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Jabuka island (Central Adriatic Sea) earthquakes of 2003

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Abstract

We present analyses of one of the strongest earthquake sequences ever recorded within the Adriatic microplate, which occurred near the Jabuka island in the very centre of the Adriatic Sea. The mainshock (29 March 2003, 17:42, M_L=5.5) was preceded by over 150 foreshocks, and followed by many aftershocks, over 4600 of which were recorded on the closest station HVAR (about 90 km to the east). As the epicentre was in the open sea and due to the absence of nearby stations, we were able to confidently locate only 597 events. Hypocentral locations were computed by a grid-search algorithm after seven iterations of refining hypocentres and adjusting station corrections. Epicentres lie in a well-defined area of about 300 km^2, just to the W and NW of the Jabuka island. The vertical cross-sections reveal that hypocentres dip to the NE, closely matching faults from the Jabuka-Andrija fault system, as identified on the available reflection profiles in the area. The fault-plane solution of the main shock based on the first-motion polarity readings agrees well with the CMT solutions and indicates faulting caused by a S–N directed tectonic pressure, on a reverse, dip-slip fault. This is in very good agreement with the seismotectonic framework of the area. These earthquakes are important as they identify the Jabuka-Andrija fault system as an active one, which can significantly influence seismic hazard on the islands in the central Adriatic archipelago and on the Croatian coast between Zadar and Split. Along with several other sequences which occurred in the last two decades, they force us to change our notion of Adria as nearly aseismic, compact and rigid block. In fact, it turns out that recent seismicity of the Central Adriatic Sea is comparable to the seismicity of several well known earthquake-prone areas in the circum-Adriatic region.

Keywords: Adria; Adriatic microplate; Seismicity

1. Introduction

Seismicity of the Adriatic Sea is mostly referred to as weak, compared to seismic activity along its coasts (Fig. 1). Such observations led to the general opinion formulated during 1980s (e.g. Mantovani et al., 1985;

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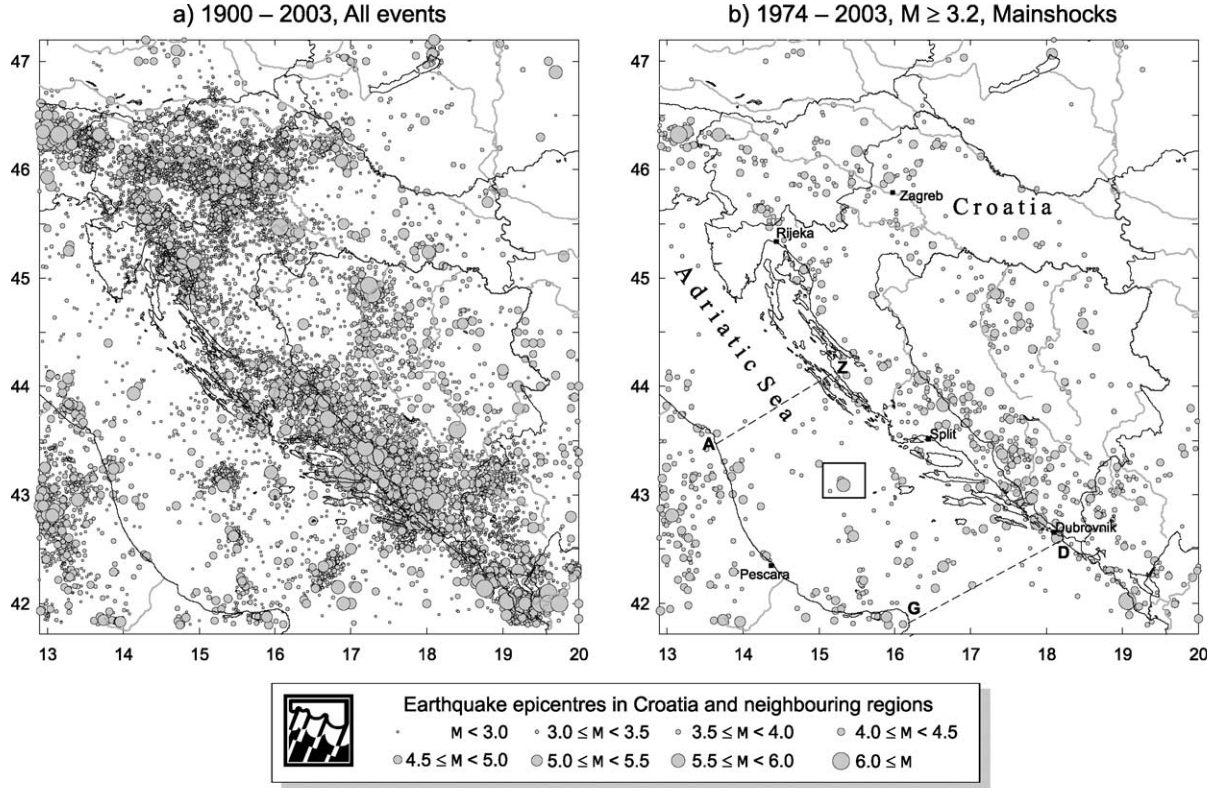

Fig. 1. Seismicity of Croatia and adjacent regions. Epicentres are from the Croatian Earthquake Catalogue (updated version of Herak et al., 1996). (a) All listed events, regardless of magnitude since 1900; (b) mainshocks only from the period 1974–2003 with magnitudes larger or equal to 3.2. The rectangle shows the epicentral region of the Jabuka earthquakes of 2003 (see Fig. 8). Lines Ancona-Zadar (AZ) and Gargano-Dubrovnik (GD) approximately delimit seismically active zone of the Central Adriatic Sea.

