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Analysis of the ground acceleration records detained during the April 15, 1979 Montenegro earthquake

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ABSTRACT: A study has been carried out to investigate the ground motion due to the April 15, 1979 Montenegro earthquake with a magnitude of $M_L = 7.2$, and to make clear, as far as possible, the causes for the heavy damage to a large number of buildings within an area stretching for about 100 to 120 km along the whole Montenegro as well as a part of the Albania coast. Twenty-six three-component strong earthquake records were obtained by the permanent strong earthquake recording instruments (SMA-1) network installed on the territory of SFR of Yugoslavia, out of which eight instruments were located within the wider epicentral area. Analysis has been carried out of several parameters which characterize the strong ground motion, such as peak acceleration, RMS-acceleration, significant duration, energy intensity and spectral content. The obtained results show that the fault rupture is of a very large scale and that the earthquake was of complex origin nature (multishock event). Therefore, the ground motion parameters of the considered sites up to 70 km northwest in the parallel direction to the fault line do not depend on the distance from the instrumentally determined earthquake epicenter. On the other hand, the difference in the values of these parameters between particular sites can be primarily explained by the effect of the site soil conditions.

1 INTRODUCTION

On the 15th of April 1979, at 06:19:42 (GMT) the Montenegro coastal area was struck by a very strong earthquake with a magnitude of $M_L = 7.2$. It is one of the strongest earthquakes which has occurred within Yugoslavia, and the Balkan Peninsula, during the current century. The event was recorded by the permanent strong earthquake recording network installed on the territory of Yugoslavia. According to the seismological data the earthquake origin is located at the depth of about 8 km of the Adriatic Sea floor with coordinates of 41.93N and 18.98E. The earthquake mechanism corresponds to an approximately vertical reverse type of fault with deep-slip motion, where the southwestern block overthrusted the northwestern block (1).

The main shock was followed by a large number of aftershocks concentrated mainly at both ends of the triggered fault. Far more aftershocks occurred at the southeast end of the fault, while the two strongest aftershocks, one with a $M_L = 6.0$ (8 hours after the main shock) and another with a $M_L = 6.4$ (on May 25, 1979) occurred at the northwest end of the fault.

The main shock is recorded at 26 recording stations of the network, located at approximately 20 km to 320 km from the earthquake epicenter which makes it one of the best recorded events in Yugoslavia by instruments placed both far-field and near-field. Eleven accelerograms, out of the mentioned number of records, taken at sites at an approximately equal epicentral distance of 20 to 150 km, and processed applying a standard strong earthquake data processing procedure (2) are used as the basis for this study. The recording sites for the records analyzed and the earthquake epicenter are shown in Fig. 1.

Based on visual inspection of all the obtained records, both close and far-distant from the earthquake origin, particularly northeast and southeast as well as according to the Husid plots for records analysis it can be concluded that the earthquake is a multishock event, composed of three or four shocks different in space and time. The parameters, which are usually used to express the demolishing effects of an earthquake, such as the peak acceleration, energy intensity, the RMS-acceleration, du-

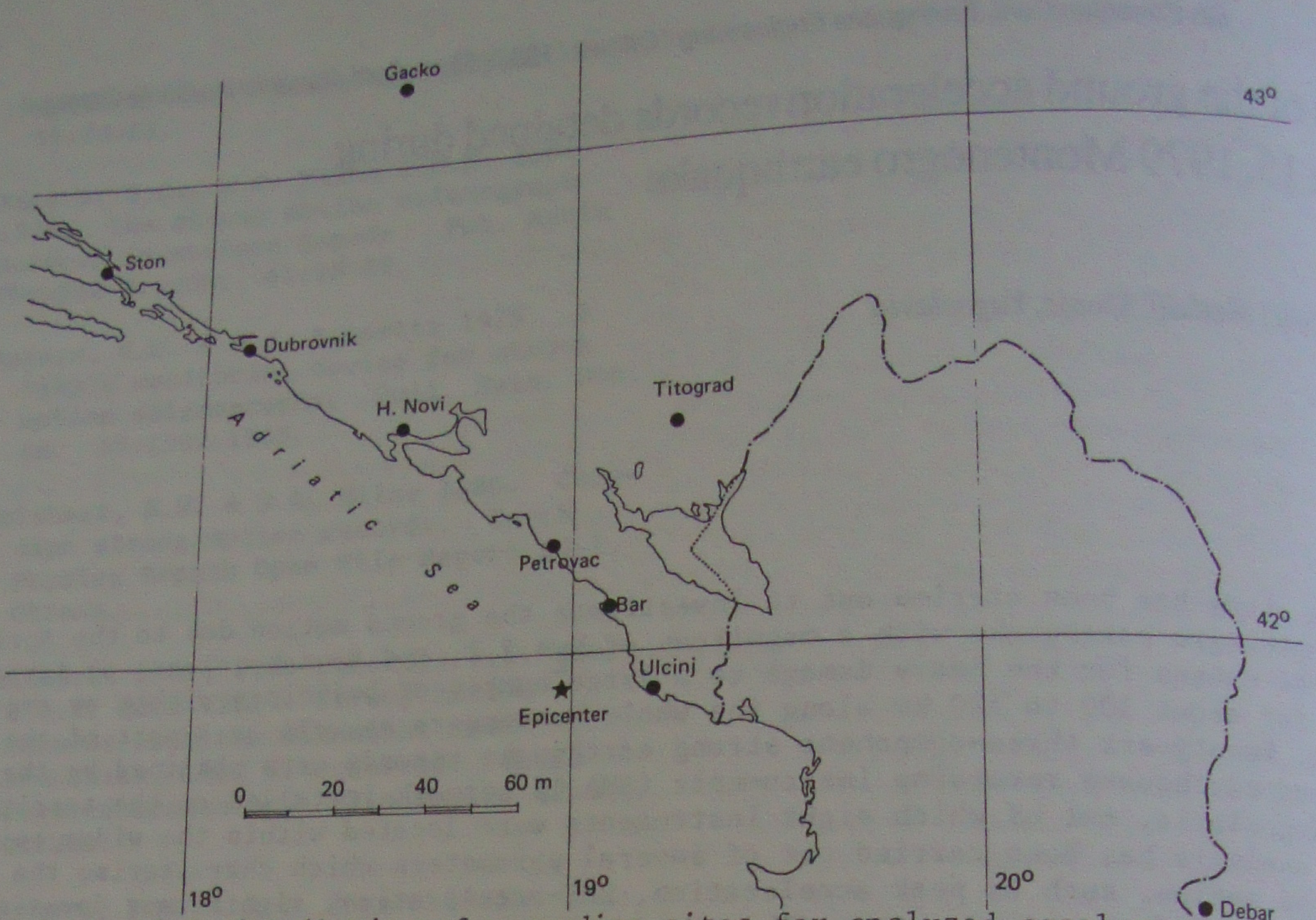

Fig. 1. Spatial distribution of recording sites for analyzed accelerograms with respect to the epicenter of April 15, 1979 main shock.

