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Seismicity of Croatia in 1989 and the Kamešnica Mt. earthquake

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The seismicity of Croatia and its surrounding areas in 1989 was analysed on the basis of the earthquake catalogue consisting of 361 earthquakes. Its completeness threshold was estimated to be $M_{LC} \geq 3.0$. Seismically the most active was the coastal part of Croatia, where the strongest earthquake in 1989 occurred on December 6 with the focus beneath the hill-sides of the Kamešnica Mt. The fault plane solution for this event indicates the presence of a tectonic stress-field directed approximately SW–NE, which is compatible with the assumed anticlockwise rotation of the Adriatic microplate around the pole in Northern Italy, and the associated subduction of the Adriatic plate under the Dinarides. The aftershocks of the Kamešnica Mt. event were numerous, with hypocentres at depths up to 20 km. Macroseismic investigations confirm the frequently observed fact that seismic energy is much more efficiently absorbed perpendicularly to the direction of the Dinaric belt than along it.

Seizmičnost Hrvatske u 1989. godini i potres od 6. prosinca u blizini planine Kamešnice

Na osnovi kataloga svih lociranih potresa u Hrvatskoj i susjednim područjima u 1989. godini te makroseizmičke obrade podataka analizirana su neka svojstva seizmičnosti. Ukupno je lociran 361 potres. Kompletnost kataloga s obzirom na magnitudu procijenjena je na $M_{LC} \geq 3.0$. Seizmički je najaktivniji bio priobalni dio Hrvatske. Tamo se – na obroncima Kamešnice – dogodio i najjači potres u toj godini. Posebnu smo pažnju posvetili tom potresu te smo ga analizirali detaljnije od ostalih. Mehanizam pomaka u žarištu određen je na osnovi podataka o prvom pomaku P-vala na 79 seizmoloških postaja te pokazuje da su tektonski pomaci uzrokovani poljem tlaka usmjerenim JZ–SI. To je u skladu s pretpostavljenom rotacijom Jadranske ploče oko pola u sjevernoj Italiji koja uzrokuje njezinu subdukciju pod kompleks Dinarida. Glavni potres slijedili su brojni naknadni potresi koji su imali žarišta na dubinama do 20 km. Izoseiste glavnog i najjačeg naknadnog potresa jako su izdužene u smjeru pružanja glavnih geoloških struktura ovog područja, što upućuje na to da je apsorpcija seizmičke energije u tom smjeru mnogo slabija nego okomito na nj.

1. Introduction

From the seismotectonic point of view, the continental part of the territory of Croatia belongs to the Pannonian Basin region, while the coastal zone belongs to the Dinarides and the Adriatic Platform. The seismicity of Croatia is concentrated along active faults and fault systems. Some of those are: the major system of longitudinal and transversal faults of the Outer Dinarides complex, including, for instance, the Velebit fault system, the fault of Dugi Otok, the fault zone Bihać-Sinj, the faults Biokovo-Dubrovnik and Korčula-Metković-Stolac; the fault Žumberak-Medvednica-Kalnik and associated faults; the fault complex Kostanjevica-Brežice-Stubica, the fault traversing the southern part of the Sava valley etc. – see e.g. Cvijanović (1966, 1971), Shebalin et al. (1974), Herak and Cabor (1989), Markušić et al. (1990). Earthquakes most frequently occur in the coastal region, the seismicity of which is commonly explained by the subduction of the Adriatic Platform underneath the Dinarides (e.g. Prelogović et al., 1982; Herak, 1986; Skoko and Prelogović, 1989). A detailed description of the geology and seismotectonics has been presented by e.g. Prelogović et al. (1978, 1982), Aljinović et al. (1984, 1987) and Herak (1986).

The aim of this paper is to summarize the regional seismicity in 1989 and to analyse the most important events, thus continuing the work on the compilation of earthquake catalogues with epicentres in Croatia and the surrounding areas, which began under the UNDP/UNESCO project (Shebalin et al., 1974).

The data were collected and processed for all recorded earthquakes in Croatia in 1989, regardless of their magnitude. Special attention was dedicated to the earthquakes with $M_L>4.0$ (February 13 at 00:35, $M_L=4.1$; May 7 at 07:15, $M_L=4.1$; December 6 at 05:33, $M_L=4.8$ and 13:55, $M_L=4.3$). Several events were macroseismically analysed.

2. Data and method

The phase arrival time data were collected by analysing the set of original seismograms from the permanent and temporary seismological stations in the Republic of Croatia. Those data were supplemented by readings reported in monthly bulletins of seismological stations in other republics in Yugoslavia and the neighbouring countries: Albania, Austria, Hungary, Italy and Romania.

The five main parametres were determined for each seismic source: hypocentral time, epicentral latitude, epicentral longitude, focal depth and earthquake magnitude (M_L).

Hypocentral time and focal coordinates were determined by the HYPOSEARCH method (Herak, 1989) using the three-layered model for the Balkan region (B.C.I.S., 1972) and both P- and S-waves arrival times. Exceptions were the Central Adriatic and the greater Dinara Mt. areas, where we used the

