GEOFIZIKA VOL.7 1990

Short comunication, with regional earthquake catal. gue
UDC 550.342.2

Seismicity of Croatia and the surrounding areas in 1988

Snježana Markušić, Ivica Sović and *Davorka Herak*

Geophysical Institute, Faculty of Sciences and Mathematics, University of Zagreb, Yugoslavia

Received 6 *March* 1990, *in final form* 26 *April* 1990

Based on the catalogue of all located earthquakes in Croatia and the surrounding areas in 1988, the map of epicentres (Figure 1), and on the macroseismic data analyses for individual earthquakes, certain seismic features have been analysed. During 1988, 588 earthquakes with 6 or more onset time data were located and the catalogue was found to be complete for the magnitudes $\geqslant 3.2$. Seismically most active were the coastal part of Croatia (the Jablanac-Velebit area and the valley of the river Neretva with Metković) and the Adriatic submarine area near the island Palagruža. The Appendix includes the main parametres for 42 earthquakes with a magnitude $M_L \geqslant 3.5$. All hypocentres have been located by means of the HYPOSEARCH location program (Herak, 1989a).

Neka obilježja seizmičnosti u Hrvatskoj i susjednim područjima u 1988. godini

Na osnovi kataloga svih lociranih potresa u SR Hrvatskoj i susjednim područjima u 1988. godini, karte epicentara (Slika 1) i makroseizmičke obrade podataka za pojedine potrese, analizirana su neka obilježja seizmičnosti. U toku 1988. godine locirano je 588 potresa sa 6 ili više podataka. S obzirom na magnitudu katalog je potpun za $M_L \geqslant 3.2$. Osobito je seizmički aktivan bio priobalni dio Hrvatske i to područje oko Jablanca (Velebit), Metković i dolina Neretve, te podmorje Jadrana oko Palagruže. U Prilogu su navedeni osnovni parametri za 42 potresa magnitude $M_L \geqslant 3.5$. Svi hipocentri su locirani metodom HYPOSEARCH (Herak, 1989a).

1. Introduction

This paper is a continuation of the compilation of earthquake catalogues with epicentres in Croatia and the surrounding areas. Systematic processing of data on earthquakes in these areas began under the UNDP/UNESCO (1974) project for earthquakes which took place before 1971. The earthquake catalogue for the period from 1971 to 1985 is presently being prepared, while Herak and Cabor (1989) published the catalogue for the years 1986 and 1987.

For 1988, data have been compiled and processed for all recorded earthquakes in Croatia, regardless of the magnitude and completeness of the earthquake catalogue in respect of magnitude is examined. The map of epicentres presents locations of all epicentres, and focal parametres for earthquakes with the local magnitude $M_L \geqslant 3.5$ are listed in the Appendix. Individual earthquakes have also been macroseismically analysed, which contributed to the more complete analysis of seismically active areas in 1988.

2. Catalogue of earthquakes and intensity maps

During 1988, 588 earthquakes were located in Croatia and the surrounding areas, of which 42 were with the magnitude $M_L \geqslant 3.5$. Only locations calculated with 6 or more onset time data were taken into consideration.

To determine the earthquake parametres, we have used data recorded by the permanent and temporary seismological stations of the Geophysical Institute of the Faculty of Science and Mathematics in Zagreb, and by seismological stations of the neighbouring countries: Albania, Austria, Italy, Hungary and Romania. We have determined four main parametres for each earthquake: hypocentral time, epicentral location (latitude and longitude), depth of focus and local earthquake magnitude.

Hypocentral time and coordinates of the focus were determined by the HYPOSEARCH method (Herak, 1989a). Earthquake magnitude M_L was calculated on the basis of seismograms from the stations ZAG and HVAR (Herak et al. 1988). The body waves velocity model for the Balkan region (B.C.I.S., 1972) was used in the program. The exceptions are Mid-Adriatic earthquakes (marked*) and the earthquakes in the Dinara mountain area (marked**), where we used the velocity models used in the publications by Herak (1990) and Herak et al. (1988).

The catalogue lists primary earthquake parametres and their standard deviations. Earthquake parametres are given in the following order:

— Date: month and day on which the earthquake occurred,

— Origin time specified by the hours, minutes and seconds UTC,

— Epicentre: geographic coordinates specified by degrees and decimals of degrees of the northern latitude and the eastern longitude, and their standard deviations in kilometres,

— Depth and its standard deviation in kilometres,

— Local magnitude (M_L),

— Remarks.

The remarks include the standard error S of the solution (in seconds), the number N of data which were used in the earthquake location process, the azimuthal gap (in degrees), and the maximum recorded intensity I_{max} for the macroseismically processed earthquakes. We have compiled the macroseismic data obtained by fieldwork and/or by the questionnaires received from the epicentral areas. The intensity I_{max} was estimated in accordance with the MSK-78 scale (Živčić, 1986). The isoseismal or intensity maps are presented for 3 earthquakes (Figures

3, 4 and 6). The maps of isoseismals have been plotted in the way that the curves are contiguous with the extreme outer points of the area of a particular intensity. Generally, it may be observed that earthquake isoseismals are elongated. In most cases the elongation suggests more efficient energy spreading along the lines parallel to the main geologic structures of the respective area (faults, mountain belts).

