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Seismicity of Croatia in the period 1990–1992

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Based on the catalogue of all located earthquakes in Croatia and the surrounding areas for the period 1990–1992 and on the macroseismic data analyses for individual earthquakes, certain seismicity features have been analysed. All together, 1188 earthquakes were located and the catalogue was found to be complete for the magnitudes $M_L \geq 3.0$. Seismically the most active was the coastal part of Croatia, where the strongest earthquake in the analysed period occurred on November 27, 1990 with the epicentre beneath the Dinara Mt. The composite fault-plane solution for the main shocks indicate the presence of a tectonic stress-field directed approximately SSW–NNE which is compatible with the assumed anticlockwise rotation of the Adriatic plate and its subduction under the Dinarides.

Seizmičnost Hrvatske i susjednih područja u razdoblju 1990–1992

Na osnovi kataloga svih lociranih potresa u Hrvatskoj i susjednim područjima za razdoblje 1990–1992, te makroseizmičke obrade podataka za pojedine potrese, analizirana su neka obilježja seizmičnosti. Ukupno je locirano 1188 potresa. Kompletnost kataloga s obzirom na magnitudu procijenjena je na $M_L \geq 3.0$. Osobito je seizmički aktivan bio priobalni dio Hrvatske i to područja oko Rijeke, Imotskog, Metkovića, te obronci Dinare gdje se dogodio najjači potres u ovom razdoblju. Posebna je pažnja posvećena tom potresu, te je analiziran detaljnije od ostalih. Zajedničko rješenje mehanizma pomaka u žarištu određeno za glavne potrese pokazuje da su tektonski pomaci uzrokovani poljem tlaka usmjerenim JJZ–SSI. To je u skladu s pretpostavljenom rotacijom Jadranske ploče oko pola u sjevernoj Italiji koja uzrokuje njezinu subdukciju pod kompleks Dinarida.

1. Introduction

This paper is a continuation of the systematic compilation of earthquake catalogues with epicentres 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), before 1901 (Part II) (Shebalin et al., 1974) and the catalogue for the period 1971–1985 (Part III) is currently being prepared. The earthquake catalogues for the years 1986 through 1989 were published by Herak and Cabor (1989), Markušić et al. (1990) and Herak et al. (1991).

For the period 1990–1992, data have been compiled and processed for all recorded earthquakes in Croatia, regardless of the magnitude. Special attention was dedicated to the earthquakes with higher magnitudes (April 3, 1990 at 22:02, July 18, 1990 at 00:10, July 31, 1990 at 15:50, September 3, 1990 at 10:48, November 27, 1990 at 04:37, December 22, 1990 at 15:06, February 21, 1992 at 20:50, May 19, 1992 at 00:04, September 21, at 20:47). Several events were macroseismically analysed which contributed to the more complete analyses of seismically active areas.

2. Data and method

A total of 1188 earthquakes were located in the period 1990–1992. The earthquake parametres were determined by using phase arrival times collected by analysing the set of original seismograms from the permanent and temporary seismological stations in Croatia. Those data were supplemented by readings reported in monthly bulletins of seismological stations in neighbouring countries. Five main parametres for each earthquake were determined: 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). 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 of the crust and upper mantle for the Balkan region (B.C.I.S., 1972) was used in the location program, except for the Central Adriatic earthquakes and the earthquakes in the central part of the Outer Dinarides, where we used the velocity models published by Herak (1990) and Herak et al. (1988).

Macroseismic investigations were carried out whenever information about the felt earthquake was received. We have compiled the macroseismic data obtained by fieldwork and/or by the questionnaires received from the shaken ares. The intensity was estimated in accordance with the MSK-78 scale. 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 main geological structures of the respective area (faults, mountain belts). The 6 intensity maps will be given in the following sections.

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):

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

to define the value of the coefficient b in the Gutenberg-Richter's (1944) relation. In the above expression $\overline{M}$ denotes the mean magnitude of all earthquakes in the catalogue which satisfy $M \geq M_c$ and N is the number of such earthquakes. It was determined that for $M_c \geq 3.0$ coefficient b assumes almost constant value, so we may assume the catalogue to be complete for the magnitudes M_L greater or equal to 3.0.

3. Main characteristics of seismicity of Croatia in the period 1990–1992

All earthquakes in the period 1990–1992 occurred within well-known epicentral areas (Fig. 1), most of which are situated in the coastal part of Croatia. The strongest event there had magnitude of M_L = 5.6. Seismic activ-

