

## Seismicity of Croatia in the period 1997–2001

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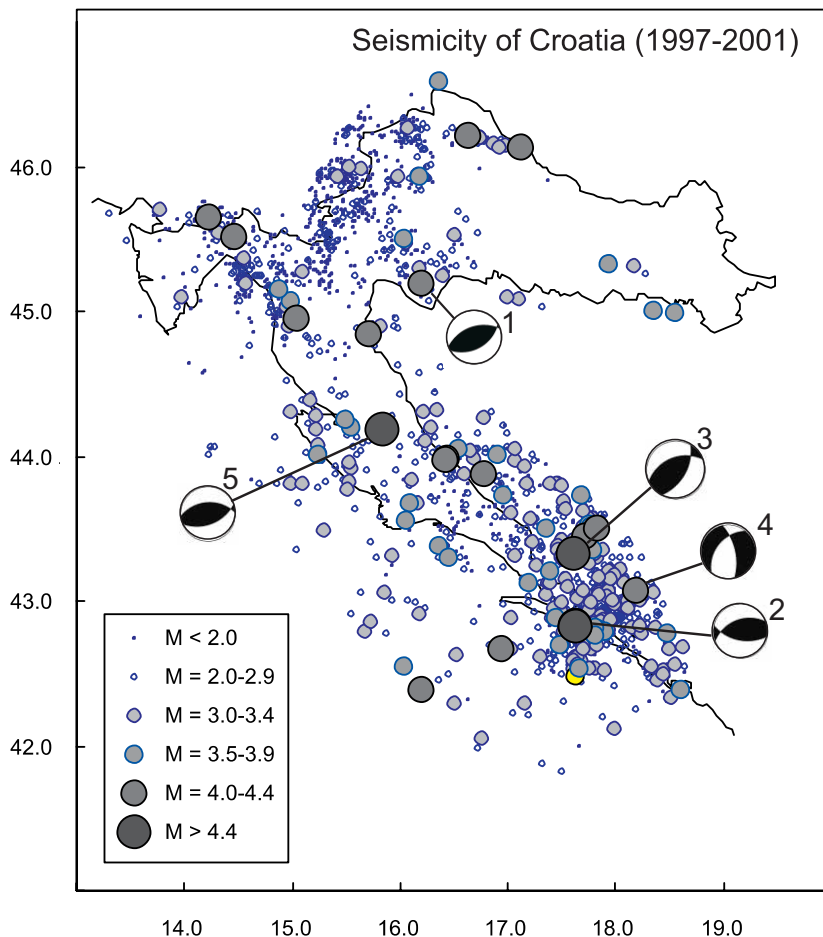
During the 1997–2001 period seismic activity of Croatia was confined to the previously identified seismically active areas. All together 1925 earthquakes were located. Seismically the most active was the coastal part of Croatia, especially its southernmost part where the Ston–Slano epicentral area exhibited the continuation of the great earthquake sequence after the September 5, 1996 main shock. The strongest aftershock was recorded on April 26, 1997 at 07:30 ( $M_L = 4.5$ ,  $I_{max} = VI$  °MSK). The earthquake with the same magnitude  $M_L = 4.5$ , recorded in the Zrmanja river valley, near Obrovac, on November 9, 2000 at 03:01 ( $I_{max} = VI$  °MSK). These two events were the strongest ones recorded in Croatia during the studied period.

*Keywords:* Seismicity, Croatia

### 1. Introduction

The regional tectonic setting of Croatia, as a part of the Mediterranean zone of the Alpine-Himalayan seismic belt, hosts several distinct geotectonic units: the Pannonian Basin, the Eastern Alps, the Dinarides, the transition zone between the Dinarides and the Adriatic Platform, and the Adriatic Platform itself. The seismicity is influenced foremost by the collision of the Adriatic Platform and the Dinarides in the coastal part (the Dinarides), (*e.g.* Prelogović et al., 1982; Aljinović et al., 1984; Herak, 1986; Anderson and Jackson, 1987). The Pannonian Basin is characterized by rare occurrence of large events, which is typical of intraplate seismicity.

The aim of this paper is to summarize the regional seismicity in the period 1997–2001 and to analyze the most important events, thus continuing the work on the compilation of earthquake catalogues with epicenters in Croatia and the surrounding areas, which began under the UNDP/UNESCO project of exploration of seismicity in the Balkan region, for the period 1901–1970 (Part I) and before 1901 (Part II) (Shebalin et al., 1974). The Croatian seismicity for the years 1986 through 1996 was described by Herak et al. (1988), Herak and Cabor (1989), Markušić et al. (1990), Herak et al.