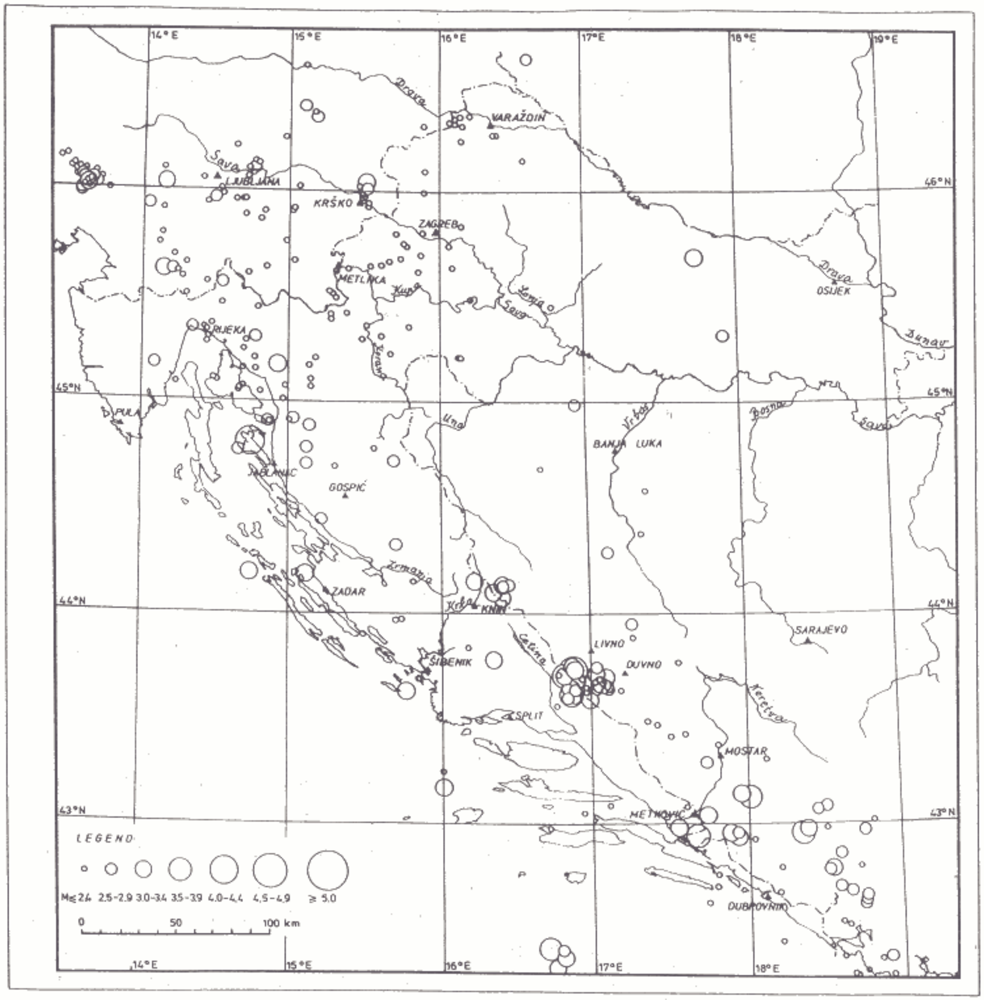

Figure 1. Map of epicentres in Croatia and the surrounding areas in 1989

velocity models used by Herak (1990) and the unpublished models for the Dinarides area also used by Herak et al. (1988), respectively.

In 1989, 361 earthquakes (for which at least 6 onset time readings were available) were located in Croatia and the surrounding areas (Fig. 1). The 1989 catalogue completeness threshold (M_{LC}) may be estimated by using the formula (Aki, 1965; Zhang and Song, 1981)

$$b = \frac{\log e}{M_L - M_{LC}} \, \frac{N-1}{N} \tag{1}$$

which gives the maximum likelihood estimate of the value of the coefficient b in the Gutenberg-Richter's (1944) relation. Figure 2 presents b-values as computed by (1) for several assumed values of M_{LC}. It is seen that the b-value stabilised for $M_{LC} \geq 3.0$, which is then considered to be the completeness threshold of the catalogue.

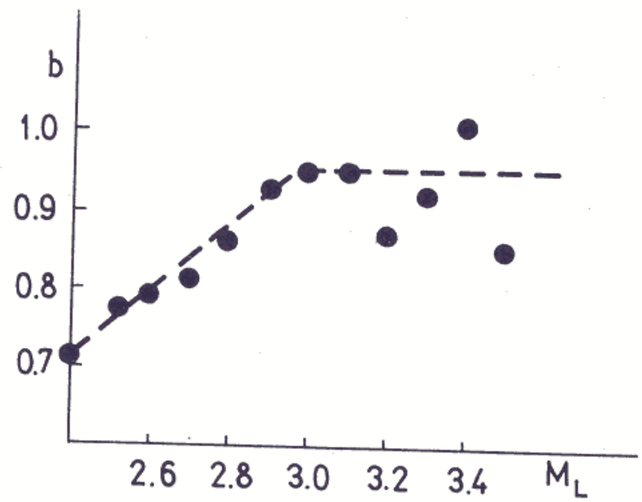

Figure 2. The b-values for 1989 obtained for several assumed catalogue completeness thresholds, M_{LC}. The b-values are stable for $M_{LC} \geq 3.0$.

Macroseismic investigations were carried out whenever information about the felt earthquake was received. The data on macroseismic intensities were obtained by field investigations and/or by questionnaires received from the shaken areas. When the description of the macroseismic effects of an earthquake was sufficiently detailed (in 4 out of 21 cases), isoseismal maps were drawn – the isoseismals were plotted to be contiguous with the extreme outer points of the area of a particular intensity. The shapes of macroseismic areas were generally irregular and asymmetrical reflecting the existence of the main geological structures of the respective area (faults, mountain belts). The 4 intensity maps and related details will be given in the following sections. The intensities were estimated according to the MSK scale whenever the data required in its definition were available (e.g. the quantitative description of damages). In all other cases MCS scale was used.

3. Some features of seismicity in Croatia in 1989

The main characteristic of the seismicity in Croatia is the concentration of hypocentres in several areas, as can be seen on the epicentre map (Fig. 1). In the continental part of Croatia only $M_L \leq 3.5$ earthquakes occurred, while in the coastal part the magnitudes ranged up to 4.8.

3.1. Zagreb area

In the continental area there is pronounced seismicity in the Zagreb area (Samobor, Krško, Ozalj-Metlika).

There were 2 earthquakes with I_{max}=V° MCS and 2 with I_{max}=IV° MCS in Zagreb and its immediate vicinity. The two I_{max}=V° MCS earthquakes occurred on February 22 at 20:42 (epicentre Zagreb-Markuševac) and on September 7 at 02:54 (Samobor). Both earthquakes caused no damage in the epicentral area, but most of the inhabitants ran outdoors. For the Samobor earthquake there was a sufficient number of intensity data for the compilation of the isoseismal map (Fig. 3). The pleistoseismal elongation is directed E-W and the intensity four isoseismal is almost circular. The microseismic epicentre (asterisk on Fig. 3) was some 6 km south of the macroseismic one. This earthquake was located by using the data from 11 stations, the distances of which ranged between 19 and 290 km; the azimuthal gap was 113°. The focal depth of 17±3 km was found. Epicentral coordinates with one standard deviation are 45.75 N±2.7 km and 15.75 E±1.9 km. According to the seismotectonic map of Croatia (Cvijanović et al., 1979) there are two longitudinal faults in the area enclosed by the IV° isoseismal (Fig. 3). It seems that the event occurred at the intersection of these faults.

