New Strategies for European Remote Sensing, Oluić (ed.)


# Model of the seismotectonic activity in wider area of Dubrovnik based on satellite data and geophysical survey

M. Oluić, S. Romandić & D. Cvijanović
*GEOSAT Ltd. for Exploration and Development, Zagreb, Croatia*
*geo-sat@zg.htnet.hr*

Keywords: Dinaric Alps, Landsat, geophysics, earthquakes

ABSTRACT: The wider area of Dubrovnik belongs to the outer range of the Dinaric Alps (Dinarides) in Croatia. That part of Dinarides is composed mostly of carbonate rocks – it is a karst area. Between the Adriatic Sea and Dinarides there is a translation zone along which the Adriatic (Apulian) microplate has been moving in relation to External Dinarides; such translation is indicated by geophysical survey results. Based on Landsat imagery there have been registered numerous faults, the majority of which strike longitudinally in the NW-SE direction. These faults are intersected with transversal faults, thus the area is dissected into larger blocks. Along the large longitudinal faults, particularly in the places of intersection with transversal/diagonal faults, stronger seismic activity has been detected most frequently. This proves that epicentres of strong earthquakes are located in intersection zones of those faults. Geophysical data measured indicate the existence of deep tectonic dislocations which are, in general, striking in the NE-SW direction, and are commonly the cause of seismotectonic activity. Locations of stronger earthquakes mainly correspond to the areas of magmatic anomalies under the sea SW of Dubrovnik. Disastrous earthquake of 1667, as well as the reinforced seismic activity in the surroundings of Dubrovnik, indicate very intensive neotectonic activity in this area.

## 1 INTRODUCTION

The wider are of Dubrovnik belongs to the mountain range of the Dinaric Alps. It composed mostly of carbonate rocks that create a very typical karst relief. They are therefore very often called Karst Dinarides or External Dinarides. The belt of carbonate Dinarides is approximately 700 km long and up to 200 km wide, having the average thickness of about 6000 m from the Middle Triassic to the Middle Eocene (*Tišljar et al., 2002*).

Several attempts have been made until now to compare the seismic activity with the geological structure and composition of the Dinarides, including the considered area ( *Blašković et al., 1984.*). However, the synthesis of the data obtained by means of satellite images, the data obtained by means of geophysical measurements, and the data about earthquakes in the Dinarides, is given in the work *Oluić et al. (2004).* This work is the continuation of those researches in the smaller area and with significantly more details. The aim of the work is to determine the relationships between the stronger seismic activity and geological-tectonic structures, and to try to reconstruct the model of seismotectonic activity in one of the seismically most active areas in Europe.

## 2 TECTONICS BASED ON SATELLITE DATA

The observed area has been intensively tectonically disturbed by the movements that have happened in several orogenetic phases. These movements have resulted in the creation of various tectonic structures: folds, faults, overthrusts etc. The created paleo-structures were disturbed and fractured by younger tectonics (Neogene and Quaternary). The neotectonic movements are mostly vertical or subvertical, so they are well registered by satellite images (Fig.1).

