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Seismotectonically Active Zones in the Dinarides

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Key words: Recent tectonic movements, Earthquake foci concentrations, Structural relations at depth, Dinarides, Croatia.

Abstract

Seismotectonically active zones are formed due to displacements of segments of the Adriatic micro-plate that differ in size and in their rate of movement, and by the resistance of the rock masses of the Dinarides. The spatial position of these zones can be determined through the locations of earthquake foci. The zones of seismotectonic activity are then correlated with the most important faults on the surface.

The seismotectonically active zones are relatively steeply inclined in the shallowest 10-20 km, which is caused by the oblique contacts between the Adriatic micro-plate and the Dinarides. The zones are curved at depth in many cases, which reflects the compression of the area. Curved parts of the zones are characterised by the greatest pressures and also by the most frequent earthquakes. Mildly inclined zones reflect the reverse displacements in the area, also probably the activity on contacts between rock masses of different density, or the extension of the Adriatic micro-plate subduction. The southern part of the plate is the most active. The greatest pressures caused by these movements occur in the area between Mljet island and Dubrovnik. Therefore the majority of earthquakes, and notably the strongest ones, occur in the area between Split, Imotski, Hvar island and Dubrovnik, as well as along the Montenegro coast in a SE direction.

1. INTRODUCTION

The frequency of earthquake occurrence and concentrations of their foci enable definition of the spatial position of seismotectonic zones. These zones are formed by the opposing displacement of relatively large rock masses and mark the area of the most extensive deformations of structural fabric. In this manner, they directly depict the principal characteristics of structural relations at depth. Six cross-sections are constructed in order to illustrate the separate zones and conditions of their formation, and also to correlate their strike and spatial position with the most important faults of the regional structural fabric of the Dinarides (Fig. 1).

The importance of the studied zones becomes observable upon correlation with the known basic structural classifications (e.g. HERAK, 1986, 1991; BLAŠKOVIĆ, 1990) and especially with the analyses of the possible structural relations at depth (e.g. MILJUSH, 1973; ZAGORAC, 1975; BIJU-DUVAL, 1977; CVIJANOVIĆ et al., 1979; ALJINOVIĆ, 1984; BLAŠKOVIĆ, 1998). A more complete insight to the relations at depth is enabled by the seismic sections and some of the identified marker horizons (SKOKO et al., 1987; ALJINOVIĆ et al., 1990; TARI-KOVAČIĆ & MRINJEK, 1994; LAWRENCE et al., 1995; PRELOGOVIĆ et al., 1995; GRANDIĆ et al., 1997). It is after the data from the earthquake catalogues were included in correlation (KARNIK, 1971; HERAK et al., 1996), that it became possible to single out the separate seismotectonically active zones at depth (ALJINOVIĆ et al., 1984, 1987; DEL BEN et al., 1991; MARKUŠIĆ et al., 1998; PRELOGOVIĆ et al., 1995). With analyses of the stress regime and the possible deformations of the structural fabric (e.g. ANDERSON & JACKSON, 1987; HERAK et al., 1995; PRELOGOVIĆ et al., 1999; ALTINER, 1999) additional data were acquired, necessary for a more detailed explanation of the presence and characteristics of the studied zones.

2. SEISMICITY

From their seismic potential, the Dinarides are the most remarkable area of Croatia. This is especially true for the SE part, where earthquakes are the most frequent and also the strongest. This statement is based not only on the measurements of recent seismic activity, but also on the historic data sources showing that around 20 earthquakes with an epicentre intensity of IX° MCS or more, occurred for example in the Dubrovnik area and on the Montenegro coast. The most reliable and detailed data pertain to the Dubrovnik earthquake of 1667, that had epicentre intensity of X° MCS. The strongest earthquake of modern times, happened in 1979 in the Montenegro coastline area. The following parameters were recorded: magnitude $M=7.2$, focal depth $h=14$ km and epicentre intensity I=IX-X° MCS.

Strong earthquakes also occurred in the Ston area, NW of Dubrovnik. In 1850 one occurred with and epicentre intensity of VIII° MCS. There was another strong

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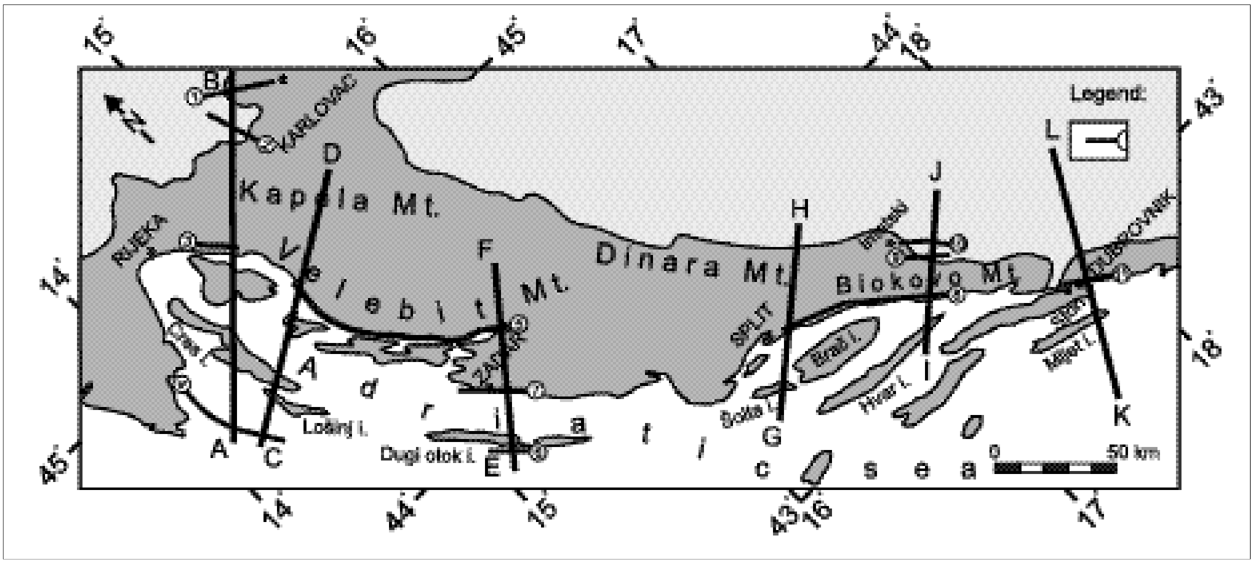