In the epicentral area of Krško (Slovenia) pronounced seismic activity began on December 28 at 20:50 with the strongest shock (I_{max}=VI° MCS, M_L=3.2). Intensity VI° MCS was felt at Krško, Leskovec pri Krškem, Libno, Narpel, Trška

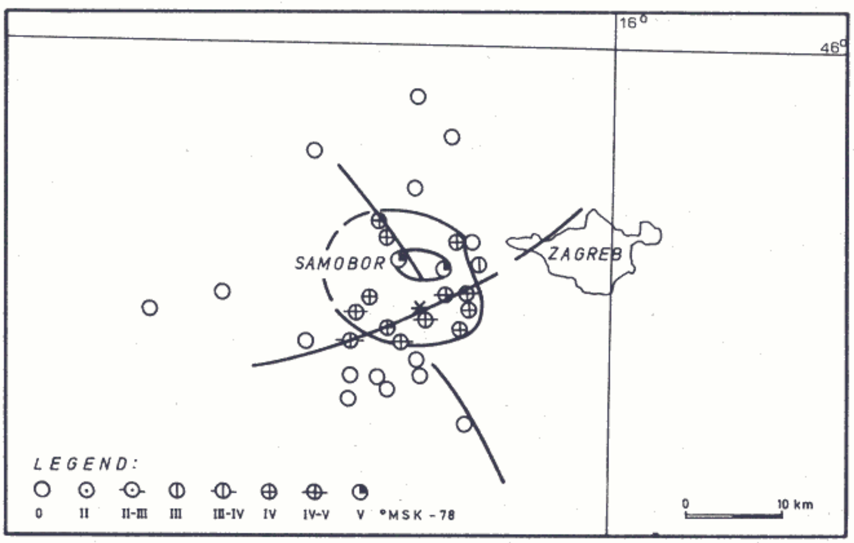

Figure 3. Isoseismal map for the Samobor earthquake of September 7 (02:54). Positions of the longitudinal faults are taken from Cvijanović et al. (1979). The asterisk indicates the position of the microseismic epicentre.

Gora and Velika Vas. The earthquake caused the falling off of mortar in the epicentral area. The isoseismal map will be published elsewhere. The seismic activity in Krško area continued during the beginning of 1990.

The third seismically active region in the vicinity of Zagreb was the Metlika area (Slovenia) which is very close to Karlovac and Ozalj (Croatia). On November 30 at 10:01 the Metlika area experienced the earthquake of intensity V° MCS. There was also a small group of very weak events (possibly explosions) around Varaždin. We have no macroseismic reports on them. All those events have very characteristic waveforms with unusually long codas.

3.2. Coastal area

The whole coastal part of Croatia was very seismically active in 1989. Nevertheless, we can discern most significant seismically active areas: Rijeka, Novi Vinodolski-Senj-Jablanac, Knin, Sinj, and the mouth of the river Neretva with Metković and Pelješac.

There were several felt earthquakes in the Rijeka area (approx. 45.2–45.7 N, 14.0–15.0 E). As stated by Milošević (1980), recent seismicity of this area is distinguished by occurrence of relatively weak earthquakes, while several destructive earthquakes reaching intensity of about IX° MCS occurred in the past (Slejko et al., 1987). The strongest event of 1989 occurred on November 19 at 23:10 (M_L=3.1) around Ilirska Bistrica (Slovenia) (I_{max}=V° MCS was felt at Klana). In Rijeka and its surroundings two earthquakes were felt: the first one at 15:27 on October 19 (III° MSK in Rijeka) and the second at 16:16 on August 20 (IV° MCS in Dražice).

The strongest earthquake in the Novi Vinodolski-Senj-Jablanac region occurred on February 30 at 00:35 with magnitude 4.1 and the maximum reported intensity V° MCS in Rab, Barbat, Jablanac, Jurjevo and Senj. The intensity map is displayed on Fig. 4 together with the most important faults of the tectonic complex (after Cvijanović et al., 1979, and Prelogović et al., 1982). As it can be seen, the pleistoseismal elongation is in direction of a long reverse fault. It is therefore likely that this fault is responsible for occurrence of the earthquake. Microseismic epicentre, however, is outside of the pleistoseismal area near the transversal fault which intersect the island of Rab. Although the pleistoseismal area is poorly defined due to the lack of data in the sea, it seems that the seismic energy propagated mainly along the reverse fault.

The second strongest earthquake in that area occurred on September 30 at 18:16 with maximal reported intensity IV-V° MCS at Novi Vinodolski and magnitude M_L=3.4.

Seismic activity in the Knin area (around 44.1 N, 16.3 E) was a continuation of the very intense seismic activity during November and December 1986. The strongest event had magnitude M_L=3.4 but did not cause high intensities. The greatest reported intensity (V° MSK at Cetina, Pađene, Civljane and Kijevo) was caused by a M_L=3.1 event of October 4, 18:13. Two earthquakes were felt with