**Figure 1.** Map of epicenters in Croatia and the surrounding areas in the period 1997–2001. Fault-plane solutions for 5 earthquakes obtained in this study are shown. The identification numbers refer to Table 2. Compressive quadrants are shaded.

(1991), Markušić et al. (1993) and Markušić et al. (1998). The Croatian Earthquake Catalogue for the period 1908–1992 was revised by Herak et al. (1996).

The data presented in this paper of the 1997–2001 period have been compiled and processed for all recorded earthquakes in Croatia, regardless of the magnitude. The map of epicenters shows the locations of all epicenters and lower hemisphere fault-plane solutions for 5 earthquakes that occurred in the studied period (Fig. 1). Special attention was paid to the earthquakes with magnitudes greater or equal to  $M_L = 4.0$  (see Table 1).

Table 1. Hypocentral parameters for earthquakes with magnitude  $M_L \geq 4.0$  in Croatia and the surrounding areas during the 1997-2001 period.

Date	Origin Time (UTC)			Epicenter		Depth (km)	$M_L$	$I_{max}$ (°MSK)
	h	m	s	$\varphi$ (°N)	$\lambda$ (°E)			
1997, January 27	0	46	17.7	45.191	16.206	17.5	4.3	IV
1997, March 15	21	29	57.7	44.844	15.711	13.9	4.0	V
1997, April 26	7	30	18.3	42.819	17.633	0.1	4.5	VI
1997, November 26	19	15	16.1	43.985	16.431	4.5	4.0	IV
1998, January 26	23	17	12.3	42.383	16.193	5.8	4.3	III
1998, February 4	14	7	7.7	45.513	14.468	9.6	4.0	V
1998, March 1	7	22	43.1	43.319	17.618	16.5	4.5	VI-VII
1998, March 13	15	14	56.8	45.649	14.237	16.3	4.1	V-VI
1998, March 13	23	7	28.2	43.068	18.197	1.2	4.4	-
1998, May 12	15	18	3.2	46.172	16.607	10	4.0	V-VI
1998, June 2	18	2	57.3	46.123	17.133	20	4.1	VI
2000, June 16	3	33	22.9	42.668	16.941	14.7	4.4	V
2000, October 8	20	17	22.6	43.442	17.723	0.1	4.0	III
2000, October 8	21	44	47.2	43.491	17.833	0.1	4.0	-
2000, November 9	3	1	1.1	44.182	15.848	8	4.5	VI
2001, February 24	9	21	25.5	43.870	16.777	0.1	4.0	-
2001, December 31	15	30	8.5	44.941	15.036	12.2	4.4	V

Table 2 summarizes the focal mechanisms results, listing main stress axes and fault plane parameters of both nodal planes. Individual earthquakes have also been macroseismically analyzed.

Table 2. Fault-plane solutions for 5 earthquakes that occurred in the period 1997–2001.

No.	Date	Origin Time (UTC)	Nodal Plane 1					Nodal Plane 2				
			Main Stress Axes		Fault Plane Parameters			Main Stress Axes		Fault Plane Parameters		
			Azimuth	Dip	Strike	Dip	Rake	Azimuth	Dip	Strike	Dip	Rake
1	1997/01/27	00:46:17.7	335.7	1.8	250.0	47.0	96.1	223.5	85.2	61.0	43.0	83.4
2	1997/04/26	07:30:18.3	176.6	4.0	101.0	51.0	110.6	72.9	73.6	250.0	43.0	66.4
3	1998/03/01	07:22:43.1	243.3	69.2	30.0	54.0	65.2	137.4	5.9	248.0	43.0	119.9
4	1998/03/13	23:07:28.2	99.8	10.3	219.0	42.0	-47.2	208.7	60.8	348.0	61.0	-121.3
5	2000/11/09	03:01:01.1	167.0	3.7	266.0	42.0	102.7	280.2	80.7	69.0	49.0	78.7

## 2. Data and method

All available earthquake related data were collected by analyzing the set of original seismograms from the permanent and temporary seismological stations in Croatia. In order to determine the earthquake parameters those data were supplemented by readings reported in monthly bulletins of seismological stations in the neighbouring countries. For each earthquake five main parameters were determined: hypocentral time, epicentral latitude, epicentral longitude, focal depth and earthquake magnitude ( $M_L$ ).

