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Ground Acceleration Measurements in Finland

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Abstract

The vertical component of peak ground acceleration (pga) caused by small local earthquakes that occurred in Finland and its vicinity, and the corresponding predominant periods have been observed directly on the bedrock-base at different epicentral distances. A rough estimate for the total attenuation of the recorded maximal acceleration amplitudes is given as a function of epicentral distance. Some ratings for the maximum vertical peak ground acceleration at epicentral distances between 10 and 1000 km for earthquakes of ML = 2, 3, and 4 are also presented. The examples given here show that the dominant frequencies of peak ground acceleration on hard bedrock exceed the previous measuring capacity of the station instruments in Finland, and are higher than those which have been reported for Scandinavian earthquakes.

1. Introduction

Some occasional recordings of local earthquakes by high-frequency field seismographs and accelerometers showed clearly that accurate measurements of the maximal acceleration caused by small earthquakes are not possible with the narrow-band instruments used at the permanent Finnish seismograph stations. *Trifuñac* and *Brady* (1975) pointed out that the peak ground accelerations (pga) are typically associated with high frequency components f>5 Hz of the ground motion. In addition to the frequency pass-band, also the insufficient dynamic range of these narrow-band instruments prevents frequently successful recordings.

At the beginning of 1980 a high frequency vertical short-period seismograph with a sampling frequency of 146 Hz and a Vibrometer corp. VM 510 accelerometer with a sampling frequency of 120 Hz were installed at the stations JOF (Ilomantsi) and NUR (Nurmijärvi).

In 1989, a three-component short-period station VAF (Ylistaro) with a sampling frequency of 100 Hz started its operation. This accelerometer and the velocity instruments were capable of producing digital data which could yield ground displacement-velocity and -acceleration within a higher limited frequency pass-band. The response curves and the instrumental constants of the above mentioned instruments are presented in more detailed form in a report (*Teikari* and *Suvilinna*, 1991).

In February 1990 a small ML= 2.4 earthquake (*Teikari*, 1990) occurred only 25 km away from the VAF station. In spite of its short epicentral distance, this event was successfully recorded with the recently installed three seismographs and the first reliable instrumental near-field observations were available. The calculated maximal acceleration of the vertical component was 1240 µm/s*s (S-phase) and the resultant of the horizontal components was calculated as 1780 µm/s*s (S-phase). The ratio $a_v/a_h = 0.7$. Macroseismic maximum intensity of the event was determined as I^{max}=IV. Later on it was decided to determine the real ground motion also of all those earthquakes for which high-frequency data already was available. Particular attention was paid to determining the maximum vertical peak acceleration (Sg-phase) of the ground movement at rock sites and to estimate the dominating frequencies as well as the total attenuation, the result of geometric spreading and internal damping of the pga. Because the annual number of earthquakes in Finland is low, so far only a few events have been recorded with these special instruments and only in two cases has the epicentral distance been shorter than 100 km. These preliminary results are presented in this paper.

2. *Earthquake data*

The local earthquakes which have been examined are listed in Table 1. Mostly the recordings of stations VAF (To = 1 s, band 1-25 Hz, sampling 100 Hz, dynamic range 138 dB) and JOF (To =.8 s, band 1.2-20 Hz, sampling 146 Hz, dynamic range 92 dB) have been analyzed and processed to obtain the pga values. The epicentral coordinates and magnitudes of these events are in Table 1. (*Uski et al.*, 1986-1990).

Table 1. List of inspected earthquakes.

#	code	date and time			coordinates				size
1.	"Kalvola"	May	02-86	08-18-33	61.1	N	24.1	E	MC=1.7
2.	"Hossa"	Feb	21-89	02-54-02	65.35	N	29.37	E	ML=3.2
3.	"Voyri"	Feb	06-90	22-55-43	63.2	N	22.3	E	ML=2.4
4.	"Pello"	Oct	28-90	02-26-12	67.0	N	24.2	E	ML=2.5
5.	"Puolanka"	Nov	09-90	19-02-36	65.07	N	27.54	E	ML=3
6.	"Uppsala"	Dec	12-90	15-28-00	59.8	N	16.8	E	ML=3.7
7.	"Harmoinen"	May	23-91	19-24-54	61.52	N	24.89	E	ML=2.1
8.	"Lulea" S	Jun	06-91	12-46-13	65.58	N	23.02	E	ML=3.5
9.	"NW USSR"R	Aug	24-91	10-56-29	65.74	N	33.07	E	ML=3.6
10.	"Gulf of B"	Sept	23-91	19-20-29	64.58	N	21.4	E	ML=3.4
11.	"Umea" S	Oct	28-91	16-21-33	63.8	N	20.1	E	ML=2.9
12.	"S-stad" S	Feb	19-92	06-39-35	59.1	N	11.6	E	ML=3.8
13.	"Botnia"	Nov	11-93	23-44-24	64.21	N	23.02	E	ML=2.9

