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GLACIER-GENERATED EARTHQUAKES FROM PRINCE WILLIAM SOUND, ALASKA

By

Lorraine W. Wolf[1] and John N. Davies[2]

Alaska Division of
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794 University Avenue, Basement
Fairbanks, Alaska 99701

[1]University of Alaska, Fairbanks, Geology Department.
[2]Division of Geological and Geophysical Surveys.

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ABSTRACT

Analysis of seismic records from stations near the Prince William Sound supports the association of monochromatic, low-frequency signals with tidewater glaciers in the area. Thirty-three of the larger, better recorded signals, with corresponding earthquake magnitudes of M_L 1.5 to 2.5, were located using routine seismological techniques. Epicenters for these "glacierquakes" clustered in the vicinity of the Harvard, Columbia, Yale and Barry glaciers. Monthly counts from one station for 1975, 1979 and part of 1976 range from less than 4 to 248 events. A sudden decrease in the number of events per month in mid-1979 raises the possibility of a single source or a common source mechanism for these glacier-related signals. The monochromatic, non-dispersive waveforms which characterize these 1-2 Hz signals may result from harmonic resonance of the glaciers in the epicentral region. We speculate that a variety of source mechanisms within or near the glaciers may provide the initial impulse for these events. However, the characteristic observed waveform is most likely the result of seismic energy which is internally reflected within the ice at fundamental resonant frequencies. Boundary conditions associated with tidewater glaciers may also allow the ice body to act as a waveguide for shear or surface waves. The signal we observe, therefore, appears to be a source-site phenomenon.

INTRODUCTION

A distinct class of low-frequency seismic signals has been routinely observed on records from stations near the Prince William Sound area in Alaska. Van Wormer and Berg (1973) identified the Harvard Glacier as a possible source for these unusual seismic signals. Weaver and Malone (1979) identified similar signals in records from stations monitoring Washington Cascade volcanoes and related these signals to glacier movement. Since the time of Van Wormer and Berg's study, the seismic network in southcentral Alaska has been expanded, making it worthwhile to reexamine the question of the source for signals from this glaciated area. Our preliminary study of seismic records from stations in the Prince William Sound area involved 1) tallying events on helicorder records from three years to examine frequency of occurrence, 2) locating some of the larger, better recorded events to identify an epicentral region, and 3) digitizing typical events to determine their relative spectral power densities and dominant frequencies. Results from the study support the association of this class of low-frequency signals with tidewater glaciers.

EVENT DESCRIPTION

Although the events referred to as glacierquakes in this study are somewhat varied in their seismic signatures, they all share some common features: 1) an emersive onset lacking a distinct first arrival, 2) a weakly developed P-phase, 3) an obscured S-arrival followed by a non-dispersive wavetrain, and 4) a monochromatic, low-frequency (1-2 Hz) signature associated with both the P- and S-phases. Figure 1 illustrates typical events, recorded on the University of Alaska Sheep Creek Mountain station (SCM), which appear to have originated near tidewater glaciers in the Prince William Sound area. Although the waveforms of these events differ significantly from common earthquake signatures, onsets were treated as P- and S-phase arrivals in data analysis because this approach yielded realistic body wave velocities (see residuals in Table 1). Larger events have magnitudes of M_L 1.5 to 2.5 and associated energies of 10^5-10^7 joules. These energies were calculated according to the relation

$$\text{Log } E = 9.9 + 1.9\, M_L - 0.024\, M_L^2 \qquad \text{(Richter, 1958)} \qquad (1)$$

where E is energy (in ergs) and M_L is the local magnitude. Magnitudes were determined by measuring the amplitudes of events seen on 1975 SCM film records.

Three events from two different glaciated areas were digitized from the onset of the first arrival through the high amplitude portion of the waveform. Digitized waveforms included at least 2/3 of the entire signature. The power spectrum for each clearly indicates a monochromatic signal at roughly 1.65 Hz (Fig. 2). Sonograms for each event show a predominant frequency range of 1-2 Hz for both the P- and S-phases (Fig. 8).

Frequency of Occurrence

Events appearing on helicorder records from SCM, a seismograph station located approximately 80 km from Prince William Sound, were tallied to determine the frequency of glacierquakes on a monthly basis (Fig. 3). SCM helicorder records were available for only parts of 1975 and 1976, and for all of 1979. Only events with amplitudes greater than 4 mm on records obtained with a helicorder amplifier setting of -18 db (corresponding to $M_L > 1.0$) were used in the tallies. Adjustments to the raw counts of events were made to accommodate for variable amplifier settings during different time periods. As many as 248 of these low-frequency events were recorded in one month (February, 1979). The average monthly count for all three years was approximately 100 events.

A marked increase in the number of events occurred during the first half of 1979, followed by a sudden decrease in the second half of that year. Average monthly counts in 1979 drop from 189 events before July 1, to less than four events thereafter. No instrument change or malfunction associated with the recording station has been discovered which might be responsible for so radical a change. The magnification of the SCM helicorder system, back calculated from the recorded amplitudes of tectonic earthquakes, does not appear to change significantly during 1979. The abrupt decrease in the number of events simultaneously throughout the entire region suggests the possibility of a single source for these glacierquakes (such as a tectonic source or a single active glacier at a given time), or perhaps a common source mechanism which might be seasonally dependent. Weaver and Malone (1979) observed an annual cycle associated with mountain glaciers which was characterized by increased activity between April and September, followed by an annual low between December and February. We observed a vaguely similar trend on our 1975 records only.

Location of Events

Thirty-three of the larger, better recorded events ($M_L > 1.4$), producing peak-to-peak deflections ≥ 10 mm on SCM helicorder records, were timed from films obtained through the U.S. Geological Survey's National Center for Earthquake Research in Menlo Park, California. Epicenter determinations were based on signals received at stations in the Prince William Sound area (Fig. 4) and were calculated using the University of Alaska's version of the program HYPOELLIPSE (Lahr, 1980).

The geometry of the station arrangement, in combination with emergent P- and S-arrivals, contributed to uncertainties in event locations. Most events were only recorded at three stations and gaps in azimuthal coverage exceeded 180°. Because these glacierquakes are presumed to be shallow and the station arrangement is less than ideal, the depth for each event was fixed at 0.1 km for the purpose of data reduction. The resulting horizontal axis of the error ellipse and RMS arrival time residual were usually less than 4.0 km and 1.0 sec, respectively, suggesting a location accuracy of ± 10 km despite the poor station geometry and the limited number of recordings available for individual events (Table 1).