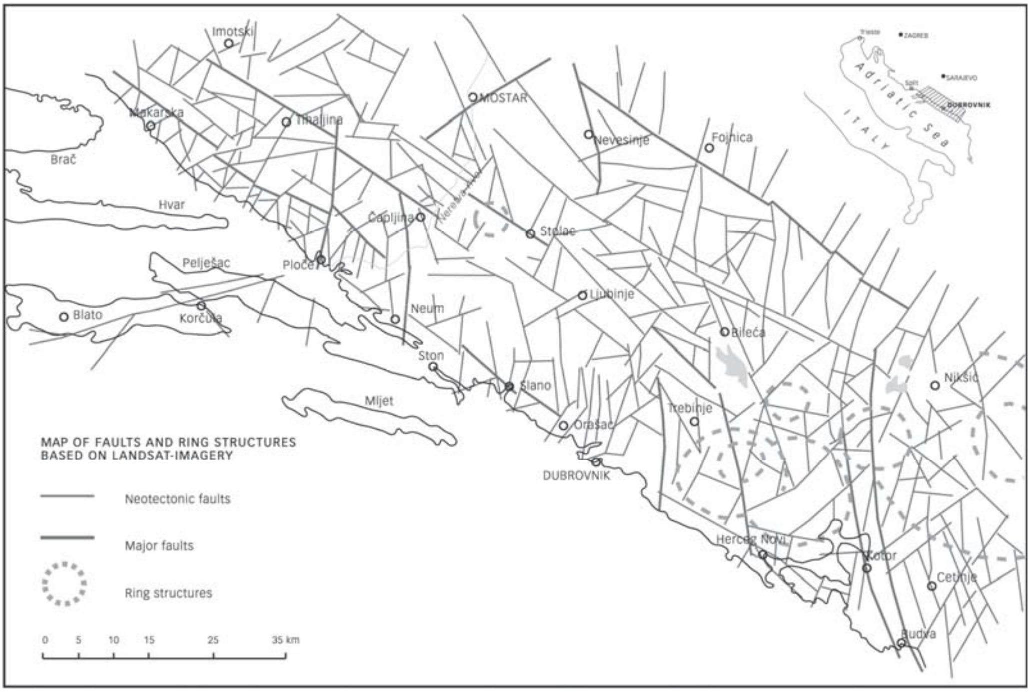


Figure 1. Map of faults and ring structures based on Landsat images

Numerous faults are registered on Landsat images (some of them for the first time) in various lengths and of various intensity. The longitudinal faults striking in the NW-SE direction, that can be traced in a length of more than tens of kilometres, are especially intensive. The examples of faults are at the area of: Dubrovnik-Neum, Ploče-Makarska, Trebinje-Čapljina-Imotski, Nikšić-Fojnica and others.

The other intensive fault directions are SW-NE and N-S, i.e. those being transversal and diagonal to the earlier mentioned direction, e.g. the faults from Budva to Nikšić, Herceg Novi-Trebinje, Neum-Čapljina, Ploče-Tihaljina and others. The transversal/diagonal faults have intersected earlier created structures of mostly longitudinally striking tectonic blocks.

Along the longitudinal faults, especially in the coastal area, there are epicentres of many earthquakes. They are located mostly along the dislocations or at the intersections of the faults having various orientations. Frequent appearance of the stronger earthquakes in the coastal area is probably caused by complex tectonic relationships between the Adriatic (Apulian) plate and the range of the Dinarides. It could cause various movements of tectonic blocks, which probably initiates the release of seismic energy in the form of earthquakes.

In the eastern part between Herceg Novi and Nikšić, the satellite images have registered several ring structures. The largest among them, i.e. the one in the area of Nikšić with a diameter of about

50 km, made through paleo-magmatic activity, and another one, placed in the area between Herceg Novi and Trebinje and having the diameter of about 20 km, have been probably created by means of diapiric and differential block movements (*Oluić, 2001)*. Between the two mentioned structures there is a very instable zone, striking generally in the direction N-S.

## 3 GEOPHYSICAL DATA

The data of geomagnetic and gravimetric measurements performed in the wider area of Dubrovnik have been used in this paper.
Geomagentic anomalies, registered south- and westwards from Dubrovnik, have been caused by submarine intrusion of paleo-magmatic rocks along the huge clefts and faults generally oriented in the north-south direction (Fig. 2).

