these reasons, all epicentres in the present study, as well as in Bungum *et al.* (1982), have been determined holding the depth fixed at 4 km.

Figure 7 shows patterns of earthquake locations obtained during four recording periods during the summers of 1977, 1979, 1980, and 1981. Only those locations are plotted for which four or more phases were recorded at three or more stations and the standard deviations of the locations were 5.0 km or less. For all four years the greatest number of earthquakes was concentrated just west of the boundary between Heer Land and Storfjorden. Few, if any, of those earthquakes appear to be associated with the Billefjorden or Lomfjorden faults; the greatest concentration of activity is

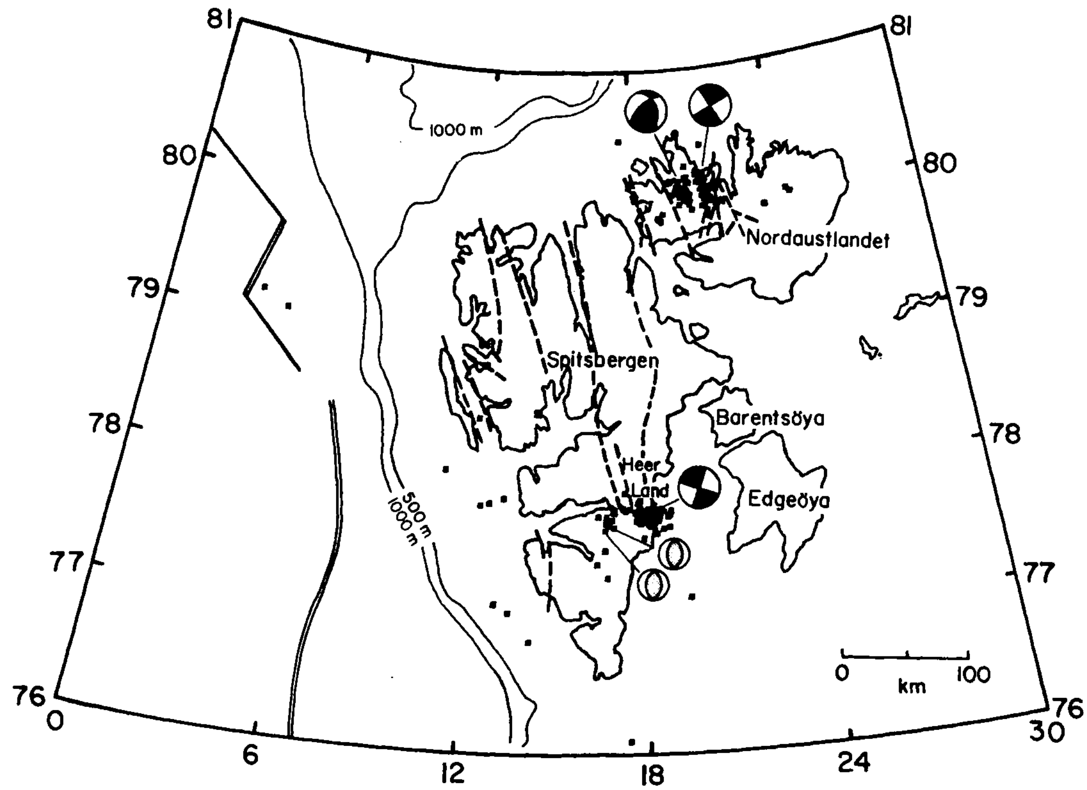

Figure 6. Earthquakes in Svalbard and surrounding regions over the period 1977–86 which were located with an uncertainty of 5 km or less by regional instruments. Large focal spheres indicate fault-plane solutions obtained by Mitchell *et al.* (1979) and Chan & Mitchell (1985b). Smaller focal spheres, with shading, denote poorly constrained solutions obtained in the present study. Heavy dashed lines denote the segments of the oceanic ridge system identified in Fig. 1 and the faults identified in Fig. 2.