The epicenters of these 33 glacierquakes are seen in Figures 5 and 6. Fourteen events cluster in the Harvard-Yale Glacier area, a distribution similar to that observed by Van Wormer and Berg (1973). A 3-event cluster occurs near the terminus of the Columbia Glacier, and another grouping of three epicenters is located in the Barry Glacier area. Six epicenters which could be related to glacier activity lie in the area between the Barry and Columbia glaciers. Other epicenters are scattered throughout and beyond the figure and are either unrelated to the glaciated areas or are incorrectly located as the result of poor signal quality or insufficient data.

POSSIBLE SOURCE MECHANISMS

Possible source mechanisms for these glacierquakes are restricted by the substantial energy release associated with larger events (10^5 to 10^7 J) and their frequency of occurrence. Ice cravassing and cracking, though common enough to be considered as possible source mechanisms, do not involve enough energy to account for the magnitudes observed. Neave and Savage (1970) calculated only a one-joule energy release for crevassing on the Athabasca Glacier. Calving probably involves considerably more energy than cravassing or cracking and occurs frequently enough in tidewater glaciers to be considered as a possible source mechanism for smaller events.

St. Lawrence and Qamar (1975) attributed the signals to hydraulic transients generated by abrupt changes in water flow through subglacial conduits. According to their model, rapid closure of a large conduit results in increased pressure within the glacial "pipe". Oscillatory pressure, similar to that which generates the "water hammer" effect in plumbing systems, displaces the conduit wall, providing an impulse for the harmonic type of signal observed. In order to produce an energy release corresponding to the larger magnitudes noted, their mechanism requires a conduit 200 m in length and 11.3 m in diameter, with a flow rate of 1000 $m^3\ s^{-1}$. Although conduits of these dimensions are possible in tidewater glaciers, they probably are not common in mountain glaciers (C. Benson and M. Sturm, personal communication). Furthermore, flow rates for the larger tidewater glaciers in the Prince William Sound area range from 500 $m^3\ s^{-1}$ for short duration, flood-induced flow, to a winter rate of 10 $m^3\ s^{-1}$ (L. Mayo, USGS, personal communication). It is conceivable that flow rates of the magnitude order required may occur occasionally, but not as frequently as required by our monthly event counts (Fig. 3). Theory suggests an inverse relationship between flow rate and pressure, making collapse of subglacial conduits and subsequent buildup of high water pressures most likely to occur in winter, when discharge is low (Röthlisberger, 1972). Collapse of conduits is least likely to occur during times of high water flow. If a "water hammer" type mechanism were responsible for the observed signals, we might expect an annual increase in the frequency of their occurrence during the late summer and early autumn, when discharge drops. Our data are not suggestive of a seasonal pattern of this sort; however, the behavior of glaciers is not easily predicted.

Weaver and Malone (1979) attributed the low-frequency character of glacier-related events to a path effect increasing with distance between source and receiver. Their field experiments in the Washington Cascades showed that events near seismic stations yielded higher frequencies and more impulsive arrivals, while distant stations yielded lower frequencies and more obscured arrivals. The conclusion drawn from these experiments was that the monochromatic, low-frequency character of the waveform was an effect of the seismic path and not of the source, for which they proposed stick-slip motion at the base of the glacier.

Inferred boundary conditions associated with tidewater glaciers support the possibility of slip at the base of the glacier as the original source of signals observed on seismic records from the Prince William Sound area. Shear stresses having average values of 10^5 Pa (1 bar) are present in the basal region (W. S. Paterson, 1981). Strain energy might release according to the formula used by Van Wormer and Berg (1973),

$$E_s = eS_b\ A_b\ d \qquad (2)$$

where E_s is the radiated seismic energy, e is the seismic efficiency, S_b is the shear basal stress, A_b is the slip area, and d is the displacement. The stick-slip mechanism would require a .01m displacement of a 1000 m^2 area, assuming an efficiency of 1% (Weaver and Malone, 1979), to produce an energy release of 10^5 J. A buildup of stress in discrete areas on the basal surface could be the result of pressure-melting effects, which may cause frozen patches on ice-bedrock interfaces (Goodman, King and Miller, 1979). We speculate that a sudden slip on some segment of the basal surface could generate shear waves which propagate near vertically through the glacier at fundamental resonant frequencies.

Basal sliding is thought to contribute significantly to glacier motion and is primarily influenced, at least in glaciers with temperate beds (near 0° C), by the glacier's drainage system. Knowledge of basal sliding and the relationship of motion to seismic activity is taken from studies dealing with different types of glaciers and it is not necessarily safe to assume that observations made with respect to one type are applicable to others. Studies made on surging glaciers (Kamb and others, 1985) suggest high basal slip is caused by high water pressures in interconnected subglacial cavities. The drainage system of nonsurging glaciers is thought to be associated with one or few main conduits rather than with an interlocking system. In either case, a hydraulic buildup of water pressures occurring during these times of low flux would increase the possibility of slip. Weaver and Malone's observation of an annual increase in the number of low frequency events on mountain glaciers during April through September does not quite follow the expected pattern for pressure buildup and subsequent discharge. One might expect to see the maximum buildup occurring shortly before spring or early summer, followed by an increase in discharge and corresponding decrease in pressure during the summer months. Our 1975 data suggest a trend in event frequency similar to that observed by Weaver and Malone, but our 1979 data do not. This lack of consistent pattern may suggest complications with a proposed stick-slip mechanism or may simply reflect differences and complexities in the mechanics of slip for surging, tidewater and mountain glaciers.

Shallow tectonic events occurring close to the base of the glacier may also provide possible sources for the events we see. Although initially comprising a spectrum of frequencies, the energy released from a tectonic event may be filtered by the ice body. Higher frequencies would attenuate quickly while frequencies near the fundamental mode of the glacier are enhanced. Given certain boundary conditions, the glacier may also constitute a waveguide for shear or surface waves originating from these shallow tectonic events.

Allowable Resonant Frequencies

To test the hypothesis that the monochromatic waveform represents a fundamental harmonic mode of the "ringing" ice, we calculated allowable resonant frequencies for two models by applying specific boundary conditions to the equations governing elastic waves in an incompressible solid. We then compared these solutions to what is actually seen on our seismic records.

If we assume the initial impulse is caused by basal slip, we can consider a model which involves only the near vertical propagation of horizontal shear waves through the ice body. In the simplest case, the equations of motion yield a one-dimensional wave equation for a glacier of infinite length and width, but with finite thickness. We orient the axes such that only horizontal shear waves are propagated along the z axis, with particle motion in the x-direction (Fig. 7).

To obtain the allowable resonant frequencies we have chosen to consider only two possibilities. The top boundary of the glacier is assumed to be a free surface in both cases. The lower boundary, however, poses several options and could easily involve bedrock, sediment or pockets of water or air.

The first case involves free surfaces at both the top and bottom, making the fundamental wavelength equal to twice the glacier's thickness. The allowable resonant frequencies are

$$f = \frac{nc}{2L} \quad , \quad n = 1, 2, 3 \ldots \tag{3}$$

where L is glacial thickness and c is shear wave velocity.