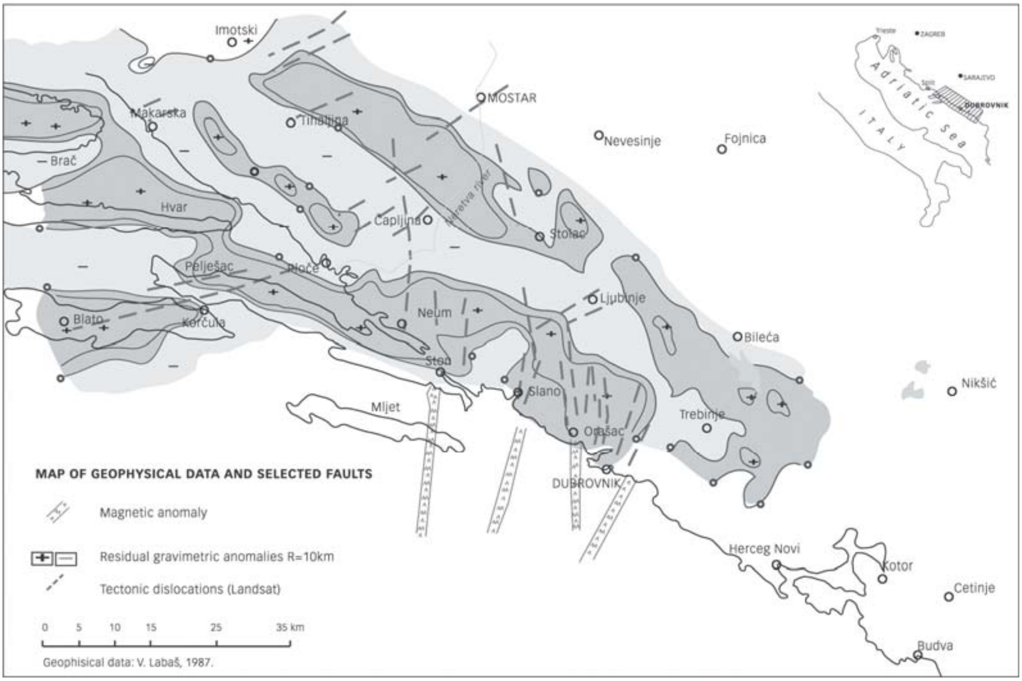


Figure 2. Map of residual gravimetric and geomagnetic anomalies with tectonic elements

Some tectonic dislocations have been registered on satellite images northwards from Dubrovnik, having the same orientation as the geomagnetic anomalies in the submarine area, which could indicate their genetic connections.

The arrangement and direction of gravimetric residual anomalies (R = 10 km) in the land area of the observed territory coincides almost completely with the intensive longitudinal faults registered on satellite images (coastal zone from Makarska to Dubrovnik and the inner zone from Bileća to Tihaljina) (Fig. 2). Longitudinal striking of positive residual gravimetric anomalies at several places is interrupted by the faults having the direction perpendicular to the longitudinal striking of anomalies (north-east of Makarska, in the area of Ploče, Slano, etc.). These interruptions coincide with the neotectonic faults that are probably the reflection of reactivated, deep, paleo-tectonic dislocations.

Residual gravimetric maximums of the islands Brač, Hvar and Korčula are oriented in the direction west-east under the angle of about 45° as related to the longitudinal striking of the anomalies in the land area. Provided that the geological structures of the mentioned island also had longitudinal striking in the past, it may be concluded that the tectonic rotational movements have brought them into the present position. The result of such movements is probably the creation of paleotectonic dislocation, oriented in the direction SW-NE.

## 4 SEISMICITY

The wider area of Dubrovnik is known as an area with the most intensive seismic activity in the Dinarides, but also in the wider area of the Mediterranean.

The first data on earthquakes in the area of Dubrovnik date as far as 373 B.C., and the first presentation of seismic activity in the area of Dubrovnik was given by *M. Kišpatić (1891*), connecting the earthquake epicentres to "earthquakes clefts". *Giessberger (1913*) connects the epicentre of the catastrophic earthquake in Dubrovnik with the main tectonic fault striking from Ston to Kotor. *J.Mihajlović (1947) and D. Cvijanović (1981)*have written a lot about the seismic activity of the wider area of Dubrovnik, and *D. Skoko (1967*) points to the seismic activity in the Adriatic submarine area. Before the catastrophic earthquake in 1667, a dozen stronger earthquakes $I_0$ = VII – IX degrees of MCS had been registered. The earthquake in 1667 was one of the most intensive in Europe ($I_0$ = $X^0$ MCS), Fig. 3; it destroyed Dubrovnik almost completely, and more than a half of its inhabitants died.