Anderson and Jackson, 1987), that Adriatic microplate is a single, rigid and nearly aseismic block, whose contemporary motion as a whole is described by anticlockwise rotation around the pole in Northern Italy (Anderson and Jackson, 1987). As the quality and number of regional seismological stations increased, especially in the last three decades, a considerably different picture started to emerge. Fig. 1b shows mainshocks with $M_L \geq 3.2$ for the last 30 years, extracted from the updated version of Croatian Earthquake Catalogue (Herak et al., 1996). Completeness analysis shows that mainshock catalogue is complete for this period at least down to $M_L=3.2$. The figure suggests that the area of Central Adriatic Sea bounded approximately by the Ancona-Zadar line to the north and the Gargano-Dubrovnik line to the south (AZ and GD in Fig. 1b, respectively), exhibits seismicity which is much more intense than in the rest of the microplate. The Catalogue lists 9 events there with magnitudes (measured or estimated from intensity) $M_L \geq 5.5$, four of them since the beginning of the 20th century. Along the Ancona-Zadar line a known epicentral area exists some 50 km offshore in front of Ancona, with the strongest event from the instrumental period (1934) having magnitude $M_L=5.7$. Several strong events there are listed from the pre-instrumental period (e.g. 361, 1280, 1300, 1304, 1626, 1828), but their locations as well as magnitudes–being in the middle of the sea–are highly uncertain. Along the Gargano-Dubrovnik line, the strongest instrumentally recorded event occurred in 1938 ($M_L=5.6$). The earliest record there is from the year 1844 with the estimated epicentral intensity of VIII °MCS. Whether the lines AZ and GD actually represent active shear zones (especially the southern one, e.g. Favali et al., 1993) is still an open question (see Mantovani et al., 2001, for numerical modelling of consequences on stress and velocity fields induced by activating the zone across the Adriatic).

Significant seismicity in the Central Adriatic has been noticed in a number of papers dealing with recent seismicity of the Adriatic Sea (e.g. Console et al., 1989, 1992, 1993; Favali et al., 1993; Renner and Slejko, 1994). In fact, in the last several decades (for which the catalogue is reasonably complete) seismicity there is comparable to that in some of the neighbouring circum-Adriatic areas as already pointed out by Console et al. (1993) (see Fig. 1b). For instance, the Croatian Earthquake Catalogue lists 7 mainshocks with magnitude 4.5 and above since 1974 in the Central Adriatic Sea (between the lines AZ and GD in Fig. 1b, counting only events located at least 40 km off-shore), and only 8 such earthquakes in the whole area along the Croatian coast and within the External Dinarides between Rijeka and Split, where many strong events have occurred in the past (Fig. 1a). Three events with $M_L \geq 5.0$ occurred in the Central Adriatic in the last 20 years (M_L=5.0 in 1986 in the open sea, M_L=5.3 in 1988 near the island of Palagruža, and M_L=5.5 in 2003 near the Jabuka island), which is more than in any of the seismic zones in Croatia or in the neighbouring territories. This suggests that seismic potential of the area may be significantly higher than assumed up to now. Every effort should therefore be made to learn about the seismotectonic framework and seismicity of the Central Adriatic Sea by studying recent activity in as much detail as possible. Such studies may contribute to solving many existing controversies and open questions regarding present-day tectonics of the Adriatic region. Identification of active faults in this area should also lead to improved hazard estimation. This may prove especially important for the inhabited Croatian islands, where hazard today (Markušić and Herak, 1999; Slejko et al., 1999; Markušić et al., 2000) is almost exclusively defined on the basis of seismicity within the Dinarides and along the collision front between the Adria and the Dinarides.

In this note we present analyses of the most recent and the largest earthquake sequence ever instrumenatlly recorded within the Adriatic microplate, which started in March 2003 near the small island of Jabuka in the very centre of the Adriatic Sea.

2. Regional geological and tectonic framework

The Jabuka earthquakes occurred within the Adriatic microplate, a block of continental lithosphere that acted as a tectonic indenter during convergence of African and European plates (Channel and Horvath, 1976). D'Ingeo et al. (1980) and Anderson and Jackson (1987) proposed Adria to be a single rigid block with the southern margin in the area between southernmost Apulia and Albania. Lort (1971), Channel et al. (1979) and Calcagnile and Panza (1990), on the other hand, considered it to be an African promontory wedged into the European plate. Westaway (1990) proposed that the microplate be divided into two blocks (the northern and the southern one), with the boundary approximately along the G–D line in Fig. 1b. Similar division, but with the boundary along the Pescara-Dubrovnik line was put forward by Gambini and Tozzi (1996). Marked differences of the bathymetry together with recently reported integrated information coming from tomography and gravimetry (Venisti et al., 2004) also speak in favour of the existence of the relevant structural units within the Adria. Oldow et al. (2002) use GPS velocities measured in the greater Adria region to propose the velocity model for Adria with the northwestern and southeastern velocity domains. GPS sites in the northwestern tectonic block show little or no residual velocity relative to Europe. The southeastern block moves together with Africa and exhibits significant N- and NW-directed velocity residual in the European reference frame (5–10 mm/year). General N–NW direction of Adria movement is reported also by Finetti (1984), Mantovani et al. (1997), Altiner (1999), Pribičević et al. (2001) and others. This is also in agreement with the results of finite-element modelling of velocity and strain fields in the central-eastern Mediterranean region reported by Mantovani et al. (2001). The boundary between the two domains proposed by Oldow et al. (2002) is seismically active and runs around the southern and eastern margins of the Tyrrhenian Basin, crosses central Italy, extends into the Adriatic Sea perpendicularly to the coasts between the AZ and GD lines in Fig. 1b (passing through the Jabuka epicentral area!), and then follows the transition zone between the Adria and the Dinarides to the Gulf of Venice.

The tectonic framework of the studied region is conditioned by the movements of the Adriatic microplate (Adria) itself, and by the resistance of the Dinarides to those movements (Fig. 2). Movements of the microplate generate a broad transitional zone (2) between the Adria (1) and the Dinarides (3) (see Fig.