In order to check up to which magnitude the catalogue could be considered complete, we have applied the relation (Aki, 1965; Zhang and Song, 1981):

$$b=\frac{\log e}{M-M_C}\cdot\frac{N-1}{N}$$

to define the value of the coefficient b in the formula (Gutenberg and Richter, 1944), $\log N(M)=a-bM$. In the above expression M denotes the mean magnitude of the earthquakes in the catalogue, M_C the one from which the catalogue is complete, and N is the number of earthquakes with a magnitude greater or equal to M_C. Figure 2 illustrates the values of coefficient b for the magnitudes $2.0 \leq M_C \leq 3.7$. It can be observed that for $M_C \geqslant 3.2$, coefficient b assumes almost constant value, so it can be said that the catalogue is complete for the magnitude M_L greater or equal to 3.2.

3. Main characteristics of seismicity of Croatia in 1988

The basic characteristic of the regional seismic lay-out is the concentration of epicentres in particular areas and localities. For this reason we have devised the map which shows the distribution of epicentres in the considered area (Figure 1).

In regard to the concentration of earthquakes, we have confined our analysis to two areas: (1) the southwestern part of the Pannonian basin and central Croatia, and (2) the coastal part of Croatia.

(1) The prevailing direction of the spreading of the concentration of epicentres in the northwestern and central parts of Croatia is northeast-southwest. The belt of intensified seismic activity is situated here, and it stretches from Ludbreg, through Kalnik, Medvednica, Žumberačka gora to Pokuplje. This belt goes on, changing direction along the valley of the river Sava, towards Ljubljana.

The earthquake with the greatest intensity ($M_L=3.5$, $I_{max}=$V°MSK) in this area occurred near Ludbreg on June 12. It was preceded by three earthquakes which occured on May 30, and which were of lesser intensity ($I_{max}=$IV—V°MSK). The earthquake on June 12 caused the falling off of mortar in some poorly built houses in Ludbreg. Besides Ludbreg, the earthquake was felt, with the intensity V°MSK, in Veliki Bukovac, Ljubešćica, Poljanac, Veliki Poganac and Rasinje, but no damage was reported there. In the area encircled by the IV° isoseismal, there are three longitudinal faults in the direction northeast-southwest (Ludbreg-Novi Marof, Kuzminec-Radljevo Selo, Pustakovec-Veliki Poganac), and a transversal fault at the edge of the Kalnik massif (Ludbreg-Bolfan). The faults are plotted onto the map of isoseismals, and it has been noticed that the places with the intensity V° are in the vicinity of the longitudinal faults. The soil consists of pre-quaternary and quaternary sediments mostly clay and sand. The microseismic epicentre is located some 10 kilometres away from the macroseismic one. The location was