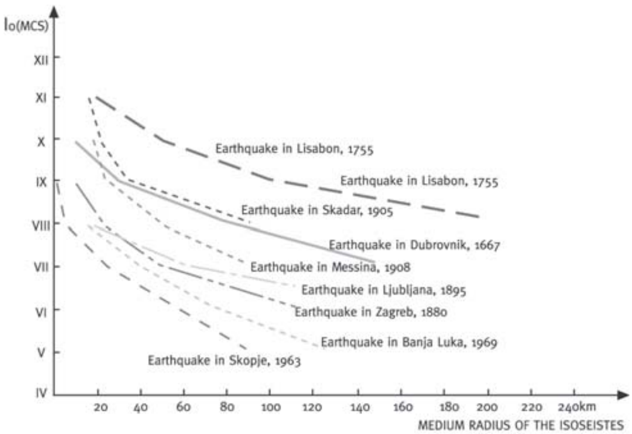

Figure 3. The comparison between the strong earthquake of Dubrovnik 1667, with the strong earthquakes in Europe

After that earthquake there have been no earthquakes in Dubrovnik more intensive than $VII^0$ MCS, but such was not the case in its wider surroundings, e.g. in Ston in 1850 ($I_0$ = $VIII^0$ MCS) and in the area of Herceg Novi-Budva in 1780 and 1979 ($I_0$ = $IX^0$ MCS**)**. Therefore, the wider area of Dubrovnik is situated in the zone $X^0$ MCS on the Seismic Map with the possibility of catastrophic earthquake events.

According to the classification of epicentres of more intensive earthquakes, there are a few epicentre areas to be listed:

- *the area of Makarska* with the mountain Biokovo is characterised by more intensive seismic activity and with the tendency of its spreading into the submarine area.

- *the area of  Slano-Ston*. At the territory between Slano and Ston there is a significant epicentre area. Several stronger earthquakes have been recorded there, and the seismic activity is spreading to the Pelješac peninsula.
- *the area of Dubrovnik*. The epicentre of the catastrophic earthquake in 1667 was near the town Dubrovnik, and in the same area other stronger earthquakes were registered.

Northwards from Dubrovnik, into the hinterland, there is a series of epicentres spreading in two directions: from Trebinje to Bileća, and from Trebinje to Ljubinje and Stolac. In the submarine area of Dubrovnik, there have been more stronger earthquakes recorded in the last 70 years.

- *the area of Herceg Novi-Kotor.* It makes a separate epicentre area that had suffered several devastating earthquakes, with the one in 1780 being the strongest.
- *the area of Budva and southwards from Budva.* In the submarine zone of that area there have been several strong earthquakes registered, and the most intensive one occurred in 1979.

On the basis of the registered epicentres of stronger earthquakes, the map of $M_{max}$ earthquakes was made (isolines are given on 0.5 $M_{max}$ ), That clearly presents the zones of stronger seismic activity and the tendency of its spreading (Fig. 4).