Hypocentral time and coordinates of the focus were determined by the HYPOSEARCH method (Herak, 1989) using the three-layered model published by B.C.I.S. (1972) and both P- and S-waves arrival times. The exceptions were the Central Adriatic earthquakes and the earthquakes in the central part of the External Dinarides, where the velocity models published by Herak (1990) and Herak and Herak (1995) were used.

Fault-plane solutions presented in this paper are evaluated using data on the first arrival polarity which were read from the original seismograms (mostly from Croatian stations) or were taken from various available bulletins and other published material. The obtained solutions are discussed in the following sections.

The macroseismic investigations were carried out whenever the information about the felt earthquake was received. The macroseismic data were obtained by fieldwork and/or by the questionnaires received from the shaken areas. According to somewhat lower seismicity during the observed period it

was possible to obtain sufficiently detailed descriptions of the macroseismic effects from only two earthquakes for isoseismal maps to be drawn.

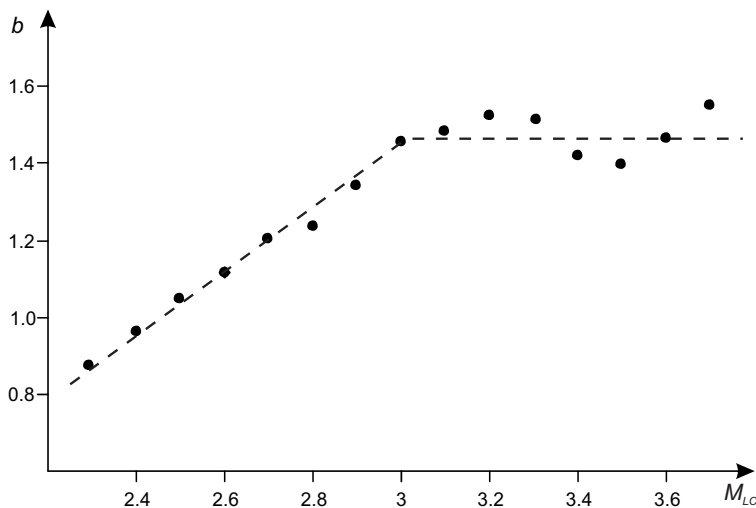
A total of 1925 earthquakes (for which at least 6 onset time readings were available) were located in Croatia and the surrounding areas in the period 1997–2001 (Fig. 1). The completeness threshold ( $M_{LC}$ ) of the obtained earthquake catalogue may be estimated by using the formula (Aki, 1965; Zhang and Song, 1981):

$$b = \frac{\log e}{M_L - M_{LC}} \cdot \frac{N - 1}{N} \quad (1)$$

which gives the maximum likelihood estimate of the value of the coefficient  $b$  in the Gutenberg-Richter's (1944) relation. In the above expression  $M_L$  denotes the mean magnitude of all earthquakes in catalogue which satisfy  $M \geq M_{LC}$  and  $N$  is the number of such earthquakes. Fig. 2 presents  $b$ -values as computed by (1) for several assumed values of  $M_{LC}$ . It is seen that for  $M_{LC} \geq 3.0$ , the coefficient  $b$  assumes almost constant value, so we may assume the catalogue to be complete for magnitudes  $M_L$  greater or equal to 3.0.

### 3. Features of seismicity in Croatia in the period 1997–2001

Regional seismic activity during the period 1997–2001 is characterized by earthquake occurrence within well-known epicentral areas, as can be seen on the epicentral map (Fig. 1).