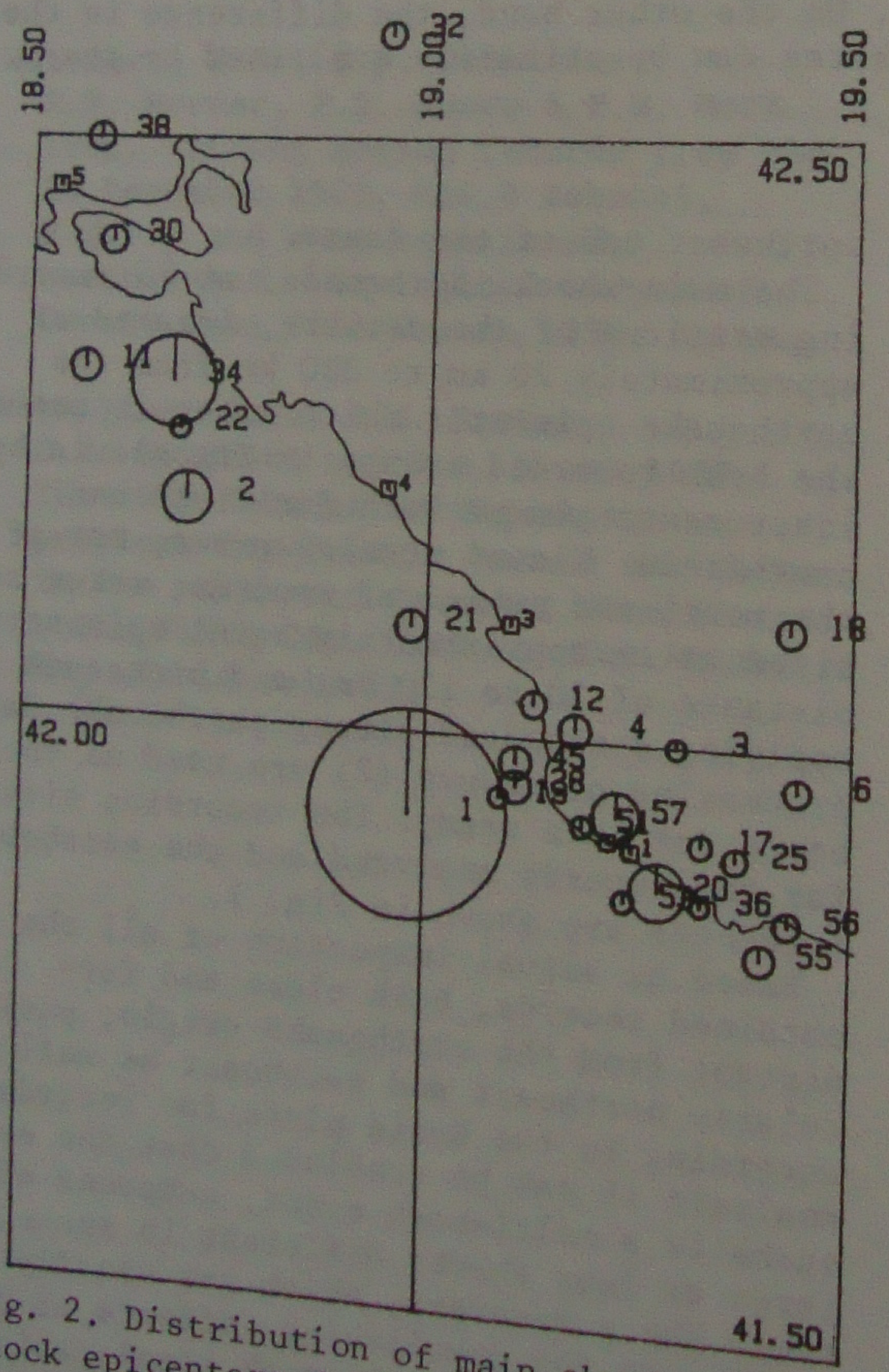

Fig. 2. Distribution of main shock and aftershock epicenters during the first twenty-four hours with $M_L > 3.5$ (map R=1:1000000).

ration of strong phase of the earthquake, for two rock sites, located at 20 km (SE) and 70 km (NW) from the epicenter, i.e., on a distance of 83 km from each other, have approximately the same values. This fact, in addition to the distribution of aftershocks during the first twenty-four hours after the main shock (Fig. 2) point to the size and the stretching direction of the fault rupture and explain the occurrence of the heavy damage and failure of structures within an area enclosing the whole Montenegro coast and a part of the Albania coast.

It is essential that the performed investigations show that the ground motion close to the fault rupture is directly influenced by the dynamic characteristics of the rupture process and that, for the considered event, the shortest distance to the trigtered part of the fault is a more important and better physical parameter of the distance.

2 ANALYSIS OF PEAK GROUND ACCELERATION

The peak ground acceleration is a parameter which is usually used to express the ground motion intensity of an earthquake. The corrected peak ground accelerations of the obtained eleven main shock accelerograms with respect to the epicentral distance are shown in Fig. 3.1. It can be