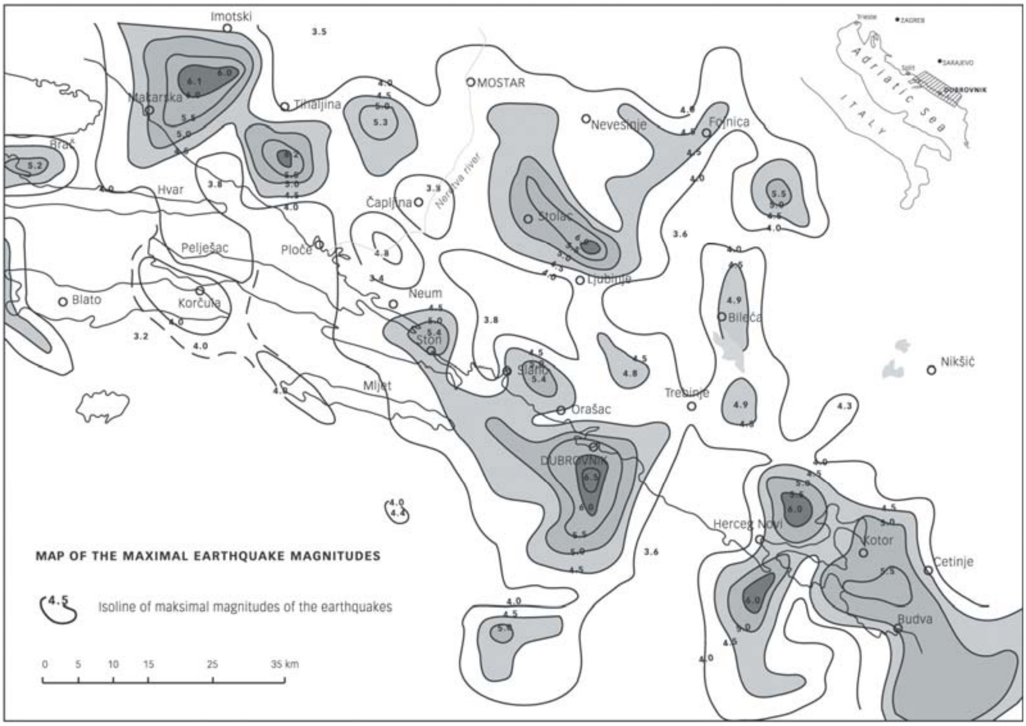


Figure 4. The map of isolines of maximal magnitudes of earthquakes in wider area of Dubrovnik

The isolines of $M_{max}$ of the earthquakes with the highest amounts up to M ≥ 6 are placed in the area of Makarska and Dubrovnik and at the territory between these two towns, then at the territory of Herceg Novi and Budva, and Stolac.

The parallel data indicate that the isolines of $M_{max}$ of the earthquake are spreading in the NW-SE direction (longitudinally) and perpendicularly/diagonally to that direction. The distinct examples are the area of Makarska, where $M_{max}$ are mostly oriented in the SW-NE direction. It is similar with the residual gravimetric anomalies that interrupted spreading in this area. Tectonic dislocations registered on Landsat images are also included into the spreading direction SW-NE.

In the area of Dubrovnik, isolines of $M_{max}$ are generally oriented in the direction SW-NE; geomagnetic anomalies are spreading in the same direction, probably caused by paleo-magmatic activity. The faults in the background of Dubrovnik and a distinctive irregularity of forms of residual gravimetric anomalies can be brought into the connection with the tectonic dislocation almost perpendicular to the SW-NE direction, along which the differential block movements have occurred.

The area of Herceg Novi-Budva represents a special earthquake zone where isolines of $M_{max}$ are oriented approximately in the same way as in the area of Dubrovnik, which could be brought into connection with the magmatic activity like in the area of Dubrovnik. The area between the ring structures (Budva – Kotor and further towards Nikšić) is more intensively tectonically disturbed than the structures themselves, and the largest number of earthquakes happened there in 1979.

## 5 RELATION BETWEEN TECTONIC AND STRONGER SEISMIC ACTIVITY

Comparing the tectonic data obtained by means of satellite images with the data obtained by means of geophysical measurements and with recorded epicentres of stronger earthquakes, it is obvious that there is a mutual relationship between tectonic structures and earthquakes (Fig. 5).