Fig. 1 Location of cross-sections. Legend: The most important faults on the surface: 1) southern boundary fault of the Pannonian basin; 2) Črnomelj - Slunj fault; 3) Ilirska Bistrica - Rijeka - Senj fault; 4) Trieste - Učka - Lošinj fault; 5) Velebit fault; 6) Dugi otok fault; 7) Zadar fault; 8) Mosor - Biokovo fault; 9) Trilj - Tihaljina - Čapljina fault; 10) Imotski - Međugorje - Popovo polje fault; 11) Ploče - Dubrovnik - Bar fault.

earthquake in 1996 which had M=6.0, h=13 km and I=VIII-IX° MCS. In the area NE of Ston, a 1927 earthquake is mentioned with M=6.0, h=17 km and I=VIII° MCS.

The area around the Neretva river valley is also characterised by marked seismic activity. There are historic records of several earthquakes with I=VIII° MCS. Undoubtedly the most important, although unreliable, is the record of an earthquake that happened in 1479 with I=IX° MCS.

The two strongest earthquakes in Mt. Biokovo occurred in January 1962. The first one had a magnitude of 5.9 (I=VIII° MCS), and a second one magnitude of 6.1 (h=10 km, I=VIII-IX° MCS). Among stronger earthquakes is also one in 1884 in Mt. Mosor, which had epicentre intensity of VII° MCS.

The area between the Imotski, Mt. Dinara and west of this mountain is also marked by strong seismic activity. Two stronger earthquakes occurred there with an epicentre intensity I=IX° MCS. The first one occurred NE of Split in 1898 and the second one near Imotski in 1942 (M=6.0, h=7 km). There was also an important earthquake from 1923 with an epicentre in the vicinity of Imotski (I=VIII-IX° MCS). Several other earthquakes with epicentre intensity in the VII-VIII° MCS range deserve to be mentioned: 1970 (M=5.6, h=14 km) with epicentre in Mt. Promina, 1986 (M=5.5, h=8 km) near Knin, 1989 (M=5.0, h=9 km) with epicentre in Mt. Dinara, and the two earthquakes (M=5.6 and 5.5, h=8 and 9 km) that happened in 14 minutes in 1990 in the Mt. Dinara area.

Recent seismic activity is less expressed in the coastal area NW of Split. There are the historic records of destructive earthquakes in 1418 and 1496, that occurred in the area between Split and Šibenik and west of Šibenik. There are also records of earthquake damage in the town of Zadar on a number of occasions between the 12th and 19th centuries, but the data are not complete enough to enable a more precise definition of the earthquake characteristics. The more reliable data pertain to the two earthquakes in the Zadar area (in 1280 and 1300) that had intensity of VIII° MCS. Of the more recent data, there is the earthquake that happened in 1949 in the Mt. Velebit channel, with a magnitude of 5.3 and an epicentre intensity of VII° MCS. There are reliable records of several stronger earthquakes in the Adriatic off-shore: in 1923 there was an earthquake of magnitude 5.3 (h=15 km) near Šibenik; in 1934 a magnitude 5.6 (h=30 km) in the off-shore area with the epicentre at 44°N, 14°E; in 1963 there was an earthquake of a magnitude 5.1 (h=30 km) near the Dugi otok island. The disastrous earthquake of the year 361 is supposed to have had occurred in the same area (44°N, 14°E) as the earthquake in 1934.

In the inner part of Mt. Velebit, the earthquake that occurred in 1959 needs to be mentioned. It had a magnitude of 4.6 and an epicentre intensity of VII° MCS (h=20 km). The seismically relatively quieter area of Mt. Velebit is an extension of the active area that strikes from the northern parts of Mt. Velebit over Rijeka in direction of Slovenia. There are historical records of a number of very strong earthquakes in the vicinity of Rijeka (in 1721 and 1750) and Senj (in 1648, 1873 and 1878) which had intensities of between the VIII and IX° MCS, but these data are not reliable. According to some sources (e.g. KARNIK, 1971) the earthquake that occurred in 1802 near Ilirska Bistrica had a maximal intensity of VIII° MCS. The most important earthquake in this century was in 1916. It had a magnitude of 5.8, focal depth of 18 km and epicentre intensity of VIII°

MCS. The latest most pronounced seismic activity was recorded in 1986, with the strongest earthquake of M=4.7, h=9 km and I=VI-VII° MCS.