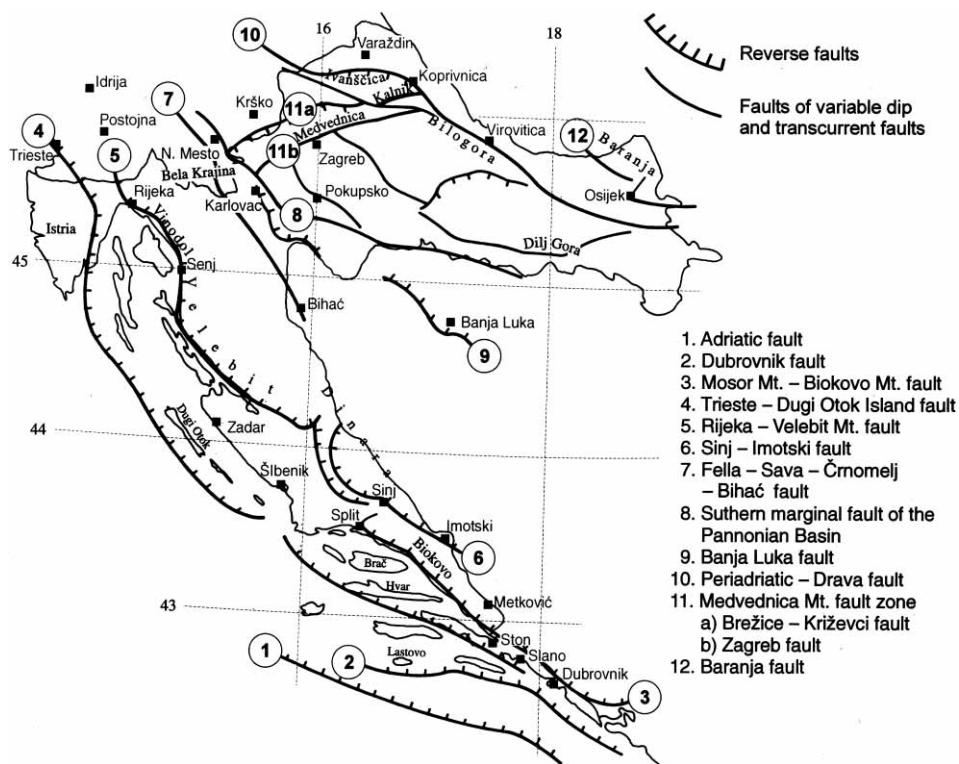
**Figure 2.** The  $b$ -values for the 1997–2001 period for several assumed catalogue completeness thresholds,  $M_{LC}$ .

In regard to the concentration of earthquakes the analysis was confined to two areas: (1) the continental part of Croatia, where only  $M_L \leq 4.3$  earthquakes occurred, and (2) seismically the most active part of Croatia – coastal area with the Dinaric mountains, where the magnitudes ranged up to 4.5.

### 3.1. Continental part of Croatia

This zone occupies the territory of the western part of the Dinarides, the western margin and the southern part of the Pannonian Basin. The primary faults related to the western margin of the Pannonian Basin strike NE–SW. The faults striking NW–SE and W–E occur as a consequence of the Dinarides and Alpine related movements, respectively (Šikić, 1976) (Fig. 3).

Seismically active areas in the continental part of Croatia are mostly covering its northwestern part spreading from Đurđevac and Koprivnica through Ivanščica Mt., Medvednica Mt. and Žumberačka gora to Pokuplje and Zrinska gora. There were also a few isolated seismic events in central Slavonia and Posavina.