Geographical locations of the events presented above in Table 1. as well as the sites of the seismograph stations JOF, NUR and VAF are displayed also on a map in Fig. 1.

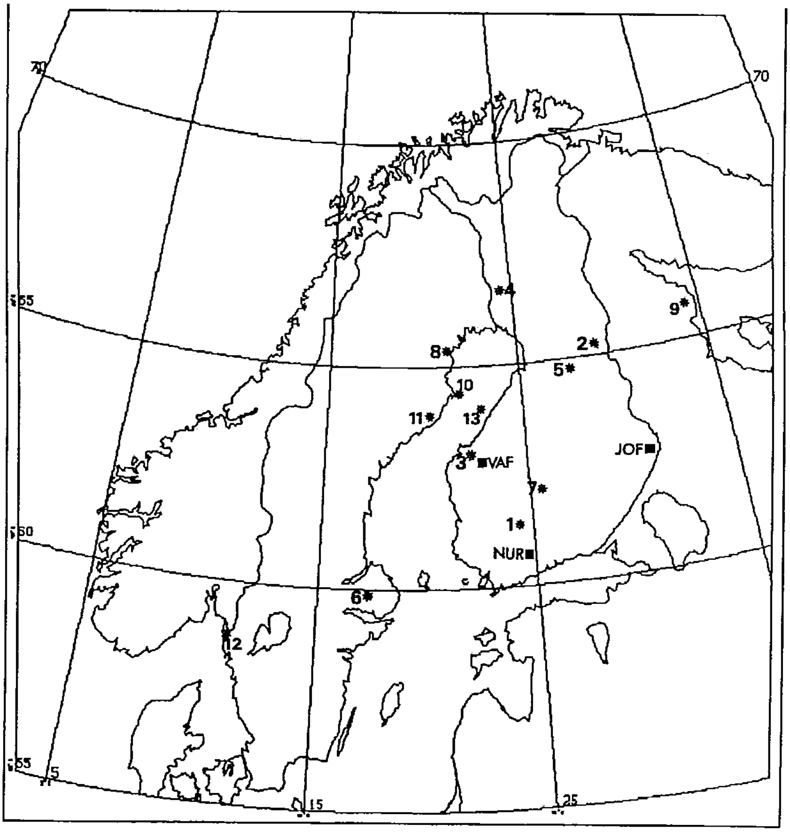

Fig. 1. The geographical locations of the Earthquakes 1-13 discussed here (Table 1) and of the seismic stations JOF, NUR and VAF.

3. *Description of the method*

The time series of recorded ground vibration have been processed with one, mostly with two of the following methods in order to achieve the maximal amplitude of the ground acceleration and to obtain the uncertainty of its determination.

i. The acceleration of the ground particle has been measured directly with an accelerometer and the maximal value has been determined.

ii. The time series of the ground velocity at the frequency band of approximately 0.5-25 Hz, where the instrument output is flat to ground velocity, have been differentiated to get the ground acceleration.

iii. The recorded trace amplitudes at different periods have been converted to amplitudes of ground displacement in the traditional manner and the corresponding periods have been defined. Then the acceleration of ground motion is obtained by multiplying the amplitude of ground displacement with $(2\pi /T)^2$, where T is the period of the harmonic wave. The biggest calculated amplitude value which has been found represents the maximum acceleration.

During this work the method (ii) was found to be most reliable. Of course when direct measurements of accelerograph are available they are capable. The methods (i) and (ii) were compared in another connection where relatively big explosions were recorded at short distances using an accelerometer and a velocity seismometer. The results were almost identical. The method (iii) is troublesome because we do not know which periods of the original seismogram contain the maximum value of acceleration and in addition the errors which are made in determining the period are increasing the final error. In this work the method (ii) always gave somewhat bigger acceleration values. One reason for it could be the fact that the acceleration amplitudes can be asymmetrical. When measuring the peak-to-peak amplitudes and taking the mean, we never get the maximal peak-value. For instance in the # 2 earthquake "Hossa" the maximum acceleration determined with method (iii) resulted 100 µm/s*s and with method (ii) 130 µm/s*s.