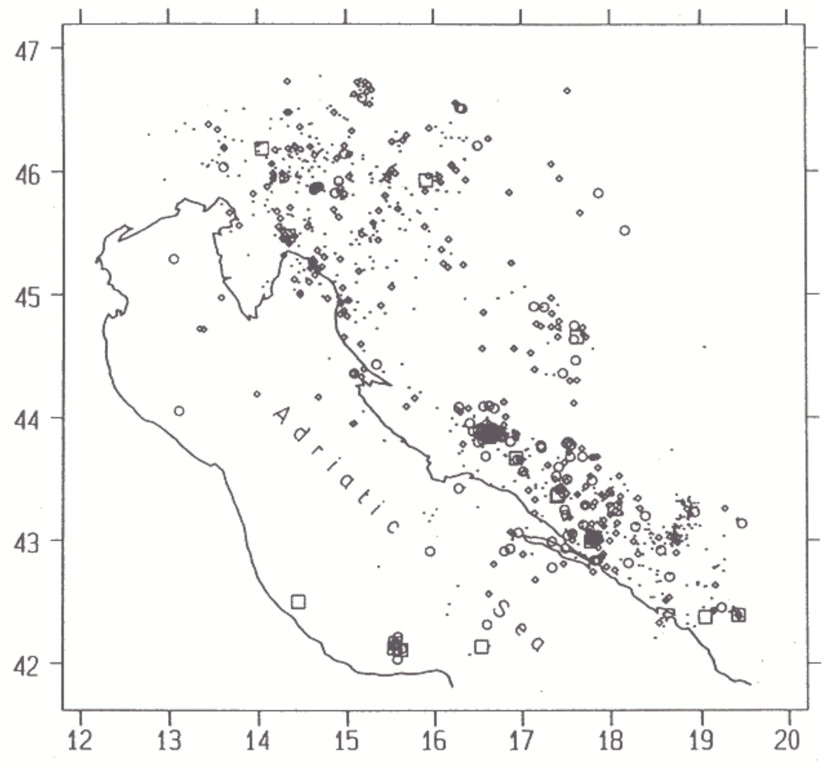

Figure 1. Map of epicentres in Croatia and the surrounding areas in the period 1990–1992. Legend: dots – $M_L \leq 2$; diamonds – $2 < M_L \leq 3$; circles – $3 < M_L \leq 4$; squares–$M_L > 4$.

ity of the continental part was lower and only earthquakes with magnitudes up to $M_L = 4.8$ occurred.

3.1. Continental part of Croatia

In the continental area there is pronounced seismicity in its northwestern part (northwest from Čakovec, Ludbreg, Zagreb, Samobor and Krško). The prevailing direction of the concentration of epicentres is northeast-southwest. The belt of intensified seismic activity 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 series of earthquakes in September 1992 was recorded at the *Croatia–Slovenia border region*, NW from Čakovec (Štrigova area). The strongest event occurred on September 21 at 20:47 ($M_L = 3.4$, I_{max} = VI °MSK). Intensity of VI °MSK was reported in Štrigova where the tiles on the roofs were displaced and the mortar cracked on few houses. The isoseismal map is displayed in Fig. 2. Microseismic epicentre (the asterisk in Fig. 2) is inside the pleistoseismal area and in vicinity of the longitudinal fault, while the transversal fault is in the direction of isoseismal elongation. The elongation of the IV° and

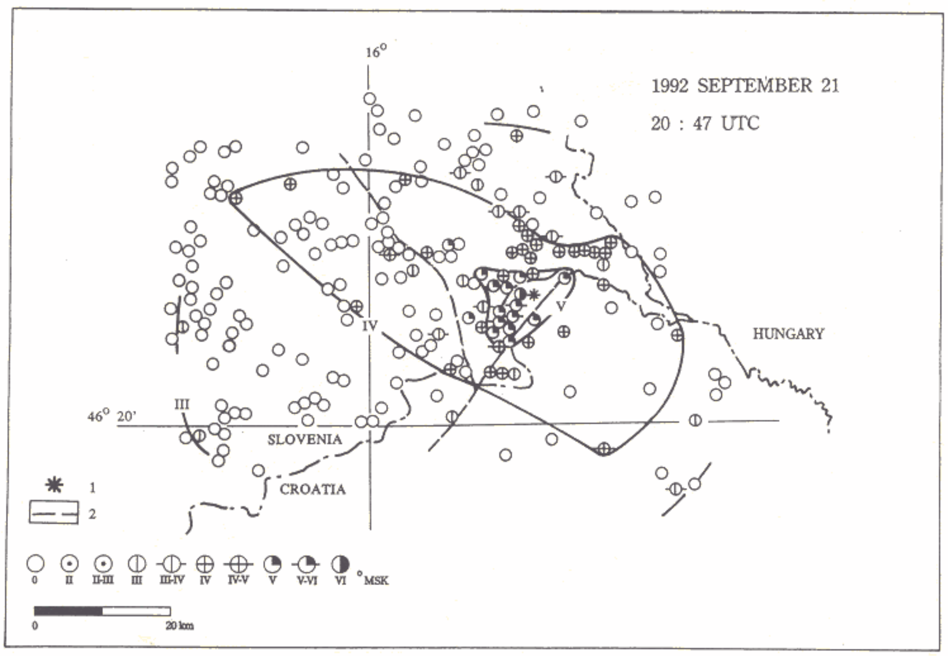

Figure 2. The isoseismal map for the Štrigova earthquake of September 21, 1992 (20:47). Positions of the faults are taken from Čubrilović et al. (1967).
Legend: 1 – position of the microseismic epicentre; 2 – assumed fault.

V° isoseismal in the NW direction on Slovenian side is probably caused by local geological conditions (alluvial deposits).

Pronounced seismic activity in the *Ludbreg area* that began in 1988, continued during the 1990–1992 period. The earthquake with the greatest intensity (M_L = 3.3, I_{max}=V °MSK) in this area occurred near Varaždinske Toplice on July 18, 1990 at 00:10.