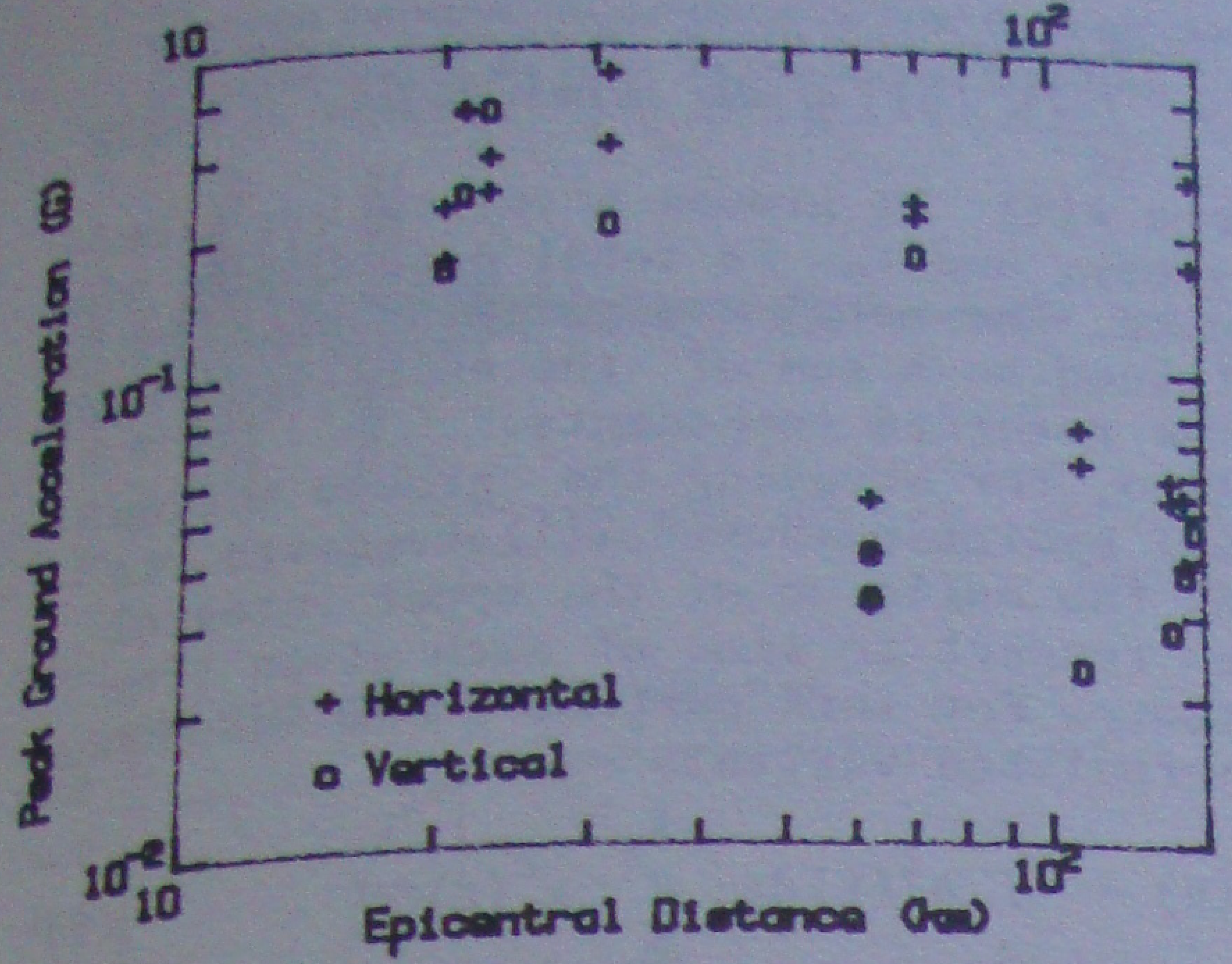

Fig. 3.1. Corrected peak ground accelerations with respect to epicentral distance.

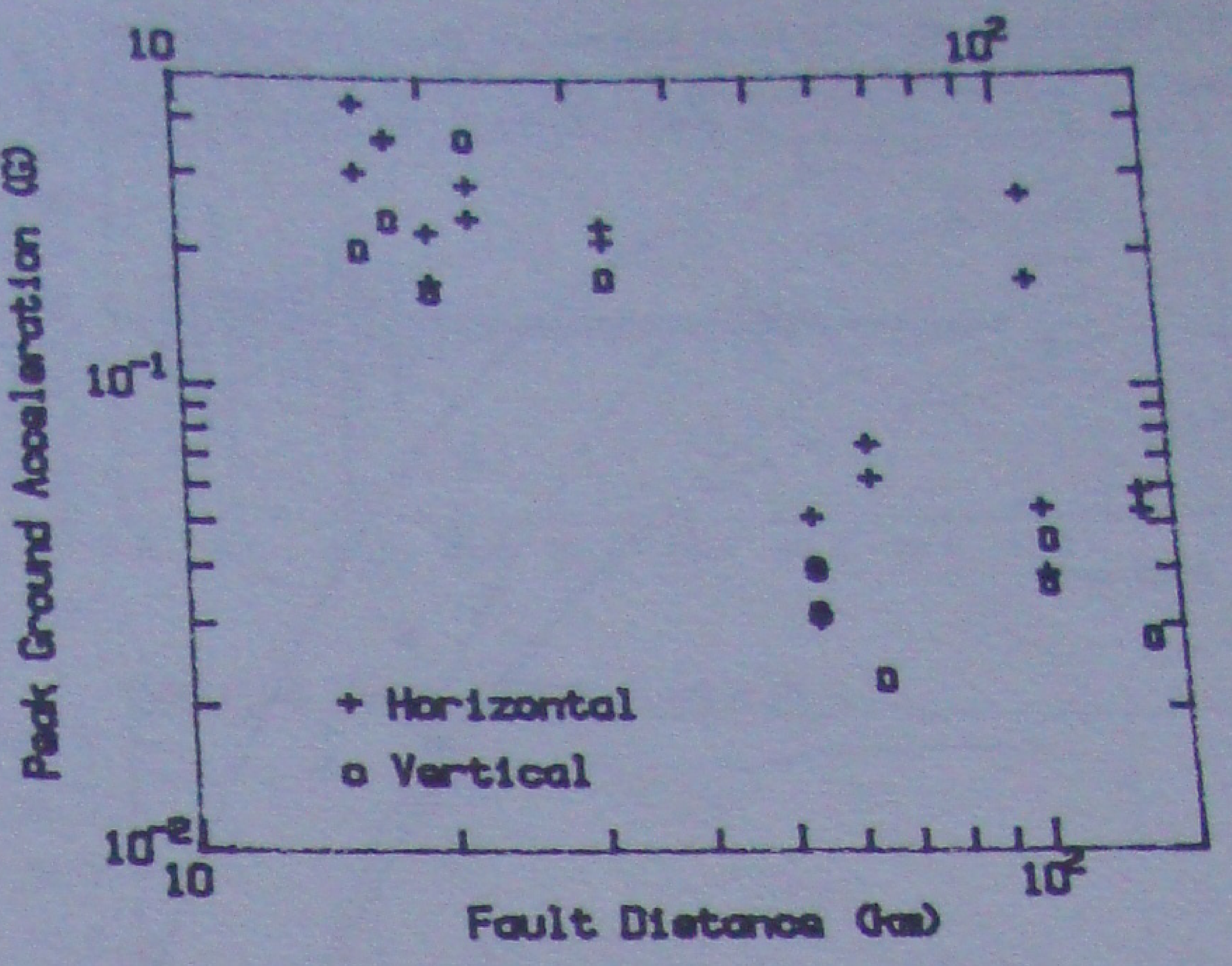

Fig. 3.2. Corrected peak ground accelerations with respect to fault distance.