3. EARTHQUAKE FOCI CONCENTRATIONS AND THE MOST ACTIVE FAULT SECTIONS

The given cross-sections are positioned in such a way as to show major earthquake concentrations and the most important structural units. The Adriatic micro-plate and the fact that it is fragmented are crucial in the search for reasons for the occurrence of the seismotectonically active zones (SKOKO et al., 1987; ALJINOVIĆ et al., 1987). Two larger parts of the plate exist - one in the northern Adriatic and Italy, and another in the southern Adriatic. There is also a smaller section in between that lies in the approximate Adriatic centre. A consequence of the micro-plate fragmentation is the various rates and directions of displacement of its parts. The spatial position of the seismotectonically active zones is conditioned by the distribution of different rock masses, and by their size and position within the Dinarides. These masses provide direct resistance to the Adriatic micro-plate movements.

3.1. CROSS-SECTION A-B, CRES ISLAND - KARLOVAC (Fig. 2)

In this cross-section, the marked zone of seismic activity is shown, that strikes from the northern Mt. Velebit over Rijeka in direction of neighbouring Slovenia. The largest earthquake concentration is in the area that dips at an angle of 60°, and is 30 km wide. Earthquakes in this zone occur at depths down to 20 km. Distribution of the earthquake foci clearly depicts two smaller zones that are correlated with the faults on the Krk island and with the Ilirska Bistrica - Rijeka - Senj fault. The second zone strikes along the border of Dinaricum and reaches a maximal thickness of 10 km. The characteristic feature of this zone is the steep inclination down to the depth of 10 km, a curved part between the 10 and 14 km depth, and the relatively mild dip down to 24 km, where it reaches the area under Mrkopalj and Vrbovsko. There is another gently dipping zone that lies between the 20 and 30 km and results from the activity of the deeper parts of the Earth's crust. The contacts between the Dinaricum and the Supradinaricum, and the Pannonian basin as well, are also marked by seismotectonic activity. The foci concentrations in the steeply dipping zones that reach depths of 15 and 20 km are observed, but with occurrence of earthquakes at maximum depths of 30 km.

The steeply inclined contours of the area with the largest concentration of earthquake foci depict the compression of the Dinarides and the oblique subduction of the Adriatic micro-plate in respect to the orientation of the structural units. The increased gravimetric gradients depict the step-like displacements of the rock masses in the subsurface. Looking at the cross-section, this means more significant subduction of the Adriatic micro-plate. Displacements of the relatively large masses influence the spatial bending of the seismotectonic zones. The greatest pressures are formed in the curved parts of the zones, where the majority of the earthquakes also occur. In addition, it is noted that the zones are spatially bent almost into the horizontal position, which marks the reverse displacements and activity of the contacts between the rock masses of different density.

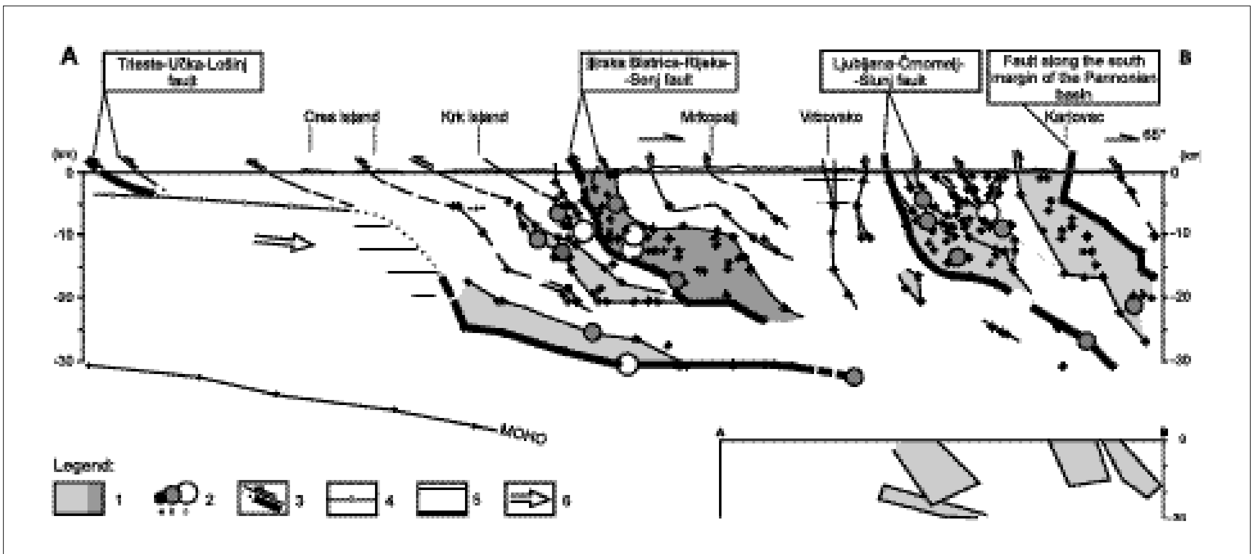

Fig. 2 Seismotectonic cross-section A-B, Cres island - Karlovac. Legend: 1) seismotectonically active zones; 2) earthquake epicentres with magnitudes: a) <4, b) 4-5, c) >5; 3) faults; 4) inferred contact between the carbonates and underlying rocks; 5) zones of higher gravimetric gradients; 6) direction of displacement of the Adriatic microplate.