In the epicentral *area of Zagreb* (northern hill-sides of Medvednica Mt.) pronounced seismic activity began in September 1990. The main shock occurred on September 3 at 10:48 with the epicentre in Kraljev Vrh (M_L = 4.8, I_{max} = VII °MSK). This was, at the same time, the strongest event in the continental part of Croatia for the period from 1990 to 1992. The main shock was recorded by many seismological stations all over the Europe. 91 P and S onset time data were collected for locating the source. The closest station, Puntijarka (PTJ), is situated 4 km southeast of the epicentre. The azimuthal gap was only 38°. The following hypocentre location was obtained: φ = 45.923 °N ± 1.9 km, λ = 15.922 °E ± 1.8 km, h = 12.8 ± 2.6 km. The fault-plane solution for the main shock is presented in Fig. 3. It was obtained on the basis of 70 first-motion polarity data collected from local, regional and distant stations. The first of the two nodal planes strikes NE–SW, dips at an angle 65° and represents a left-lateral reverse fault. The second one, striking WNW–ESE and dipping 49° is equivalent to a right-lateral reverse fault. The azimuths of pressure (P) and tension (T) axes are N158°E and N260°E, respectively. A detailed macroseismic research was carried out. The intensity was estimated for 1437 places, 704 of which are in Croatia and the rest of them are in Slovenia. Many damages were reported and they were heaviest in Kraljev Vrh

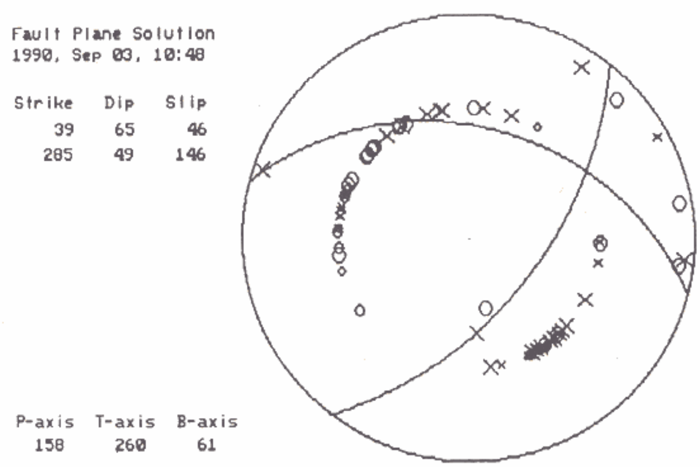

Figure 3. Fault-plane solution (lower hemisphere equal-area projection) for the September 3, 1990 (10:48) earthquake. Compressions are indicated by circles, while the dilatational first motions are shown as crosses.

where the wall of a new house cracked in the height of the first floor and was dislocated by 2 cm. The change in water level of the brook was also observed. Not far away from Kraljev Vrh a crack appeared in the ground in the length of approximately 2 metres. The map of isoseismals is displayed in Fig. 4 together with the most important faults of the tectonic complex (after Cvijanović et al., 1979). As it can be seen, pleistoseismal and isoseismals of VI° and V° are elongated in the direction of the longitudinal fault (NE–SW) with protrusions in the direction of the transversal fault (NW–SE).

The seismic activity in the *Krško area* was not very pronounced. The strongest earthquake in that region occurred on December 22, 1990 at 15:06 ($M_L = 2.4$).

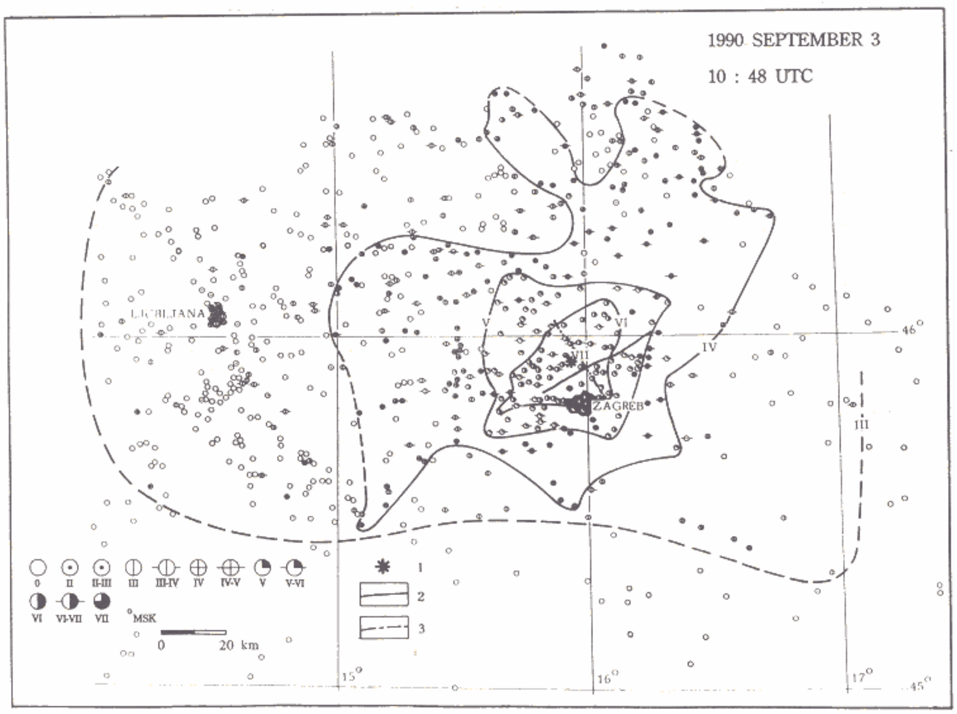

Figure 4. The map of isoseismals for the earthquake which occurred near Kraljev Vrh on September 3, 1990 at 10:48. Faults positions and types are taken from Cvijanović et al. (1979). Legend: 1 – position of the microseismic epicentre; 2 – longitudinal fault; 3 – transversal fault.