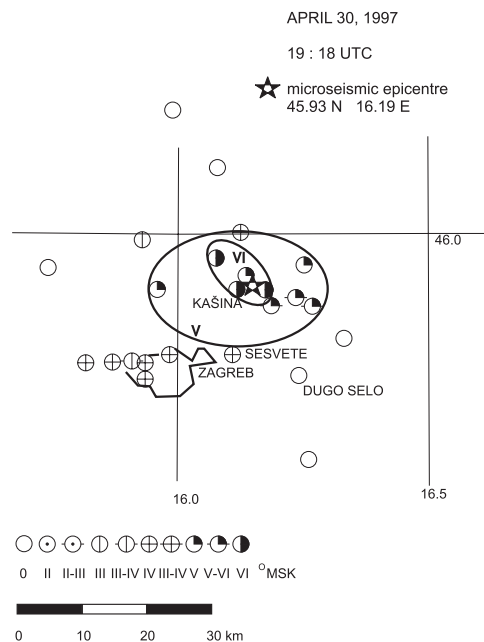


**Figure 3.** Map of the most important seismogenic faults (from Markušić and Herak, 1998).

The *Durđevac – Koprivnica epicentral area* can be considered to have had a moderate seismicity during the observed period. The main geological structures are of the W-E direction and the pattern of earthquake activity follows roughly the same direction. The majority of epicenters are located in the zone where the Periadriatic Drava fault system meets the faults from the Medvednica zone (Fig. 3). The earthquake with the largest intensity ( $M_L = 4.1$ ,  $I_{max} = VI$  °MSK) occurred on June 2, 1998 at 18:02 with the epicenter near Đurđevac (Table 1). The event was felt in the northwestern part of Croatia. The maximum intensity of VI °MSK was reported in Sigetec where observers felt trembling of the buildings, liquids oscillated, cracks in mortar up to 5 cm wide occurred and small pieces of mortar fell from walls. This earthquake was preceded by several foreshocks. The strongest of them was the one that occurred on May 12, 1998 at 15:18 with the epicenter near Koprivnica ( $M_L = 4.0$ ,  $I_{max} = V-VI$  °MSK), and was felt in Koprivnica, Križevci and Bjelovar.

The seismicity in the *Petrinja – Zrinska Gora epicentral area* is characterized by notable occurrence of small events with the exception of one moderate event. It occurred on January 27, 1997 at 00:46 with magnitude  $M_L = 4.3$  (Table 1). This was the strongest event in the continental part of Croatia for the period from 1997 to 2001. The collection of macroseismic data was restricted by the fact that just two years after the war in that part of Croatia it was still an uninhabited area. The maximum reported intensity was  $I_{max} = IV$  °MSK in Dvor na Uni. The calculated FPS (Fig. 1) describes reverse faulting on a fault striking WSW-ESE with predominantly dip-slip motion. The azimuth of the P-axis is constrained to NNW-SSE direction, and its dip indicates horizontal pressure (Table 2).

During the observed period seismic activity in epicentral areas in the westernmost regions of the continental part of Croatia: *Brežice–Krško* in the Croatia-Slovenia border region and *Zagreb area* (northern hill-sides of Medvednica Mt.) decreased. The strongest earthquake occurred here on April 30, 1997 at 19:18 near Kašina ( $M_L = 3.7$ ,  $I_{max} = VI$  °MSK). The distribution of intensities is displayed in Fig. 4. The microseis-



**Figure 4.** Isoseismal map for the Kašina earthquake of April 30, 1997 (19:18). The star indicates the position of the microseismic epicenter.

mic epicenter is located within the pleistoseismal. The maximum intensity of VI °MSK was reported in Sv. Matej near Kašina, where mortar fell from the walls, some walls cracked and the roof-tiles slipped off from some old houses. The elongation of the pleistoseismal in NW-SE direction is probably caused by the transversal fault that strikes Medvednica Mt. fault zone at Kašina (Fig. 3).

Few weak earthquakes occurred in the vicinity of *Plitvice Lakes* in the border region between the coastal and the continental part of Croatia, near Fella-Sava-Črnomelj-Bihać fault, with the exception of one moderate event that occurred on March 15, 1997 at 21:29, with magnitude  $M_L = 4.0$  and the maximum intensity of  $I_{max} = V$  °MSK (Table 1).

### 3.2. Coastal part of Croatia

The coastal part of Croatia with the Dinaric mountains is seismically deeply affected by the subduction of the Adriatic microplate under the Dinaric massif. The most significant seismically active areas during 1997–2001 period were those of Rijeka, Velebit Mt., Plješevica Mt., Obrovac, Dinara Mt., the Neretva Valley, Palagruža, Lastovo and Ston-Slano.

The seismic activity of the *greater Rijeka epicentral area*, spreading from Ilirska Bistrica in Slovenia towards Crikvenica and the Krk island, is known for the frequent occurrence of relatively weak earthquakes ( $M_L < 4.0$ ) and occasional occurrence of moderate or large earthquakes ( $M_L \geq 4.0$ ). There were several felt earthquakes in this area during the observed period. Only two of them were with magnitudes  $M_L \geq 4.0$ . The first one occurred on February 4, 1998 at 14:07 on Snežnik Mt. with magnitude  $M_L = 4.0$  and the maximum intensity  $I_{max} = V$  °MSK reported in Viškovo. The second one occurred on March 13, 1998 at 15:14 with magnitude  $M_L = 4.1$  and the maximum intensity  $I_{max} = V$ –VI °MSK near Ilirska Bistrica in Slovenia (Table 1). It was the strongest event that occurred in Rijeka epicentral area during the 1997–2001 period. In the northern part of the island of Krk, weak earthquakes with magnitudes up to  $M_L = 3.4$  were frequently recorded.