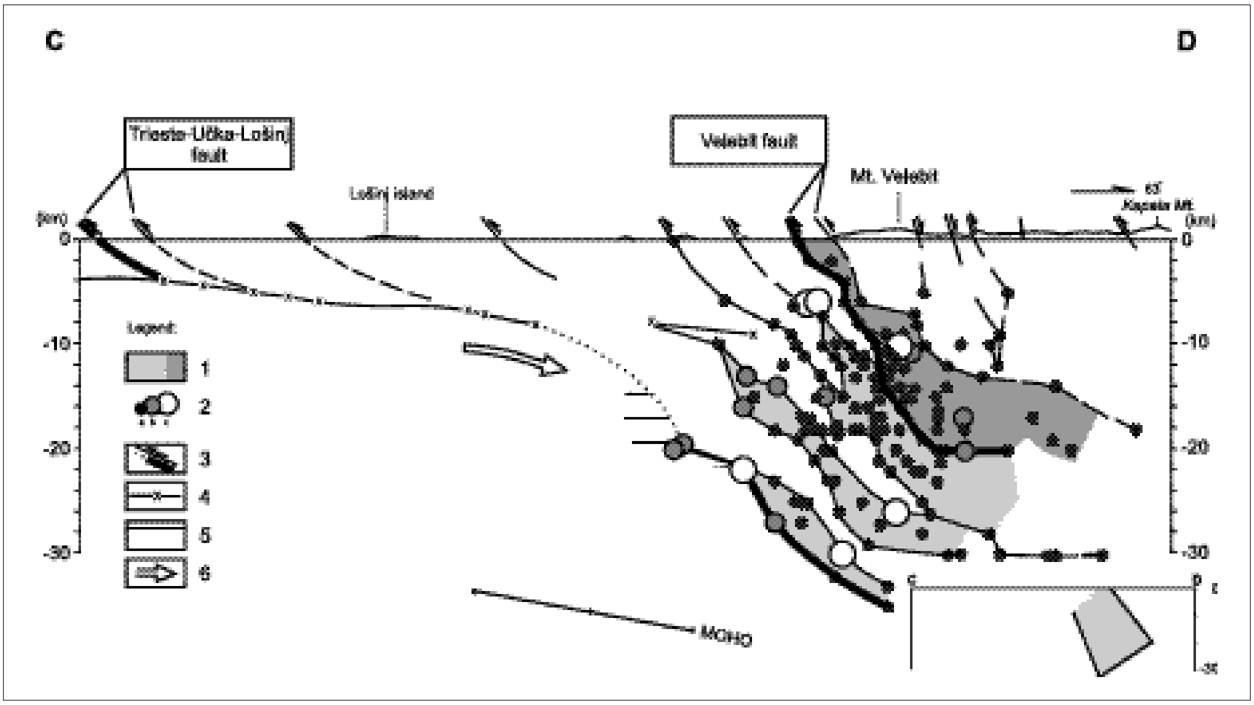

Fig. 3 Seismotectonic cross-section C-D, Lošinj island - Mt. Kapela. Legend: 1) seismotectonically active zones; 2) earthquake epicentres with magnitudes: a) <4, b) 4-5, c) >5; 3) faults; 4) inferred contact between the carbonates and underlying rocks; 5) zones of higher gravimetric gradients; 6) direction of displacement of the Adriatic microplate.

3.2. CROSS-SECTION C-D, LOŠINJ ISLAND - MT. KAPELA (Fig. 3)

Concentration of the earthquake foci is particularly observable in this section. The zone dips at 55-60°, has a width of 20 km, and the earthquake foci are located at depths down to 34 km. The foci locations enable separation of the seismotectonically active zones that are correlated with the Velebit fault and some of the faults that strike parallel to the islands. The position of the area with the greatest concentration of earthquakes clearly illustrates the oblique contact between the Adriatic micro-plate and the Dinarides.

3.3. CROSS-SECTION E-F, DUGI OTOK ISLAND - ZADAR - MT. VELEBIT (Fig. 4)

The seismotectonically active zones are singled out along the section and correlated with faults on the surface. The first one is the zone connected to the Velebit fault. It dips at 55°, has a width of 10 km, and is marked by earthquakes to a depth of 13 km. The relatively narrow zones with a dip range of 20-30° are correlated with the Dugi otok fault and the Zadar fault. The spatial position of these zones depicts the reverse/overthrust relations and displacements of the structural units. The strongest earthquakes occurred outside of these zones at depths of 20 to 30 km. They are probably connected with the faults that reach the surface in the middle of the Adriatic sea bottom, or otherwise reflect recent deformations of the relatively deeper parts of the Earth's crust.

3.4. CROSS-SECTION G-H, ŠOLTA ISLAND - SPLIT - MT. DINARA (Fig. 5)

The largest concentrations of earthquake foci are located in the Mosor - Biokovo fault zone, or along its branching faults that partly strike along Mt. Dinara. A major zone of seismotectonic activity is steeply inclined at depths less than 7 km, and then acquires a dip of 25° in order to reach the maximum depth of 20 km under Mt. Dinara. The zone is 6 to 8 km wide and obviously a curved one. The curved section in the depth range of 13 to 20 km is marked by foci of the strongest earthquakes recorded so far. The 15 km wide area of the largest earthquake concentration is connected with the branching faults of the main zone and dips at an angle of 55-65°. A deeply situated zone of seismotectonic activity that has a mild inclination (of 25°) and particular concentration of earthquakes in the depth range of 20 to 32 km is very interesting. It is probably connected with the faults around Šolta island and is spatially parallel to the main zone of the Mosor - Biokovo fault. In both of the observed zones there is a more prominent concentration of the earthquake foci in the section that has a dip angle of approximately 25° some 30-40 km in length. This points to the possible position and activity of the contacts between the rock complexes of different density. It is also observed that some of the earthquake foci concentration zones are spatially located very close to each other, or are even overlapping. This indicates a significant compression of the area.