The shape of the attenuation curve, as well as its position on the vertical axis were created in this paper by normalizing the observed and measured pga values caused by earthquakes of different magnitude to those which correspond to an earthquake of fixed magnitude ML=3 and by drawing a fitted curve through the normalized values.

The predominant frequencies corresponding to the measured pga have been determined by analyzing the time series of the processed acceleration of S-phase and/or calculating its Fourier spectrum. In some cases the determining of the period corresponding to the maximal acceleration is difficult and tedious. The time series of ground vibration resembles not a single harmonic sine-wave but rather a complicated sum of different waves. In spite of which method of those described above has been used, the most practical way to determine the corresponding predominant periods or frequencies is to employ the Fourier transform and search the frequencies from the spectrum.

4. *Results*

The following peak ground acceleration values and corresponding frequencies listed in Table 2. have been determined.

Table 2. Calculated pga values, epicentral distances and the corresponding frequencies.

#	code	size	pga (µm/s*s) / distance (km), frequency (Hz)					
1.	"Kalvola"	MC=1.7	70/71,	25	Hz:			
2.	"Hossa"	ML=3.2	130/286,	12	Hz:			
3.	"Voyri"	ML=2.4	1240/25,	16	Hz:	2.4/455,	5	Hz
4.	"Pello"	ML=2.5	6.2/445,	17	Hz			
5.	"Puolanka"	ML=3	37/306,	6.5	Hz:	40/327,	17.5	Hz
6.	"Uppsala"	ML=3.7	87/476,	8	Hz:	10/847,	7	Hz
7.	"Harmoinen"	ML=2.1	20/205,	12	Hz:			
8.	"Lulea"	ML=3.5	298/283,	10	Hz:	46/530,	12	Hz
9.	"NW USSR"	ML=3.	210/322,	5.3	Hz:	63/585,	15	Hz
10.	"Gulf of B"	ML=3.4	900/183,	10-12	Hz:	30/523,	8-10	Hz
11.	"Umea"	ML=2.9	192/154,	14	Hz:	5/571,	9	Hz
12.	"S-stad"	ML=3.8	16/745,	2.5	Hz:	7/1150,	3	Hz
13.	"Botnia"	ML=2.9	311/127,	18	Hz:			

The computed values of ground acceleration listed above are plotted as a function of epicentral distance in Fig. 2. These empirical values represent the vertical component of the pga measured on the bedrock.

The magnitude determinations of the events in Table 1 were made using equation 1. (*Ahjos* and *Uski*, 1992).

$$ML = \log a + 1.27 \log \Delta + 1.56 \qquad (1)$$

where a = amplitude of ground displacement in µm and Δ = epicentral distance in km.

To create the shape of the pga attenuation curve versus epicentral distance the computed values of the ground accelerations listed above have been converted to correspond to the acceleration values caused by an earthquake of magnitude ML=3 at the same epicentral distance. If we assume that the motion is a harmonic seismic wave equation (1) can be written

$$ML = \log (\bar{a}/(2\pi/T)^2 * \Delta^{1.27} * 36.3078) \qquad (2)$$

where $\bar{a}$ = amplitude of ground acceleration instead of displacement and T is the period of the harmonic ground movement.

The normalized pga value for an earthquake of magnitude ML = 3 was calculated using equation (3)

$$\bar{a}3 = 10^3/10^k * \bar{a}k \qquad (3)$$

where $\bar{a}k$ = the measured pga value for an earthquake of magnitude k at distance Δ km and $\bar{a}3$ = the normalized pga value for an earthquake of magnitude ML = 3 at the same epicentral distance.