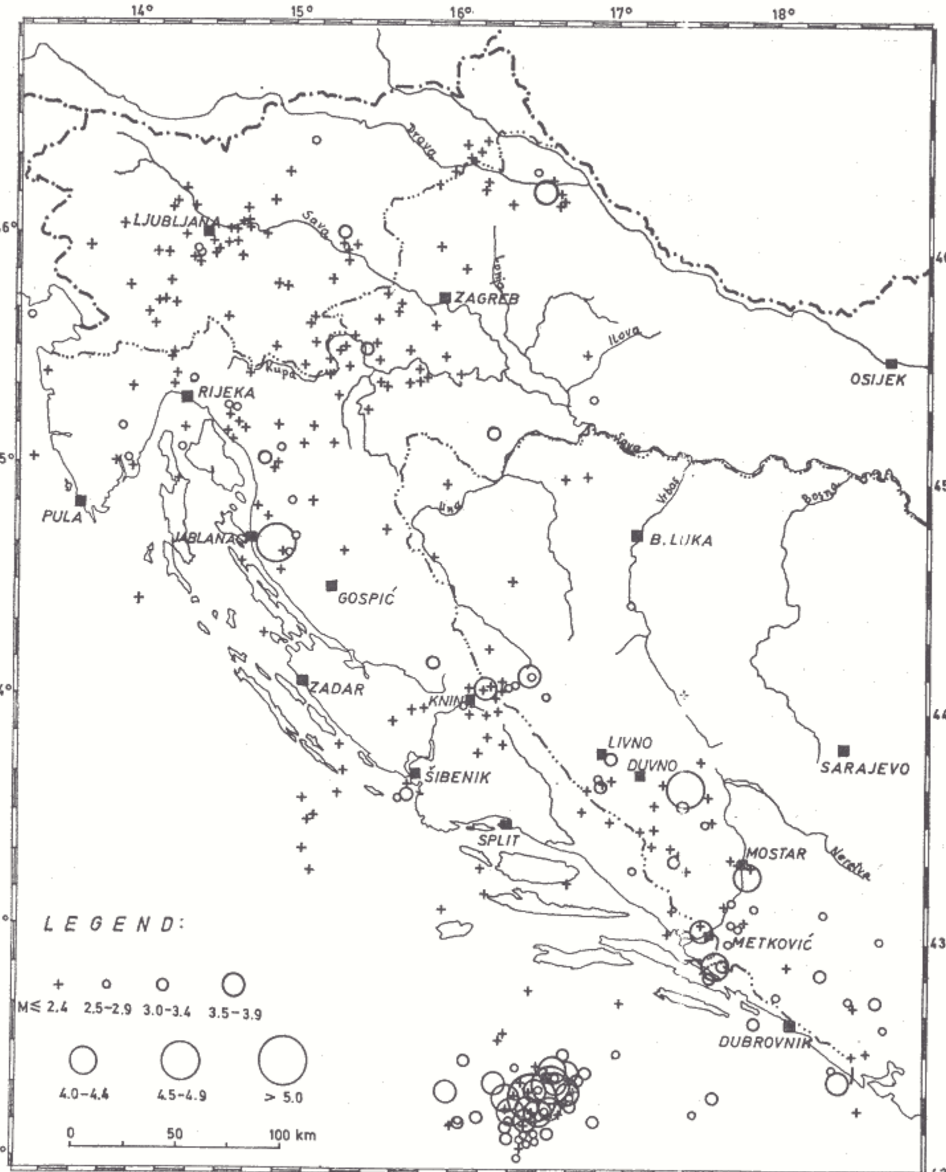

Figure 1. Map of epicentres in Croatia and the surrounding areas in 1988.

calculated on the basis of a large number of data ($N=51$), standard error of the solution is relatively small ($S=0.82$ s), as well as the azimuthal gap (Gap$=94°$). Standard deviations of the focus coordinates are also small (± 1.96 km for the latitude, ± 3.00 km for the longitude and ± 4.1 km for the depth). The distance between the microseismic epicentre and the centre of the pleistoseismal is too

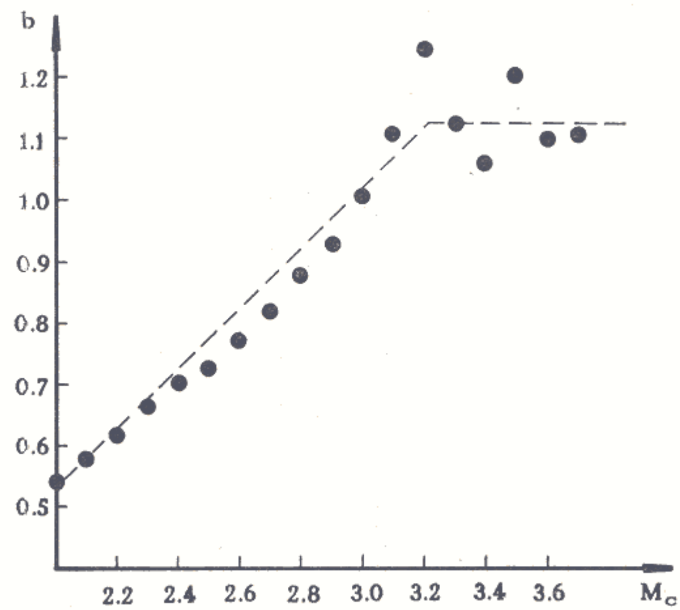

Figure 2. The b-values as a function of the assumed catalogue completeness threshold (Mc).

large to be caused by the fault length. The explanation should probably be sought in the local soil conditions, but a more detailed investigation of the local geology is needed for a final conclusion.

(2) The coastal part of Croatia with the Dinaric mountains is seismically most active — the seismicity is thought to be generated primarily by the subduction of the Adriatic microplate under the Dinara massif. In 1988 earthquakes occurred mostly in its NW part, which stretches from Ilirska Bistrica in Slovenia to Senj and Jablanac (the Velebit area).

Greater seismic activity in this area began od December 16, 1988 with a moderate earthquake near Jablanac (H=11h 35m (UTC), $\varphi=44.75°$N, $\lambda=15.00°$E, $h=20.0$ km, $M_L=4.5$, I_{max}=V°MSK). According to the magnitudes reported from the other stations ($M_L=4.7$ (HCY), 4.6 (SKO), 4.6 (SDA), 4.5 (TTG), 4.5 (BRY), 4.5 (BLY)), we can conclude that our magnitude M_L is well determined. Despite the considerable earthquake magnitude, the greatest reported intensity was V°MSK, but the intensity in the epicentre estimated from the magnitude (Herak, 1989b) equals $I_0=6.0$°MSK. The data on the intensity in the epicentre are deficient because of the relatively low population density in the area of Velebit. Most observers stressed that the earthquake was of short duration, which could explain the relatively low intensities. Besides, at the time when the earthquake occurred, a strong northeastern wind (bora) blew in the coastal region under the Velebit mountain, so that the observers, in some cases when the earthquake was felt with lesser intensity (II or III°MSK), could not discern the effects caused by the earthquake from those caused by the wind. Damage was not recorded, except in Lipovo Polje, where a small piece of mortar, of approximately three