The second case involves a free surface at the top and a fixed surface at the bottom of the glacier. The fundamental wavelength is then four times the glacier's thickness, making the allowable resonant frequencies

$$f = \frac{(2n - 1)c}{4L} \quad , \quad n = 1, 2, 3 \ldots . \tag{4}$$

If we assume that the low frequency signals result from a waveguide effect, we can consider a second model such as that proposed by Crary (1954) in his study of Fletcher's Ice Island, T-3. Crary observed low frequency, fairly monochromatic signals showing little dispersion and large amplitudes on long distance records. He attributed these signals to multi-reflected SV waves and related resonant frequencies to the thickness of ice on the island. Given an air-ice upper interface and a water-ice lower interface, the relationship for the fundamental mode is

$$L = \frac{\beta}{f \cos \theta} \tag{5}$$

where β is the shear wave velocity, f is the frequency and θ is the incident angle of an SV wave given total reflection (Press and Ewing, 1951). The critical angle for total reflection is given by

$$\theta = \sin^{-1} \frac{\beta}{\gamma} \qquad (6)$$

Assuming compressional and shear wave velocities of 3.6 kms^{-1} and 1.8 kms^{-1}, respectively, the critical angle, θ, is approximately 30 degrees.

Frequencies observed on the 1975 SCM film records of the 33 events located in the Prince William Sound area fall into a 1.0 -2.0 Hz range and are listed in Table 1. Individual values do not appear to be associated with any particular glacier or epicentral cluster, suggesting either a similarity in the thicknesses of major tidewater glaciers in the area or a path effect which might yield frequencies associated with the average thickness of a glacier. Sonograms for the three digitized events show that the observed frequencies are close to the fundamental mode and that higher modes are not seen. The lack of energy partitioned into higher modes may be related to the initial impulse itself or to the distance from source to receiver.

Applying observed frequencies to solutions for allowable resonant frequencies suggested by our two models, we can compare computed glacial thicknesses to what little is known about the actual thicknesses of tidewater glaciers in the Prince William sound area. Few direct measurements of these glaciers have been made, with the exception of studies made on Columbia Glacier, which has a maximum average thickness of 1.0 km (L. Mayo, U.S.G.S., personal communication). Using slopes measured from topographic maps, however, we can estimate thickness for other typical tidewater glaciers by the relation

$$H = \frac{\tau_b}{s\rho g\ (\sin \Upsilon)} \qquad (7)$$

where τ_b is the basal shear stress, ρ is density, g is the gravitational constant, Υ is the surface slope and s is a shape factor (Paterson, 1981). Equation 5 yields average maximum thicknesses of approximately 0.5 to 1.0 km. Applying these values for thickness to our first model, which involves near vertical propagation of horizontal shear waves through the ice body, we get fundamental resonant frequencies of 0.9 to 1.8 Hz for our first case (Equation 3) and 0.45 - 0.9 Hz for the second (Equation 4). If we apply observed frequencies to the Crary model, Equation 6 yields an average maximum thickness of 1.3 km, a value too large for most tidewater glaciers.

Energy Transmission

If the monochromatic signal observed is the result of resonating ice, we would require the lower glacial boundary to provide an impedance contrast such that a certain amount of energy is reflected into the ice. If we assume that the original impulse generates a vertically propagating SH wave, then almost all energy will be reflected at the top surface. Using Zoeppritz's equations, (Telford, 1980), we can approximate the amount of reflected energy at the lower interface based on the impedance contrast of the adjacent layers. The acoustic impedance, Z_i, is the product of density, ρ_i, and velocity, v_i. The reflection coefficient, E_R, is given by the relation

$$E_R = \left(\frac{\delta - 1}{\delta + 1}\right)^2 \qquad (8)$$

where $\delta = Z_1/Z_2$ is the impedance contrast. The transmission coefficient, E_T, is

$$E_T = \frac{4\delta}{(\delta + 1)^2} . \qquad (9)$$

A regional shear wave velocity for bedrock of approximately 2.9 km s^{-1} (Davies, in press) and a 1.8 km s^{-1} velocity for temperate ice, with corresponding densities of 2500 kg m^{-3} and 900 kg m^{-3}, yield a reflected fraction of incident energy enough to allow for several oscillations within the ice body. The number of oscillations we see on our records, however, may also be influenced by filtering and dispersion. If the glacier is acting as a waveguide for incident SV waves, almost all energy would be reflected internally (Crary, 1954).

CONCLUSIONS

Recent epicenter locations confirm that sources for a distinct class of monochromatic, low-frequency signals lie predominantly in heavily glaciated areas near Prince William Sound. Energies associated with these events are significantly larger than those related to ice crevassing or cracking, and therefore other source mechanisms appear more plausible. Calving and hydraulic transients associated with subglacial conduit systems may be sources for smaller events, but neither involves enough energy to account for the larger events seen. Although specific boundary conditions at the base of tidewater glaciers are currently unknown and most probably vary from place to place on each glacier, shear stresses on the order of 10^5 Pa in the basal region, once released, would provide a large enough source of energy to allow the required seismic radiation of approximately 10^5 J. Shallow tectonic events, occurring close to the base of the glacier, could also provide the amount of energy required. The tectonic setting in southcentral Alaska and, in particular, the Prince William Sound area make these events likely to occur frequently. Therefore a variety of source mechanisms may provide the initial impulse for the events we see; however, the monochromatic, high-amplitude, low-frequency signature common to all these events is most likely a source-site phenomenon. Higher frequencies associated with the initial impulse quickly die out while those frequencies near the fundamental mode of the glacier are enhanced. Thus the signal we see may be attributed to resonance within or to waveguide effects of the ice body.

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Table Caption

Table 1. Event parameters. (RMS = root mean square error; ERH and ERZ = horizontal and vertical error ellipse axes; GAP = azimuthal gap in station arrangement; Epicentral clusters: (CL) Columbia, (HY) Harvard-Yale, (B) Barry, (O) other.)