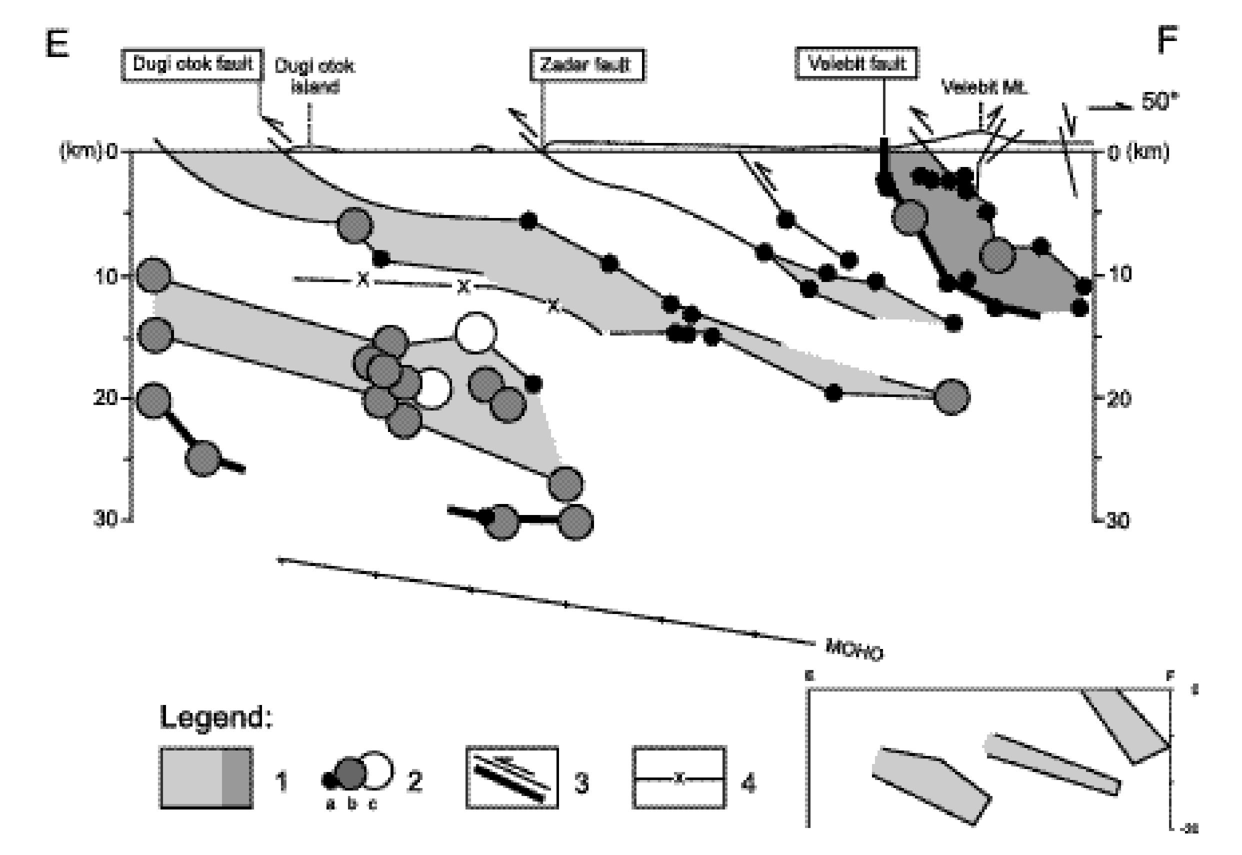

Fig. 4 Seismotectonic cross-section E-F, Dugi otok island - Zadar - Mt. Velebit. Legend: 1) seismotectonically active zones; 2) earthquake epicentres with magnitudes: a) <4, b) 4-5, c) >5; 3) faults; 4) inferred contact between the carbonates and underlying rocks.

3.5. CROSS-SECTION I-J, HVAR ISLAND - MT. BIOKOVO - IMOTSKO POLJE (Fig. 6)

The greatest concentrations of earthquake foci encompass the hinterland of Mt. Biokovo. The seismotectonically active zone connected to the Mosor - Biokovo fault zone is very pronounced. The spatial position of the zone is the most important: a steeply inclined part dips at 60° in the first 10 km, a curved section between 10 and 16 km, and a mild inclination of 20° from 16-22 km which influenced a large extent to the Imotsko polje. The zone is up to 5 km wide. The strongest earthquakes occurred in the curved section of the zone. There is also a branch of this zone that is characterised by seismotectonic activity, where earthquake foci depict an inclination of 60°. The concentration of earthquakes is observable in the almost vertical zone in the Imotsko polje area. This zone is around 8 km wide with earthquake foci at depths between 2 and 14 km. The relatively higher activity of the Adriaticum area also exists, and the active zones are correlated with the faults near the Middle Dalmatian islands. They are situated above the basement of the carbonate rock complex, but there are also the two zones that lie below this contact. They illustrate the deformations or displacements at the 16 to 30 km depth range, probably along the contacts between rock complexes of different density.

The following observations are the most important:

- stacking of a number of seismotectonic zones at various depths implies the greater activity of the area;
- mildly inclined zones, and especially the length of the 30 km of the zone correlated with the Mosor - Biokovo fault depict the reverse-overthrust displacements;
- the strongly expressed bending of the zone correlated with the Mosor - Biokovo fault, formation of the branching fault and the vertical faults around the Imotsko polje point out to the possibility of rotation of structural units, and to the oblique spatial movements in respect of their strike, as well as to the horizontal displacement on the vertical faults.