3.2. Coastal part of Croatia

The coastal part with the Dinaric mountains is seismically most active in Croatia – the seismicity is thought to be generated primarily by the subduction of the Adriatic microplate under the Dinaric massif. The most significant seismically active areas are those of Rijeka, Novi Vinodolski–Senj–Jablanac, Dinara, Imotski and the mouth of the river Neretva with Metković and Pelješac peninsula.

A series of earthquakes occurred in February 1992 in the *Rijeka area* (45.2–45.7 °N, 14.2–14.8 °E). The epicentres were near Lipa, northwest of Rijeka. The main shock occurred on February 21 at 20:50 ($M_L = 4.1$, I_{max} = V–VI °MSK – Lipa, Rupe). This was also the strongest event in the whole epicentral area of Rijeka during the period 1990–1992. The earthquake was

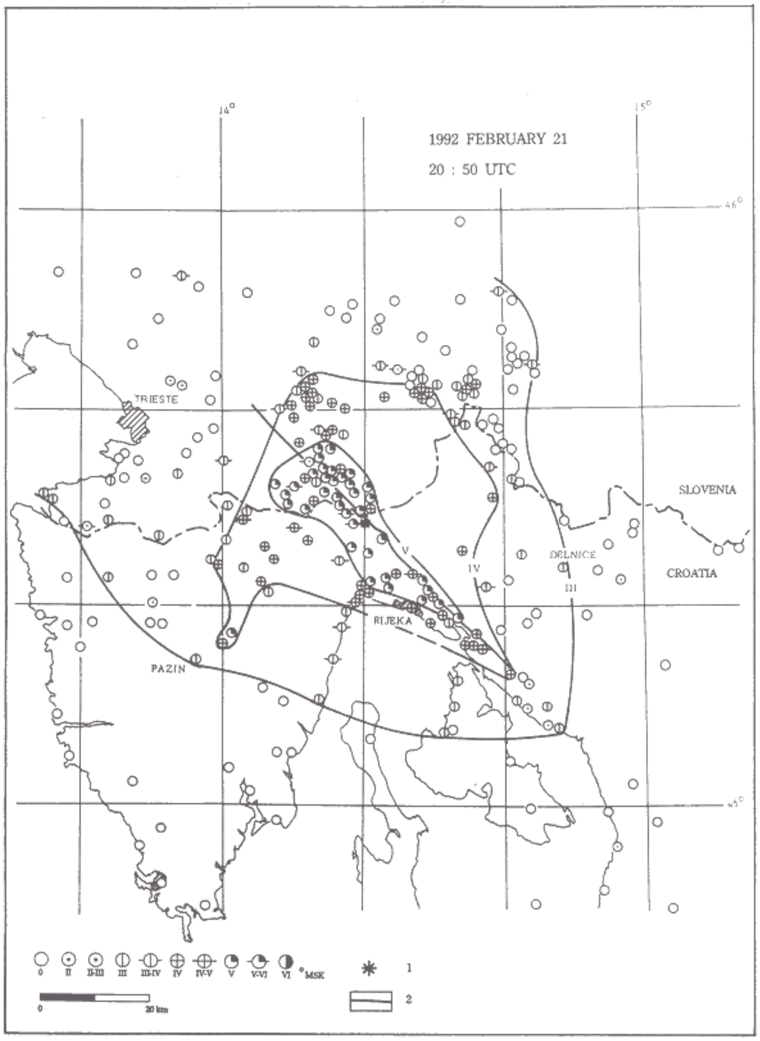

Figure 5. The isoseismal map for the earthquake which occurred on February 21, 1992 near Lipa. Position of the fault is taken from Kuk et al. (1993).
Legend: 1 – position of the microseismic epicentre; 2 – reverse boundary fault of seismogenetic structures (Klana-Bakar).

accompanied with an explosion-like sound and occurred while the war was ranging in this part of Croatia. Since massive explosions of military repositories occurred nearby earlier in February the possibility exists that some intensities were overestimated, because the population was frightened of possible military attack and not of an earthquake. The map of isoseismals is displayed in Fig. 5 together with the most important regional fault (Kuk et al., 1993). The isoseismals' elongation is in the direction of the reverse boundary fault between seismogenetic structures (Klana–Bakar). As the macroseismic epicentre is also situated near this fault, it seems it was responsible for occurrence of this earthquake.

The epicentral a*rea of Novi Vinodolski, Senj and Jablanac* was mostly quiet during the observed period, with earthquakes of magnitude up to 2.7. The strongest event here occurred on May 19, 1992 at 00:04 (M_L = 2.7) with the epicentre in the vicinity of Senj.