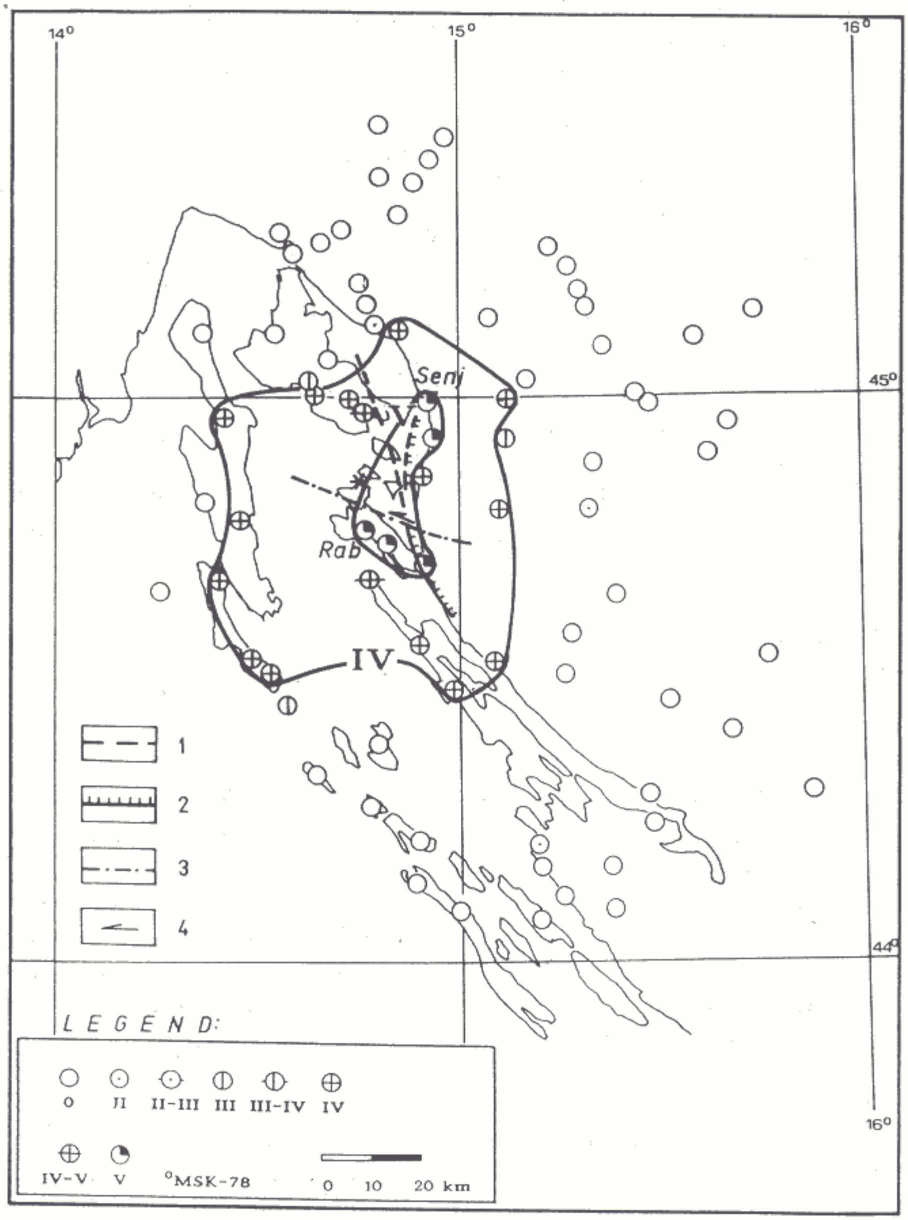

Figure 4. Isoseismal map for the earthquake which occurred on the Rab island on February 13, at 00:35. Fault positions and types are taken from Cvijanović et al. (1979) and Prelogović et al. (1982). The asterisk indicates the microseismic epicentre.
Legend: 1 – assumed fault; 2 – reverse fault; 3 – transverse fault; 4 – horizontal shearing of tectonic units.

I_{max}=IV° MSK: the one of March 14 (15:16) at Pađene and Mokro Polje and the one of June 4 (15:00) at Golubić.

The area of the mouth of the Neretva river and Pelješac peninsula exhibited significant seismic activity too. On May 7 at 15:39 a M_L=4.1 earthquake occurred, but no macroseismic effects were reported. The microseismic epicentre was placed near Metković. The depth of the focus was 13 km. In total, 9 events with magnitude range 1.6–4.1 were located in this region in 1989. In Fig. 1 we can also notice the continuation of the seismic activity in the area of the island Palagruža, where a burst of seismic activity started on April 24, 1988.

The strongest earthquake in 1989 in Croatia occurred beneath the hill-sides of Mt. Kamešnica on December 6 (05:33) with maximum intensity VII-VIII° MSK. A series of earthquakes which commenced with the M_L=4.8 event on December 6 (OT=05:33:11.9, see Table 2) was really remarkable. The nearest seismological station at Trilj (TLJ, a temporary one) recorded thousands of earthquakes within the week after the main shock, with epicentral distances of 19–33 km. At least one aftershock was recorded almost every minute during 48 hours following the main shock. In order to understand the tectonic significance of the Kamešnica earthquake, we decided to dedicate more attention to that seismic sequence.

4. The Kamešnica earthquake of December 6, 1989

The Kamešnica earthquake was the largest event in this area since 1962 when a series of earthquakes occurred in the Biokovo Mt. region. It was felt some 250 km around the epicentre where the maximum intensity of VII-VIII° MSK was reported. After the main event the burst of seismic activity occurred in an 18×13 km area. The earthquake occurred 19 km from the temporary seismic station of Trilj (TLJ), which has been operating since 1978. Two days after the main shock the Geophysical Institute of Zagreb installed high gain analog short period vertical component seismograph at Ričice (RIC), on the same distance as TLJ but SE from the epicentral area. The aftershock activity lasted for about a month and the temporary seismic station RIC together with the third nearest station HVAR (some 70 km distant) enabled us to locate 45 aftershocks (Fig. 6).

4.1. Seismic history

The Kamešnica epicentral area is surrounded by several seismically very active areas: Dinara Mt., Sinjsko polje, Imotsko polje, Biokovo Mt., Buško blato and Livanjsko polje, which all belong to the Outer Dinarides region. The seismic history of those areas is long and rich. From the end of the past century until December 6 1989, some 20 earthquakes with intensities $I_o \geq$ VII° MCS occurred in those regions. The four strongest events which occurred there were: the earthquake in Sinjsko Polje (1898) with I_o=IX° MCS (21 km from studied epicentre), the one of 1942 in Imotsko Polje with I_o=IX° MCS (35 km distant) and two events which occurred beneath the Biokovo Mt. in 1962 at an interval of four days with intensities I_o=VIII° MCS and I_o=VIII-IX° MCS (50 and 54 km respectively from the epicentre of the Kamešnica earthquake). The basic parameters of these four earthquakes are presented in Table 1 (data from the Archive of Geophysical Institute).

Table 1. Data on the strongest earthquakes close to the Kamešnica Mt. area.

Date	φ°(N)	λ°(E)	h(km)	M	I_o (°MCS)
1898, July 2	43.6	16.7	–	–	IX
1942, December 29	43.4	17.2	7	6.0	IX
1962, January 7	43.2	17.1	13	5.9	VIII
1962, January 11	43.2	17.2	10	6.1	VIII–IX

Since June 1978 the temporary station TLJ has been operating near Kamešnica epicentral area and together with other somewhat more distant stations we could control the microseismicity of the region. The last $M_L \geq 4.0$ earthquake occurred on January 8, 1987 (M_L=4.2), 5 km away from the studied Kamešnica earthquake. Since October 31 (36 days before the December 6 earthquake) there was no seismic activity in the region of Fig. 6, according to the TLJ seismograms.