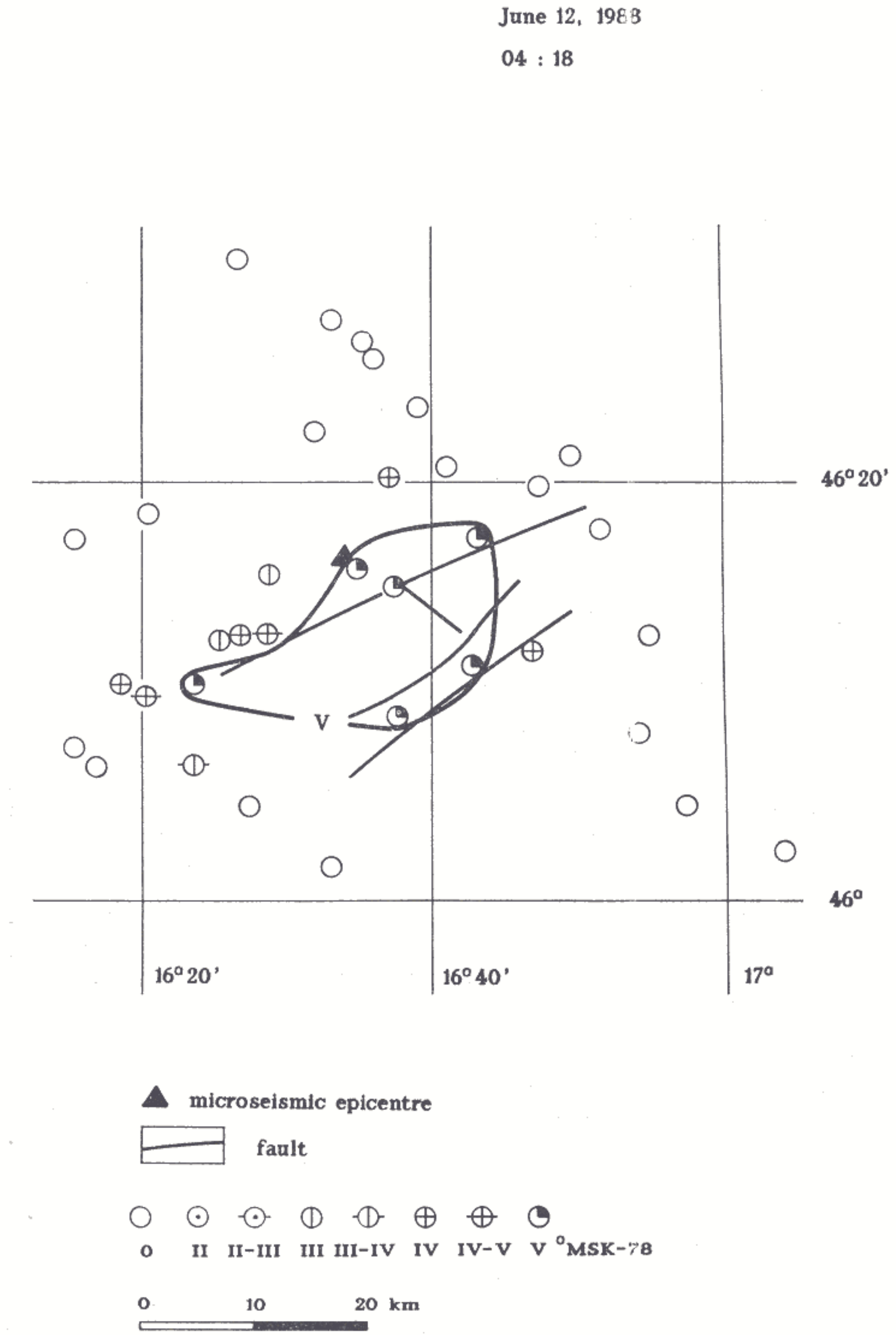

Figure 3. Map of isoseismals for the earthquake which occurred on June 12 near Ludbreg. Positions of the faults are taken from Cvijanović et al. (1976).