seen from the Figure that the maximum horizontal peak ground acceleration of 0.44 g is recorded at Petrovac, which is 31 km far from the earthquake epicenter. Two closer sites at a distance of 21 km and 22.5 km also located on characteristic soil have maximum peak ground accelerations of 0.36 g and 0.29 g, respectively. For the vertical peak ground acceleration components, the maximum peak ground acceleration is recorded at Ulcinj-1 (22,5 km) and it is 0.36 g, while considerably lower values of 0.24 g and 0.20 g are obtained at Bar and Petrovac, respectively. By comparison of the peak ground accelerations of the three components at the two rock sites of Ulcinj-2 and Herceg Novi, which are 20 km southeast and 70 km northwest of the earthquake epicenter it can be seen that the larger ones are at the further-distant site. It should be noted that peak ground accelerations of as much as 0.27 g (NS) and 0.17 g (EW) are obtained for the recording site of Ston, which is 146 km far from the earthquake epicenter. This data scatter of peak ground acceleration in respect to the epicentral distance points that the shorter distance to the fault rupture along which the motion process occurs might be a better distance parameter. This distance can be determined either based on the ground surface manifestations of the ruptured fault or from the earthquake aftershocks distribution. In the considered case, since the rupture process developed along the fault line in the sea floor, the approximate shortest fault distances of the sites are determined based on the aftershocks distribution during the twenty-four hours after the main event. Presented in Fig. 3.2 are the peak ground accelerations in respect to the fault distance. It can be seen from the Figure that the data scatter with respect to the shortest distance is considerably smaller.

To verify the above presentation, Fig. 4 shows the same data together with several attenuation curves using the shortest fault distance as a variable. It is obvious that the peak ground accelerations are within the zone enclosed with those curves. However, the comparison of the data with the individual curves shows that the least coincidence is with the curves suggested by Bolt (3) and Campbell (4), i.e., it is evident that the suggested relationships have a tendency to underestimate the peak ground acceleration close to the earthquake origin. It is also similar with the Joyner and Boore (5) relationships, except that in this case the data discrepancy is smaller compared to the two previous ones. Unlike this, the relationship suggested by Esteva (6), tends towards overestimating the peak ground acceleration taken closer to the fault line. However, one should keep in mind that the insufficient number of data, in particular those taken close to the fault rupture zone and in the direction normal to the fault line, it is still difficult to establish a general relationship for the peak ground acceleration attenuation for the territory of Yugoslavia, and for a magnitude equal to or larger than 7.

3 ANALYSIS OF ENERGY PARAMETERS AND SIGNIFICANT DURATION

From engineering viewpoint, expressing the

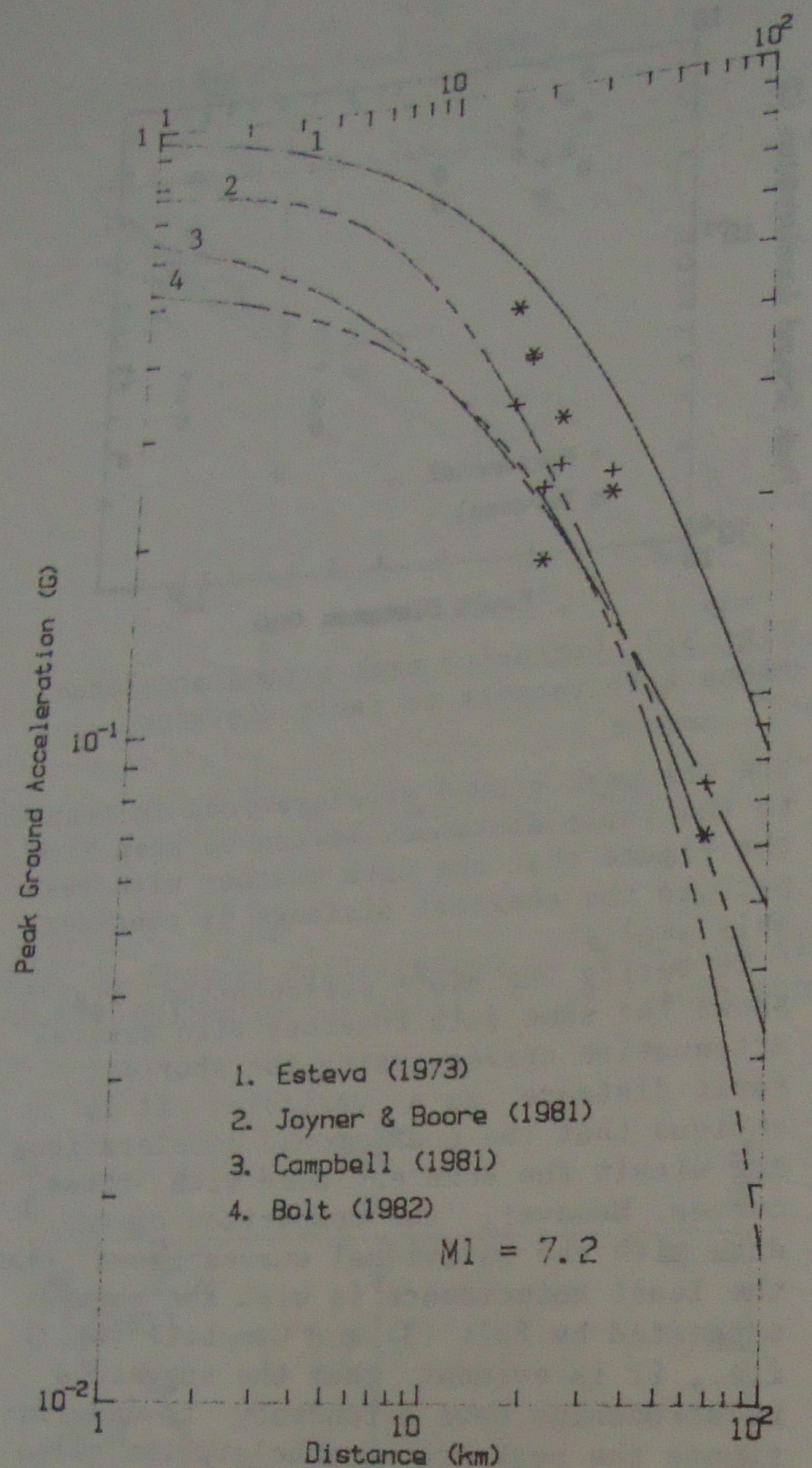

Fig. 4. Comparison between corrected peak ground accelerations and suggested attenuation relationships for magnitude 7.2.

demolishing effects of an earthquake in terms of the peak ground acceleration is not mainly a reliable measure as concluded in the recent investigations of Seekins & Hanks (7), McCann & Shah (8) and Haroun & Housner (9). Also, the duration of the strong phase of the earthquake, its effective level and its frequency content are essential for determining the earthquake damage potential.