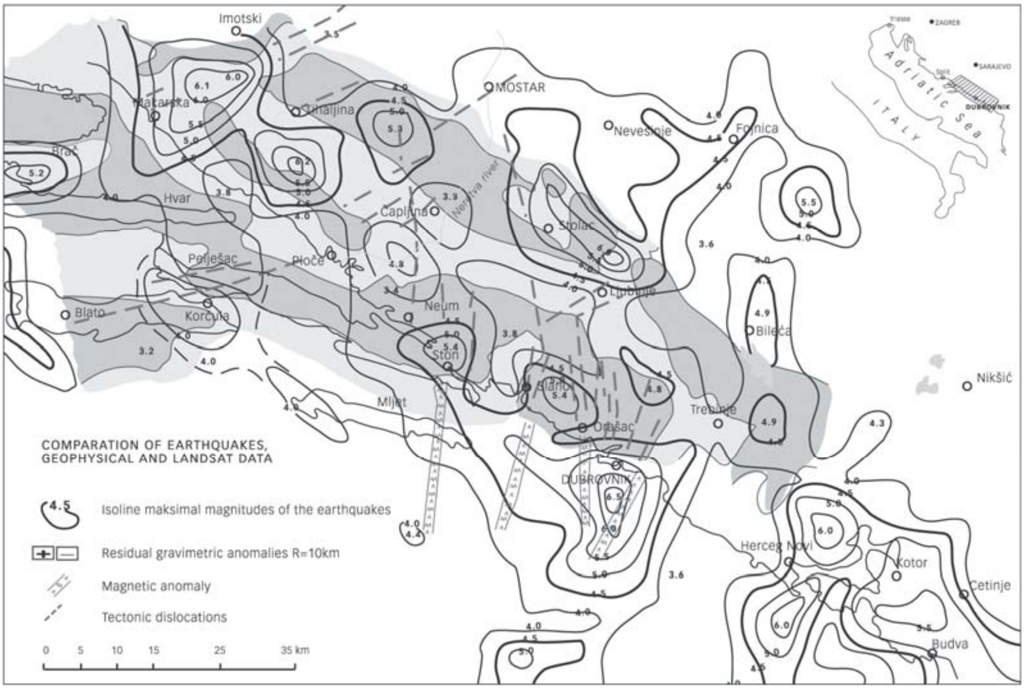


Figure 5. Map of comparison of seismic, geophysical, and Landsat data

On the basis of the above-mentioned data it can be concluded that the strongest seismic activity occurs at the boundaries of geotectonic units, then along the longitudinal dislocations, at the intersections of longitudinal and transversal/diagonal faults, as well as in the convergence zones. It has also been found that stronger seismic activity occurs in the areas between the ring-shaped structures, that are, as a rule, more intensively disturbed than the structures themselves (the area of Budva-Kotor).

For the occurrence of earthquakes in the observed area, the seismotectonic processes at the contact between the Adriatic plate and the Outer Dinaric Alps are very important. This contact is characterized by a fault zone, with the fault surfaces declining toward the continental part, probably because the Adriatic plate is sinking under the Dinaric Alps. It could indicate that deep tectonic motions cause compression of rocks in the contact zone, as well as differential block movements. It results in the creation of folds, faults and overthrust, and vertical uplifting/lowering and horizontal shearing of tectonic structures (strike-slip faults). Since certain tectonic movements in the depth occur perpendicularly/diagonally to the longitudinal extension of tectonic structures, it produces the rotation of certain tectonic units and blocks, and thus they move along transversal/diagonal faults. It is believed that the energy released by such movements presents the main cause of earthquakes in the Dinaric Alps, especially in the coastal zone.

The isolated isolines of $M_{max}$ in the continental part of the observed area are closely connected with the tectonic dislocations that are determined by, or they could be brought into connection with, very irregular forms of residual gravimetric anomalies, which indicates tectonic disturbances in the underground area.