Event No.	Date	Origin	Lat. N.	Long. W.	Period-P	Period-S	Gap	Cluster	RMS	ERH	ERZ
1	750414	10 1 44.06	61N13.83	147W43.84	0.51	0.55	246	HY	1.09	4.8	2.0
2	750326	2 0 15.11	61N 4.47	148W30.34	0.57	0.61	257	HY	1.90	4.6	22.8
3	750820	1732 6.58	60N58.73	147W19.02	0.50	0.61	232	HY	0.70	9.7	4.0
4	751128	822 36.09	61N16.78	147W40.17	0.58	0.61	255	HY	0.43	7.4	99.0
5	751122	1318 15.07	61N51.17	146W 7.30	0.48	0.61	360	O	0.76	99.0	99.0
6	751213	13 5 59.04	61N13.42	148W 6.50	0.47	0.62	171	HY	0.99	4.3	99.0
7	750417	2122 52.24	61N35.71	146W59.15	0.52	0.66	168	O	0.50	18.0	7.8
8	750512	1813 35.22	61N17.30	147W37.79	0.56	0.65	251	HY	0.11	13.6	99.0
9	750512	651 36.32	61N43.68	146W10.52	0.47	0.55	195	O	1.03	5.0	6.1
10	750823	948 49.98	61N 0.67	147W 2.67	0.52	0.62	314	O	0.59	5.6	99.0
11	750203	2 3 59.50	61N17.64	147W38.03	0.47	0.62	250	HY	0.34	4.7	3.1
12	750203	2147 55.94	61N10.19	147W29.68	0.58	0.64	193	HY	2.01	2.5	3.7
13	750208	1212 36.95	61N11.74	147W39.91	0.63	0.63	238	HY	1.09	3.4	4.6
14	750207	2232 0.18	61N16.92	147W41.58	0.51	0.61	266	HY	0.29	8.2	4.0
15	750208	1626 19.02	61N 6.71	147W39.83	0.47	0.61	210	O	0.77	6.7	7.1
16	750316	1134 4.13	61N15.98	147W40.87	0.45	0.63	266	HY	0.18	5.0	7.0
17	750513	1938 1.27	61N17.19	147W41.60	0.46	0.61	268	HY	0.36	4.2	5.2
18	750513	2228 59.23	61N17.28	147W37.56	0.38	0.57	251	B	0.25	2.6	3.9
19	750515	1345 9.75	61N13.29	147W40.44	0.53	0.62	242	HY	0.73	3.3	99.0
20	750527	5 1 30.05	61N11.24	147W50.49	0.48	0.74	238	O	0.82	3.2	3.2
21	750527	515 5.73	61N15.11	147W43.21	0.62	0.77	269	O	0.22	5.7	3.6
22	750527	542 54.77	61N15.19	147W41.53	0.83	0.83	268	CL	0.32	5.3	4.1
23	750726	8 8 11.67	61N14.19	148W 4.20	0.51	0.61	159	B	0.71	3.6	2.8
24	750801	120 12.14	61N17.08	147W35.12	0.70	0.76	234	CL	0.10	6.1	3.2
25	750807	1050 51.43	61N 2.07	147W22.95	0.72	0.79	231	O	0.15	7.9	4.7
26	750908	223 48.46	61N11.78	148W 5.68	0.57	0.75	316	CL	0.49	6.4	3.9
27	750913	1211 20.02	61N 2.02	147W 4.64	0.61	0.18	135	HY	0.58	3.4	5.5
28	750915	144 15.73	61N 4.06	147W22.71	0.58	0.63	181	HY	0.22	99.0	99.0
29	750920	8 6 6.77	61N 2.61	147W 2.20	0.48	0.74	138	O	0.36	5.7	8.3
30	751114	1954 56.53	61N16.21	147W42.73	0.57	0.60	255	O	0.48	5.3	99.0
31	751116	729 24.30	61N13.79	147W38.53	0.51	0.61	260	O	0.96	14.4	99.0
32	751117	1433 39.44	61N 4.24	147W34.64	0.60	0.64	297	HY	0.19	22.6	99.0
33	751121	559 35.38	61N56.40	147W57.30	0.64	0.70	204	B	0.53	31.1	27.3

Figure Captions

Figure 1. Comparison of typical waveforms from glacierquakes in the Prince William Sound area. Events 10 and 26 are associated with the Columbia and Barry glacier clusters, respectively. Events 11, 18, 19 and 20 are associated with the Harvard-Yale glacier cluster (Figures 5 and 6).

Figure 2. Power spectra for three digitized 1975 events from the vicinity of the Harvard and Yale glaciers.

Figure 3. Monthly event counts at Sheep Creek Mountain (SCM), a University of Alaska high-gain station in the Prince William Sound area.

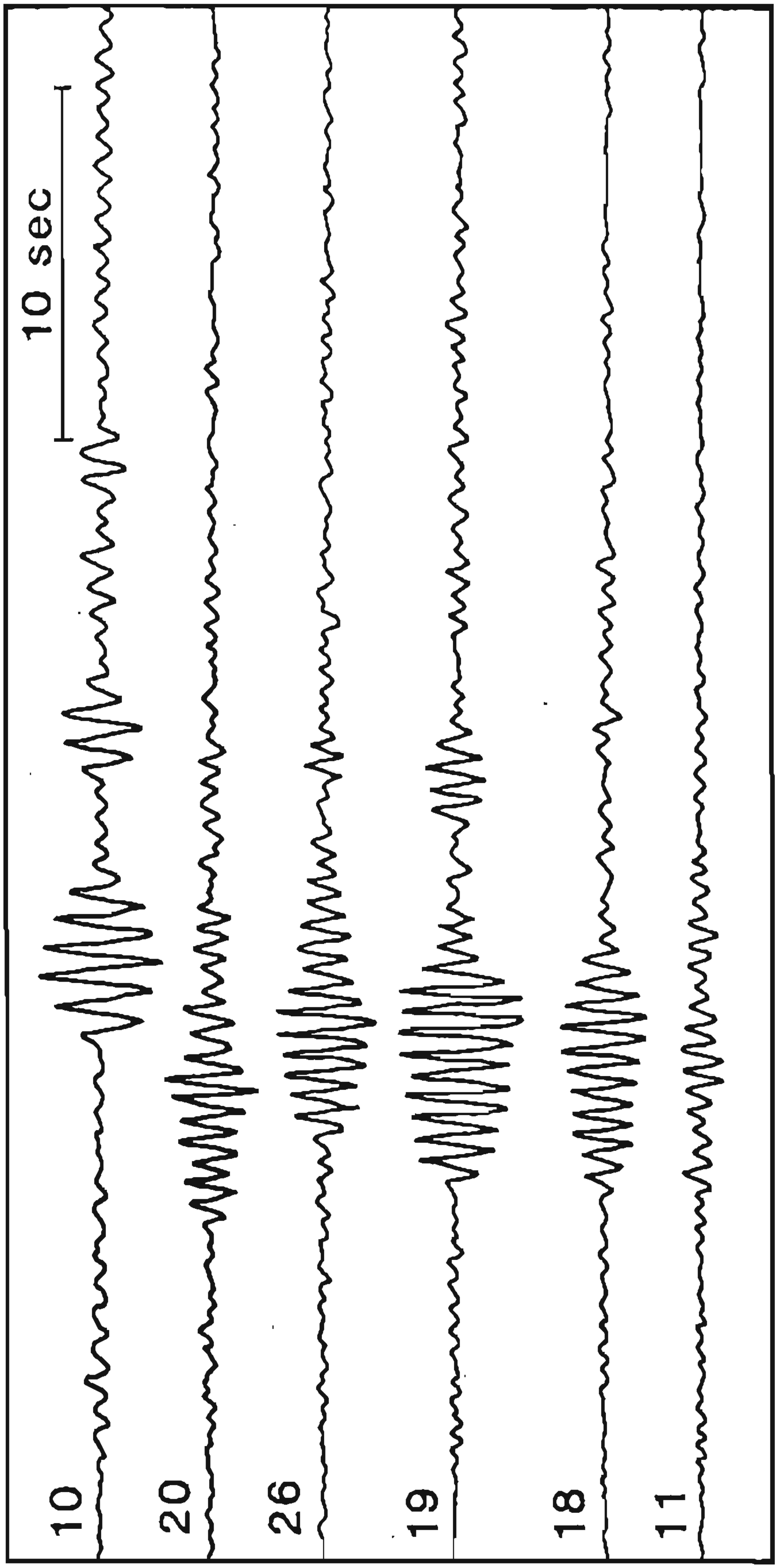
Figure 4. Location map for southern Alaska seismograph stations used in epicenter determinations.