Arias (10) shows that the integral $\int a^2(t)dt$ is a measure of the energy input for a set of single degree-of-freedom oscillators with a natural frequency uniformly distributed along the frequency axis while all having the same damping coefficient, and he suggests to define the total energy for a component by the following expression:

$$I_i = \int_0^{t_e} [a^2(t)]_i \, dt \quad i=1,2,3 \tag{1}$$

where $a(t)$ is ground acceleration time history, and t_e is total duration of the record. The total energy at a site can be obtained as a sum of the energies of the three recorded components.

Also, for studying the ground motion level evolution Husid (11) suggests to plot the build up of the upper integral with respect to time of each given time history. For this purpose Husid introduces a normalized variable

$$h(t) = \int_0^t a^2(t)dt / \int_0^{t_e} a^2(t)dt \tag{2}$$

where $h(t) = 0$ at the beginning, and $h(t) = 100\%$ at the end of the record. Based on this expression and according to the definition of Trifunac & Brady (12), the significant duration T_{sd} is defined as the time elapsed between 5% and 95% of the value of $h(t)$. On the other hand if T_1 and T_2 are taken for the beginning and the end of the significant duration, the average intensity and the RMS-acceleration can be determined by

$$I_a = 1/T_{sd} \int_{T_1}^{T_2} a^2(t)dt \tag{3}$$

$$\text{RMS-acc.} = \left[1/T_{sd} \int_{T_1}^{T_2} a^2(t)dt\right]^{1/2} \tag{4}$$

Two examples of the Husid plots of the horizontal components for the Ulcinj-2 and Debar sites and the corresponding parameters of I, T_{sd}, I_a and RMS-acceleration are shown in Figs 5 and 6, respectively. The results obtained by analysis of all the considered accelerograms with respect to the epicentral and the fault distance are given in Table 1.

It is obvious from the obtained horizontal components records and the corresponding Husid plots, shown in Figs 5 and 6, that there are two clearly distinguished areas of S-wave arrival times, whereat the time difference between the two strong phases of the records are considerably larger for the further distant site. This proves that the earthquake energy has been released from different parts of the fault and probably at different time. Also, the investigations proved that the sections of the Ulcinj-1 and Ulcinj-2 records after the 25th second result from an earthquake with a magnitude larger that 5, while there are indications that the initial sections of the records taken at Bar and Petrovac result from a shock of a similar magnitude.

By comparison of the energy parameters for the three rock sites, in a direction

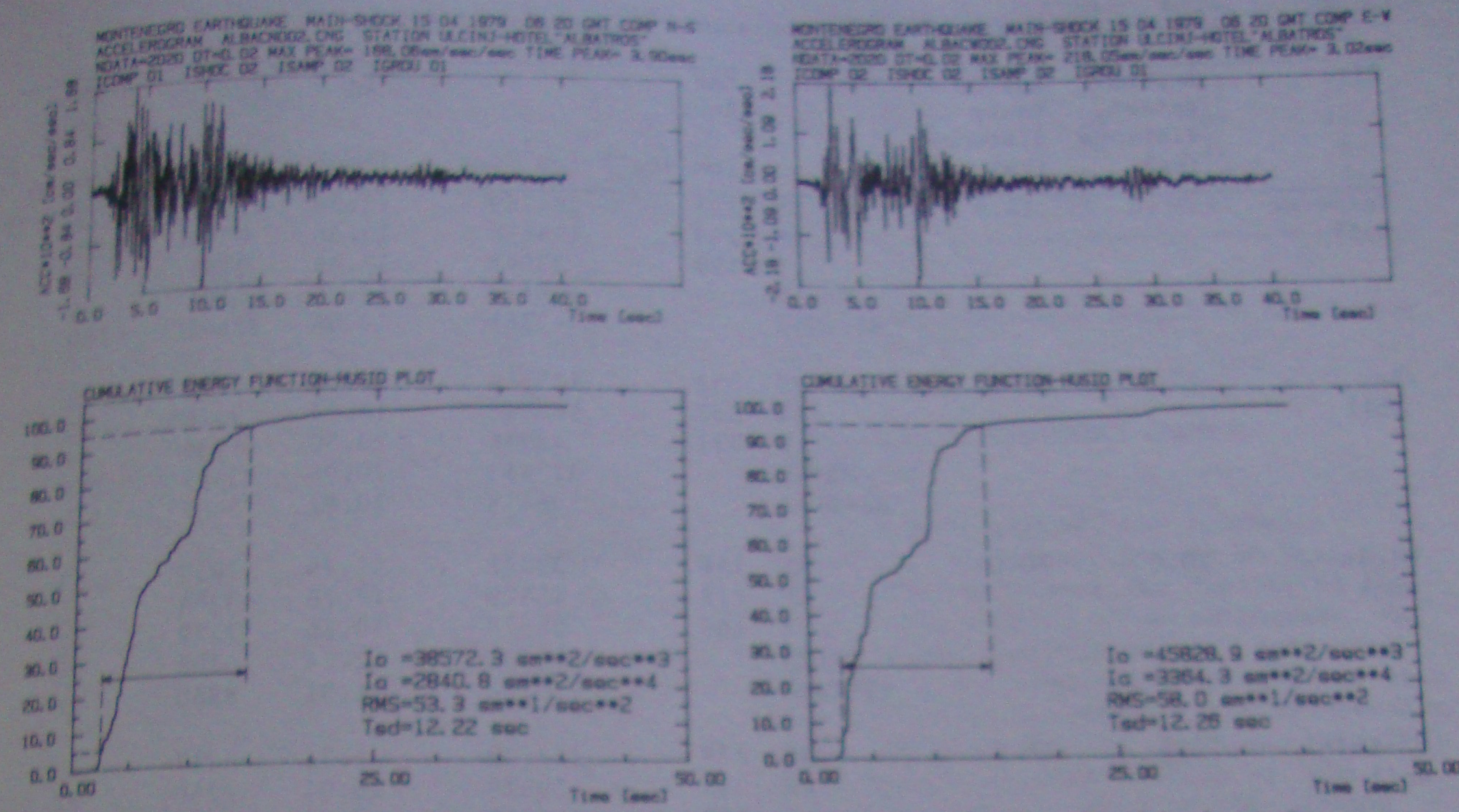

Fig. 5. Time histories of horizontal components and corresponding Husid plots for Ulcinj-2 site.