The strongest earthquake in the period 1990–1992 in Croatia occurred in the *Dinara Mt. area* on November 27, 1990 with a maximum intensity of VII–VIII °MSK. A series of earthquakes which commenced with the M_L = 5.6 event on November 27 (OT=04:37:57.5) was a remarkable one. In order to understand the tectonic significance of the Dinara earthquake, we decided to dedicate more attention to that seismic sequence in a separate section.

Pronounced seismic activity in the *Imotski area* began in April 1990. The strongest event occurred on April 3 at 22:02 (M_L = 5.0, I_{max} = VI–VII °MSK). The results of the macroseismic field survey show that plaster on the walls and water tanks cracked. Plaster fell from the walls and ceilings and the pantiles (and slates) slipped off. The isoseismal map for this earthquake together with the most important faults (Cvijanović et al., 1979) is displayed in Fig. 6. The isoseismals are elongated in the direction of extension of seismically active sections within the system of longitudinal faults (NW–SE). The microseismic epicentre is in the vicinity of one of the sections. This fact could point to the connection between the longitudinal faults and the focus, especially because the microseismic epicentre is placed near the fault.

The *area of the mouth of the Neretva river, Metković and Pelješac peninsula* exhibited significant seismic activity too. Pronounced seismic activity was recorded in July and August 1990, when 3 earthquakes of magnitudes greater than 4.5 occurred. The strongest event occurred on July 31 at 15:50 (M_L = 4.9, I_{max} = VII °MSK – Čapljina, Domanovići). Macroseismic investigations revealed that the mortar fell from the walls and ceilings, the walls cracked, the slates slipped off (Počitelj) and a chimney was pulled down (Čapljina). The isoseismal map together with the most important faults (Cvijanović et al., 1979) is presented in Fig. 7. The microseismic epicentre is located some 10 kilometres away from the macroseismic one. The location was calculated on the basis of a large number of data (N = 111), standard error of the solution is relatively small (S = 0.83 s), as well as the azimuthal gap (Gap

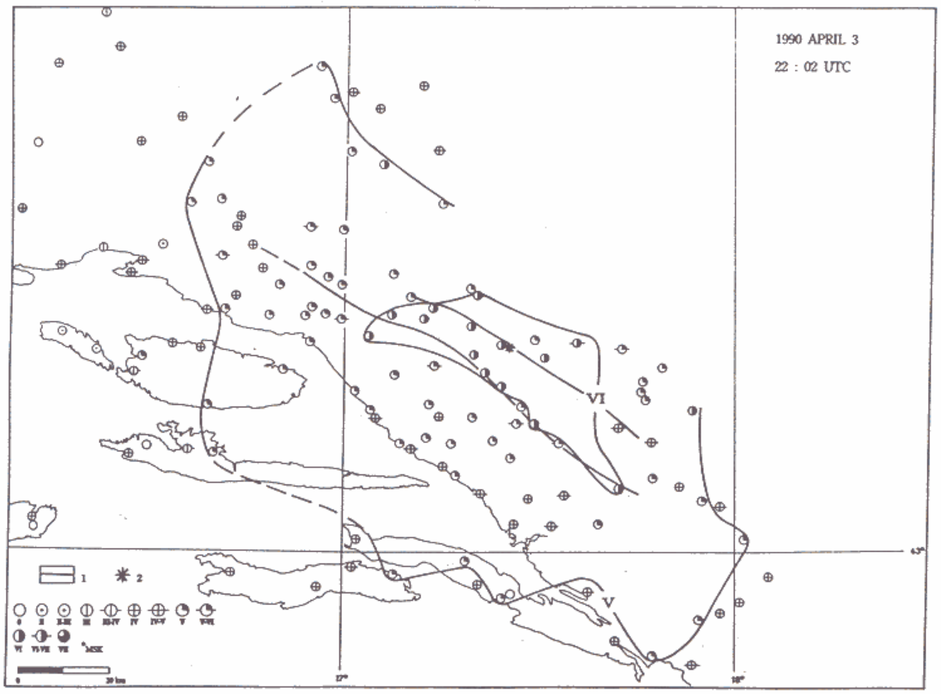

Figure 6. Isoseismal map for the earthquake which occurred in the Imotski area on April 3, 1990 at 22:02 (M_L = 5.0). Fault positions are taken from Cvijanović et al. (1979).
Legend: 1 – seismically active section within the system of longitudinal faults; 2 – position of the microseismic epicentre.

= 39°). Standard errors of the focal coordinates are also small (±1.56 km for the latitude, ±1.39 km for the longitude and ±2.8 km for the depth). The distance between the microseismic epicentre and the centre of the pleistoseismal is too 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.