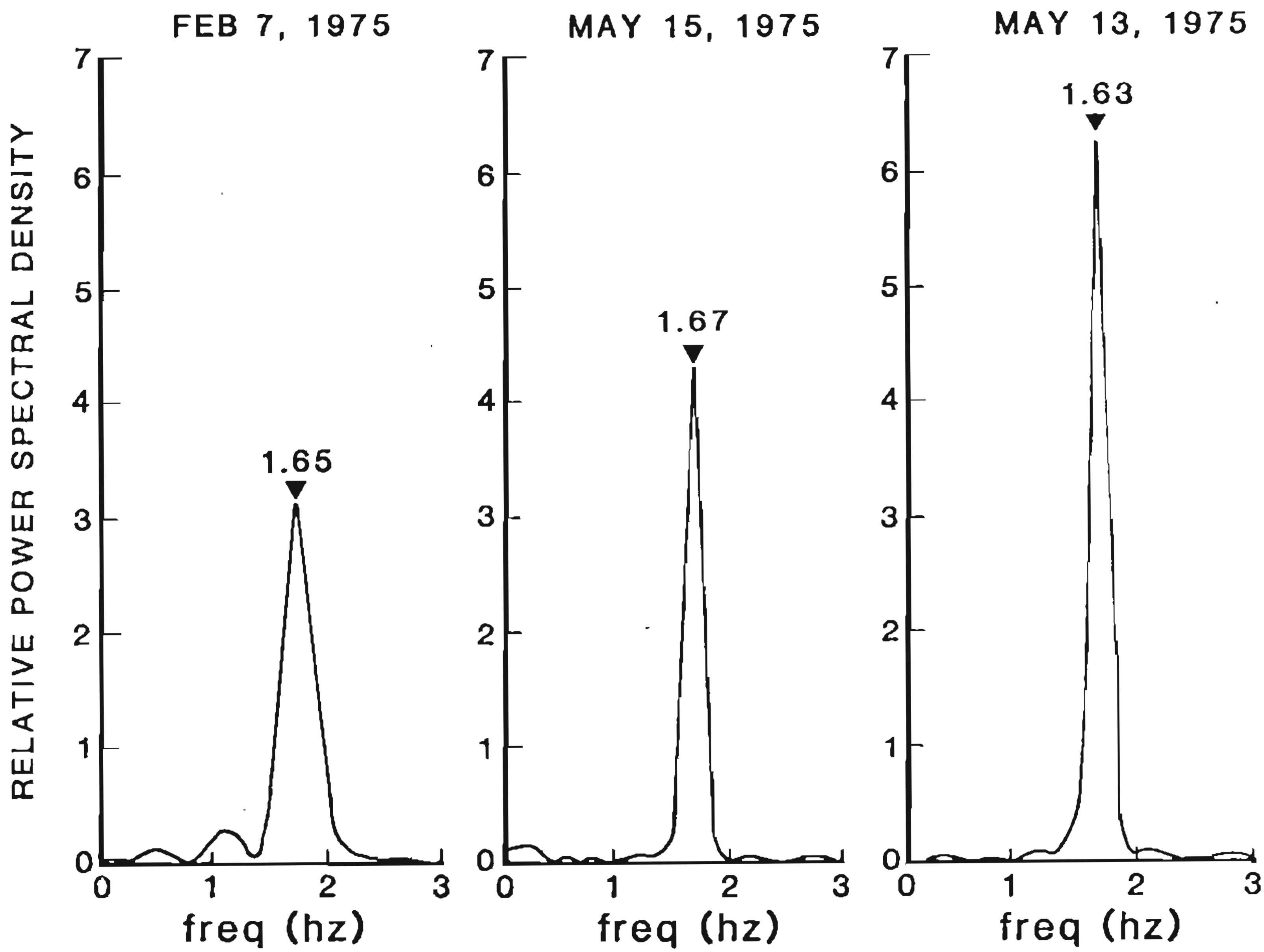
Figure 5. Epicenter location map.

Figure 6. Epicenter locations in vicinity of Harvard and Yale glaciers. (Unshaded areas represent ice.)