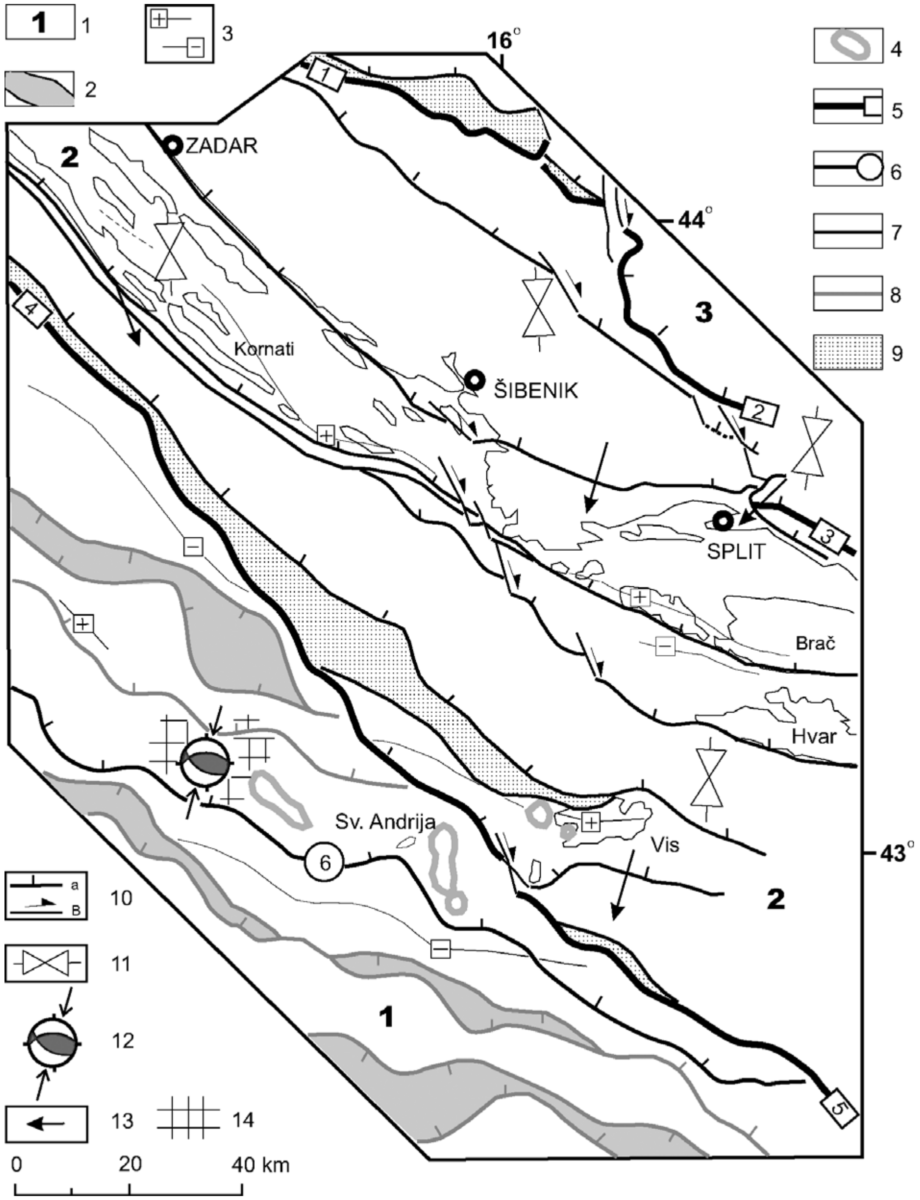

Fig. 2. Geological structural framework: 1—regional structural units: Adriatic microplate (1), transitional zone (2), Dinarides (3); 2—raised structures within the Adriatic microplate bounded by the reverse faults of opposite vergence; 3—axes of minima and maxima of the Bouguer anomalies; 4—eruptive intrusions; 5—boundary faults of regional structural units: Velebit fault (1), Knin-Muć faults (2), Mosor-Biokovo fault (3), Susak-Vis fault (4), Vis-Southern Adriatic fault (5); 6—Jabuka-Andrija fault (6); 7—boundary faults of structural units within the transitional zone; 8—most important faults within the Adriatic microplate; 9—fault zones; 10—a: reverse faults, b: dextral faults; 11—direction of maximal compressive stress; 12—P-axes and fault plane solution for the Jabuka mainshock; 13—prevailing direction of displacement of structures near the surface; 14—Jabuka epicentral area.

2) that extends further to the NW and SE along the Adriatic coast. The most prominent traits of the area are the reverse structures of the NW–SE strike (Herak, 1991, 1999). Surface data indicate presence of mostly vertical and slanted, even overturned, but always faulted folds. Structural relationships at depth were studied by use of gravimetric data and relatively dense network of exploration seismic profiles. Comparisons between features at depth and on the surface were made by e.g. Skoko et al. (1987), Aljinović et al. (1990), Lawrence et al. (1995) and Prelogović et al. (1995).

Seismic reflection profiles indicate that the transitional zone between Adria and the Dinarides (Fig. 2) is characterized by broad fault-zones in the SW related to the Susak-Vis and Vis-Southern Adriatic faults (‘4’ and ‘5’ in Fig. 2, respectively). The zone begins with gently inclined faults and overthrust displacements, usually between rock complexes of different properties. The faults are buried except near the island of Vis. Approaching the Dinarides, the amount of compression grows, causing the dip of faults to increase. The displacements of hanging walls also increase, and faults reach the surface (between Kornati and Vis). Border with the Dinarides in the NE is also represented by a broad zone of large reverse faults, most important of which are the Velebit, Knin-Muć, and Mosor-Biokovo faults (‘1’, ‘2’, and ‘3’, respectively in Fig. 2).

Ever-present tectonic activity during Neogene and Quaternary causes constant narrowing of the microplate area (e.g. Favali et al., 1993; Gambini and Tozzi, 1996; Mantovani et al., 1997; Oldow et al., 2002) thus inducing changes of the structural framework within all structural units in the region, including Adria itself. The sequences of structures identified in seismic profiles may be distinguished within the microplate. Some of them are bounded by reverse faults (Fig. 2). One should also notice several intrusions of evaporites and igneous rocks, which is a peculiarity to be found only in this area of the microplate, i.e. between the islands of Jabuka and Vis. Maximal compressive stress and measured displacements of structures at the surface are consistent with prevailing compression of the area (Fig. 2). The compressive stress is oriented nearly N–S and varies between directions of 15–195° and 340–160° (Herak et al., 1995; Prelogović et al., 1999, 2003; Pribičević et al., 2001). The long-term motion of the structural units has a direction towards SW near Split, S and SW near Šibenik and Vis, and towards S and SE near Kornati (Prelogović et al., 1999). These data are consistent with the observed rotation of parts of the structural framework with dextral tectonic transport (Fig. 2).

Epicentral area of the Jabuka earthquakes of 2003 is located to the W and NW of the large eruptive intrusion (Figs. 2 and 8) around the Jabuka island. Seismic profiles show presence of reverse structures bounded to the SW by the Jabuka-Andrija fault (‘6’ in Figs. 2 and 8).