4.2. Main shock

The Kamešnica Mt. main shock was recorded by many seismological stations all over Europe. 103 P and S onset time data were collected for locating the source. The closest station, Trilj (TLJ), was located 19 km southwest of the epicentre. The crustal models for the greater area of the Dinara Mt. used to locate the main shock and aftershocks were the same as those used in the paper of Herak et al. (1988). For the main shock, the azimuthal gap was only 35. The following hypocentre location was obtained: latitude=43.653° N±1.7 km, longitude=16.947° E±1.7 km, depth=6.2±4.1 km.

The fault-plane solution for the main shock is presented in Fig. 5. It was obtained on the basis of 79 first-motion polarity data collected from local, regional and distant stations. The first of the two nodal planes strikes ENE-WSW, dips at an angle of 53° and represents a left-lateral reverse fault. The second one, striking NW-SE and dipping 69° is equivalent to a dextral reverse fault with nearly equal strike- and dip-components of slip. The azimuths of pressure (P) and tension (T) axes are N20°E and N100°E respectively.

4.3. Aftershock sequence

The Kamešnica Mt. earthquake was followed by a remarkable aftershock sequence. Unfortunately, only one seismic station was operating in the region at that time, which prevented us from locating the majority of those earthquakes. Because of the great number of earthquakes recorded at the closest station TLJ it was impossible even to count them up. We succeeded to locate 45 aftershocks,

Table 2. The Kamešnica Mt. earthquake sequence, December 1989. Latitude (N) and longitude (E) are given in degrees and their standard deviations are expressed in km.

OT = Origin time (UTC)
Dep = Depth (in km)
M_L = Local magnitude
S = Standard error of the solution (in s)
N = Number of data
Gap = Azimuthal gap
D = Distance to nearest station (in km)

Day & OT	Lat.	Long.	Dep.	M_L	S	N	Gap	D
06 05:33:11.9	43.653 ±1.7	16.947 ±1.7	6.2 ±4.1	4.8	0.89	103	35	19
06 05:41:11.5	43.729 ±2.1	16.892 ±3.4	2.9 ±4.9	3.4	0.62	22	119	19
06 05:42:57.8	43.709 ±2.5	17.026 ±2.5	3.0 ±4.8	3.4	0.77	28	95	27
06 05:44:13.6	43.696 ±5.8	16.832 ±11.2	1.8 ±8.9	3.2	0.76	8	121	26
06 05:45:41.3	43.741 ±1.9	16.929 ±2.1	7.1 ±4.2	3.5	0.79	45	92	22
06 05:56:52.5	43.660 ±2.2	17.048 ±7.8	0.0 ±3.6	2.7	0.27	8	240	74
06 05:57:51.9	43.715 ±3.2	17.043 ±4.8	6.8 ±6.8	3.0	0.82	20	135	28
06 06:25:13.1	43.710 ±3.1	16.783 ±12.0	19.0 ±4.9	2.3	0.46	8	148	33
06 06:40:48.2	43.669 ±4.5	17.067 ±7.6	4.1 ±6.6	2.5	0.40	7	158	29
06 06:43:09.6	43.696 ±2.7	16.885 ±3.5	10.5 ±5.4	3.1	0.83	31	107	16
06 06:50:54.4	43.630 ±4.0	17.080 ±5.2	9.8 ±5.5	2.1	0.57	10	173	29
06 07:07:35.6	43.608 ±4.7	16.990 ±10.3	10.0 ±6.7	2.2	0.61	9	239	22
06 07:16:50.8	43.689 ±3.1	17.053 ±7.8	3.2 ±5.4	2.3	0.50	10	239	28
06 07:23:31.9	43.685 ±3.3	16.975 ±7.7	7.8 ±6.5	2.8	0.71	16	155	22
06 07:58:02.2	43.660 ±4.1	16.941 ±11.6	10.8 ±5.2	2.3	0.55	9	169	19
06 08:05:44.7	43.631 ±2.1	16.983 ±2.1	6.9 ±3.8	2.9	0.73	30	92	21
06 09:14:39.2	43.684 ±2.0	16.973 ±2.0	4.5 ±4.2	3.2	0.79	45	93	22
06 09:54:22.2	43.694 ±2.0	16.948 ±2.3	8.3 ±4.5	3.2	0.81	42	92	21
06 10:00:30.0	43.675 ±2.8	16.927 ±8.0	4.4 ±4.4	2.6	0.62	16	152	18
06 11:17:03.1	43.686 ±3.6	17.093 ±6.3	7.1 ±5.0	3.0	0.71	18	137	31
06 11:19:19.5	43.681 ±2.4	16.968 ±3.8	11.5 ±3.2	3.0	0.56	21	123	21
06 11:22:34.9	43.668 ±2.4	17.075 ±4.1	4.2 ±3.6	2.9	0.54	22	135	29
06 13:55:40.9	43.670 ±1.7	16.933 ±1.6	8.5 ±4.1	4.3	0.82	90	75	18
06 14:02:11.3	43.743 ±2.1	17.036 ±2.4	5.4 ±4.8	2.9	0.70	29	121	30
06 14:04:17.2	43.672 ±2.0	16.948 ±1.9	12.2 ±3.4	3.3	0.79	51	91	20
06 15:37:09.2	43.692 ±2.6	16.997 ±4.2	6.8 ±4.3	3.0	0.67	23	124	24
06 17:39:42.7	43.728 ±2.0	16.998 ±2.0	5.3 ±5.3	3.4	0.91	61	95	26
06 20:49:36.2	43.660 ±3.7	17.074 ±8.1	3.2 ±5.8	2.6	0.71	14	242	29
06 22:15:25.7	43.675 ±2.5	17.049 ±4.0	4.2 ±4.2	2.8	0.64	25	126	27
07 01:18:11.5	43.673 ±3.2	17.049 ±6.1	8.8 ±4.7	2.3	0.67	15	151	27
07 04:09:38.5	43.679 ±2.5	16.990 ±4.4	8.0 ±4.4	2.9	0.71	30	124	23
07 16:11:41.1	43.692 ±1.8	16.967 ±1.8	3.4 ±4.0	3.5	0.80	58	88	22
09 04:10:43.5	43.716 ±6.5	16.997 ±3.5	21.0 ±7.5	2.0	0.21	6	275	25
09 05:05:09.0	43.650 ±1.7	16.966 ±0.9	20.3 ±2.0	1.4	0.06	6	245	20
11 02:22:20.9	43.649 ±3.0	17.030 ±4.6	7.9 ±4.5	2.6	0.75	19	132	19
11 23:19:58.3	43.640 ±2.7	16.968 ±3.2	9.5 ±3.5	2.3	0.43	10	153	20
12 12:10:43.9	43.670 ±5.9	16.929 ±2.8	16.5 ±7.2	1.9	0.20	6	253	18
12 17:20:25.4	43.677 ±7.8	16.960 ±4.0	17.5 ±9.7	1.4	0.33	7	250	21
13 17:50:29.3	43.678 ±2.8	17.018 ±4.2	6.8 ±6.8	2.3	0.64	13	148	22
14 11:18:34.6	43.712 ±3.3	17.005 ±1.7	16.9 ±4.3	1.7	0.11	6	274	26
14 11:43:53.8	43.596 ±1.8	16.994 ±1.8	7.8 ±3.1	3.1	0.67	39	91	16
15 03:31:56.1	43.673 ±5.3	16.988 ±2.6	13.7 ±10.2	1.7	0.18	6	258	23
18 10:14:25.7	43.662 ±1.9	16.956 ±1.8	14.8 ±4.5	2.1	0.17	7	188	20
19 04:44:44.5	43.711 ±1.8	16.989 ±2.0	3.0 ±3.6	3.1	0.76	45	109	24
21 06:39:35.0	43.678 ±7.0	16.982 ±2.9	12.6 ±7.8	1.7	0.38	8	249	22
22 06:22:45.4	43.676 ±6.6	16.985 ±3.5	16.7 ±7.7	1.6	0.29	7	248	23