3.6. CROSS-SECTION K-L, ADRIATIC OFF-SHORE - MLJET ISLAND - STON (Fig. 7)

The largest concentration of earthquake foci is in an area 20-30 km wide and has a variable dip angle of 30°-60°. Earthquakes occur there at depths less than 30 km. The earthquake foci concentrations depict the strongest activity in the zone that is associated with the Ploče - Dubrovnik - Bar fault, but there are also some active faults within the Adriaticum unit (Fig. 7). Particularly increased activity is observed along the Adriaticum - Dinaricum contact, in the fault zones parallel to Mljet island and the Pelješac peninsula. The locations of

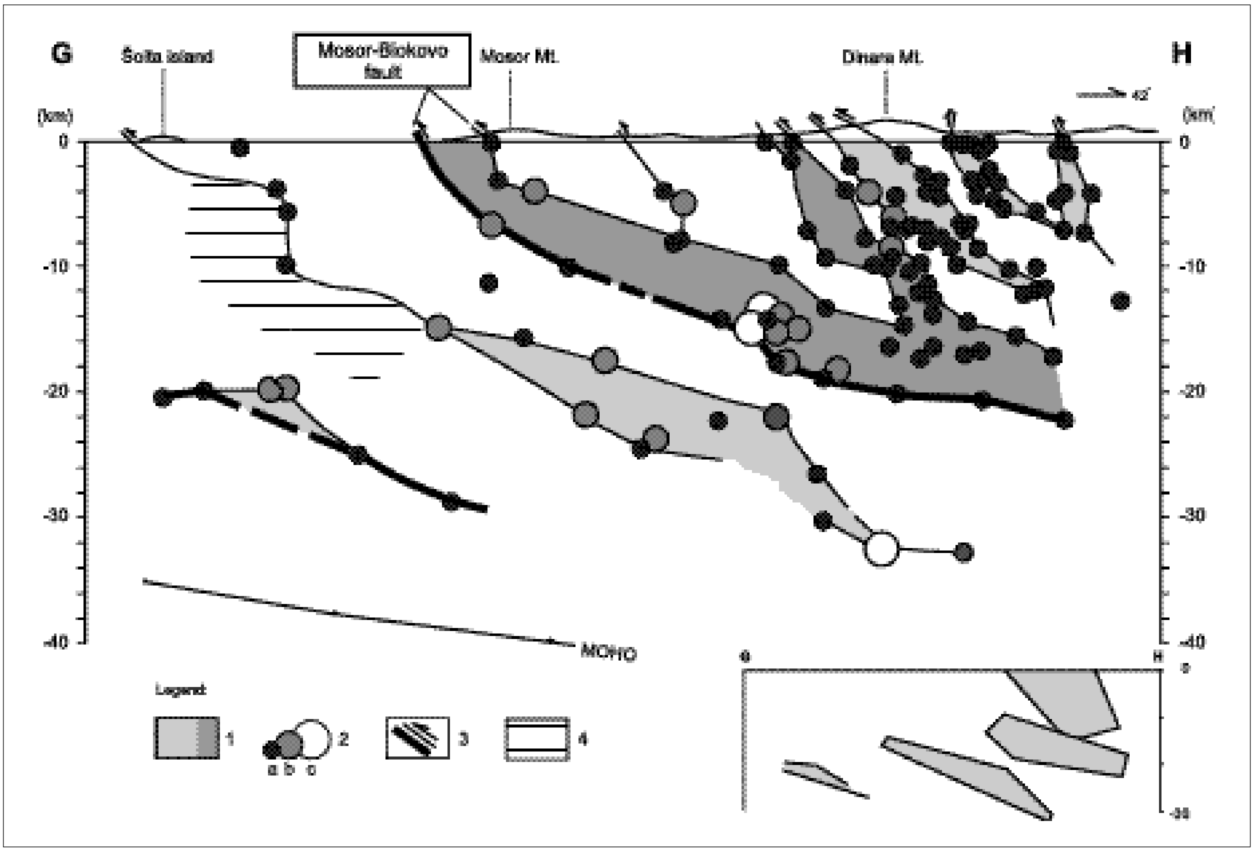

Fig. 5 Seismotectonic cross-section G-H, Šolta island - Split - Mt. Dinara. Legend: 1) seismotectonically active zones; 2) earthquake epicentres with magnitudes: a) <4, b) 4-5, c) >5; 3) faults; 4) zones of higher gravimetric gradients.