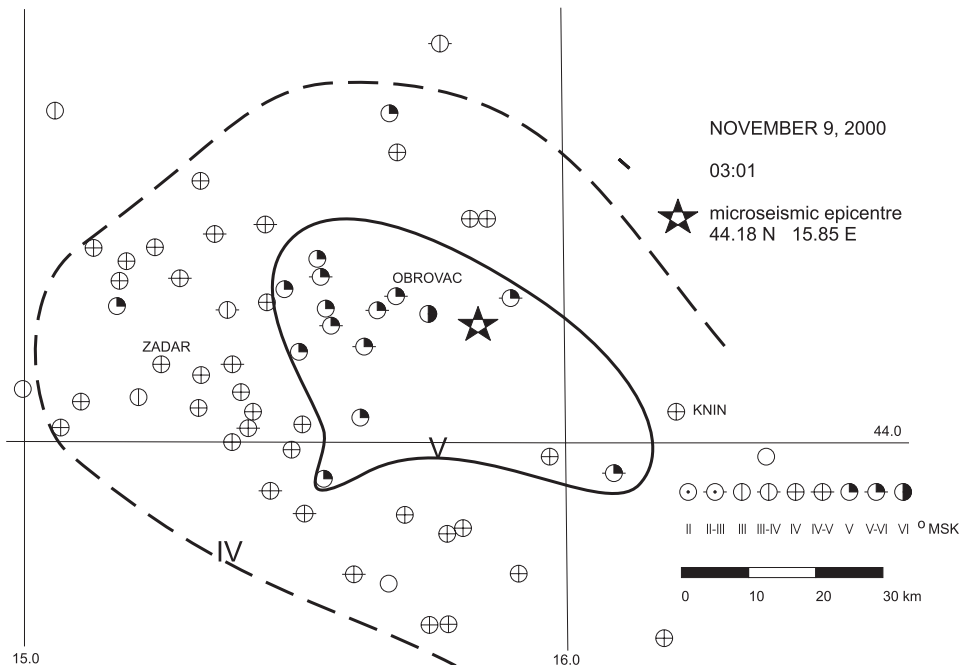
The epicentral area of *Novi Vinodolski, Senj and Jablanac* experienced moderate seismicity, with earthquake epicenters spreading in the NW – SE direction following the Rijeka – Velebit Mt. Fault (Fig. 3). The strongest earthquake occurred on December 31, 2001 at 15:30, with magnitude  $M_L = 4.4$  (Table 1). Despite the considerable earthquake magnitude the greatest reported intensity was V °MSK due to the fact that the epicentre was located in the uninhabited area of the Velebit Mt. The greatest intensity was reported in Senj where most observers stressed that they felt strong shaking, but only few ran outdoors. Windows, doors and light furniture trembled.

The Rijeka-Velebit Mt. fault, on its southernmost part (Fig. 3), is probably responsible for the occurrence of the one of the three strongest earthquakes recorded in Croatia during the period 1997–2001. In the vicinity of *Obrovac* in Zrmanja river valley the earthquake occurred on November 9,



2000 at 03:01, with magnitude  $M_L = 4.5$  and the maximum intensity of  $I_{max} = VI$  °MSK (Table 1). The macroseismic field survey revealed that all inhabitants in Bilišane felt the earthquake, dogs became uneasy and frightened, and some tiles slipped from the roofs. Some smaller objects overturned, furniture shifted and one chimney tube was driven out by one centimetre in Obrovac. Some walls cracked in Kruševo and Maslenica. The isoseismal map is displayed in Fig. 5. According to the map of the most important seismogenic faults (Fig. 3), the Rijeka-Velebit Mt. fault zone is responsible for the enhanced seismic energy propagation in NW-SE direction. The microseismic epicenter is located within the pleistoseismal. The pleistoseismal protrusion on its southeastern side is probably caused by the local soil amplification. This area is characterized by mostly W-E to NW-SE striking structures, which is consistent with right-lateral reverse motion on a W-E striking fault as obtained here (Fig. 1). One of the nodal planes dips to the N, and this is in agreement with the geometry of the system of faults in this area. Also, the FPS solution indicates subhorizontal SSE-NNW directed pressure axis (Table 2).

The belt of the highest seismic activity in Croatia stretches southeastwards from the Dinara Mt. towards the Neretva valley, Pelješac peninsula and Dubrovnik.