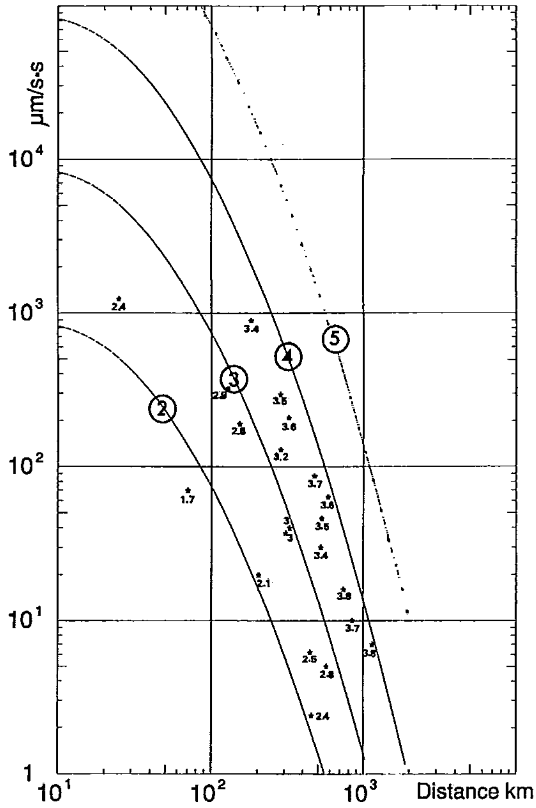

Fig. 2. The empirical values of the maximal vertical peak ground accelerations of different earthquakes versus epicentral distance. The numbers denote the local magnitude of each event. Solid lines present the pga limits for magnitudes 2, 3, and 4.

All those normalized pga values are plotted against epicentral distance in Fig. 3. The fitted solid curve, which represents the attenuation of ground acceleration is a part of an inverted parabola

$$y = -0.849x^2 + 1.504x + 3.2597 \tag{4}$$

The attenuation of the pga for short ranges of distances follows a factor R^{-n} (*Schnabel* and *Seed*, 1973) and (*Båth et al.*, 1976). The values for *n* determined in this study were 2.8, 150<R<1000 km and if we use the only two "near-to-the-source" values too 1.4, 25<R<150. The curve in Fig. 3, equation (4), is realized here as a sum of linear expressions for many narrow ranges of distances, as a broken line and it anticipates that the total attenuation increases when extending the observation distance.

The family of curves in Fig. 2, which displays the pga limits for magnitude grades of ML=

2, 3 and 4, are separated vertically from each other by a decade. This separation is in accordance with the logarithmic character of the magnitude scale. The family of the curves is placed on the Log-Log scale by keeping vertically the ML=3 curve in its right place and drawing the curves for ML=2 and ML= 4 vertically one decade down and up.

The empirically observed peak-accelerations and the determined magnitude values in Fig. 2 fit reasonably well the attenuation curves at distances greater than 150 km. The attenuation at shorter distances (the shape of the curve at distances 25 - 150 km) can not be commented on because there is not enough empirical data available.

However, as a first approximation for the attenuation between 25 and 1000 km, this curve is presented here. For an earthquake of magnitude ML=2 at a average depth h = 10-15 km (*Ahjos* and *Uski*, 1992) this figure predicts a maximal vertical acceleration of 0.5 mm/s*s at a distance of 25 km from the epicentrum. The uppermost line which represents magnitude ML=4 gives an acceleration of 5 cm/s*s at the same distance. If an extrapolated imaginary curve, which is not based upon any real experimental value, were plotted for magnitude ML=5, it could give a peak acceleration of 50 cm/s*s at the same distance. This magnitude ML=5 is taken as the highest possible magnitude rate in Finland (*Ahjos et al.*, 1984).

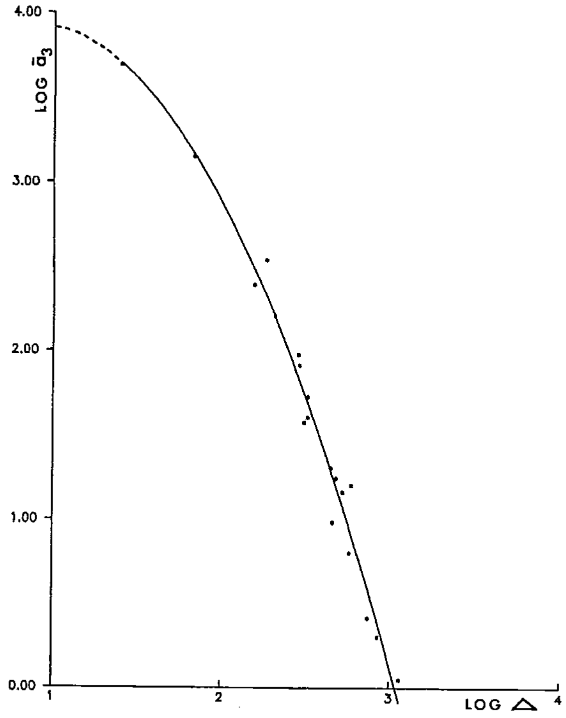

Fig. 3. The normalized vertical peak ground accelerations in µm/s*s versus epicentral distance in km. The solid curve is a fitted polynomial.