well separated from those faults and the epicentre pattern is oriented E–W at right angles to them. Those faults are, however, the closest mapped faults to the concentrated seismic zone; if their southern ends are covered by surface deposits it is possible that they extend into that zone and that some earthquakes occur on them. Outside the concentrated zone the level of activity varies considerably. During some years, especially 1981, activity occurred to the south and east of the mapped portions of the Billefjorden fault zone. The lower two panels of Fig. 7 show the total number of events located in Heer Land over the period 1977–1981 using three stations and four phases or more, and using four stations or more, and standard deviations of 5 km or less. The three-station locations indicate that several earthquakes are located to the south of the mapped portion of the Billefjorden fault zone. Locations using four or more stations are plotted because of the possibility that inaccurate readings might cause large errors in the three-station locations. Several of those locations also lie to the south of the mapped fault zone. Modest earthquake activity does therefore appear to occur in that region, but few, if any of them, are aligned with the Billefjorden fault zone. Most of the earthquakes occur well to the west of the fault zone and they extend about 50 km southward from it. It is, of course, possible that the Billefjorden fault is obscured by surface deposits there and dips at shallow angles to the west producing earthquake locations at depth which are significantly offset from an extension of the surface exposure of the fault. Such dip angles do not, however, seem appropriate for a fault known to have primarily undergone transcurrent movement in the past.

Seismicity from records obtained in Nordaustlandet in 1982 and 1986 appears in Fig. 8, where we have plotted all events which were recorded at four stations. The lower part of the figure shows the total number of earthquakes located during the two seasons by four stations and by three stations and four phases. The similarity of the earthquake patterns using different numbers of stations indicates that the three-station locations yield patterns which can be related to tectonic features. There are two major concentrations of earthquakes, both forming patterns with a NNW trend and separated from one another by about 15 km. The NNW trend is in the same direction as the major mapped faults of the region, but it is difficult to associate either concentration with particular faults. The westernmost concentration lies 10–20 km east of the Lady Franklinfjorden fault and appears to be unrelated to it. Harland (1979) describes this fault as being characterized by dip–slip movement with downthrow to the west. Thus, any deep-seated seismicity associated with it should be located to the west of the fault rather than to the east as indicated in Fig. 8.

Some of the earthquakes in the eastern concentration appear to be situated along segments of a fault system mapped by Flood *et al.* (1969). Harland (1979), however, shows only the easternmost NNW trending branch of that system and designates it the Rijpdalen fault. The seismicity of Fig. 8 is all to the west of that fault and does not appear to be associated with it. The seismicity patterns do, however, coincide with some of the more westerly branches of the system of faults mapped by Flood *et al.* (1969). If the earthquakes are associated with that system the apparent NNW trend of the seismicity pattern must be illusory