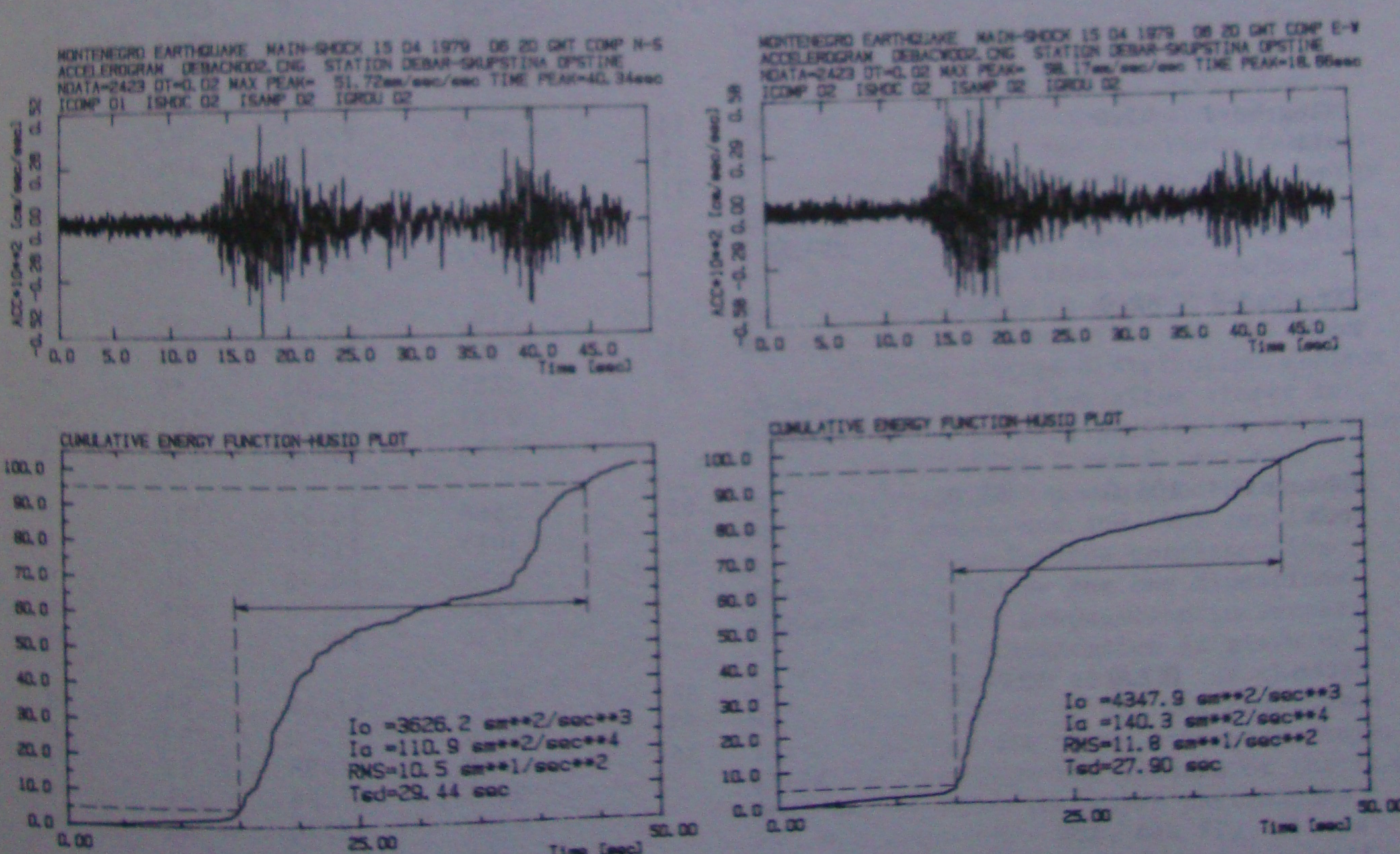

Fig. 6. Time histories of horizontal components and corresponding Husid plots for Debar site.

Table 1. Characteristic ground motion parameters of analysed sites

Site	Approx. epicen. distance (km)	Approx. fault distance (km)	Comp.	Max. Acc. (cm/sec^2)	I (cm^2/sec^3)	T_{sd} (sec)	I_a (cm^2/sec^4)	RMS Acc. (cm/sec
Petrovac soil	31.0	16.5	NS	427	284789	12.00	21359	146
			EW	299	124630	13.36	8396	92
			Z	198	33948	13.94	2191	47
			NS+EW		409419	12.24	30104	174
			NS+EW+Z		443361	12.30	32441	180
Bar soil	21.0	18.0	NS	357	123516	21.32	5214	72
			EW	352	188948	18.84	9026	95
			Z	231	43956	20.50	1930	44
			NS+EW		312463	20.96	13417	116
			NS+EW+Z		356419	20.82	15407	124
Ulcinj-2 rock	20.0	20.0	NS	168	38572	12.24	2836	53
			EW	218	45829	12.26	3364	58
			Z	160	26323	10.66	2222	47
			NS+EW		84401	12.24	6206	79
			NS+EW+Z		110724	11.92	8360	91
Ulcinj-1 soil	22.5	22.5	NS	279	112739	25.26	4017	63
			EW	235	79579	26.04	2750	52
			Z	355	115821	9.86	10572	103
			NS+EW		192318	25.76	6719	82
			NS+EW+Z		308139	18.36	15105	123
H. Novi rock	70.0	32.5	NS	209	45577	10.94	3749	61
			EW	226	28530	12.20	2105	46
			Z	171	17820	12.60	1273	36
			NS+EW		74106	11.30	5902	77
			NS+EW+Z		91933	11.40	7258	85
Titograd-1 soil	62.0	55.0	NS	39	3124	27.37	103	10
			EW	51	3159	27.20	106	10
			Z	31	1944	27.32	64	8
			NS+EW		6283	27.46	206	14
			NS+EW+Z		8227	27.54	269	16
Titograd-2 rock	62.0	55,0	NS	32	1194	25.26	43	7
			EW	31	1587	24.10	59	8
			Z	39	1435	22.04	59	8
			NS+EW		2781	24.74	101	10
			NS+EW+Z		4216	24.10	157	13
Dubrovnik rock	108.0	65.0	NS	62	2568	14.70	157	13
			EW	74	3015	11.66	232	15
			Z	23	652	16.46	40	6
			NS+EW		5583	12.60	399	20
			NS+EW+Z		6234	12.92	434	21
Gacko soil	142.0	104.0	NS	38	2035	21.24	86	9
			EW	53	3640	15.70	209	14
			Z	36	1279	21.98	55	7
			NS+EW		5675	17.58	291	17
			NS+EW+Z		6954	18.20	344	19
Ston soil	146.0	105.0	NS	264	57467	9.84	5256	72
			EW	170	19359	14.70	1185	34
			Z	45	1921	17.36	100	10