The extrapolated rough estimates for the extreme values of vertical pga on the bedrock at the area near the epicentrum R≈10 km for different magnitudes are also displayed in Fig. 2. The vertical component of the maximal pga (extrapolated value) which possibly could exist on the Finnish bedrock (magnitude ML=5) is thus in accordance with approximately 80 cm/s*s.

The frequencies which correspond to the maximal peak ground accelerations measured at different distances vary from 2 to 25 Hz. Near the epicentrum (25-300 km) the frequencies vary between 12-25 Hz and at distances round 1000 km between 2.5-7 Hz. Fig. 4. The distribution of observed frequencies versus epicentral distance differs greatly on a case by case basis particularly at distances of 300-600 km. This scattering can probably be explained as being due to the different size, depth and azimuth of the events as well as the different travel paths of the waves. In some cases the broad shape of the Fourier spectra indicates that almost the same values of acceleration occur at several frequencies.

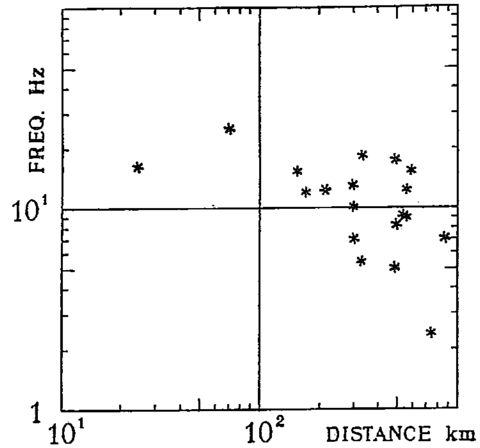

Fig. 4. The observed frequencies of the maximal ground acceleration versus epicentral distance. ML= 1.7-3.8.

For instance in Fig. 5 the Fourier spectrum of the Puolanka earthquake ML=3, 1990-11-09 gives almost the same acceleration amplitudes at frequencies of 22 and 17.5 Hz and nearly the same even at 10.5 Hz.

If we compare this same acceleration spectra calculated from the recordings of stations VAF (R=327 km) Fig. 5 and that of JOF (R=306 km) Fig. 6, the effect of a different azimuth and travel path is obvious. The frequency of the maximum peak ground acceleration at VAF is much higher than at JOF in spite of almost the same observing distances and instrumental response.

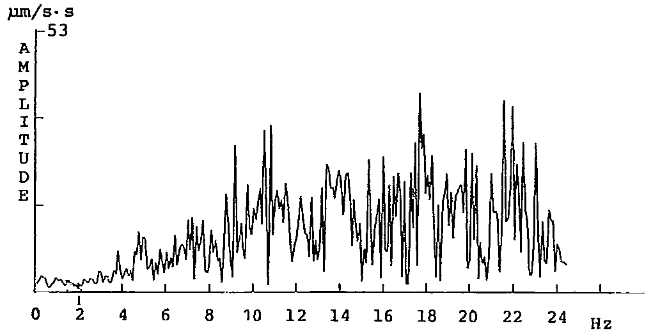

Fig. 5. The Fourier spectrum of the vertical acceleration component (S-phase) recorded at VAF, R= 327 km. Puolanka earthquake 1990-11-09. ML=3.

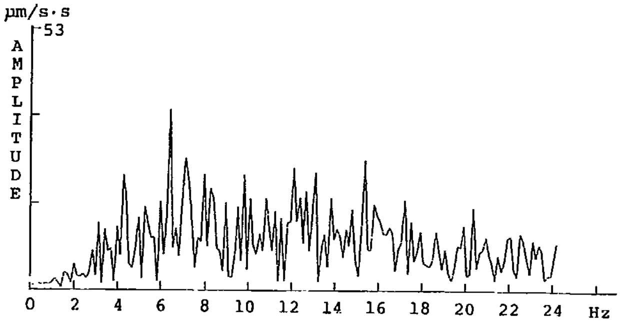

Fig. 6. The Fourier spectrum of the vertical acceleration component (S-phase) recorded at JOF, R=306 km. Puolanka earthquake 1990-11-09. ML=3.