4. The Dinara Mt. earthquake of November 27, 1990

The event of November 27, 1990 was the largest earthquake in the greater area of the Dinara Mt. since 1962 when a series of earthquakes occurred in the Mt. Biokovo region. It was felt in the area some 250 km around the epicentre. The characteristic of the Mt. Dinara earthquake sequence in 1990 is that two main events occurred (the first and the second main shock) with

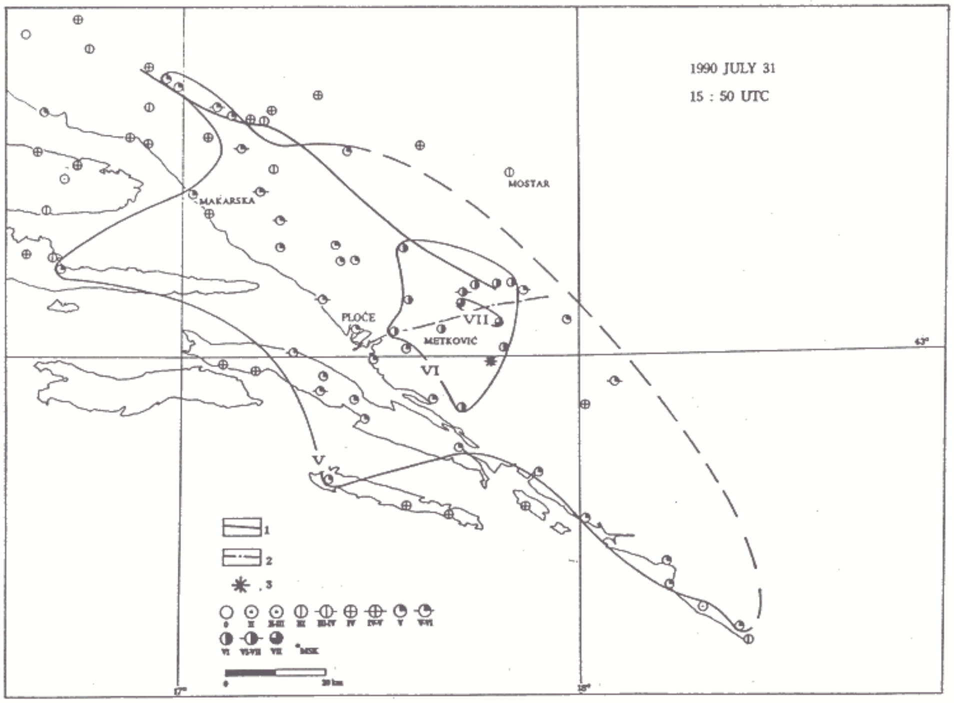

Figure 7. Isoseismal map for the earthquake which occurred on July 31, 1990 near Metković. Positions of the faults are taken from Cvijanović et al. (1979).
Legend: 1 – longitudinal fault; 2 – transversal fault; 3 – position of the microseismic epicentre.

almost same magnitudes (5.6 and 5.5) in an interval of 14 minutes. The aftershock activity lasted for about two months (7 earthquakes had magnitudes greater than or equal to 4.0) and we were able to locate 88 aftershocks (Fig. 8).

4.1. Seismic history

The Dinara Mt. is neotectonically raised structure and is seismically very active with a long and rich seismic history. The seven strongest events which occurred there were: the earthquakes in Sinjsko Polje in 1769 (I_{max}=VIII °MCS), 1844 (I_{max} = VIII °MCS), 1898 (I_{max} = VIII–IX °MCS) and 1899 (I_{max} = VIII °MCS) that occurred 32, 42, 32 and 32 km respectively from the epicentre of the Dinara earthquake, the one of 1942 in Imotsko polje with I_{max}=IX °MCS (64 km distant) and the two events which occurred beneath the Biokovo Mt. in 1962 with intensities I_{max}=VIII °MCS and I_{max} = VIII–IX °MCS (62 and 65 km respectively from the studied epicentre).

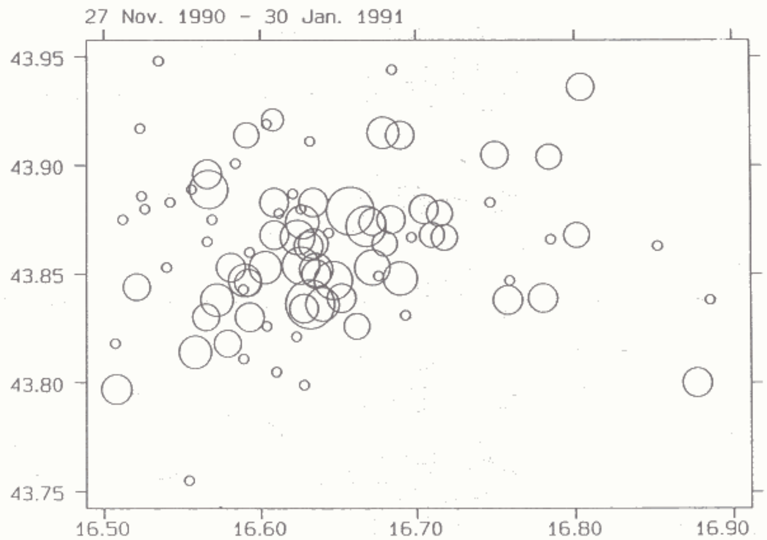

Figure 8. Epicentres of the Dinara Mt. seismic sequence in the period November 27, 1990 – January 30, 1991. The size of circles is proportional to the magnitude.