			NS+EW		76826	10.76	6426	80
			NS+EW+Z		78748	10.95	6478	80
Debar soil	137.0	137.0	NS	52	3626	29.44	111	11
			EW	58	4348	27.90	140	12
			Z	27	1276	37.60	31	6
			NS+EW		7974	28.80	249	16
			NS+EW+Z		9250	2916	285	17

parallel to the fault line, it can be seen that the obtained values are approximately of the same order for the sites of Ulcinj-2 and Herceg Novi, while for the Dubrovnik site the obtained parameters are considerably smaller. The significant duration of all three sites for the resultant horizontal component ranges between 11.30 sec and 12.60 sec and can be related to the time duration of the rupture process for the two strongest shocks. However, the comparison of the corresponding parameters of the three characteristic soil sites, which are parallel and close to the fault line, shows that the highest values are obtained for the Petrovac site, which is at an epicentral distance of 31 km or at a fault distance of 16.5 km. Lower parameter values are obtained for the Bar site, with an epicentral distance of 21 km and a fault distance of 18 km. The lowest values are obtained for the Ulcinj-1 site, for which both distances are 22.5 km. On the other hand, the significant duration values show an opposite tendency of decreasing, whereat the obtained resultant horizontal component values are 25.76, 20.96 and 12.24 sec for the sites of Ulcinj-1, Bar and Petrovac, respectively.

The energy parameters of the remaining sites in parallel direction, at an epicentral distance larger than 100 km, are approximately the same of larger than those obtained at the two sites of Titograd-1 and Titograd-2, which are in a direction normal to the fault line and at a distance of 62 km (see Table 2).

As a result of the analysis of the energy parameters of the individual sites within the narrower and wider zone of the fault rupture, it can be assumed that the stretching direction of the fault rupture is from the southeast towards the northwest end along the fault, which coincides with the maximum seismic energy propagation direction. Therefore, based on the approximately same values of these parameters for the two rock sites, which are 83 km far from each other and correspond to the end points of the rupture part of the fault, it can be explained the occurrence of the heavy damage and failure of structures along the whole length of the Montenegro coast.

4 ANALYSIS OF FREQUENCY CONTENT OF RECORDS

As previously stated, the frequency content of the ground motion at a site is of primary importance for explaining the demolishing effects of an earthquake. For that purpose analysis of the frequency content of the considered records has been carried out to determine the corresponding power spectral density functions, which in turns gives the distribution of the average energy or power of the ground motion by frequencies. The total area enclosed by the power spectral density function gives the mean square value of the data, i.e., if only the portion of the record with the significant duration T_{sd} is analyzed the same value is equal to the squared RMS-acceleration, given in Eq. 3. The obtained power spectral density functions are normalized to have a unit area so that each discrete value of the functions ordinate, for a certain frequency, is a percentage of the harmonic energy participation in the total motion energy. Generally considered, the spectra obtained for the individual sites show various energy distribution in respect to the same components for different sites, while for some sites the energy distribution differs by components. The five sites closer to the fault will be paid particular attention.

Presented in Figs 7 and 8 are the obtained normalized power spectra for the horizontal components and the amplification functions for the corresponding sites determined by the one dimensional theory for S-wave propagation in vertical direction. The presentation is given up to 6.0 Hz, since 80 to 97 % of the total motion energy of all the considered sites is within the shown frequency range. It can be seen from the spectra of the three soil sites that the major part of the motion energy (70 - 80%, see Fig. 7) is within the frequency range of 0.5 to 2.5 Hz, whereby some components have enormous energy concentration in one or two narrow