ranging in magnitude from 1.4 to 4.3. The hypocentral parameters for all earthquakes are presented in Table 2. The basic parameters of hypocentres associated with additional data on the number of readings (P and S), azimuthal gap, distance to nearest station, standard deviations of geographic coordinates and standard error of the solution, are listed to enable estimation of the reliability of a single location. The earthquake locations are presented in the map view (Fig. 6) and

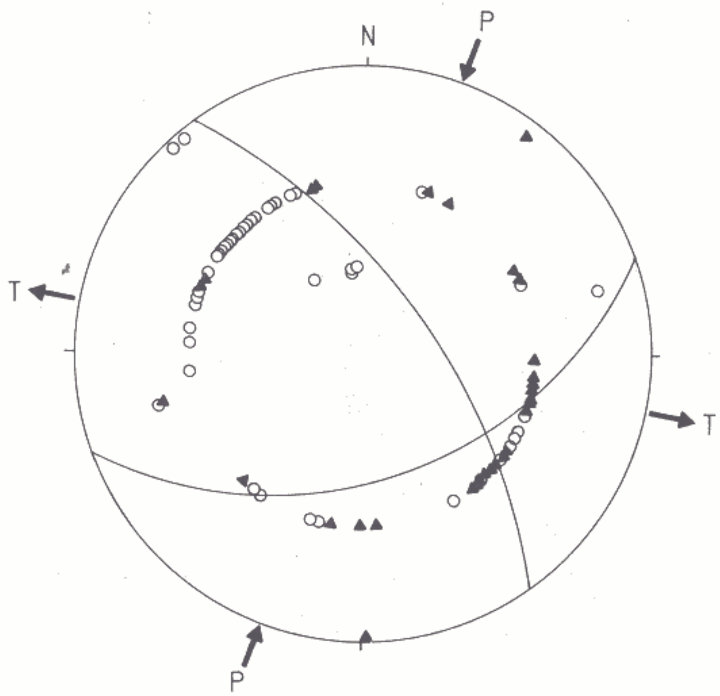

Figure 5. Fault-plane solution (lower hemisphere equal-area projection) for the December 6, M_L = 4.8 earthquake. The nodal plane oriented ENE-WSW has a strike of 70°, dip of 53° and slip of 27°. The second nodal plane (in the NW-SE direction) strikes at 323°, dips at 69° while the slip is at 140°. The tension (*T*) and pressure (*P*) axes have azimuths of 100° and 20°, respectively.
The 79 P-wave first motions used to obtain the above solution are also shown. Compressions are indicated by empty circles, while the dilatational first motions are shown as full triangles.

in cross sections (Fig. 7). It can be seen that the aftershocks fell into a cluster some 20 km in diameter. Cross sections (AA' and BB') are perpendicular to the strikes of the two nodal planes obtained by the fault-plane solution (presented in Fig. 5).

The great majority of aftershocks were located in the upper 15 km of the crust. This fact is compatible with observations that earthquakes in the coastal part of Croatia occur almost exclusively within the uppermost, sedimentary crustal layer which consists mainly of Mesosoic limestones and dolomites (Herak and Herak, 1990).

4.4. Macroseismic survey

The Kamešnica Mt. earthquake of December 6 was the strongest event which occurred during 1989 in Croatia. The earthquake was widely felt throughout Croatia and Bosnia and Herzegovina. The shock was felt as far as 250 km from the epicentre (e.g. at Zagreb on higher floors).