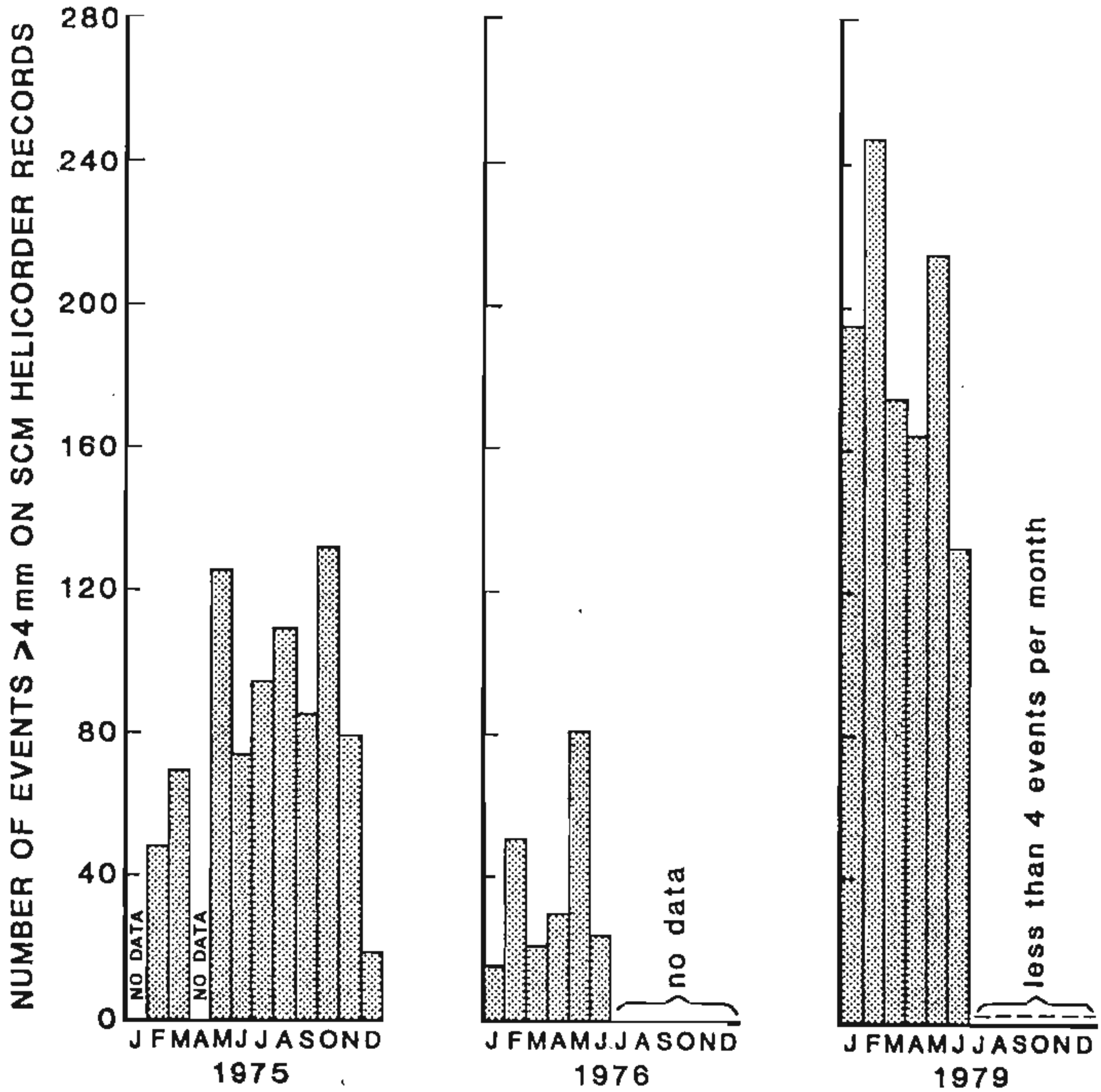
Figure 7. Coordinate system of parallel-sided slab model for glacier.

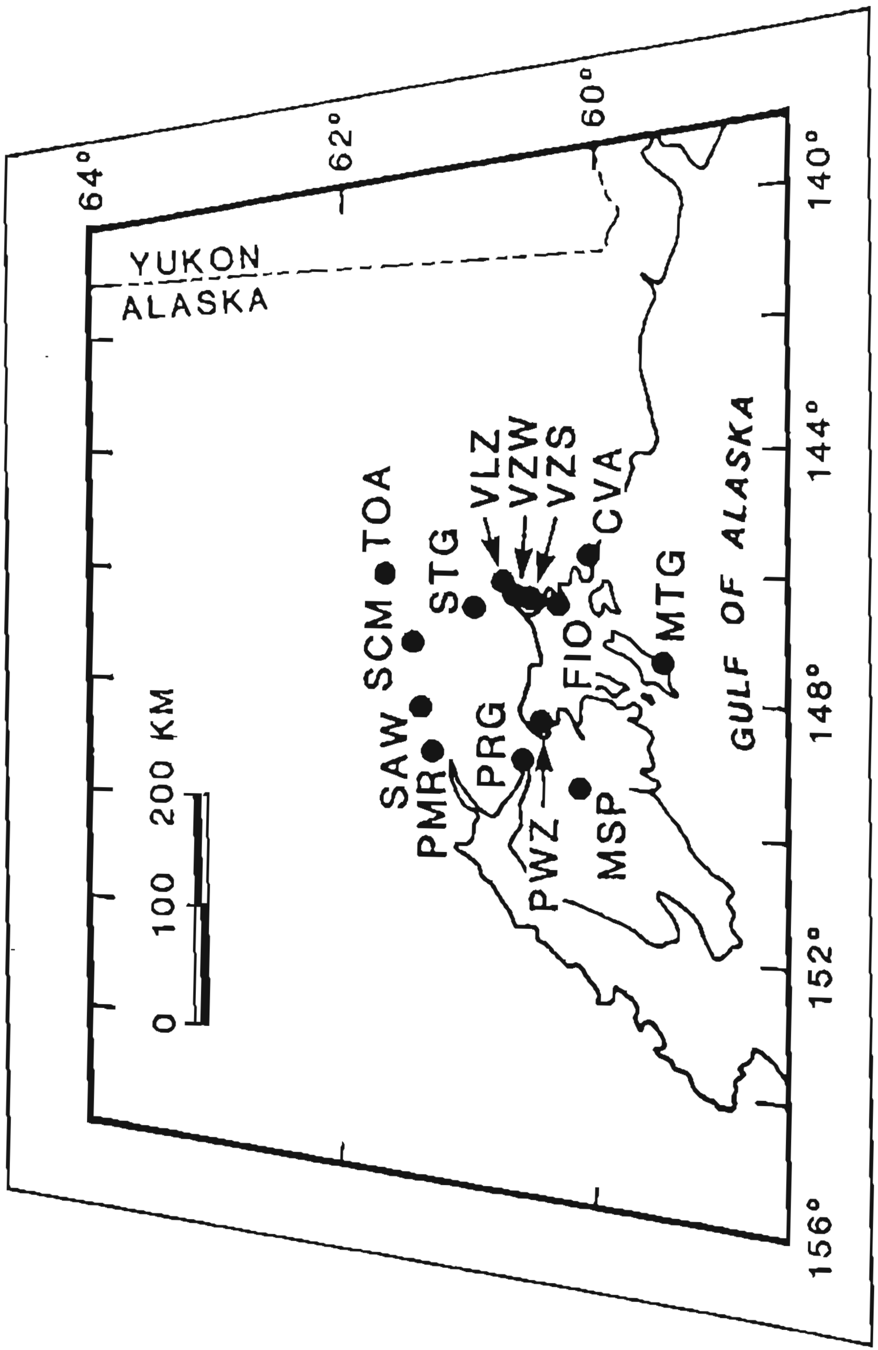
Figure 8. Sonogram for a digitized event from the vicinity of Harvard Glacier, May 13, 1975. (Darker areas represent higher densities.)