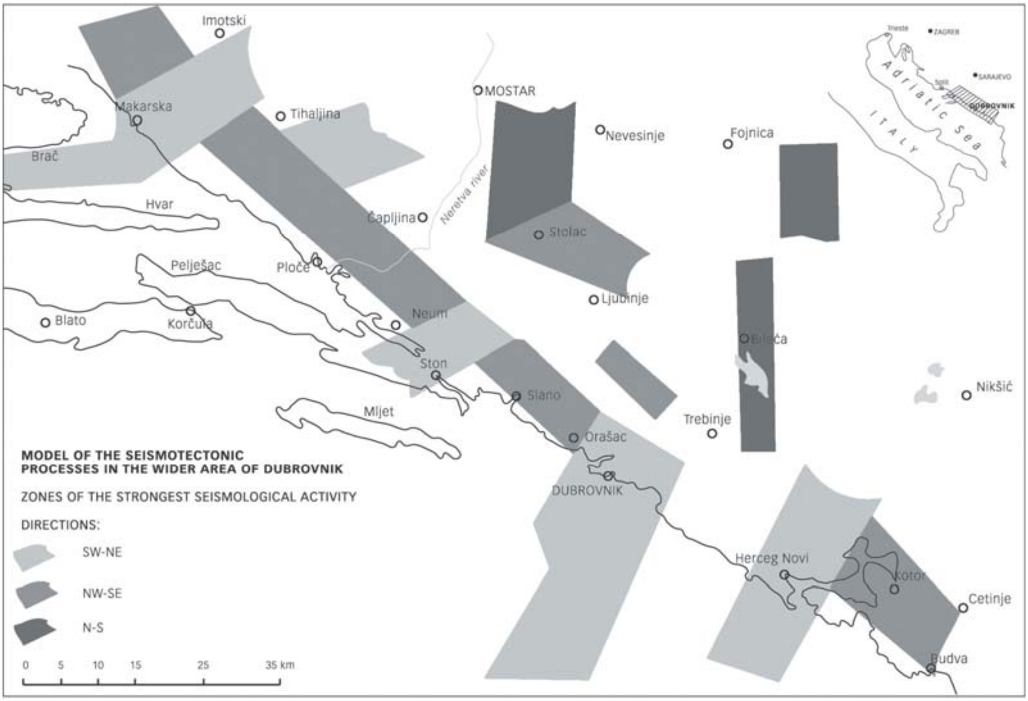


Figure. 6. Model of seismotectonic activity in wider area of Dubrovnik

## 6 MODEL OF THE SEISMOTECTONIC PROCESSES IN THE WIDER AREA OF DUBROVNIK

On the basis of available data, a *model of seismotectonic activity* of the researched area has been made (Fig. 6). According to this model, there are three emphasis directions separated, along which the seismic activity of high intensity is occurring, and these are: NW-SE, SW-NE and N-S The extending of seismic activity in the NW-SE direction is traced in the coastal area from Makarska over Ston to Dubrovnik. Between Dubrovnik and Herceg Novi it is interrupted, and then continues again in the area of Herceg Novi-Budva (Fig. 6). The north-east direction of seismotectonic activity extension is noticed in the area of Makarska, Tihaljina, Ston and Dubrovnik and Herceg Novi. It intersects the zones of longitudinal seismotectonic activity extension or appeared perpendiculariy to it. The extension of seismotectonic activity in the north-south direction is inferior to that of the first two directions and it is noticed northwards from Trebinje and southward from Mostar.

The most intensive seismic activity occurs exactly at the places of intersection or contact between tectonic structures, and along large neotectonic dislocations. Very clear examples are the areas of Makarska, Ston, Dubrovnik, Kotor and Budva and further towards SE.

The presented model makes it possible to partially explain the mechanism of the occurrence of the earthquakes that happened in the past, but also of those as well that might happen, unfortunately in the future, which should be taken into consideration, especially in setting up large technical projects and building activities.