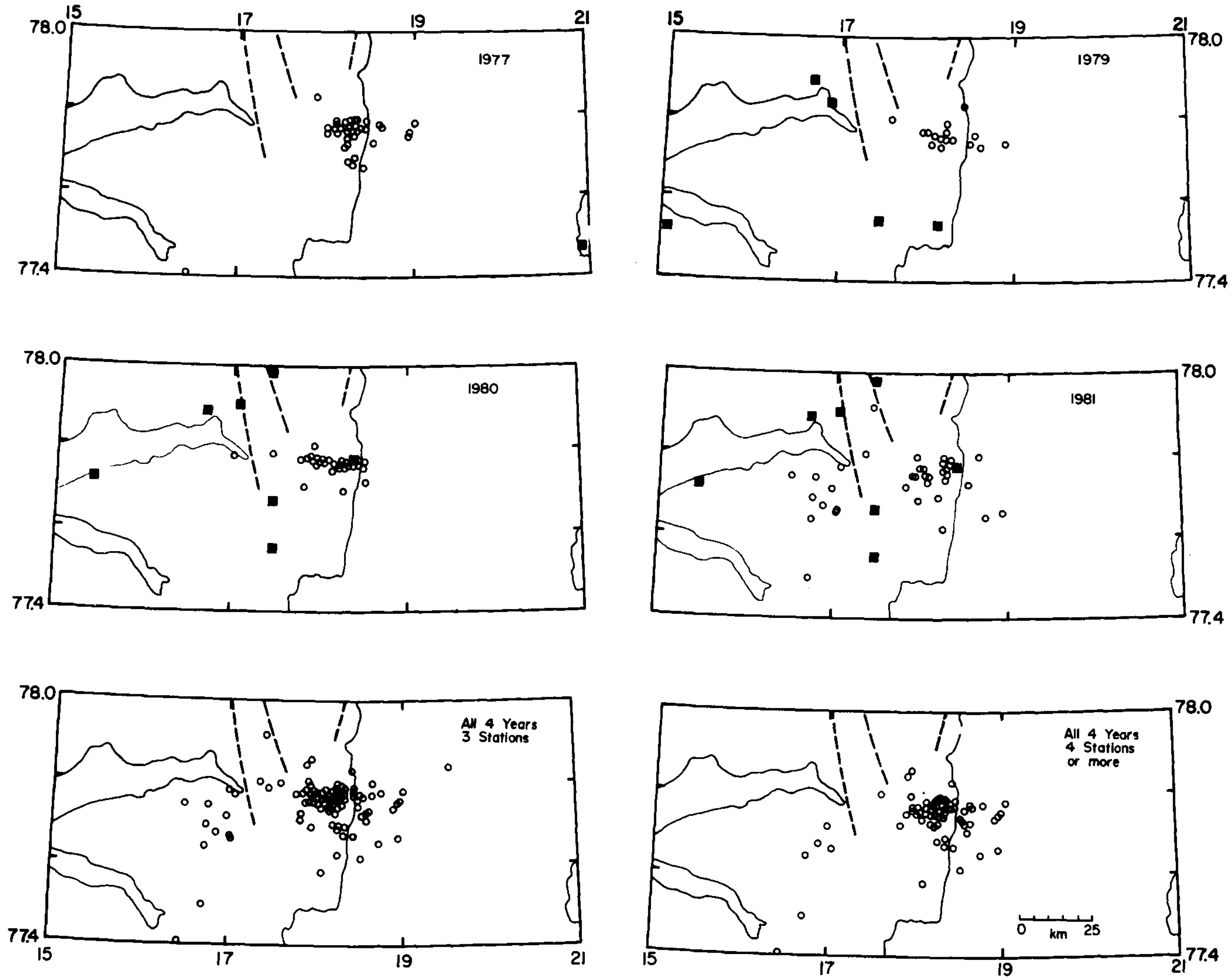

Figure 7. Earthquakes located in, and off the coast of, Heer Land during portions of the years 1977, 1979, 1980, and 1981 using three or more instruments and four or more phases. The total number of earthquakes located using three or more instruments and four or more phases and the total number located using four or more stations are also shown. Dashed lines indicate the southern end of the mapped portions of the Billefjorden fault zone (left) and the Lomfjorden fault zone (right) and squares denote seismic stations. Several stations are also situated outside the areas of the plots.

and various groups of earthquakes must be associated with different NNE trending branches of the fault system. This possibility will be considered further in the section on fault-plane solutions.

Our studies over several years indicate that the major earthquake zones in Svalbard are of very limited extent, at most only about 40 km in length. Moreover, these concentrations of seismicity are spatially stable over periods of several years. These results, along with the lack of activity of the major mapped faults of Svalbard, indicate that there are no long throughgoing lines of activity within the archipelago that could be interpreted as active plate boundaries as proposed by Savostin & Karasik (1981). It appears preferable to interpret the concentrated zones as zones of weakness in which accumulated stress is released along old faults as proposed by Sbar & Sykes (1973), even though the active faults or portions of faults may not have been mapped.

A further question is why only some faults or portions of them are currently active, even though numerous faults appear to be properly oriented in the stress field for motion to occur. Al-Shukri & Mitchell (1988) proposed an answer to this problem for the New Madrid seismic zone in the central United States which may also be applicable to Svalbard. At New Madrid, those authors observed significant reductions in crustal velocities in the most active part of the seismic zone. The magnitude of those reductions is consistent with the velocity reduction produced by fluids in microcracks in laboratory experiments (Nur & Simmons 1969). Al-Shukri & Mitchell (1988) suggest that the presence of fluids for which the pressure is a significant fraction of total pressure in cracks and microcracks in fault zones could reduce the effective stress levels sufficiently to initiate fault movement. Thus, only those faults or portions of faults where sufficient amounts of fluids are present would be active. Others, even if oriented favourably in the regional stress field, would be inactive. It would be interesting to pursue similar studies in Svalbard to investigate the