5. *Discussion*

Schnabel and *Seed* (1973) presented an exponent of $1.5<n<2$ for total attenuation factor $1/R^n$ at distances of $32 \text{ km}<R<112 \text{ km}$, for an earthquake M= 5.6, which is in good agreement with attenuation factors proposed by many other authors. They also presented an attenuation curve for the average values of maximum acceleration in rock at short distances R = 3.2 - 100 km from causative fault (*Schnabel* and *Seed*, 1973). For an earthquake of magnitude M= 5.2 they gave as maximal acceleration the value in rock 0.1 g (98.1 cm/s*s) at 10 km and 0.2 g (196 cm/s*s) at 3.2 km distance. The extrapolated value for an imaginary ML=5 earthquake predicted here in Fig. 2 is 80 cm/s*s at a distance of 10 km.

Slunga (1976) presented a relative attenuation curve for accelerations of Scandinavian earthquakes at distances 1-2000 km. This curve is remarkably less inclined than that given here at distances R=100-500 km and nearly the same at distances 20<R<80 and R≈1000 km.

In the Finnish data-archives there are no experimental data for earthquakes 1.5<ML<5 measured closer than 25 km from the computed epicentrum.

The extrapolation of the attenuation lines to equal or closer than a distance of 10 km is doubtful so far we do not have more nearfield observations and a sufficiently understanding of the source mechanisms.

If we compare the acceleration 24 cm/s*s as predicted here for an earthquake of ML=5 at a distance of 50 km with that given by *Båth et al.*, (1976). Formulae 24 and 25, it is probably 4 times higher. (Formula 24, $\log A_i = M_L - 0.40 - 2\log T - F(\Delta,T)$ and formula 25, $\log A_i = M_L - G(\Delta,T)$ where A_i = instrumental ground acceleration (μm/s*s), M_L=Richters original magnitude, T= wave period (s), $F(\Delta,T)$ and $G(\Delta,T)$ are calibrating terms).

The shortest distance and period which can be used in formulae (24, 25) are 50 km and 0.3 s (3.3 Hz). Perhaps the much higher dominating frequencies 5<f<25 Hz can eventually produce values which are even 4 times higher.

Selnes (1978) compared the ground motion in Scandinavia and California and stated among other things that the frequencies may be higher, the attenuation slighter and that the predominant frequencies will decrease less quickly with increasing distance in Scandinavia than in California.

6. *Conclusions*

The largest measured value for the vertical component of the pga on the bedrock at a distance of 25 km from the calculated epicentrum of a ML=2.4 earthquake which occurred in Finland is 1240 μm/s*s at a frequency of 16 Hz. An estimate for the course of the attenuation curve of the peak-acceleration versus epicentral distance in hard rock has been found to be like a section of an inverted parabola at distances between 10 and 1000 km. As a rough estimate for the extreme value of the vertical pga, which possibly could appear on the area adjacent to the epicentrum $R \approx 10$ km of earthquakes of different size at average depth h=10-15 km (*Ahjos* and *Uski*, 1992) the following approximate values are given:

ML = 2, $\bar{a}$ = .08 cm/s*s; ML = 3, $\bar{a}$ = 0.8 cm/s*s;

ML = 4, $\bar{a}$ = 8 cm/s*s and ML = 5, $\bar{a}$ = 80 cm/s*s.

These values have a very strong dependence on the total attenuation near the source ($R <$ 25 km). This is an area in Finland where to the present time no observations are available. Near-to-the-source values will be improved as soon as more and better observations are recorded.

The observed frequencies of the maximal acceleration (2.5 - 25 Hz) at different epicentral distances differ greatly event by event. At distances near 1000 km the predominant frequencies are 2.5 - 7 Hz and near the epicentrum 16 - 25 Hz. Scattering of frequencies is particularly strong at distances 300-600 km. Probably in addition to the effect of distance, size and depth, also the azimuth and different travel paths affect the frequency content.

Acknowledgments

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