**Figure 5.** Isoseismal map for the Obrovac earthquake of November 9, 2000 (03:01). The star indicates the position of the microseismic epicenter.

Seismic activity of the *Dinara Mt. area* decreased during the 1997–2001 period with regard to the seismicity in the past decade. Only two earthquakes with magnitude  $M_L = 4.0$  were recorded during the observed period. The first one occurred on November 26, 1997 at 19:15, with maximum intensity of  $I_{max} = IV$  °MSK (Table 1) near Troglav. The second earthquake occurred in the carst field Livanjsko polje in Bosnia and Herzegovina on February 24, 2001 at 09:21.

The most significant seismically active areas during the 1997–2001 period in Croatia and its surrounding areas were Ljubuški–Mostar area in the border region with Bosnia and Herzegovina, and the Ston–Slano epicentral area, as the continuation of the great Ston–Slano earthquake sequence which started in 1996.

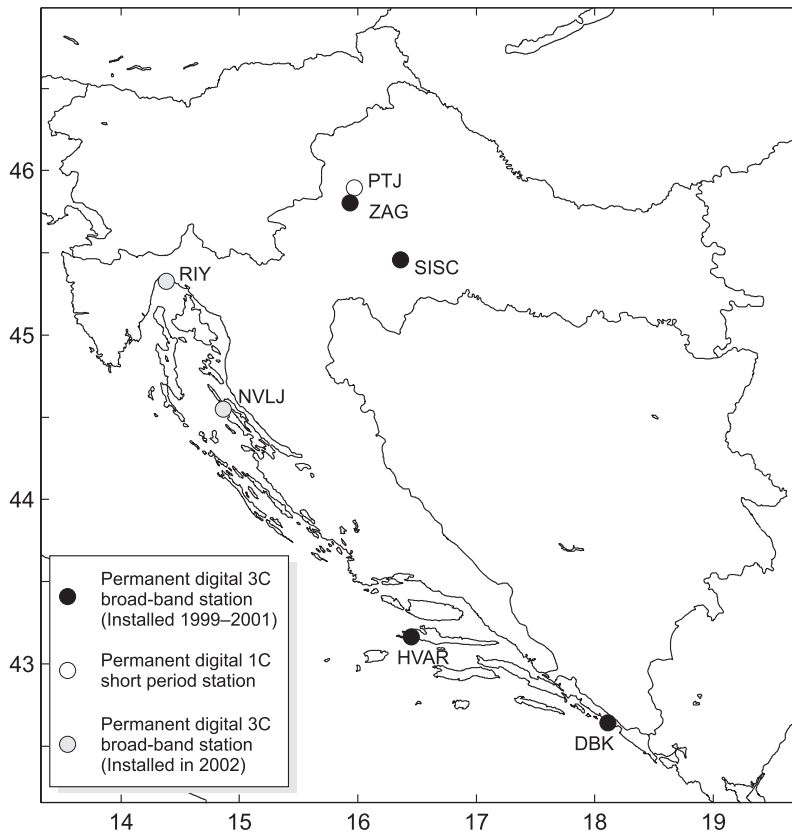
The *Ljubuški–Mostar epicentral area* in the Bosnia and Herzegovina-Croatia border region experienced pronounced seismicity during the observed period. Among 138 recorded earthquakes in this epicentral area the strongest event occurred in the vicinity of Ljubuški, on March 1, 1998 at 07:22, with magnitude  $M_L = 4.5$  and maximum intensity of  $I_{max} = VI$ – $VII$  °MSK (Table 1). The fault-plane solution (Fig. 1) with well constrained axes, indicates reverse faulting, probably on a WSW-ENE striking fault. The azimuths of pressure (P) and tension (T) axes are  $N243^\circ E$  and  $N137^\circ E$ , respectively (Table 2). There were two more moderate earthquakes with magnitude  $M_L = 4.0$  recorded near Mostar, on October 8, 2000. The first one occurred at 20:17 followed by the second one at 21:44.