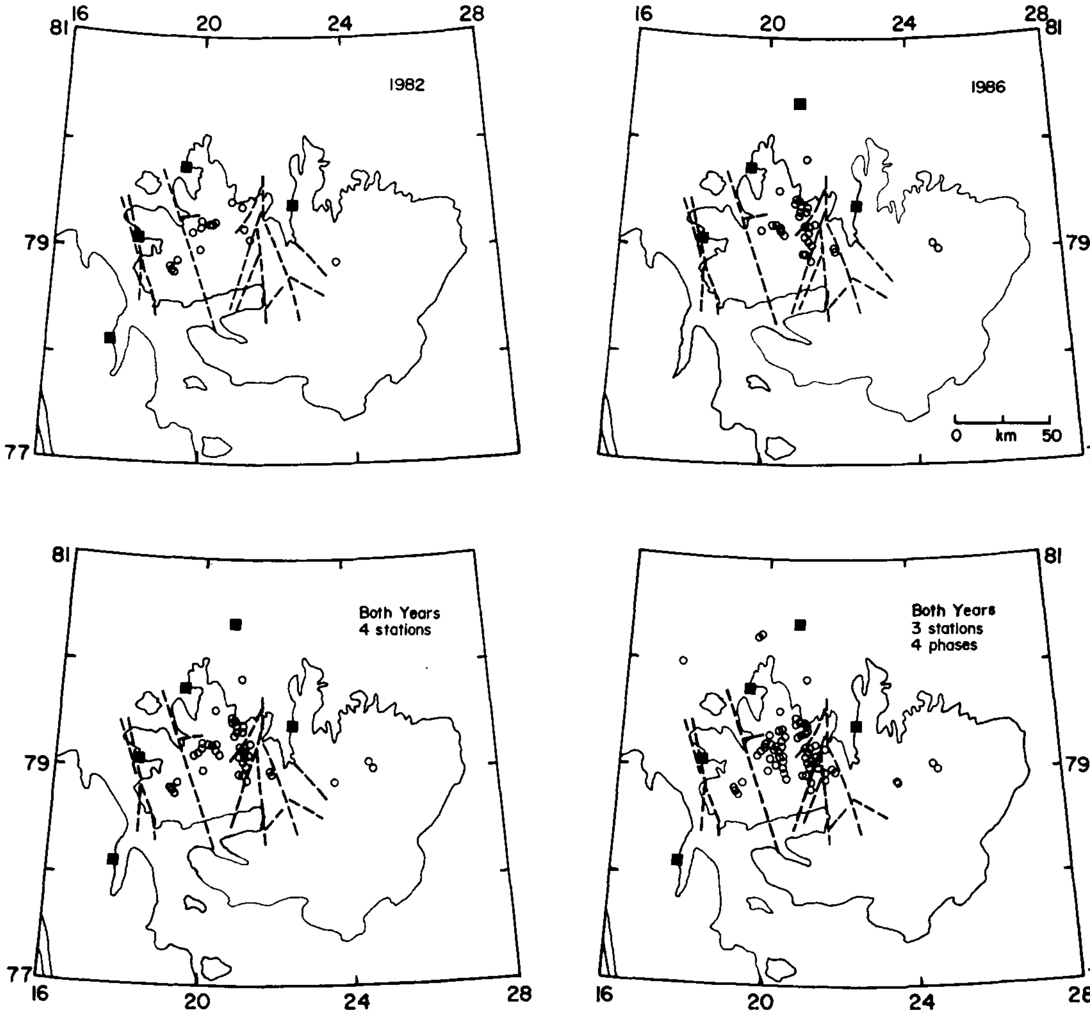

Figure 8. Earthquakes located in Nordaustlandet. Earthquakes located using four instruments are plotted for 1982, 1986, and for both years. Earthquakes located for both years using three stations or four or more phases are also shown. Dashed lines indicate the Lady Franklinfjorden fault and the Ripdalen fault (Flood *et al.* 1969) as identified in Fig. 2, as well as other mapped, but unnamed faults. Squares denote seismograph stations which operated for approximate 1-month periods in 1982 and 1986.

possibility of reduced velocities, and by inference, the presence of fluid-filled cracks, in the seismically active zones of that region.

MAGNITUDES

Noise levels on Svalbard, except for windy days, are very low at the frequencies at which our instruments operated (5–10 Hz). Thus, very small earthquakes could be detected and often located. The range of magnitudes for locatable events during our 7 yr of recording was 0.3–4.5, but the magnitude thresholds varied greatly from region to region and for different time periods for a given region, depending on the density of seismic stations. The lowest threshold was about 0.3 for the Heer Land seismic zone at times when it was well-instrumented, such as the summers of 1977 and 1979. Earthquakes in regions more distant from the stations have much higher thresholds. For instance, Nordaustlandet earthquakes, when recorded by a network around Heer Land in 1979, had a threshold of about 2.0 (Bungum *et al.* 1982). The threshold for earthquakes on the oceanic ridge system east of Svalbard can be expected to be even higher.