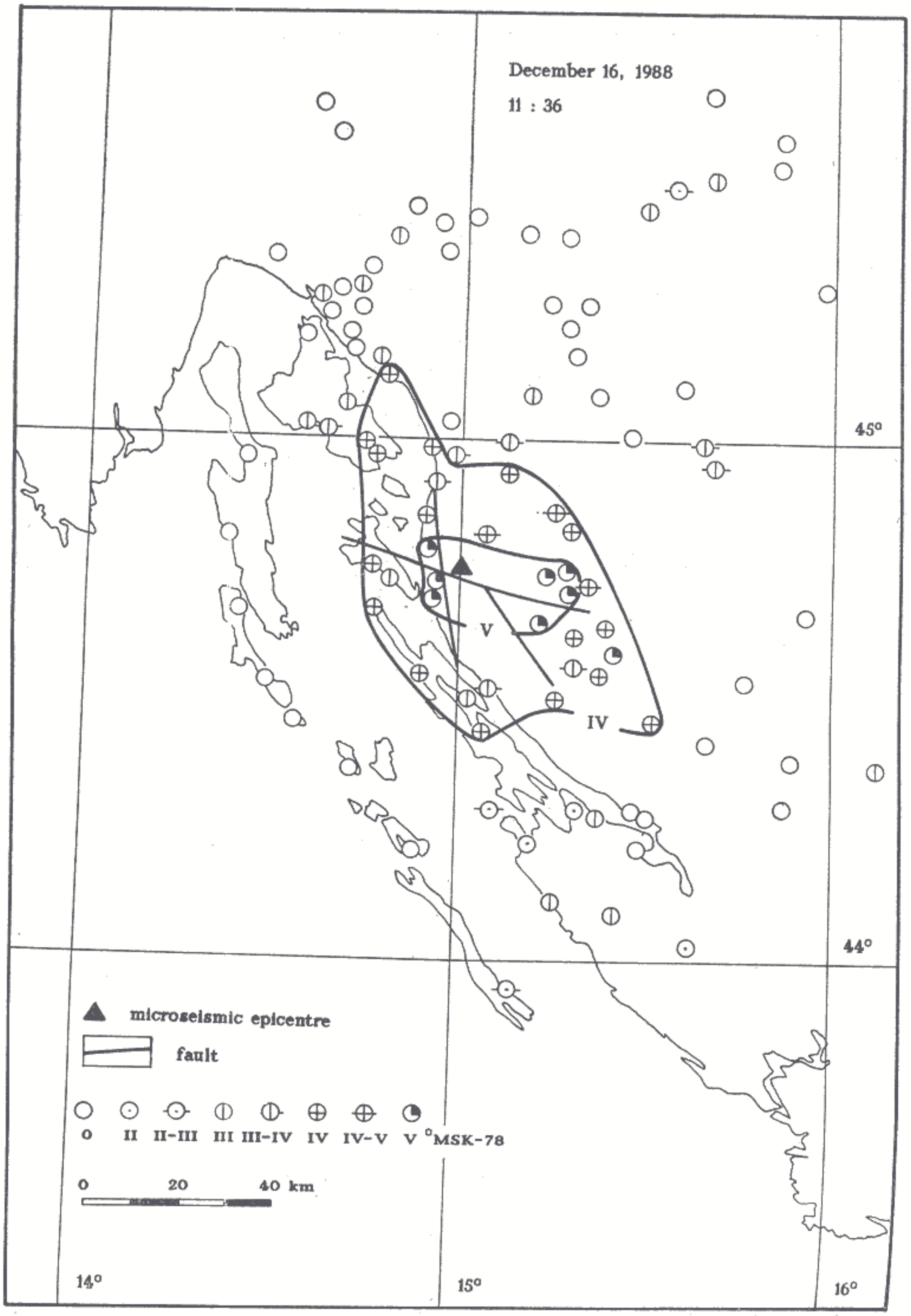

Figure 4. Map of isoseismals for the earthquake which occurred on December 16 near Jablanac. Positions of the faults are taken from Cvijanović et. al. (1979).

square decimetres, fell off the ceiling in an old house. The mortar had been plastered on wooden lattices. On Figure 4 we can see that the IV° isoseismal is elongated in the direction of the extension of the Velebit mountain (NNW-SSE). The V° isoseismal is elongated in the direction of the transversal fault (WNW-ESE). This fact can point to the connection between the fault and the earthquake focus, especially because the microseismic epicentre is located in the fault's vicinity.

The area of seismic activity around Knin (directed northeast-southwest) spreads from Mt Šator through Knin, Mt Promina along the Krka valley and towards the Adriatic submarine region. As a result of the settling of the intense seismic activity in the area of Knin (after the damaging earthquake on November 25, 1986) only two earthquakes were registered which had a magnitude greater than 3.5 (on October 25 and December 2).

The belt of seismic activity is stretching through the Dinara, the carst fields of Sinj and Imotski, towards Dubrovnik. This belt is intersected by the lines of the concentration of earthquake epicentres extending in a perpendicular direction around Livno, Duvno, and particularly marked from Mostar, along the valley of the Neretva river, towards Metković, and down the sea, towards Palagruža. The valley of the Neretva was particularly active in 1988, and the greatest recorded earthquakes occured on January 25 (M_L=4.0, I_{max}=V°MSK) and September 20 (M_L=4.4, I_{max}=V°MSK). Unfortunately, we could not macroseismically process these earthquakes, because of deficient data.

A very intense activity of the Adriatic submarine area began on April 26, with the great earthquake (M_L=5.3) near Palagruža (seismically the most active area in 1988), and it lasted throughout the year. This series of earthquakes has

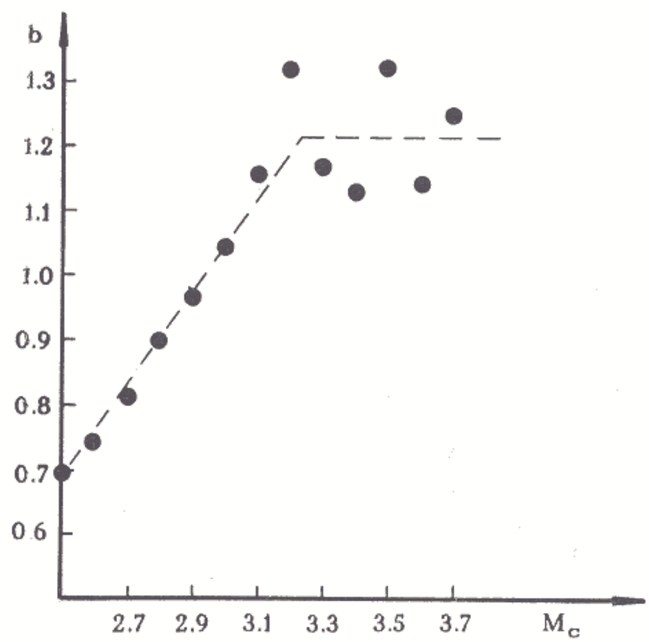

Figure 5. The b-values for the Palagruža earthquakes catalogue vs. the assumed catalogue completeness threshold (M_C).