## 7 CONCLUSION

The analysis and comparison of data have been made by means of satellite images, geophyisical measurements and data about strong earthquakes in the last two centuries.

On the basis of the observed data, it can be concluded that the most intensive seismotectonic activity occurs in the zones along large neotectonic faults in the NW-SE direction, and along those that are transversal and diagonal to that direction.

Apart from the zones along the mentioned directions, the most intensive seismic activity is noticed at the intersections or contacts of faults with various orientations. Geophysical anomalies coincide completely with the above mentioned directions of large faults.

There are three general directions in which large faults, geophysical anomalies, and isolines of $M_{max}$ extend, and these are: NW-SE, SW-NE and N-S. The direction NW-SE is traced at the territory from Makarska over Ploče to Dubrovnik, and from Kotor over Budva and further towards SE. This coastal zone is abounding in earthquakes. However, it is intersected with transversal/diagonal zones of stronger tectonic activity and earthquakes, which can be noticed in the area of Makarska, Ston, Dubrovnik, Herceg Novi etc. These intersections or contacts are the places where the most intensive north-south direction seismic activity is occurring (northwards from Trebinje and southwards from Mostar).

The occurrence of strong earthquakes can be connected to intensive tectonic movements, in the first place, along the contact line between the Adriatic plate and Dinaric Alps, and with the paleomagmatic activity, especially in the submarine area of Dubrovnik. Thereby, the main routes of earthquake energy extension towards more shallow levels are neotectonic dislocations. The model explains partly how the earthquakes in the wider area of Dubrovnik occur and points to the area in which earthquakes of higher intensity could occur in the future.

REFERENCES

Aljinović, B.,Cvijanović, D., Labaš, V., Prelogović, E. & D. Skoko. 1984. Geološka građa područja Dubrovnika na temelju seizmotektonskih i geofizičkih istraživanja. *10 kongres geologa Jugoslavije,* Budva, 527-539.

Blašković, I., Cvijanović, D., Prelogović, E., Skoko, D. & N. Brdarević. 1984. Correlation of geophysical, geological and seismological data in the Coastal part of Yugoslavia. *Bullettino di Oceanologica ed Aplicata, Vol. Ii, No. 2 Aprille 1984.*

Cvijanović, D., 1981. *Seizmičnost područja SR Hrvatske. Sveučilište u Zagrebu-* Prir. mat. fakultet. Doktorska disertacija, Zagreb

Gissberg, H., 1913. *Das Ragusanische Erdbeben von 1667,* Münch. Geogr. Studion. München.

*Kišpatić, M., 1891. Potresi u Hrvatskoj, Zagreb, 1891* (preštampano iz knj. 107, 109 i 122, rada Jug akad. znan. umj., Zagreb)

Mihajlović, J., 1947. *Seizmički karakter i trusne katastrofe našeg južnog primorja od Stona do Ulcinja,* Srpska akad. nauka-posebno izd., knj. CXL, prir.-mat spisi, knj. 39, Beograd.

Oluić, M., 2001. *Earth Imaging and Exploration from Space – Satellites, Sensors, Application (in Croatian).* Croatian academy of Sci. and Arts and GEOSAT, Zagreb, 516 pp.

Oluić, M., Romandić, S. & D. Cvijanović. 2004. Seismotectonics of the Dinarides and a Part of Pannonian Basin Based on Satellite Data and Geophysical Survey. *First Mediterranean Conf. on Earth Observation - Remote Sensing, Belgrade, 317-325.*

Tišljar, J., Vlahović, I., Velić, I. & B. Sokač. 2002. Carbonate Platform Megafacies of the Jurassic and cretaceous deposits of the Karst Dinarides. *Geol. croatica* 55/2, 139-170.

Tollmann, A., 1978. Plattentektonische fragen in den Ostalpen und der plattentektonische Mechanismus des Mediterranean Orogens. Mitt. Österr. Geol.Ges. 69/1976, Wien, 291-351