With the exception of one event, magnitudes for earthquakes located throughout southern Spitsbergen, including the Heer Land region, ranged from 0.3 to 2.4 during the time of recording by regional networks. The one exception was the Heer Land earthquake of 1977 July 17 for which $m_b = 4.5$. Seven other events between 1964 and 1976 had body wave magnitudes of 4.0 or greater, the largest having occurred on 1976 January 18 for which $m_b = 5.5$ (Bungum & Kristoffersen 1980). Magnitudes for located Nordaustlandet earthquakes ranged from 0.6 to 3.9, with all earthquakes with magnitudes greater than 2.3 occuring during the recording period of 1979 when all instruments were in the Heer Land region. *b* values obtained from frequency–magnitude distributions varied widely with time in both Heer Land and Nordaustlandet. The Heer Land value was about −1.4 over a 5-month period in early 1978 (Bungum & Kristoffersen 1980) and about −0.85 over two 3-month periods in 1980 and 1981 (Chan 1983). The Nordaustandet *b* value in 1979 was about −0.5 (Bungum *et al.* 1982) as compared to −0.85 in 1982 (Chan & Mitchell 1985b).

FAULT-PLANE SOLUTIONS AND CRUSTAL STRESSES

Teleseismic data for the Heer Land earthquake of 1976 January 18 ($m_b = 5.5$) has provided the only well-determined fault-plane solution of an individual earthquake in Svalbard (Bungum 1978; Mitchell *et al.* 1979; Bungum & Kristofferson 1980). The Bungum & Kristofferson solution used the combined data of the previous solutions and had one fault plane striking N108°E and dipping 85°S and the other striking N17°E and dipping 88°E. Both nodal planes are nearly vertical and one of them (see Fig. 6) is aligned in the same direction as the trend of seismicity in the Heer Land zone. If that is the fault plane, then movement on the fault for that earthquake was in a sinistral sense. First-motion data for the earthquakes with magnitude values of 1.5–2.4 in the Heer Land zone in 1977 were consistent with the solution obtained from teleseimic data (Mitchell *et al.* 1979); thus the first motions for the small earthquakes in that region reflect the same stress field as does the larger event.

The earthquakes in Fig. 6 which occur to the south of the Billefjorden fault zone are of special interest because they could provide information on the present nature of movement on a N–S trending fault. Only four well-determined first motions are available for two of those events, so only the crudest fault-plane solutions can be obtained. The available data, from recordings to the east of the earthquakes, are all dilatations. Although their distribution is limited, they appear to rule out significant strike–slip faulting in that region and suggest that reverse motion is dominant.

Two composite fault-plane solutions were obtained for groups of earthquakes which occurred on Nordaustlandet in 1982 (Chan & Mitchell 1985b). When the best data collected in the 1982 and 1986 field seasons are combined and only earthquakes with well-defined locations are used, we find that they provide well-determined composite fault-plane solutions for two segments of the fault systems (Fig. 6). The first-motion data for these regions can be explained by mechanisms which are predominantly strike–slip, but the incomplete data coverage permits reverse motion. Regardless of the specific mechanism, compressive stresses in an approximate E–W direction are required in both cases. Comparisons of the mechanisms with the trends of seismicity indicate that one nodal plane of the solution is aligned with the trend of seismicity in both solutions. This is perhaps relevant to the discussion in an earlier section where the question of whether the eastern zone of seismicity was associated with a single NNW trending fault or with more than one NNE trending fault was considered. The first motion data are consistent with the interpretation of a single NNW trending fault, but if this interpretation is correct it would mean that the presently active fault cuts across branches of the older mapped fault system. The alternative interpretation, that the first motions are produced by two or more separate faults oriented in the same direction, also requires that the nature of fault movement on those faults be the same. Because the former interpretation would require active faults to cut across previously existing faults, we favour the latter interpretation which implies dextral strike–slip motion on two or more NE–SW trending faults.

All of the fault-plane solutions for Svalbard are consistent with a stress field in which the maximum principal stress axis is oriented approximately E–W. The fault-plane solutions for both the Heer Land seismic zone and Nordaustlandet imply that the minimum principal stress axis is oriented approximately N–S, whereas the poorly determined solutions for the two earthquakes south of the Billefjorden fault suggest that it is oriented vertically. If those solutions are correct either the minimum principal stress axis changes orientation from N–S to vertical going westward from Heer Land or the direction of fault motion is controlled by the orientation of the faults in that region.