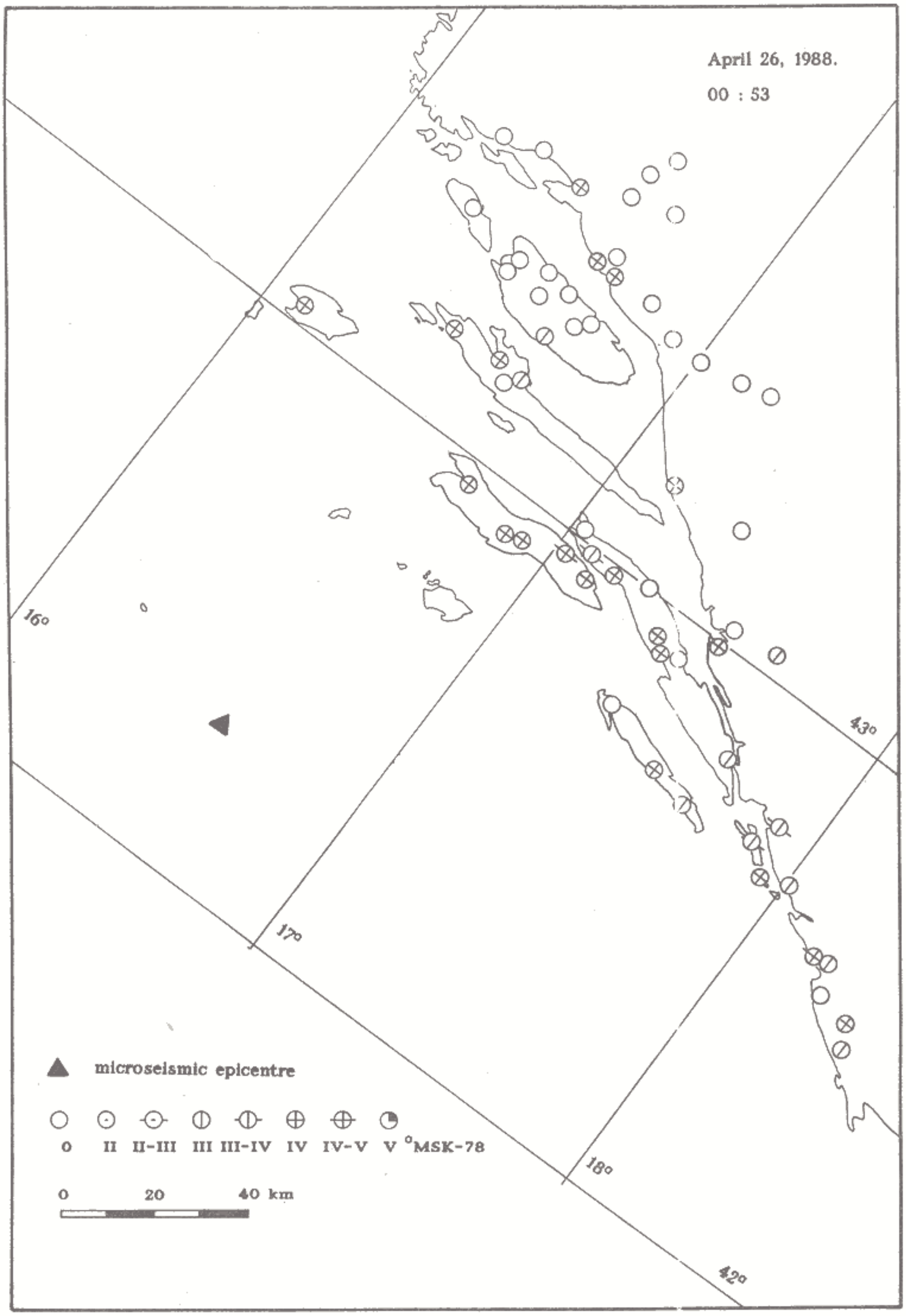

Figure 6. Map of intensities for the earthquake which occurred on April 26 near Palagruža.

been the most numerous in the Adriatic Sea so far. The number of located earthquakes is 287, and 37 of them had a magnitude of $M_L \geqslant 3.5$. Seismic activity started on February 28 with the first of 14 foreshocks, which preceded the main shock on April 26. It is interesting that almost all of the foreshocks occurred to the east of the main shock, separated from the majority of earthquakes, spreading in the northeast-southwest direction. The completeness of the catalogue, containing only the data from the epicentral area around Palagruža, has also been examined. From Figure 5 it can be concluded that all the earthquakes with the magnitude $M_L \geqslant 3.2$ have been included in it. Macroseismic data for the main shock were compiled by questionnaires only and we have plotted the map of intensities (Figure 6). The greatest estimated intensity was IV—V °MSK, in Račišće and Kupari, but this was probably not the greatest intensity felt during this earthquake, since the data for Lastovo and Palagruža are missing. The intensity in the epicentre has been estimated by the relation of Herak (1989b) equaling $I_0 = 7.8$ °MSK.

4. Conclusion

Seismic activity in Croatia and the surrounding areas in 1988 was confined to the well known epicentral areas (especially the coastal part of Croatia with the Dinaric mountains). The most epicentres occurred, however, in a poorly known area, near the island Palagruža. This series of earthquakes may prove to be very important for the investigation of the seismicity of the Adriatic microplate. It is possible that today's improved instrumental monitoring may change our view of the Adriatic submarine area as being nearly aseismic.

Acknowledgement

We are grateful to Marijan Herak, who has read the manuscript and made valuable suggestions and additions. Also, we wish to thank Ines Ivančić for her help in collecting data.

References

Aki, K. (1965): Maximum likelihood estimate of b in the formula log N=a−bM and its confidence limits. Bulletin of the Earthquake Research Institute, University of Tokyo, **43,** 237 −239.

B.C.I.S. (1972): Tables des tempts de propagation des ondes séismiques (Hodochrones) pour la region des Balkans. Manuel d'utilisation. Strasbourg.