4.2. The main shocks

The first and the second Dinara Mt. main shock were recorded by many seismological stations. For the purpose of locating their foci we were able to collect a total of 108 and 102, local and regional P- and S-wave onset time data. The crustal models for the Dinara area used to locate the main shocks and the aftershocks were the same as those reported in the paper of Herak et al. (1988). The azimuthal coverage of seismic stations was good, and the gaps for the first and the second shocks were only 35° and 39°, respectively. The following hypocentre locations were obtained: for the first main shock – φ = 43.833 °N ± 1.7 km, λ = 16.627 °E ± 1.5 km, h = 8.6 ± 4.1 km; for the second main shock – φ = 43.860 °N ± 1.2 km, λ = 16.650 °E ± 1.2 km, h = 9.4 ± 3.5 km. The attempts to calculate fault-plane solutions for each of the events yielded very poorly constrained results. If, however, we assume that the same type of faulting took place in both cases, we may try to improve the reliability of results by considering only those P-wave polarity readings that are the same for both of the main shocks, i.e. to attempt composite fault-plane solution. A strong indication that faulting mechanisms may indeed be nearly the same exists in the similarity of acceleration wave-forms for the two shocks recorded at the Ričice Dam accelerographic station (Fig. 9). The composite fault-plane solution is shown in Fig. 10. It is well constrained and successfully predict over 85% of observed polarities. The first of two nodal planes, striking NW–SE and dipping at 43° represents a right-lateral thrust fault. The second one

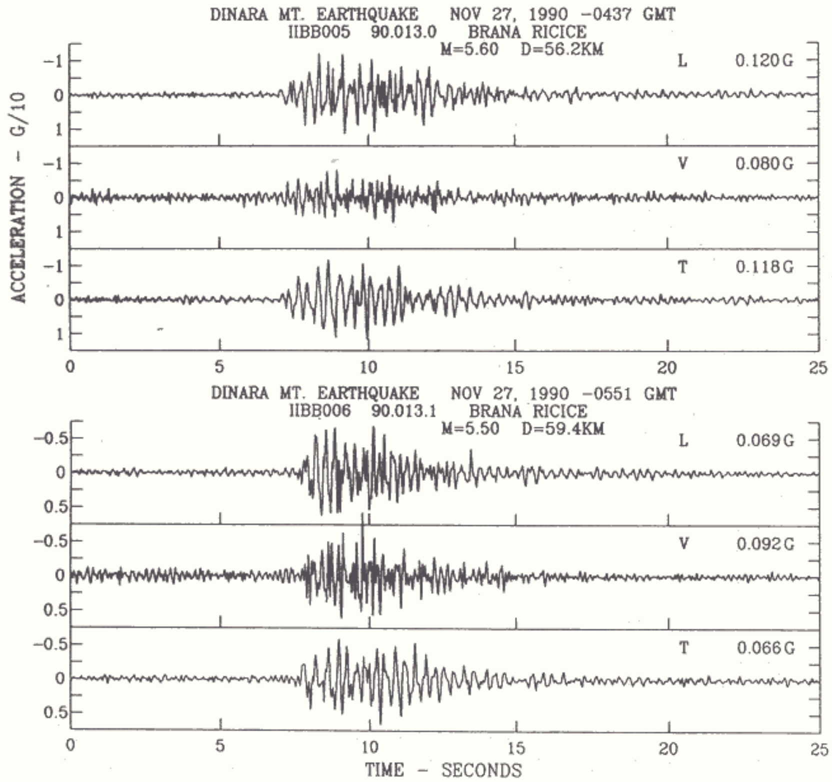

Figure 9. The accelerograms of the first and the second main shock on November 27, 1990 at 04:37 ($M_L = 5.6$) and at 04:51 ($M_L = 5.5$) recorded at Ričice Dam station.

strikes WNW–ESE, dips at an angle of 55° and is equivalent to a left-lateral reverse fault. The directions of pressure (P) and tension (T) axes are N214°E and N319°E, respectively, which is compatible with the assumed anticlockwise rotation of the Adriatic platform around the pole in Northern Italy (Anderson and Jackson, 1987).

4.3. Aftershock sequence

The Dinara Mt. earthquake was followed by a remarkable aftershock sequence. Unfortunately, the nearest seismological station at Trilj (TLJ), a temporary one, was for a short time out of operation, which prevented us from locating the majority of aftershocks. We were able to locate 88 aftershocks with magnitudes ranging from 1.7 to 4.6. The earthquake locations are presented in map view on Fig. 8. It can be seen that the aftershocks fell into a cluster some 29 km in diameter. The great majority of aftershocks were

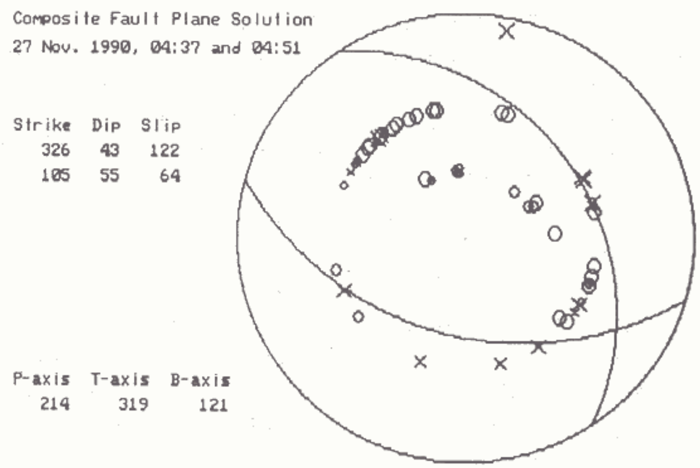

Figure 10. Composite fault-plane solution for the first and the second main shock on November 27, 1990 at 04:37 and at 04:51. Compressions and dilatations are indicated by circles and crosses, respectively.

located in the upper 15 km of the crust. This fact verifies the observations that earthquakes in the coastal part of Croatia occur within the uppermost, sedimentary crustal layer (Herak and Herak, 1990).