3. The Jabuka earthquakes

The Jabuka earthquake sequence started on March 27, 2003 with a foreshock of M_L=1.6 at 07:08 UTC. The strongest foreshock [M_w=5.0 (HRV), M_L=4.8 (average of regional stations)] occurred 9 h later. The mainshock [M_w=5.5 (NEIC), M_L=5.5 (average of regional stations)] occurred on March 29, 2003 at 17:42, and was followed by a large number of aftershocks. Intense activity ceased about 8 months later, in November 2003, but sporadically earthquakes still occur there at the time the manuscript is revised (September 2004). The nearest seismological station (HVAR), situated about 90 km to the east, recorded

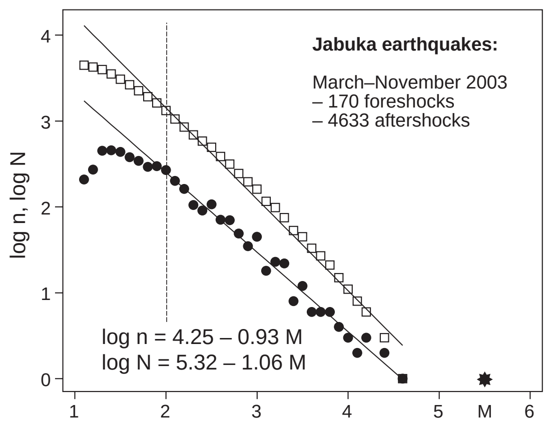

Fig. 3. Frequency-magnitude graphs for the Jabuka events. Cumulative (N, empty squares) and noncumulative frequencies (n, solid circles) indicate completeness threshold at about M_L=2.0 (dashed vertical line). Mainshock is shown by a star. Magnitude values are local magnitudes determined from the records of the HVAR station.

until the end of November 170 foreshocks and 4633 aftershocks, with estimated completeness threshold of M_L=2.0 (Fig. 3). The frequency-magnitude graphs are presented in Fig. 3, and coefficient b is found to have a value close to b=1.0.

The rate of aftershocks (Fig. 4) is computed by considering 20 consecutive events at the time, with a window shift of one event, for three assumed minimal magnitudes $M_{\min}$. Computed rates are then modelled by assuming validity of the modified Omori law (MOL) (Utsu, 1961):

$$n(t) = K(t + c)^{-p}$$

where $n(t)$ is the number of aftershocks per unit time interval (1 day) at time t, and K, c, p are parameters. K depends on the lowest magnitude considered, whereas c takes care of possibly missed events in the earliest part of the sequence by flattening the curve, and usually has small values. Parameter p has the worldwide median of about 1.1, and no correlation of p and the mainshock magnitude has been found so far.

Values of p between 0.99 and 1.13 obtained here (Fig. 4) are consistent with those expected for a normal aftershock sequence. However, the fit of MOL curves to the data is far from perfect, especially for $M_{\min}$=2.0 where more events than predicted are observed in the first 5 hours ($\approx$0.2 days) after the mainshock. Furthermore, the sequence is clearly a superposition of many secondary sequences (after-

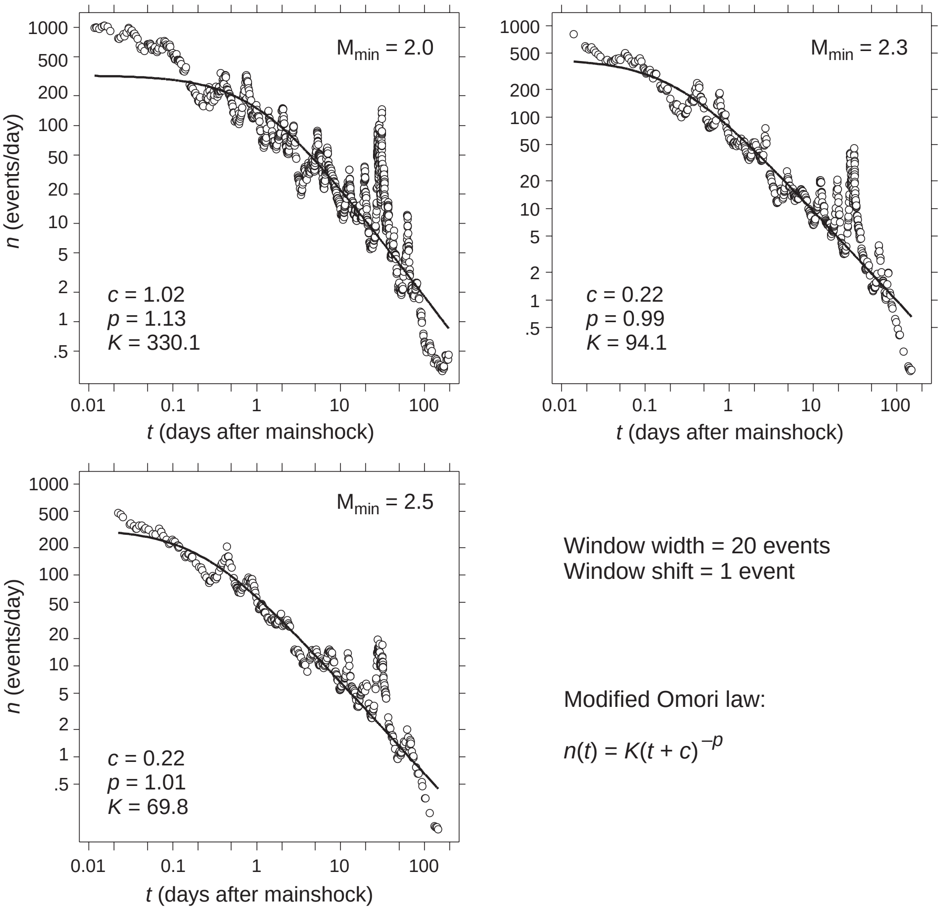

Fig. 4. Rate of occurrence of aftershocks for three minimal magnitudes considered. The rate is computed for windows containing 20 consecutive events. The fit to the modified Omori law was computed by the maximum likelihood method.

shocks of large aftershocks) which are best described by an epidemic type aftershock sequence (ETAS) model (Ogata, 1986, 1988; Guo and Ogata, 1997, see also Herak et al., 2001). Detailed analyses of the properties of this aftershock series by ETAS modelling will be the topic of a separate study.