Cvijanović, D., Prelogović, E. Mokrović, J. and D. Skoko (1976): Seizimička mikrorajonizacija Koprivnice. Geofizički zavod PMF-a, Zagreb, p. 29 (in Croatian).

Cvijanović, D., Prelogović, E. and D. Skoko (1979): Seizmotektonska karta SR Hrvatske i susjednih područja. Geofizički zavod PMF-a, Zagreb.

Gutenberg, B. and C.F. Richter (1944): Frequency of earthquakes in California. Bulletin of the Seismological Society of America, **34,** 185−188.

Herak, D., Herak, M. and S. Cabor (1988): Neka obilježja seizmičnosti i katalog potresa šireg područja Dinare za razdoblje 1979−1987. Acta Seismologica Iugoslavica, No. 14, 27−59 (in Croatian with English abstr.)

Herak, D. and S. Cabor (1989): Katalog potresa s epicentrima u SR Hrvatskoj i susjednim područjima 1986. i 1987. godine. Geofizika, **6,** 101−121 (in Croatian with English abstract).

Herak, M. (1989a): HYPOSEARCH-An earthquake location program. Computers & Geosciences, **15,** No. 7, 1157—1162.

Herak, M. (1989b): The magnitude-intensity-focal depth relation for the earthquakes in the wider Dinara region. Geofizika, Vol. **6**, 13—21.

Herak, M. (1990): Velocities of body waves in the Adriatic region. Bolletino di geofisica teorica ed applicata (in press).

Shebalin, N.V., Karnik, V. and D. Hadžievski (editors) (1974): Catalogue of earthquakes I—III, UNDP/UNESCO Survey of the seismicity of the Balkan region, Skopje.

Zhang, J.Z. and L.Y. Song (1981): On the method of estimating b-value and its standard error. Acta Seismologica Sinica, **3,** 292—301.

Živčić, M. (1986): Određivanje parametara makroseizmičkog polja. Magistarski rad, Sveučilište u Zagrebu, Prirodoslovno-matematički fakultet, Zagreb, p. 79 (in Croatian).

Corresponding author's address: S. Markušić, Geophysical Institute, Faculty of Sciences and Mathematics, University of Zagreb, P. O. Box 224, 41000 Zagreb, Yugoslavia

Appendix: The catalogue of earthquakes in Croatia and the surrounding areas in 1988 ($M_L \geqslant 3.5$)

Day	Origin time h	m	s	Epicentre (°N) (±km)	(°E)	Depth (km)	M_L	Remarks
January 1988								
25	20	02	06 6	42.935 ±2.01	17.732 ±1.99	3.5 ±3.6	4.0	S=0.9 s, N=78 Gap=43° I_{max}=V°MSK at Donja Banda, Potomje, Slano, Ston, Metković, Mali Prolog and Opuzen.
March 1988								
5*	16	53	44.3	42.352 ±3.12	16.147 ±2.90	4.0 ±4.0	3.5	S=0.7 s, N=32 Gap=226°
20*	13	57	42.2	42.310 ±3.21	16.496 ±2.60	2.9 ±4.7	4.1	S=0.9 s, N=50 Gap=199°
April 1988								
26*	00	53	45.7	42.305 ±1.83	16.618 ±1.36	8.2 ±3.3	5.3	S=0.7 s, N=100 Gap=26° I_{max}=IV–V°MSK at Račišće and Kupari.
26*	01	10	05.3	42.458 ±8.07	16.781 ±9.16	12.9 ±12.9	3.6	S=0.9 s, N=8 Gap=206°
26*	01	10	30.0	42.356 ±4.88	16.741 ±4.13	10.9 ±6.1	4.1	S=0.9 s, N=27 Gap=154°
26*	01	31	53.6	42.389 ±6.60	16.675 ±6.25	10.0 ±10.0	3.7	S=0.9 s, N=17 Gap=220°