10 sec
10
20
26
19
18
11

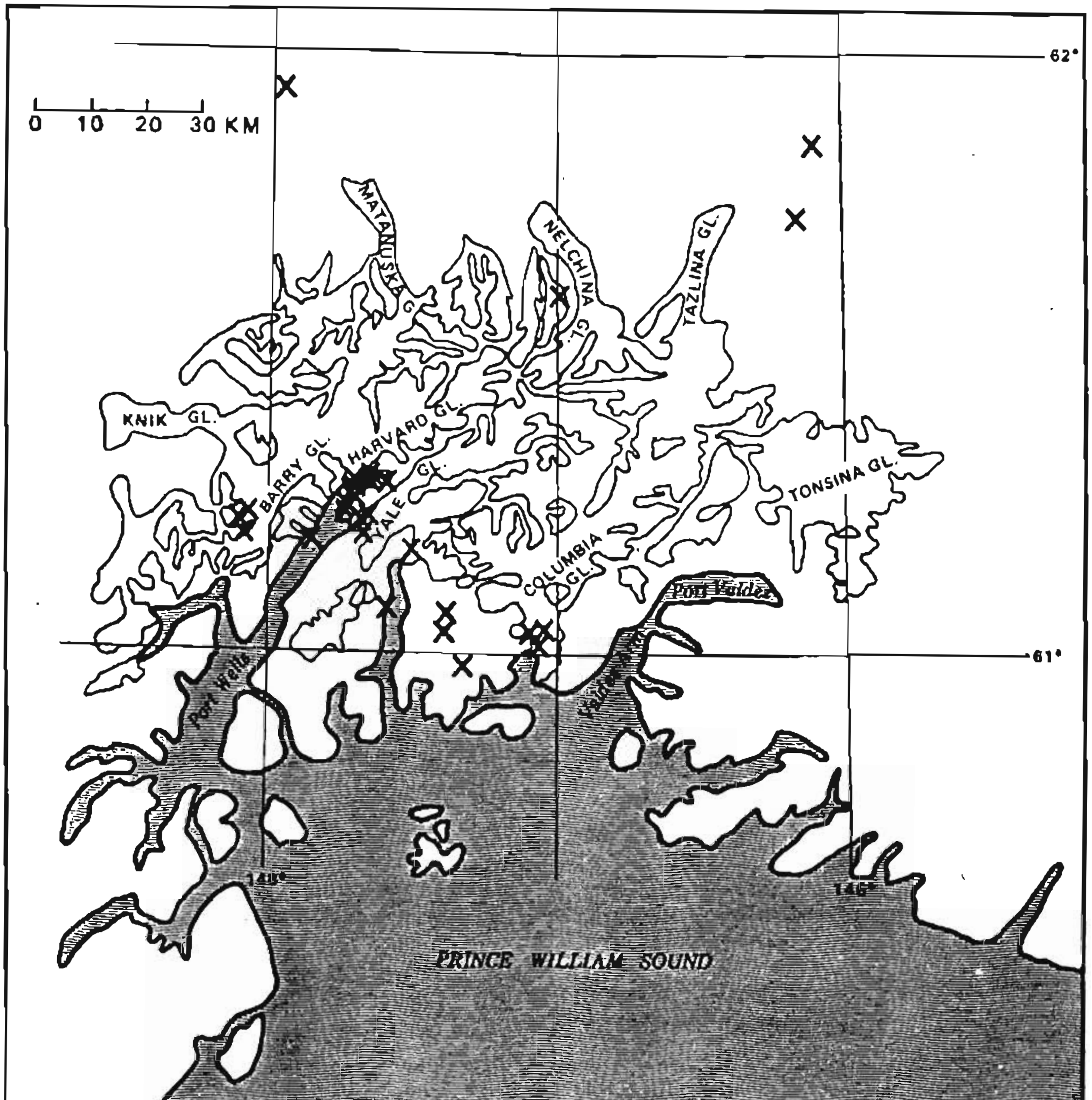


POWER SPECTRUM

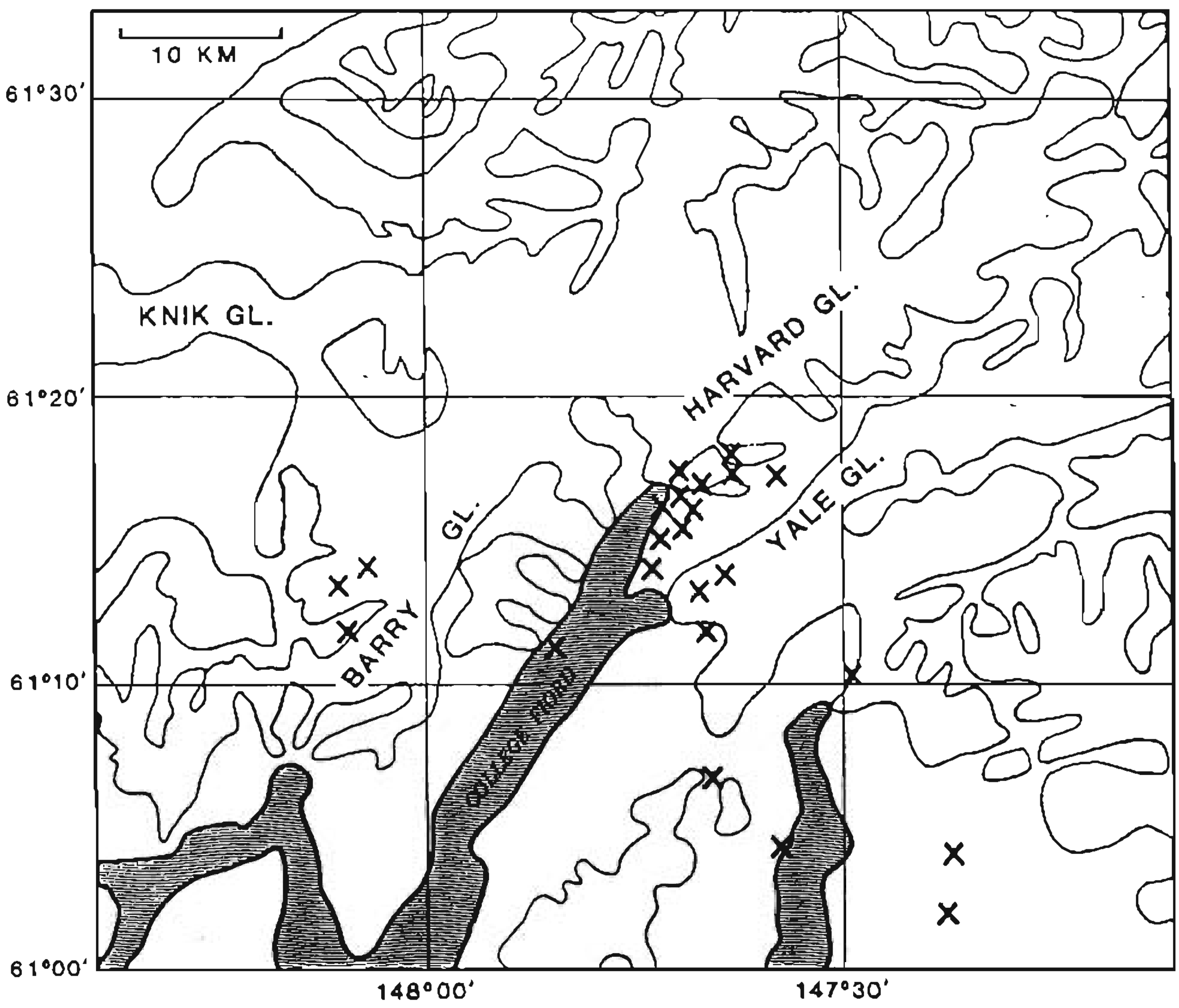

NUMBER OF EVENTS >4 mm ON SCM HELICORDER RECORDS
280
240
200
160
120
80
40
0
NO DATA
NO DATA
J F M A M J J A S O N D
1975
no data
J F M A M J J A S O N D
1976
less than 4 events per month
J F M A M J J A S O N D
1979



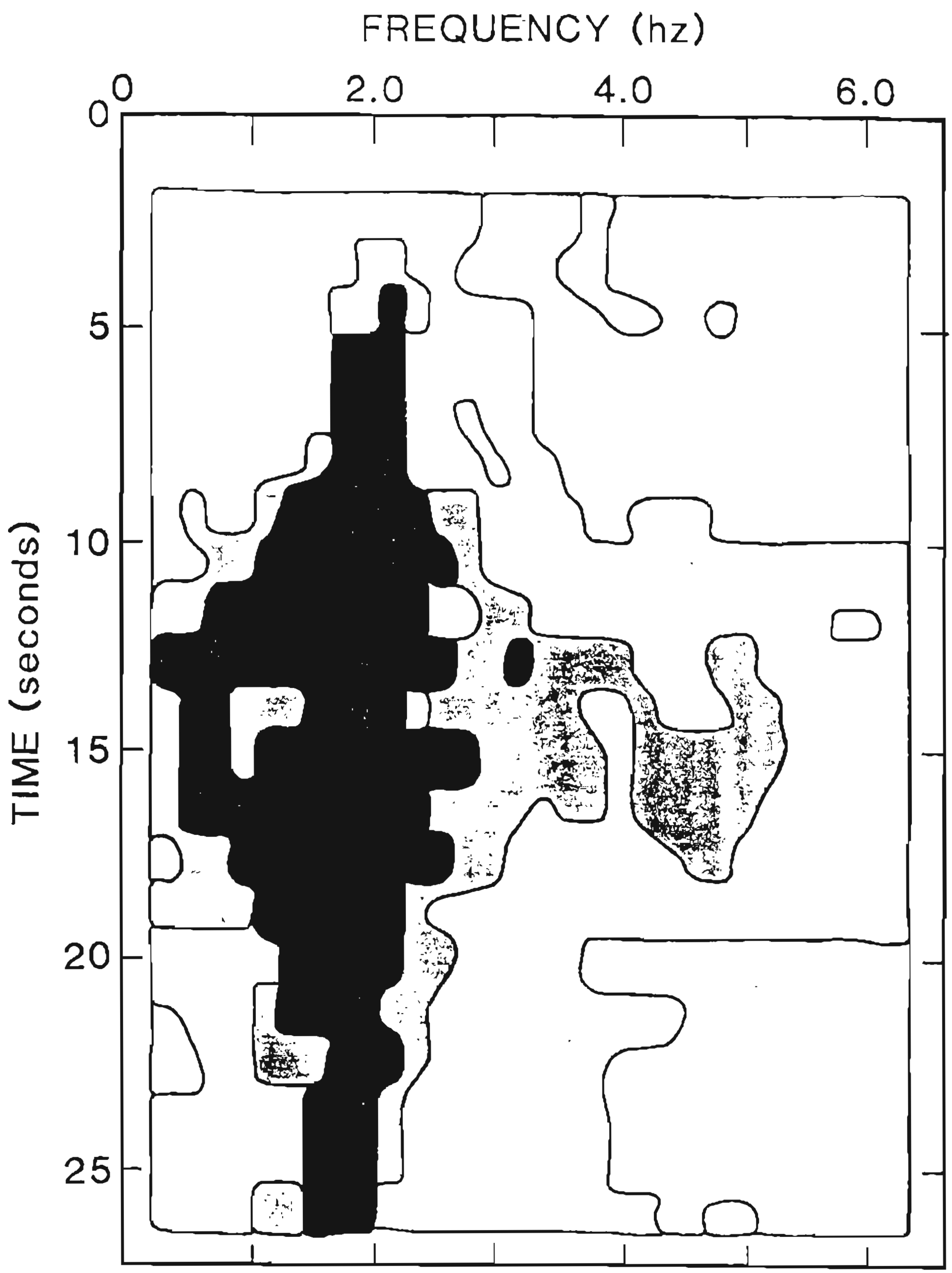
YUKON
ALASKA
64°