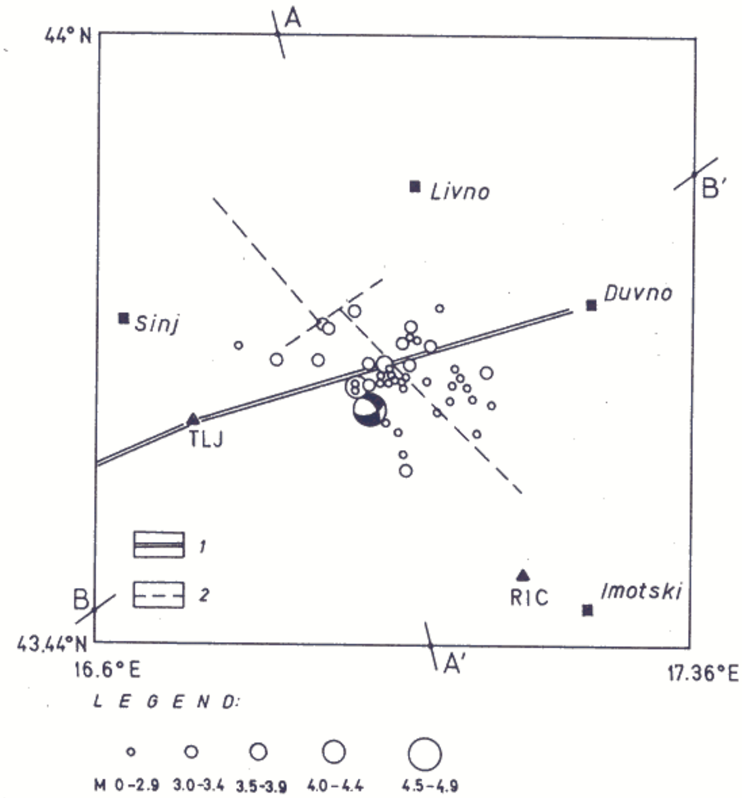

Figure 6. Epicentres of the Kamešnica Mt. seismic sequence. The triangles show positions of the seismometric temporary stations. The symbols scale events by magnitude. The fault-plane solution is indicated on the main-shock's symbol. The traces of faults shown are those of the deep fault zone Duvno-Trilj (1) indicated by the geophysical prospecting and of the complex of transverse faults (2) (after Cvijanović et al, 1979 and Prelogović et al, 1982). The cross-section directions AA' and BB' (see. Fig. 7) are *perpendicular* to the two nodal planes presented in Fig. 5.

Intensity data were collected during field trip to the shaken area. In addition questionnaires were sent to 465 addresses in Croatia, but only 35 % were returned. The distribution of intensity and the isoseismals are displayed in Fig. 8. The maximum isoseismal elongation is along the Kamešnica Mt., that is in the direction of the extension of the Outer Dinarides. The maximum intensity was VII-VIII° MSK. This shock caused considerable damages in the Ruda and Gljev villages. Several concrete pools of the fish-pond at Ruda cracked. Many newly built family houses were also damaged in the neighbouring villages. During the earthquake several injuries were reported to be caused by panic while running outdoors. It was also reported that during the earthquake smoke (or fog) started emerging out of a chasm near Tijarica, covering the whole field. This phenomenon lasted for about 3 hours. The intensity VII° MSK was reported at

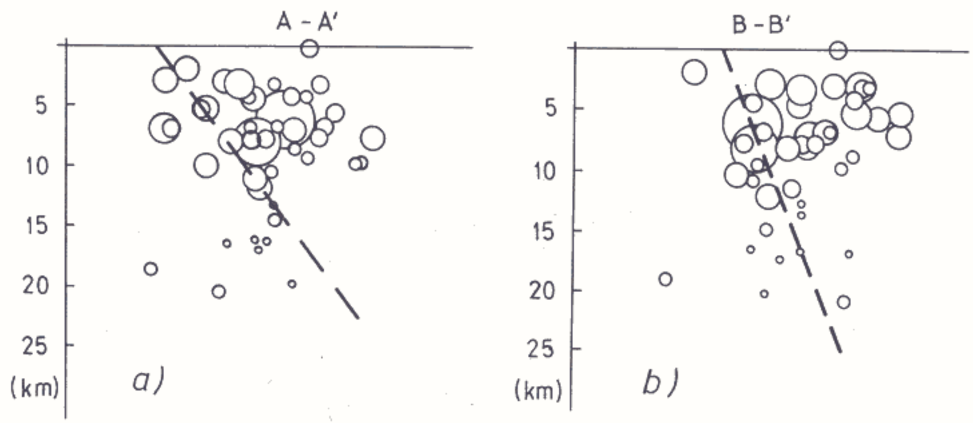

Figure 7. Cross-sections AA' (a) and BB' (b) (see Fig. 6) which are perpendicular to the strikes of the two nodal-planes obtained by the fault plane solution for the Kamešnica Mt. main shock. The dips of respective nodal planes are indicated by dashed lines. The symbol sizes are proportional to the magnitude.

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The microseismic epicentre was within the pleistoseismal area, and lay in the vicinity of several transversal faults and a reverse one. One can observe that the seismic energy propagated very efficiently along those transversal faults – the intensities VII° and VI° were felt far from the epicentre, strongly distorting the shape of isoseismals.

The macroseismic data were collected also for the strongest aftershock which occurred on the same day (at 13:55), although it was difficult to discriminate between the effects of the main shock and those caused by the aftershocks. The intensity data on the aftershock of 13:55 are displayed in Fig.9. The pleistoseismal elongation is similar to the one of the main shock.

4.5. Discussion of results of the Kamešnica earthquake study

The Kamešnica earthquake of December 6, 1989 occurred in the seismically well known area. The seismicity of Kamešnica may be considered within the framework of the seismicity of greater area of Dinara Mt. It is generally believed that earthquakes in the region of Outer Dinarides occur as a consequence of the subduction process of the Adriatic platform underneath the Dinarides. These tectonic movements may be described by the anticlockwise rotation of the Adriatic microplate around the pole in the Northern Italy (see e.g. Anderson and Jackson, 1987), thus causing pressure in the SW–NE direction. This corresponds with the direction of the P-axis as obtained by the fault-plane solution (Fig. 5).

In the geological sense the whole area is broken by a system of very steep faults (e.g. Prelogović et al., 1982; Milošević et al., 1984; Aljinović et al., 1984).