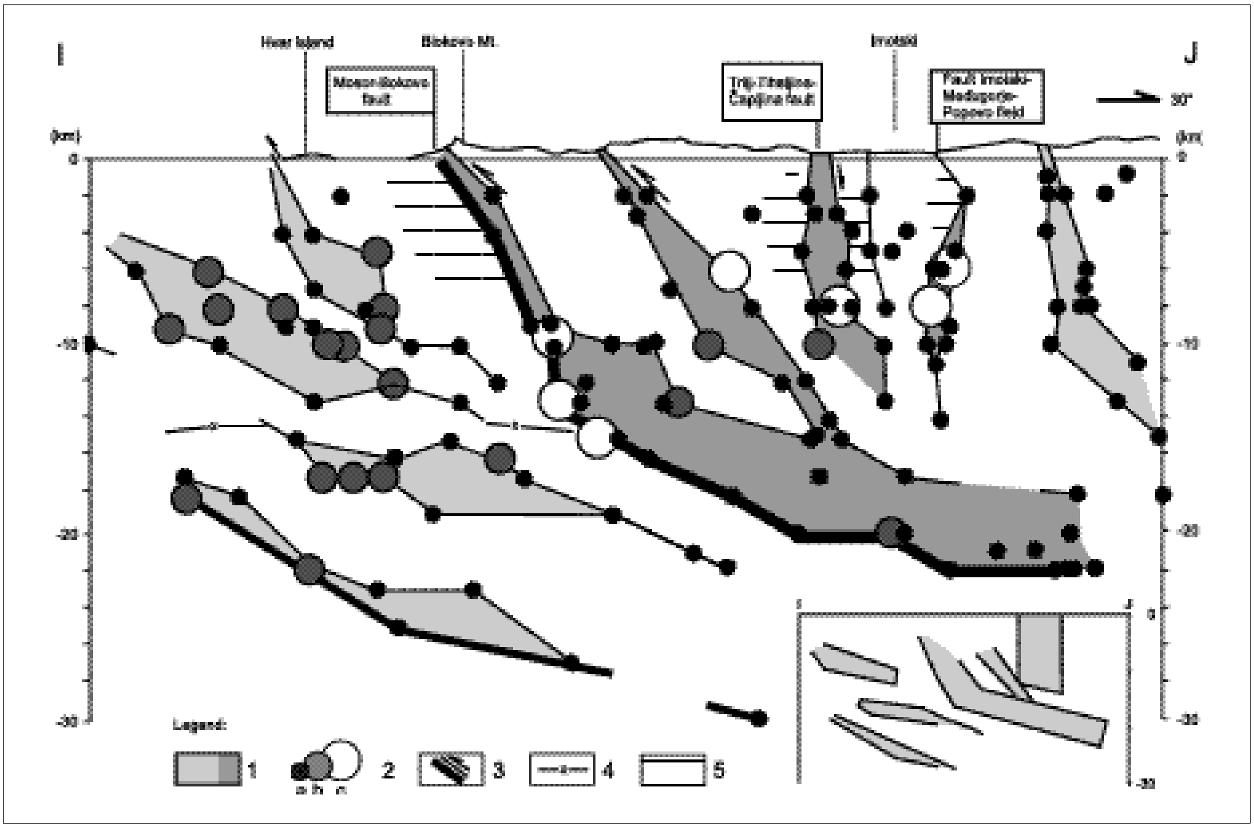

Fig. 6 Seismotectonic cross-section I-J, Hvar island - Mt. Biokovo - Imotsko polje. Legend: 1) seismotectonically active zones; 2) earthquake epicentres with magnitudes: a) <4, b) 4-5, c) >5; 3) faults; 4) inferred contact between the carbonates and underlying rocks; 5) zones of higher gravimetric gradients.