Hast (1969) obtained an *in situ* stress measurement in central Spitsbergen for which the maximum principal stress is horizontal with a strike of N102°E. The directions of the maximum principal stress axes inferred from the fault-plane solutions of this study vary between N62°E and N110°E. There is therefore rough agreement between the two types of measurement that the direction of the maximum principal stress axis throughout Svalbard is approximately E–W and roughly perpendicular to the trend of the ridge system west of the archipelago.

The consistency of the directions of the maximum principal stress axes suggests that they are caused by a single mechanism and that it is related to plate tectonic forces. Stresses are extensional along the ridge system to the west of Svalbard and compressional on Svalbard itself. It is known that ridge pushing forces are important factors in producing compressive stresses at some distance from spreading ridges (e.g. Solomon, Sleep & Richardson 1975; Richardson, Solomon & Sleep 1979). Since that pushing force is restricted to oceanic lithosphere sufficiently young that density structure continues to change with age (Hager 1978), extension occurs over a very narrow zone and compression should then dominate at greater distances from the ridge. The present study shows that the compressive stress field increases sufficiently over distances of about 200 km in Heer Land and about 300 km in Nordaustlandet to produce a high level of seismicity in those regions. Assuming an age of 35 Myr (mid-Tertiary) for the oceanic crust at the Svalbard continental margin (about 40 km from the ridge system), the stress calculations of Dahlen (1981) for an oceanic lithosphere adjacent to a ridge system in isostatic equilibrium, predict deviatoric compressive stress levels of about 200 bar at a depth of 5 km in the crust. That level of stress is, apparently, great enough to cause earthquakes at the rifted and sheared continental margin off western Svalbard. On the continental side of the margin, the stress calculations of Dahlen (1981) may no longer be applicable, but if stresses continue to increase with increasing distance from the ridge in continental regions, then they will be higher within Svalbard than they are at the margin.

CONCLUSIONS AND DISCUSSION

The seismicity of Svalbard is dominated by a concentrated earthquake zone in Heer Land and two zones in NW Nordaustlandet. The Heer Land zone forms a pattern with a linear trend which is oriented at nearly right angles to major mapped faults in the region. The two in Nordaustlandet are near mapped fault zones, but cannot be associated with major faulting. All seismic activity on Svalbard therefore appears to be occurring on relatively minor faults and the major N–S trending faults, the sites of major movements up to Devonian time, are now nearly devoid of earthquake activity. Few earthquakes currently occur in western Spitsbergen, the site of major Tertiary orogenic activity. Minor activity south and east of the mapped southern terminus of the Billefjorden fault zone indicates that a zone of minor activity extends 50 km further south. *b* values in both Heer Land and Nordaustlandet appear to be variable with time, perhaps reflecting variations in the crustal stress field over relatively short periods of time. The concentrated earthquake zones of Svalbard are limited in extent and have been stable in position over a period of at least 10 yr. Thus there is no evidence for long throughgoing active faults which could be interpreted as plate boundaries.

Fault-plane solutions indicate that the maximum principal stress axis is uniformly oriented in an E–W direction throughout Svalbard in a direction roughly normal to the western continental margin and in the same direction as that of the minimum principal stress axis at the active plate boundary further to the west. The E–W compression in Heer Land and Nordaustlandet is of sufficient magnitude to generate significant earthquake activity there. The increases from zero values near the ridge axis to magnitudes large enough to generate that activity occur over a distance of about 200 km in southern Svalbard (Heer Land) and about 300 km in northern Svalbard (Nordaustlandet). It is not possible to explain this difference at the present time, but one explanation could be that E–W ridge push forces are greater in the ridge system west of Heer Land than they are further to the north. A second explanation might be appropriate if the conclusions of Al-Shukri & Mitchell (1988) concerning earthquake generation in the New Madrid seismic zone of the central United States also apply to Svalbard. If so, then differences in the nature of earthquake activity might be due to differences in pore pressure in crustal rocks between the two regions. Fault zones with lower pore pressure would require greater ridge-push forces to be activated and fault zones with very small pore pressure would have little activity. That mechanism would explain why many faults in Svalbard, at similar distances from the ridge system and having orientations which are similar to those of active faults, are presently inactive.

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