The fault-plane solution of the main shock computed on the basis of the first motion polarity analyses (Fig. 5) indicates mostly dip-slip faulting with a small reverse component. The pressure axis, which is nearly horizontal and directed almost S–N, is well aligned with the orientation of regional compressive stress based on geological measurements (Prelogović et al., 2003). This direction also agrees well with the direction of recent tectonic movements estimated by geodetic measurements (Altiner, 1999; Oldow et al., 2002; Pribičević et al., 2001). The CMT solutions for the largest foreshock and the mainshock as listed in the Harvard catalogue are in very good agreement with our solution.

Due to lack of seismological stations in the epicentral area, we were able to reliably locate only 597 earthquakes. These are the ones that fulfilled the conditions that at least 7 arrival times of P- and S-phases were reported with at least two of them being S-phases. In practice it means that besides HVAR at least three other stations reported onset times.

Locations were calculated by the grid-search based HYPOSEARCH program (Herak, 1989), taking station corrections into account. Final solutions were obtained after seven iteration cycles of refining station corrections, which were defined only for stations reporting more than six arrival times for a particular phase. Final corrections are shown in Fig. 6. Although the analysis of spatial distribution of station corrections is not the topic of this study, it is interesting to note their regional grouping—e.g. Alpine stations reporting Pn phases with negative corrections on one hand and those in the Northern Apennines, forealpine regions of Slovenia and Croatia, and in the External Dinarides with mostly positive corrections on the other.

Due to remoteness of the epicentral area location uncertainties are somewhat larger than elsewhere in

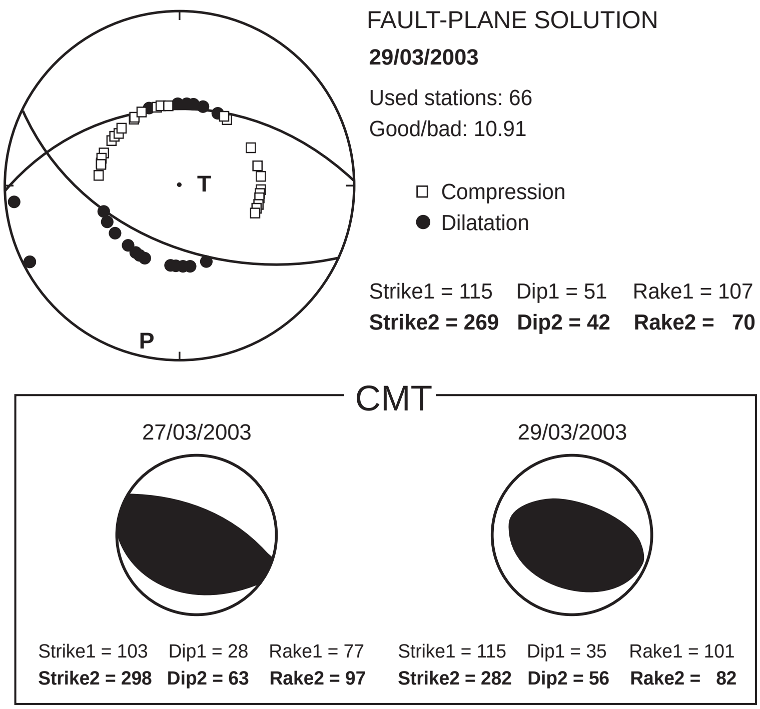

Fig. 5. Top: fault plane solution for the mainshock obtained by analyses of first-motion polarity readings on regional seismological stations. Bottom: CMT solutions for the largest foreshock and the mainshock from the Harvard CMT database (2004).

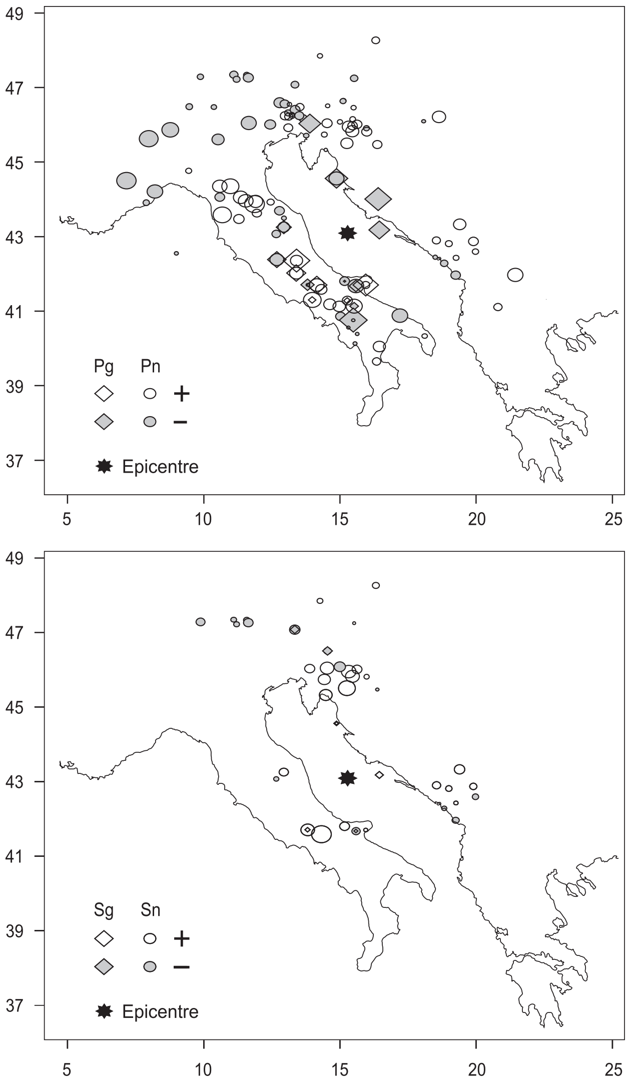

Fig. 6. Final station corrections for station-phase pairs used in locating the Jabuka events. Corrections were computed only for stations reporting the corresponding phase for six or more times. Positive corrections indicate that the model used is too slow. Symbol size is scaled with the absolute correction value, the largest ones corresponding to corrections of ±1.5 s for P-waves (top subplot), and ±2.4 s for S-waves (bottom subplot).

the region (Fig. 7). Most of the epicentres for events with magnitudes of 2.8 and above have numerical uncertainty of less than 5 km. For the focal depth, numerical uncertainties are on the average 2 times larger than for the horizontal coordinates. The focal depth for only about 5% of events diverged to zero, which suggests that the velocity model (B.C.I.S., 1972) together with station corrections produced representative travel-time curves for the region.