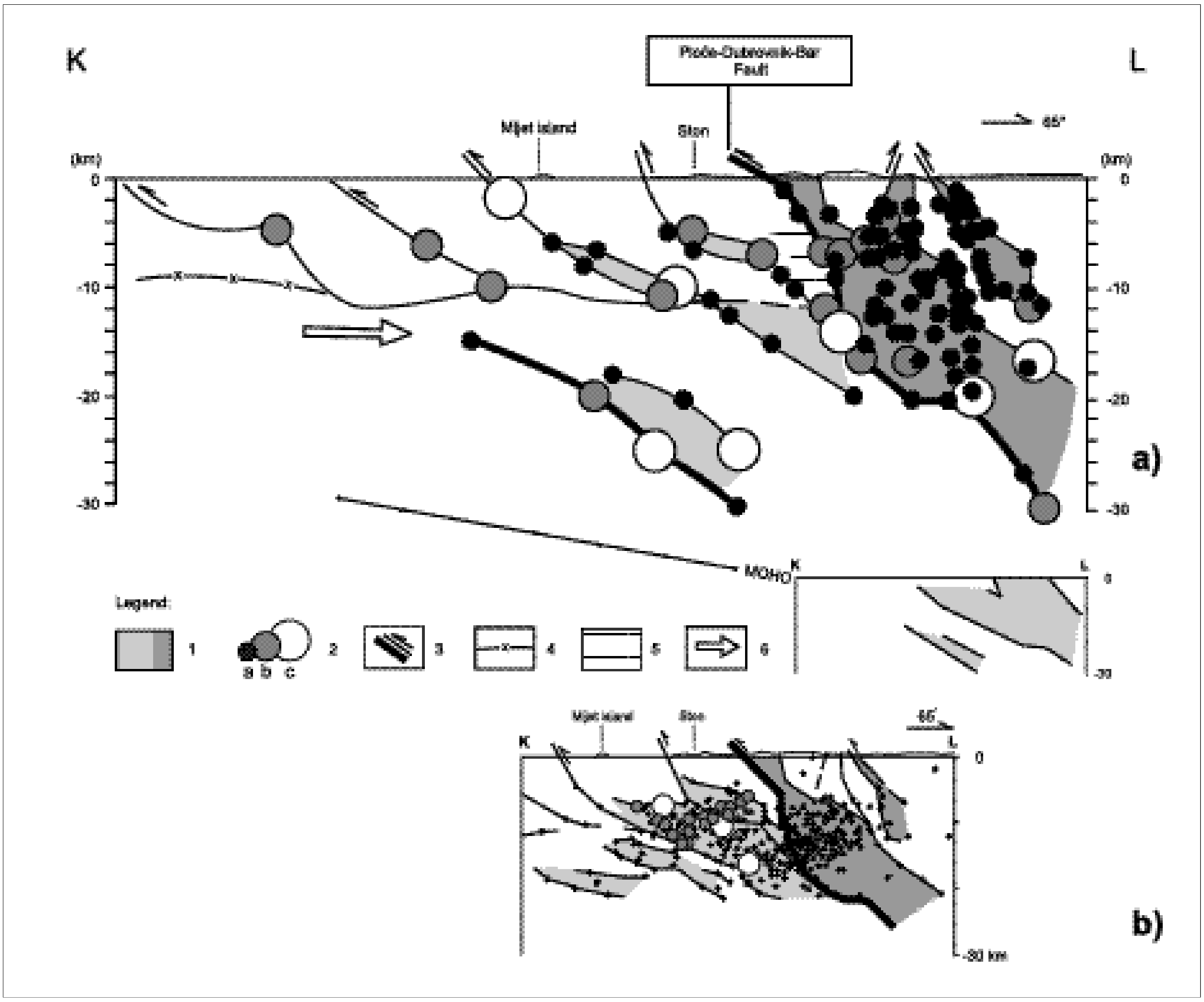

Fig. 7 Seismotectonic cross-section K-L, Adriatic off-shore - Mljet island - Ston. Legend: 1) seismotectonically active zones; 2) earthquake epicentres with magnitudes: a) <4, b) 4-5, c) >5; 3) faults; 4) inferred contact between the carbonates and underlying rocks; 5) zones of higher gravimetric gradients; 6) direction of displacement of the Adriatic microplate.

earthquake foci show that this is actually a single area of seismic activity, which means that there is extensive compression in this area. What also has to be emphasised is the significant subduction of the Adriatic micro-plate, that reaches 40 km inland from the coastline. As a consequence, there is activity of the carbonate complex basement and the reverse-overthrust displacements on the faults within the Adriaticum, together with formation of a broad active zone marked by deformations of structural fabric and the permanent occurrence of earthquakes.

The last significant earthquake occurred near Ston in 1996. It had a magnitude of 6.0. Focus of the main earthquake and of the subsequent ones are shown in Fig. 6b (MARKUŠIĆ et al., 1998). The spatial concentration of earthquakes in the area of the above described zone of seismotectonic activity is discerned. Numerous earthquake foci enable the more detailed separation of minor zones connected with some of the faults.

4. CONCLUSION

The Adriatic micro-plate movements and the resistance of the Dinarides are of key importance in tectonic movements. Two facts are vital for the formation of the seismotectonically active zones that are curved at depth:

- three sections of the micro-plate exist, differing in size and in their rate of movement;
- there are major rock masses in the Dinarides area that resist the micro-plate movements.

The differences in appearance of the seismotectonically active zones in the northern, central and the southern part of the study area are illustrated in the cross-sections. This indicates that there are the rock masses that differ in size and orientation. In addition, the micro-plate movements cause the formation of the stress field that influences deformation and displacement of separate rock masses and the seismotectonic activity.

The area shown in cross-sections A-B and C-D has one significant feature - marked compression of the Southern Alps and the northern Dinarides area. Due to the almost perpendicular micro-plate movement in respect to the strike of structures, reverse displacements are present. Further east, in the area of Rijeka, there is oblique subduction of the Adriatic micro-plate under the Dinarides. The most recent measurements of the regional stress orientation have yielded results in the range between the 20-200° and the 170-350° (ALTINER, 1999; PRELOGOVIĆ et al., 1999). The faults are markedly characterised by dextral tectonic transport. The relatively steeply inclined zones of seismotectonic activity are formed at depth due to the oblique contact between the Adriatic micro-plate and the Dinarides. Mt. Velebit together with its hinterland has an orientation of the principal horizontal stress in the range between 180-360° and 160-340°. This is also favourable for displacements of structural units in the SE direction. In the cross-section E-F, the seismotectonically active zone associated with the Velebit fault is relatively steeply dipping and depicts the spatial oblique displacements of the rock masses. In the same cross-section, the strongest earthquakes occur in the mildly inclined zone that reaches a depth of 30 km. Formation of this zone reflects the pressure caused by the southern part of the Adriatic micro-plate.

The southern part of the micro-plate moves in a N-NW direction. The regional stress in the area south of Split, within the Adriaticum and Dinaricum, most commonly has an orientation between the 15-195° and 170-350°. This is almost at right angles to the strike of the structural units. Compression of the area occurs. Data on the Ston earthquake of 1996 have demonstrated that the largest pressures were caused by the micro-plate movements in the area between Mljet island and Dubrovnik. This is confirmed by displacements of the parts of structural units close to the surface, for instance: near Split in part of Mt. Biokovo, on the Hvar and Korčula islands in the S-SW direction, inside Mt. Biokovo and in its hinterland, as well as in the surroundings of Dubrovnik to the S-SE. Significant subduction of the Adriatic micro-plate is illustrated in these cross-sections, particularly in section K-L. The G-H and I-J cross-sections also depict the mildly inclined zones of seismotectonic activity. These zones reflect the reverse-overthrust displacements in the area, and also probably the activity of the contacts between rock complexes of different density. The steeply dipping seismotectonic zones are interpreted in terms of the oblique spatial displacements of rock masses, while in the Imotsko polje area horizontal displacements of tectonic blocks occur.

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