62°
60°
140°
144°
148°
152°
156°
0
100
200 KM
TOA
SCM
STG
VLZ
VZW
VZS
CVA
MTG
FIO
SAW
PMR
PRG
PWZ
MSP
GULF OF ALASKA



Epicenter location Map.



Epicenter locations in vicinity of Harvard and Yale glaciers.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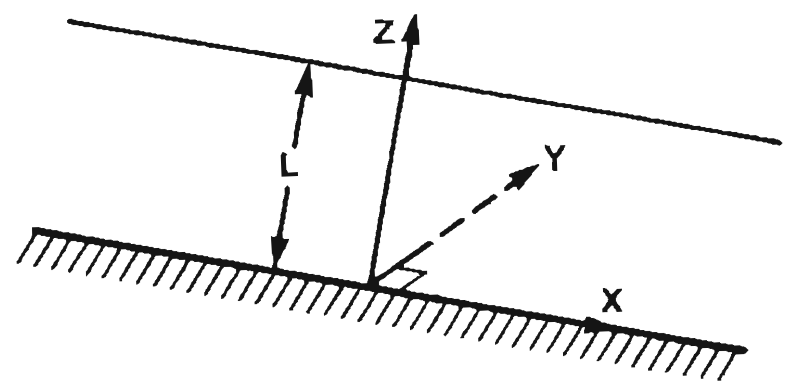
2.0
4.0
6.0
0
5
10
15
20
25
TIME (seconds)



Coordinate system of parallel-sided slab model for glacier