Final epicentres are shown in Fig. 8. All the largest events are located at the south-western end of the group, close to the surface trace of the Jabuka-Andrija fault. Smaller events have foci to the north of the mainshock, within the reverse geological structure. The aftershocks cover an area of approximately 300 km^2, which is about three times larger than expected for an earthquake of this size (e.g. Utsu, 2002). This may reflect reality, but can also be due to scatter of

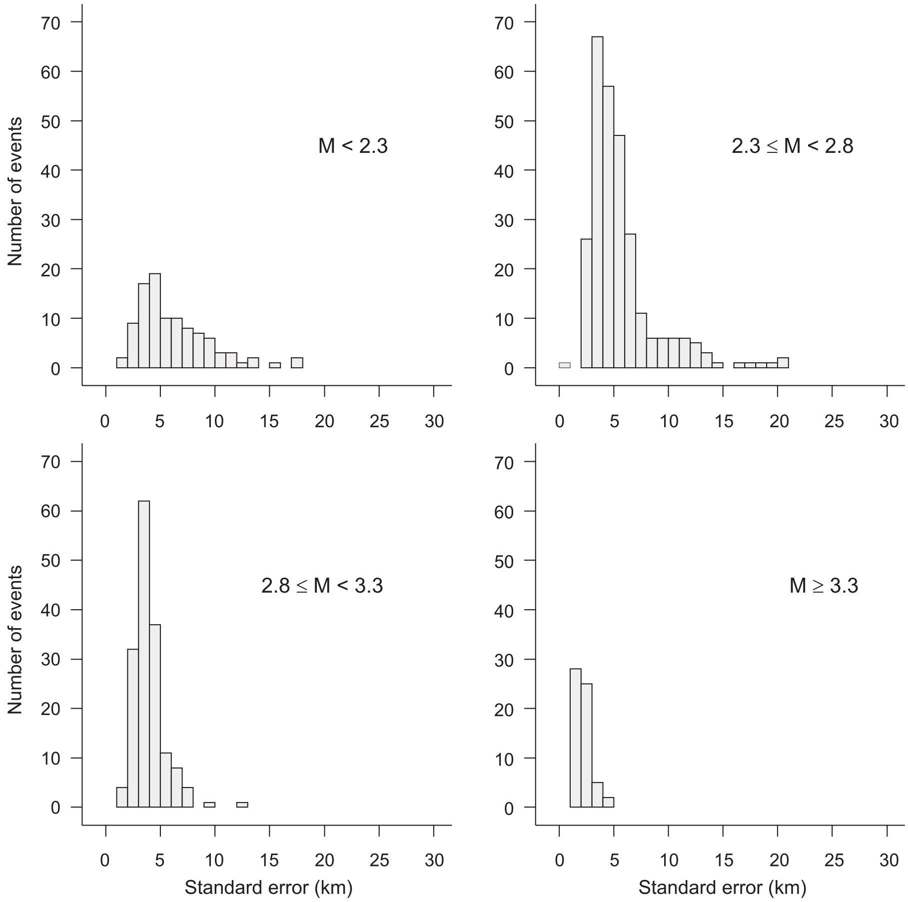

Fig. 7. Histograms of standard errors of epicentre locations for four classes of earthquake magnitudes.

locations caused by insufficient number of data used to compute focal positions for small events. Clear separation of small and large events may also raise a question whether systematic errors caused by insufficient number of data are present.

In order to check the stability of locations with respect to the number of onset times used for locations, we performed the sensitivity test using three well located earthquakes (with the number of reported onset times N>100) as ‘ground truth’ events. The three chosen earthquakes are: the mainshock (29 March 2003, 17:42, M_L=5.5, φ_o=43.08, λ_o=15.32, h_o=5 km, N=126), and the two aftershocks (30 March 2003, 11:09, M_L=4.9, φ_o=43.07, λ_o=15.30, h_o=8 km, N=112; 15 April 2003, 03:54, M_L=3.7, φ_o=43.10, λ_o=15.31, h_o=15 km, N=129). Each of them was then located using 1000 subsets of arrival times generated by randomly selecting N_{dat} onset times ($7 \le N_{dat} \le N$) from the original dataset, but always keeping the two readings from the HVAR station (Pg and Sg), which are reported for all 597 earthquakes. Each of the resulting 3×1000 locations was then compared to the corresponding ‘ground truth’ location (φ_o, λ_o, h_o) (Fig. 9). The two horizontal coordinates are seen to be better constrained than the depth by about a factor of two. The distributions are nearly symmetrical, which means that systematic errors are small. For $N_{dat} \le 10$, mean errors in latitude, longitude and depth are −0.8, −1.3 and+0.7 km, respectively. The corresponding standard deviations are 4.7, 4.0 and 8.8 km. For N_{dat}>10, mean errors are −0.3, −0.4 and +1.2 km, with the respective standard deviations of 2.1, 1.9 and 4.4 km. This experiment suggests that the hypocentres of the smallest events may have been mislocated