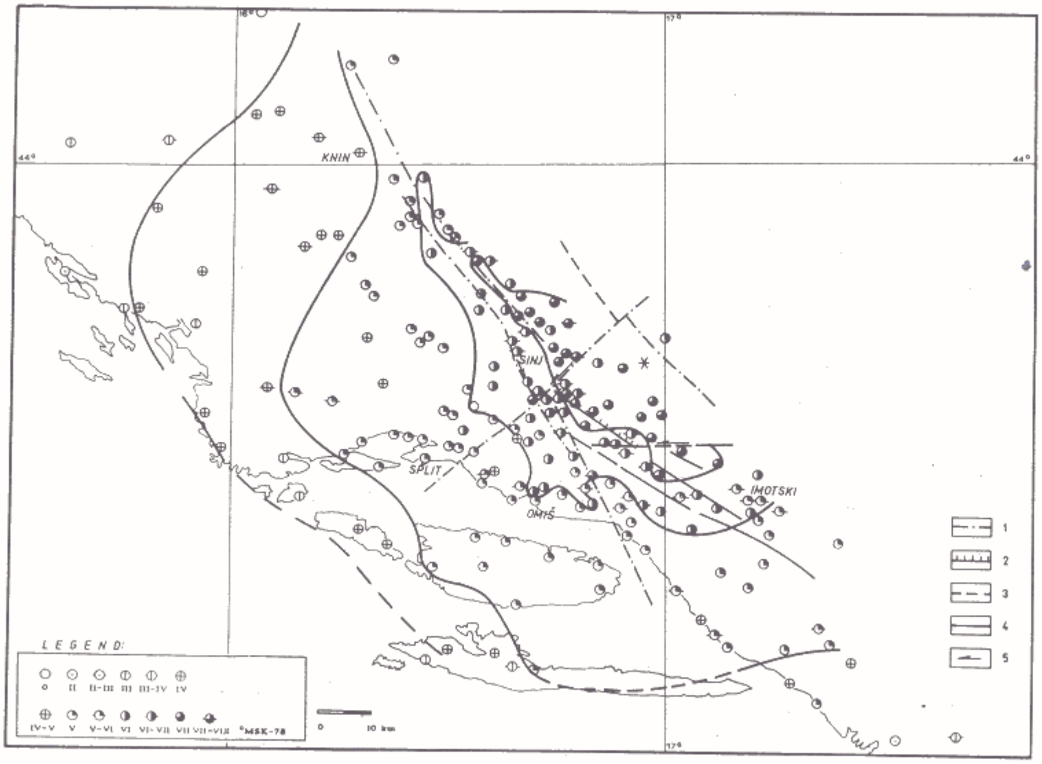

Figure 8. Isoseismal map for the main Kamešnica Mt. event (05:33 December 6, 1989, $M_L = 4.8$). Faults are indicated after Cvijanović et al. (1979), Prelogović et al. (1982) and Milošević et al. (1984). The microseismically located epicentre is shown by the asterisk. The macroseismic data in the NE quadrant (the territory of Bosnia and Herzegovina) were not available at the time the manuscript was prepared.
Legend: 1 – transverse faults; 2 – reverse faults; 3 – assumed faults; 4 – longitudinal faults; 5 – horizontal shearing of tectonic units.

The hypocentral area is crossed by two faults: the Duvno-Trilj assumed deep fault, and the NE–SW striking system of longitudinal faults (see Fig. 6). Their strikes agree almost perfectly with the strikes of the two nodal planes obtained by the fault-plane solution. This fact makes it impossible to distinguish between the fault and the auxiliary plane on the basis of geological considerations. The dips of nodal planes are indicated on cross-sections displayed in Figs. 7a and 7b by broken lines. Although the hypocentres are more or less clustered on both cross-sections they may be said to roughly follow the dips of the nodal planes – again, no clear indication is seen which would help to resolve the fault plane–auxiliary plane ambiguity. Instead, the earthquakes seem to have originated on both nearby faults.

The isoseismal shape is a strong indication that seismic energy is absorbed much more efficiently in the direction perpendicular to the Dinaric belt than along it.

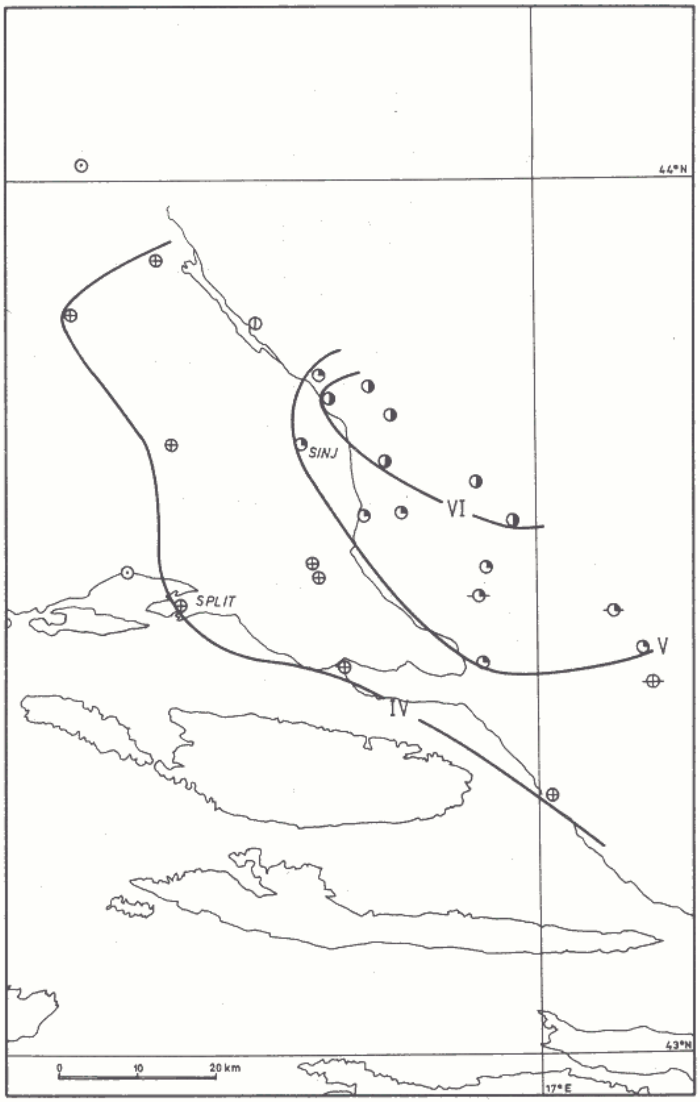

Figure 9. Isoseismal map for the strongest aftershock (13:55 December 6, 1989, $M_L = 4.3$) of the Kamešnica Mt. event

5. Conclusion

Seismic activity in Croatia and the surrounding areas in 1989 was confined to the previously identified seismically active areas. The majority of earthquakes occurred in the coastal part of Croatia. The strongest event in 1989 occurred under the hill-sides of Kamešnica Mt. on December 6 at 05:33 UTC ($M_L = 4.8$,

I_{max} = VII-VIII° MSK). The fault plane solution indicates that this earthquake was caused by tectonic movements characterised by SW–NE directed pressure, which is congruent with the subduction of the Adriatic microplate under the Dinarides.

Altogether 361 earthquakes were located. All well located earthquakes occurred in the upper part of the earth's crust with a range in depth between surface and 20 km.

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