4.4. Macroseismic survey

The Dinara Mt. first main shock of November 27, 1990 was the strongest earthquake which occurred in the period 1990–1992 in Croatia. It was widely felt through-out Croatia and Bosnia and Herzegovina, as far as 250 km from the epicentre (e.g. at Zagreb on higher floors with intensity of II °MSK).

Intensity data were collected by fieldwork in the shaken region but because of war-time circumstances in Croatia we couldn't visit some areas. In addition questionnaires were sent to 477 addresses in Croatia and 63% of them were returned. The maximum reported intensity was VII–VIII °MSK at Ježević.

Inside the isoseismal of VII° many buildings with reinforced concrete skeleton suffered slight damage. In many buildings built of bricks cracks occurred in the walls and the tiles slipped off. A few old rubble masonries collapsed and many cracked. The cracks were large and extensive. The rockfalls occurred on the road between Podosoje and Otišić (15 m^3) and near Maljkovo and Vrlika. The water in the lake Peruča became turbid.

The isoseismal map is displayed in Fig. 11. The microseismic epicentres are within the pleistoseismal area and lay some 5 km and 7 km respectively, from the longitudinal fault characterized by predominantly horizontal displacement striking NW–SE. We can observe that the seismic energy propagated very efficiently along this fault system, which strongly distorted the shape of isoseismals. The geologically determined strike and sense of motion characterizing this fault agree well with the properties of NW–SE striking fault obtained by the fault-plane solution.

5. Conclusion

In the period 1990–1992 the seismic activity of Croatia and the surrounding areas was confined to the well known epicentral areas. Altogether, 1188 earthquakes were located and the most of them occurred in the coastal areas. The strongest event in this time period occurred on November 27, 1990 at

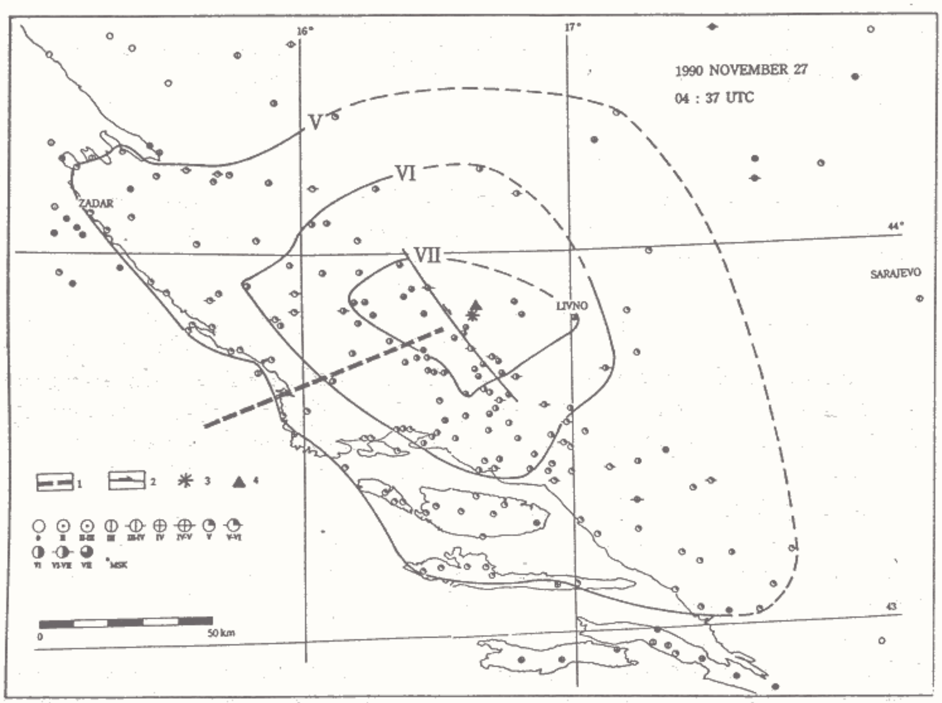

Figure 11. Isoseismal map for the first main Dinara Mt. event (04:37, November 27, 1990, M_L = 5.6). Faults are indicated after Aljinović et al. (1990).
Legend: 1 – boundary between southern and central part of the Adriatic platform at depth of 8–15 km; 2 – longitudinal fault with horizontal displacements; 3 – position of the microseismically located epicentre of the first main shock; 4 – position of the microseismically located epicentre of the second main shock.

04:37 (UTC) in Dinara Mt. area (M_L = 5.6, I_{max} = VII–VIII °MSK). The composite fault-plane solution for the first and the second m°MSK). The composite fault-plane solution for the first and the second main shock indicates that these earthquakes were caused by the tectonic movements characterised by the SSW–NNE directed pressure, which is congruent with the subduction of the Adriatic microplate underneath the Dinarides.

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