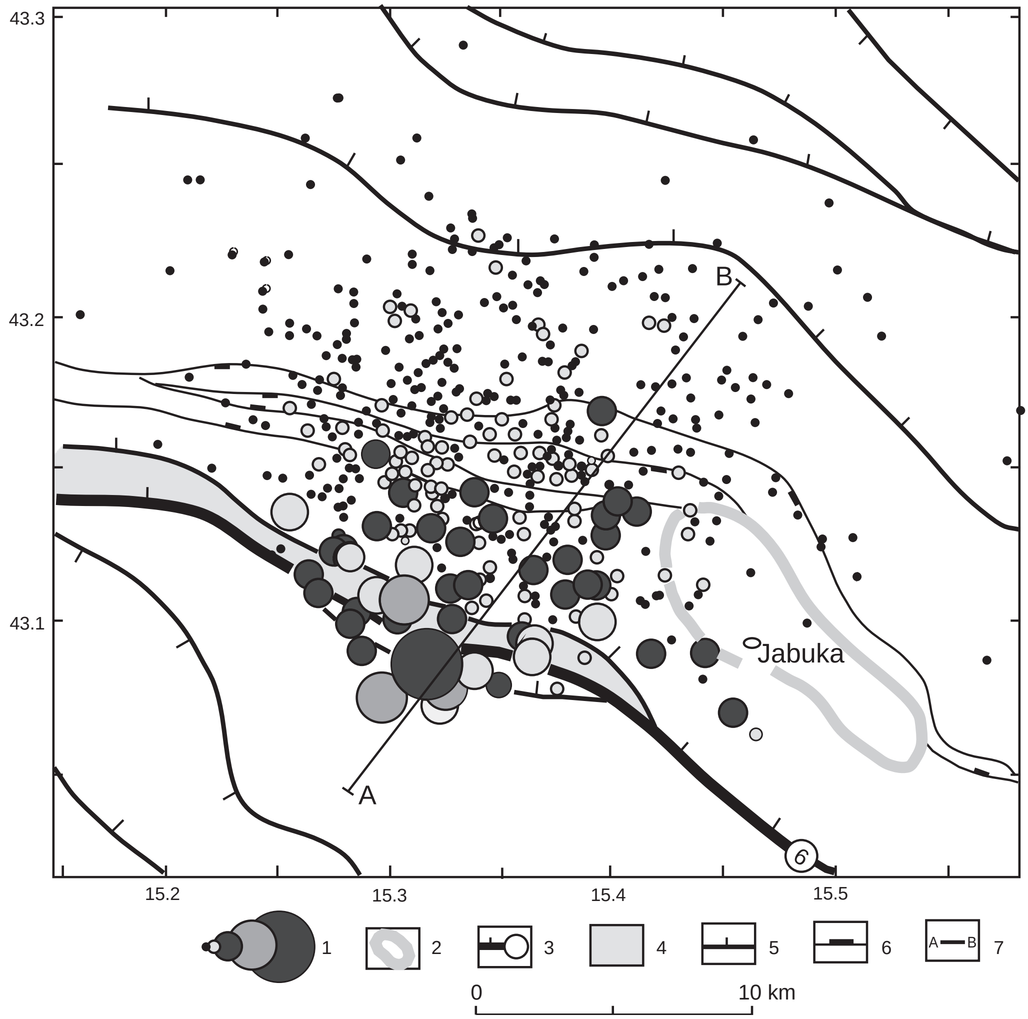

Fig. 8. Jabuka epicentral area. For geographical location see the rectangle in Fig. 1b. 1—Earthquake epicentres (the smallest symbols correspond to magnitudes smaller than 1.8, the largest one is M_L=5.5); 2—contours of eruptive intrusions around the Jabuka island; 3—Jabuka-Andrija reverse fault (6); 4—zone of the Jabuka-Andrija fault; 5—other reverse faults; 6—normal faults; 7—seismotectonic profile (see Fig. 10).

about a kilometre to the east-northeast and less than a kilometre too shallow, probably due to uneven azimuthal distribution of the reporting stations. The uncertainties as estimated above are within reasonable expectations if one considers the remoteness of the epicentral area and the spatial distribution of regional seismological stations. The magnitudes of uncertainties are such that they permit the located hypocentre clouds to be associated with large geological units in the area.

The section AB in Fig. 8 is a part of the seismic reflection profile, cutting through the focal volume. Its interpretation led to identification of the basements of Neogene clastic rocks and of the Paleogene and Mesozoic mostly carbonate rocks. We could also identify the contours of probably eruptive rocks, as well as the positions of faults at depths of up to 15 km (Fig. 10). Hypocentres are mostly concentrated in the slanted seismotectonically active zone related to the Jabuka-Andrija fault system. For depths of up to approximately 8 km most stress accumulated on main faults seems to have been released by large events, while numerous small earthquakes occurred on deeper parts of the fault system. The mainshock rupture

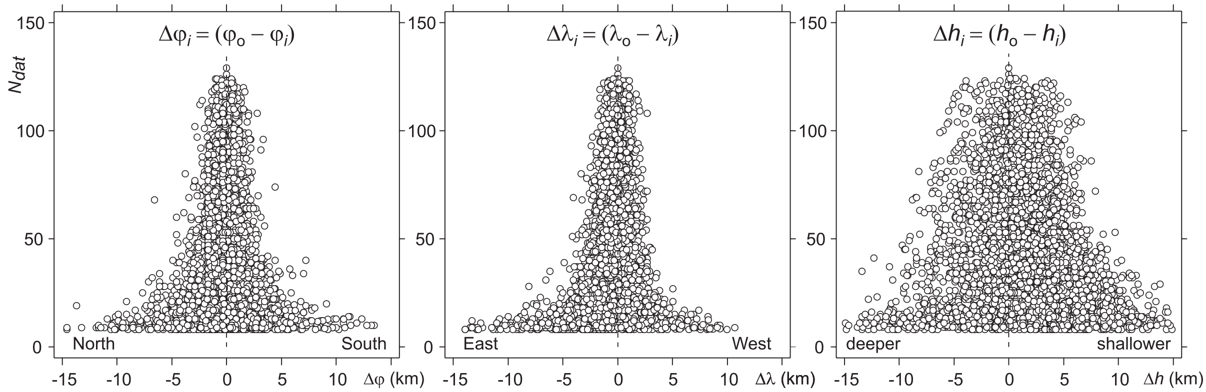

Fig. 9. Results of the analyses of the hypocentral location sensitivity to the number of data used. Three well-located earthquakes (with number of reported onset times N>100, see text) were used as the 'ground truth' events. Each of them was relocated using 1000 subsets of original arrival times generated by randomly selecting N_{dat} onset times ($7 \le N_{dat} \le N$) from the complete dataset, but always keeping the two readings from the HVAR station (Pg and Sg), which are reported for all 597 earthquakes. The plots present differences ($\Delta\varphi$, $\Delta\lambda$, Δh, in km) in the three coordinates for all locations (φ_i, λ_i, h_i, i=1, …, 3000) with respect to the 'ground truth' locations (φ_o, λ_o, h_o, computed using complete datasets) vs. the number of data used (N_{dat}).

initiated at a depth of about 5±3 km, which is considerably shallower than the average focal depth of 12 km for this magnitude class in the Dinarides and the surrounding regions (Herak and Herak, 1990). This shallow focal depth is, nevertheless, consistent with a possible sea-bottom rupture indicated by the observation of a small tsunami on the tide-gauge record in Split (M. Orlić, 2003, personal communication). The reasons for shallow rupture initiation may be various—e.g. enhanced fault lubrication by pore fluids at shallow depths, local increase of the stresses induced by the presence of the magmatic intrusion in the focal volume, etc. They are, however, all speculative and not supported by any data on our disposal, and will therefore not be further elaborated.