The *Ston–Slano epicentral area* exhibited significant seismic activity as the continuation of the great earthquake sequence which started in 1996 (main shock September 5, 1996 at 20:44,  $M_L = 6.0$ ,  $I_{max} = VIII$  °MSK) (Markušić et al., 1998; Herak et al. 2001). During the 1997–2001 period 457 events occurred in the Ston–Slano epicentral area. The majority (420 events) of aftershock sequence was recorded throughout 1997. Among them was the strongest earthquake recorded in the Ston–Slano aftershock sequence during the observed period, on April 26, 1997 at 07:30 with magnitude  $M_L = 4.5$  (Table 1). It was also one of the strongest earthquakes recorded during the 1997–2001 period in Croatia. The maximum intensity of  $VI$  °MSK was reported in Ston, where poorly built old fieldstone houses, that sustained damage due to the main shock suffered new severe damages. Tiles slipped from the roofs, mortar fell from the walls, some walls and chimneys cracked and furniture was shifted. The FPS (Fig. 1) shows reverse faulting, probably on a WSW–ENE striking fault that dips to the NNW. The azimuth of the P-axis is  $N177^\circ E$ , and its dip indicates predominantly horizontal pressure (Table 2). In the vicinity of Ljubinje the earthquake with magnitude  $M_L = 4.4$  was recorded on March 13, 1998, at 23:07. The obtained fault-plane solution (Fig. 1) describes normal faulting, probably on a fault striking NNW–SSE and steeply dipping to the ENE (Table 2).

In the Adriatic submarine area two moderate earthquakes with magnitude  $M_L \geq 4.0$  occurred during the observed period. The earthquake with magnitude  $M_L = 4.4$  occurred on June 16, 2000 at 03:33, near Lastovo island, where it was felt with maximum intensity of  $I_{max} = V$  °MSK. Near the Croatia's southernmost island Palagruža the earthquake with magnitude  $M_L = 4.3$  occurred on January 26, 1998 at 23:17 (Table 1). It was felt on Palagruža with the intensity of  $I = III$  °MSK.

#### 4. Instrumentation

Currently the Croatian seismological network consists of 7 permanent stations: Zagreb (ZAG), Puntijarka (PTJ), Hvar (HVAR), Dubrovnik (DBK), Rijeka (RIY), Sisak (SISC) and Novalja (NVLJ). The Puntijarka digital seismological station is equipped with 1-component short period digital seismo-



**Figure 6.** Locations of permanent seismological stations in Croatia.

graph. During 1999 – 2000 period 3-component digital broadband seismometers were installed in Zagreb, Hvar and Dubrovnik. On June 13, 2000 new permanent seismological station equipped with 3-component broadband seismometer was opened in Sisak. A recent addition to our network is an installation of one 3-component, broadband digital seismograph in Rijeka, and on April 1, 2002 new permanent digital seismological station was opened in Novalja on the Pag island. The locations of the permanent stations in Croatia are presented in Figure 6.

## 5. Conclusion

Seismic activity of Croatia and its surrounding areas in the period 1997–2001 was confined to the previously identified seismically active zones. The majority of 1925 located earthquakes occurred in the coastal region of Croatia, especially in its southernmost part where Ston–Slano epicentral area exhibited the continuation of the great earthquake sequence after the September 5, 1996 main shock. The strongest aftershock was recorded on April 26, 1997 at 07:30 ( $M_L = 4.5$ ,  $I_{max} = VI$  °MSK). The earthquake with the same magnitude  $M_L = 4.5$ , recorded in the Zrmanja river valley, near Obrovac, on November 9, 2000 at 03:01 ( $I_{max} = VI$  °MSK) was the second strongest event recorded in Croatia during the studied period. All well located earthquakes occurred in the upper part of the Earth's crust with range in depth between surface and 20 km.

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## SAŽETAK

**Seizmičnost Hrvatske u razdoblju 1997–2001.**

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Tijekom razmatranog petogodišnjeg razdoblja seizmičnost je u Hrvatskoj bila ograničena na poznata epicentralna područja. Ukupno je locirano 1925 potresa. Najaktivniji je bio obalni dio Hrvatske, posebno njegov najjužniji dio, gdje je nastavljena pojačana aktivnost u epicentralnom području Ston-Slano nakon velikog potresa iz 1996. godine. Njegov najjači naknadni potres zabilježen je 26. travnja 1997. u 7:30 ( $M_L = 4.5$ ,  $I_{max} = VI$  °MSK). Potres jednake magnitude dogodio se i u dolini rijeke Zrmanje blizu Obrovca 9. studenog 2000. godine u 03:01 ( $I_{max} = VI$  °MSK). Ova su dva potresa ujedno i najjača u Hrvatskoj u razmatranom razdoblju.

*Ključne riječi:* seizmičnost, Hrvatska

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