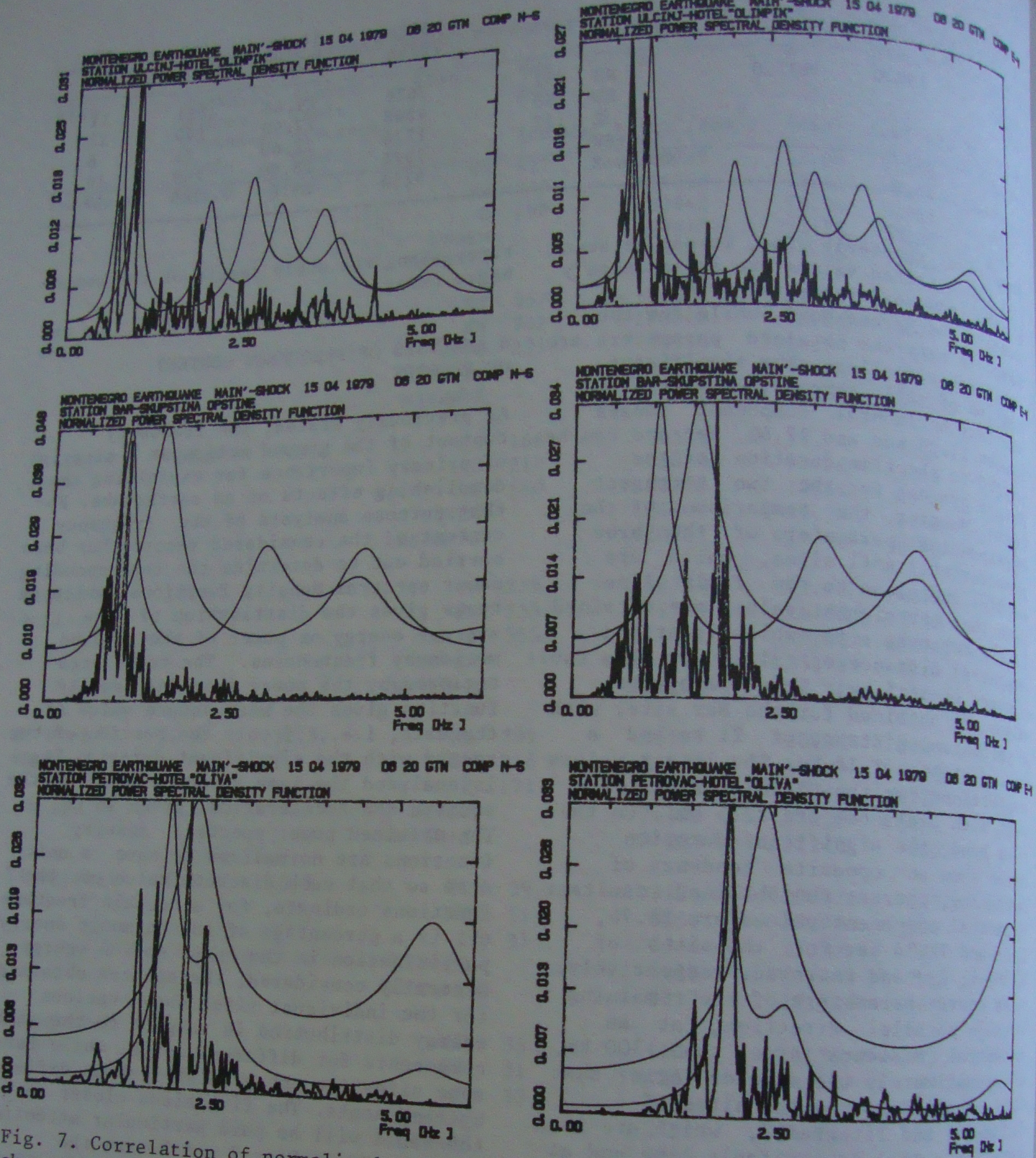

Fig. 7. Correlation of normalized power density spectra and amplification functions for characteristic soil sites.

frequency intervals, corresponding to the vibration natural frequencies of the soil deposit. On the other hand, although the spectra of the rock sites point to certain concentration of motion energy in some narrow frequency intervals, their percentage in the total energy is very low, i.e., the individual components spectra do not exhibit predominant energy concentration in the ranges corresponding to the vibration characteristics of the rock sites.

5 CONCLUSION

In conclusion of the performed investigations and the obtained results on the recorded accelerograms it can be stated that the Montenegro earthquake is a multishock event consisting of several individual shocks. On the basis of the analyzed peak ground acceleration and the energy parameters, it has been found out that the fault distance is a better and more important physical parameter for the

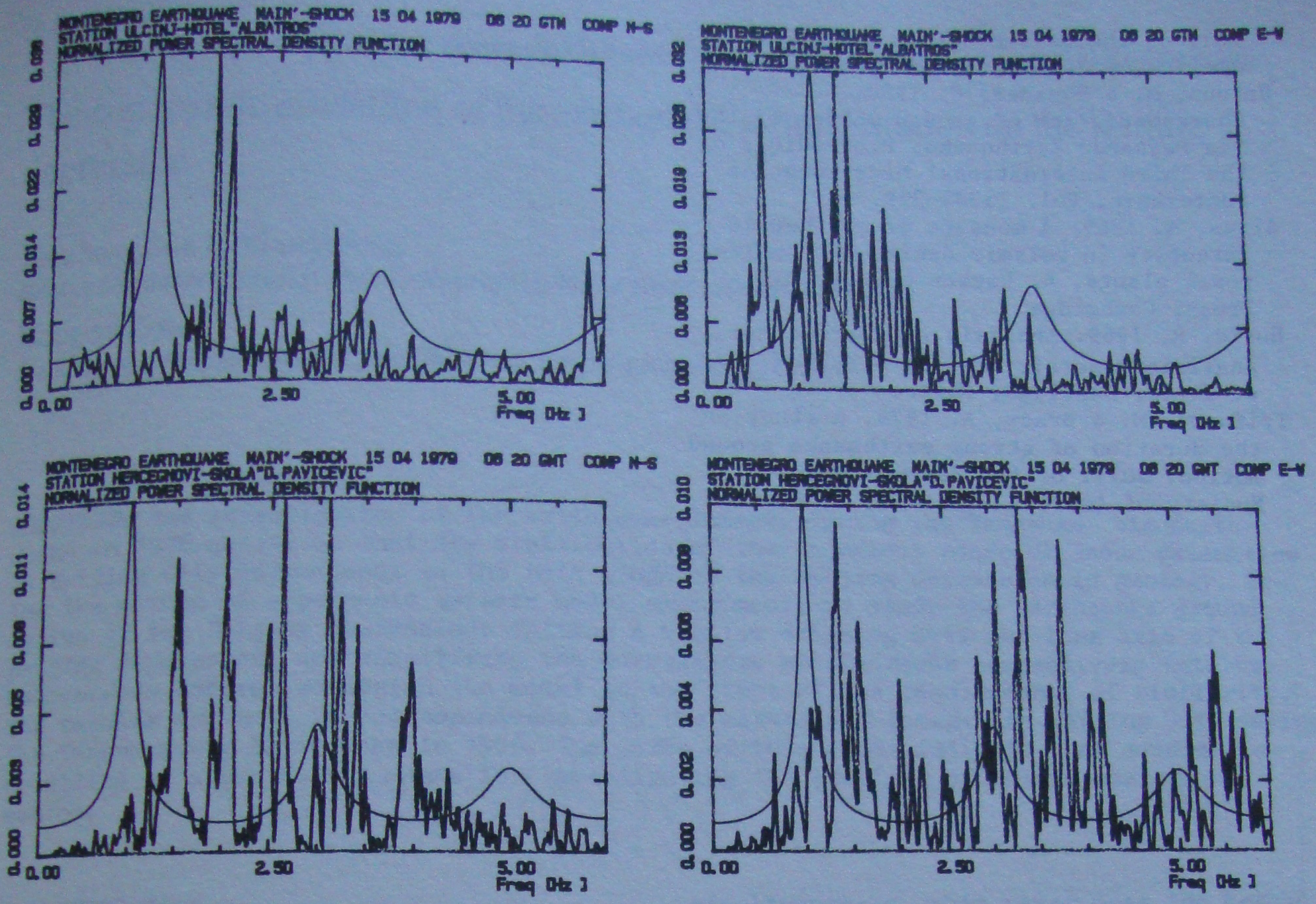

Fig. 8. Correlation of normalized power density spectra and amplification functions for bedrock sites.

distance that the epicentral distance is. Considerably larger energy parameter values for some of the sites can be explained by the amplification effect of the site soil conditions. It is evident from the normalized power spectra, where the motion energy is concentrated in narrow frequency intervals, which corresponds to the vibration characteristics of the soil deposit.

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