4. Conclusions

The occurrence of Jabuka earthquakes enabled us to gain more insight into the seismotectonic properties of this remote part of the Central Adriatic. In particular, positions of hypocentres, as well as the focal mechanisms, are in excellent agreement with the geometrical properties of the previously mapped Jabuka-Andrija fault system, which is thus hereby identified as an active one, capable of generating strong earthquakes. This fact can significantly influence seismic hazard on the islands in the central Adriatic archipelago and on the Croatian coast between Zadar and Split. Before this influence is quantified, more observations are needed from the rapidly growing modern seismograph networks in the area, which will hopefully enable identification and characterisation of all active parts of the causative fault(s).

Activation of this part of the Jabuka-Andrija fault system, along with several other earthquake sequences in the Central Adriatic in the last 20 years clearly characterize this as a seismically active region whose seismicity is comparable to or even higher than some of the well known and recognized neighbouring epicentral areas. Rather frequent occurrence of moderate-to-strong events there is uncharacteristic of intraplate seismicity, which, along with the results of geodetic, gravimetric and tomographic observations lead to conclusion that an active margin may exist across the Central Adriatic. However, neither the fault-plane solution of the Jabuka main shock, nor the seismic profiles on our disposal, indicate presence of the SW–NE striking faults in this area. This apparent mismatch can be resolved only by additional seismic exploration, and by further improving the quality and quantity of seismological observations. In particular, new stations are needed on the isolated and remote islands (e.g. Palagruža, Sušac, Andrija, Vis, Lastovo—unfortunately not on Jabuka itself because of its inaccessibility and frequent lightning strikes caused by iron-rich eruptive rocks it consists of) whose data

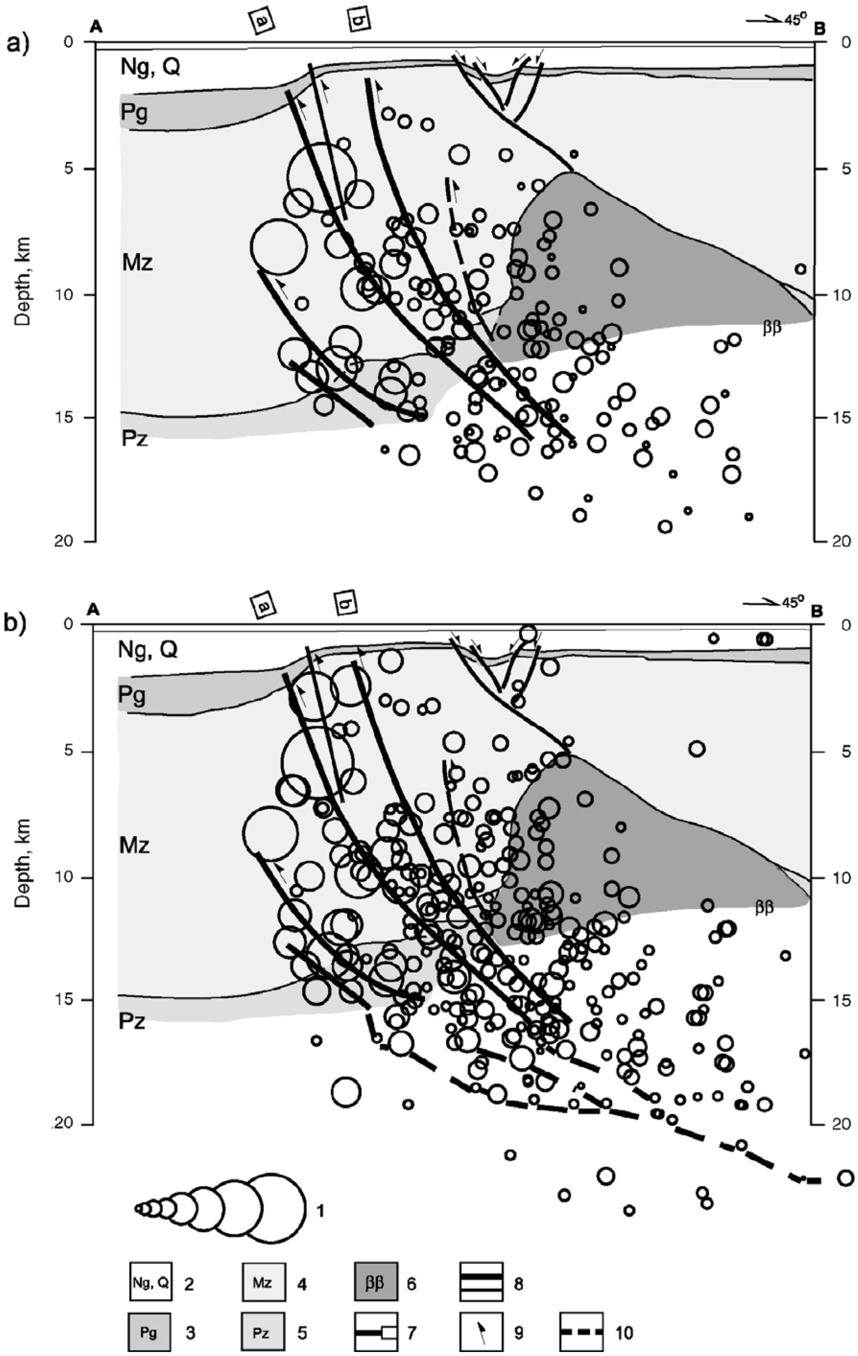

Fig. 10. Seismotectonic profile AB from Fig. 8, constructed on the basis of interpretation of seismic exploration profiles. 1—Earthquake hypocentres. The smallest symbols correspond to magnitudes smaller than 1.8, the largest one is M_L=5.5. Only earthquakes with foci within 2 km (a, upper subplot) and 4 km (b, lower subplot) from the profile AB in Fig. 8 are shown; 2—clastic Neogene and Quaternary rocks (Ng, Q); 3—carbonate Paleogene rocks (Pg); 4—mostly carbonate Mesozoic rocks (Mz); 5—mostly clastic, evaporites and carbonate Paleozoic rocks (Pz); 6—probably diabase (ββ); 7—Jabuka-Andrija fault (6, a,b: boundary faults of the zone); 8—other faults; 9—direction of motion of the hanging wall; 10—assumed faults, based on positions of hypocentres.

would help to reveal the true nature of the seismicity in the Central Adriatic region.

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