Day	Origin time h	m	s	Epicentre (°N) (±km)	(°E)	Depth (km)	M_L	Remarks
26*	01	32	44.4	42.294 ±4.87	16.682 ±3.63	15.2 ±4.6	3.7	S=0.4 s, N=10 Gap=259°
26*	01	55	35.3	42.351 ±1.95	16.563 ±2.41	7.2 ±4.9	4.3	S=0.7 s N=47 Gap=57°
26*	01	57	09.5	42.195 ±3.97	16.587 ±2.89	19.0 ±4.9	3.8	S=0.2 s, N=6 Gap=287°
26*	02	05	17.4	42.355 ±5.25	16.437 ±4.44	8.0 ±8.0	3.8	S=0.9 s, N=24 Gap=140°
26*	02	31	28.9	42.336 ±2.13	16.677 ±2.43	14.9 ±4.7	4.1	S=0.7 s,N=51 Gap=71°
26*	03	54	16.6	42.451 ±7.20	16.690 ±9.66	18.0 ±12.3	3.5	S=1.1 s, H=13 Gap=193°
26*	04	14	34.4	42.346 ±3.47	16.711 ±2.43	5.3 ±5.3	3.5	S=0.7 s, N=29 Gap=163°
26*	04	48	58.9	42.378 ±4.14	16.742 ±3.84	6.7 ±6.7	3.6	S=0,8 s,N=24 Gap=140°
26*	06	43	08.4	42.351 ±3.00	16.696 ±2.50	6.9 ±5.6	3.7	S=0.7 s, N=40 Gap=141°
26*	12	59	41.4	42.367 ±3.47	16.701 ±2.42	5.4 ±5.4	3.5	S=0.7 s, N=32 Gap=220°
26*	13	45	18.6	42.410 ±3.53	16.703 ±3.22	8.0 ±8.0	3.5	S=0.9 s, N=36 Gap=197°
26*	19	10	13.4	42.328 ±3.24	16.657 ±2.48	7.7 ±5.1	3.5	S=0.8 s, N=41 Gap=164°
26*	19	17	58.0	42.301 ±3.19	16.678 ±2.37	7.2 ±5.2	4.7	S=0.9 s, N=62 Gap=132°.
26*	20	11	14.7	42.369 ±3.43	16.716 ±2.48	6.1 ±5.1	3.5	S=0.8 s, N=34 Gap=156°
27*	06	31	05.8	42.340 ±2.44	16.701 ±1.85	9.4 ±4.1	3.7	S=0.7 s, N=50 Gap=63°
27*	16	28	50.0	42.346 ±2.58	16.711 ±2.35	4.2 ±4.9	3.5	S=0.8 s, N=46 Gap=46°
27*	17	58	12.6	42.343 ±2.33	16.644 ±1.92	7.3 ±4.1	4.2	S=0.9 s, N=67 Gap=60°
27*	22	15	27.3	42.422 ±3.83	16.730 ±2.75	8.7 ±5.3	3.8	S=0.9 s, N=42 Gap=197°
27*	22	44	42.5	42.387 ±3.37	16.678 ±2.78	5.3 ±4.9	3.5	S=0.8 s, N=33 Gap=140°
28*	06	45	00.1	42.414 ±3.40	16.766 ±3.09	8.3 ±4.8	3.5	S=0.8 s, N=27 Gap=146°

Day	Origin time h	m	s	Epicentre (°N) (±km)	(°E)	Depth (km)	M_L	Remarks
28*	15	59	00.6	42.392 ±2.23	16.708 ±2.01	6.7 ±4.1	3.7	S=0.7 s, N=43 Gap=68°
28*	23	08	27.1	42.402 ±2.69	16.775 ±2.03	7.7 ±4.5	3.6	S=0.8 s, N=49 Gap=70°
29*	07	24	26.4	42.315 ±6.30	16.638 ±4.75	5.3 ±5.6	3.5	S=0.8 s, N=15 Gap=220°
May 1988								
25*	06	24	33.0	42.339 ±2.42	16.765 ±2.24	6.3 ±4.4	3.8	S=0.9 s, N=56 Gap=49°
June 1988								
3*	04	42	00.6	42.336 ±2.03	16.822 ±1.75	0.0 ±3.0	3.7	S=0.8 s, N=59 Gap=56°
3*	07	10	31.2	42.302 ±2.28	16.784 ±1.89	0.0 ±2.6	3.6	S=0.8 s, N=61 Gap=58°
12	04	17	57.0	46.273 ±1.96	16.568 ±3.00	13.5 ±4.1	3.5	S=0.8 s, N=51 Gap=94° I_{max}=V°MSK at Ludbreg, Veliki Bukovac, Poljanac, Ljubešćica, Veliki Poganac and Rasinje.
August 1988								
11*	07	02	55.1	42.333 ±3.84	16.741 ±2.44	11.4 ±6.6	3.7	S=1.0 s, N=48 Gap=63°
23	04	34	50.2	43.089 ±2.54	17.637 ±1.94	10.1 ±4.1	3.7	S=0.9 s, N=62 Gap=53° I_{max}=IV°MSK at Komin, Grabovac and Veliki Prolog.
23**	17	38	48.5	43.692 ±1.43	17.524 ±1.45	15.7 ±2.9	4.5	S=0.8 s, N=90 Gap=42° Felt IV–V°MSK at Imotski and Oskorušno.
September 1988								
20	16	02	03.5	43.323 ±1.74	17.898 ±1.55	9.0 ±3.3	4.4	S=0.8 s, N=86 Gap=35° I_{max}=V°MSC at Potoci and Blatnice.
24	08	26	14.1	42.415 ±2.85	18.423 ±1.99	0.0 ±3.1	3.6	S=0.9 s, N=54 Gap=60°
October 1988								
25**	14	34	07.0	44.162 ±1.61	16.564 ±1.92	2.0 ±3.6	3.6	S=0.8 s, N=62 Gap=39°
28*	23	22	02.5	42.349 ±2.88	16.652 ±2.24	0.0 ±3.3	3.5	S=0.9 s, N=56 Gap=61°
November 1988								
28*	05	32	29.4	42.371 ±2.35	16.776 ±1.91	10.5 ±3.9	3.7	S=1.0 s N=53 Gap=69°

Day	Origin time h	m	s	Epicentre (°N) (±km)	(°E)	Depth (km)	M_L	Remarks
December 1988								
2**	04	11	55.8	44.105 ±2.32	16 308 ±2.21	8.1 ±4.3	3.6	S=0.9 s, N=59 Gap=36° I_{max}=V° MSK at Pađene, Strmica, and Zrmanja.
16	11	35	51.8	44.751 ±1.76	15.004 ±1.85	20.0 ±10.4	4.5	S=0.8 s, N=87 Gap=51° I_{max}=V°MSK at Starigrad, Jablanac, Seni, Perušić, Kosinj, Gornji Kosinj, Lipovo Polje and Lički Osik.