Identification of tectonically active areas in the Panonnain basin: a combination of DEM based morphotectonic and structural analysis of Bilogora Mt. area (NE Croatia)

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I. INTRODUCTION

Integration of available and newly obtained geomorphic, geological and geophysical data sets into the CROTEC project database (GIS platform) represent principal research strategy used to correlate subsurface fault geometrical properties and their possible expressions at the surface in Croatia. With focus on delineation of neotectonic and recently active faults and fault zones, quantitative description of their orientation, reconstruction of their kinematic history, and the assessment of their recent seismogenic potential our goal is to present here results of DEM based morphometric analysis combined with structural analysis of 2D seismic reflection sections in Bilogora Mt. area (NE Croatia). In addition, we present here results of computations of empirical geometrical fault-scaling relationships and estimation of seismogenic potential for active faults that cut across the base Pliocene-Quaternary horizon and propagate towards the surface.

II. NEOTECTONIC EVOLUTION & GEOLOGICAL SETTINGS

Bilogora Mt. as part of SW Pannonian basin, represent low hilly terrain with average elevation distribution less than 200 m. Predominantly, it is composed of highly deformed Pliocene-Quaternary clastic sediments variable in thickness (500-1500 m) which is conditioned by significant paleorelief and differential uplift during Neogene and Quaternary **(Fig. 1).** More than 90 km long and 10 km wide, Bilogora Mt. represent young transpressional morphostructure related to the NW-striking Drava basin boundary fault (DBBF, **Fig. 2**). DBBF was reactivated from originally normal into dextral fault during final Pliocene and Quaternary transpressional stage in tectonic evolution of the southern part of the Pannonian Basin accommodating c. 10 km displacement (Hećimović & Prelogović, 1987;Prelogović et al., 1998 & Saftić et al., 2003).

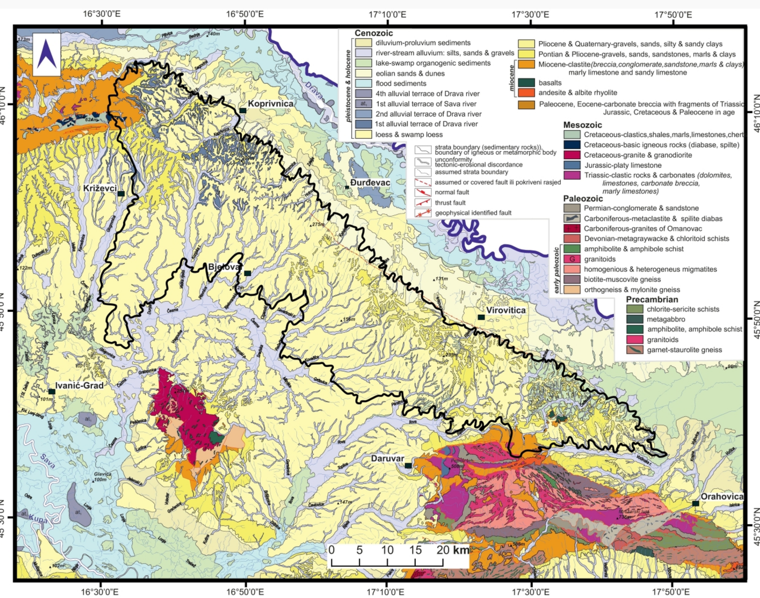

Fig 1. Simplified geological map of Bilogora Mt. area based on geological maps of Yugoslavia (1:100 000), sheets: Koprivnica (Šimunić et al., 1994), Đurđevac (Hećimović, 1986), Bjelovar (Korolija & Crnko, 1985), Virovitica (Galović & Marković, 1979), Podravska Slatina (Marković, 1985), Kutina (Crnko), Daruvar (Jamičić, 1989), Orahovica (Jamičić & Brkić, 1987) & Sisak (Pikija, 1987).

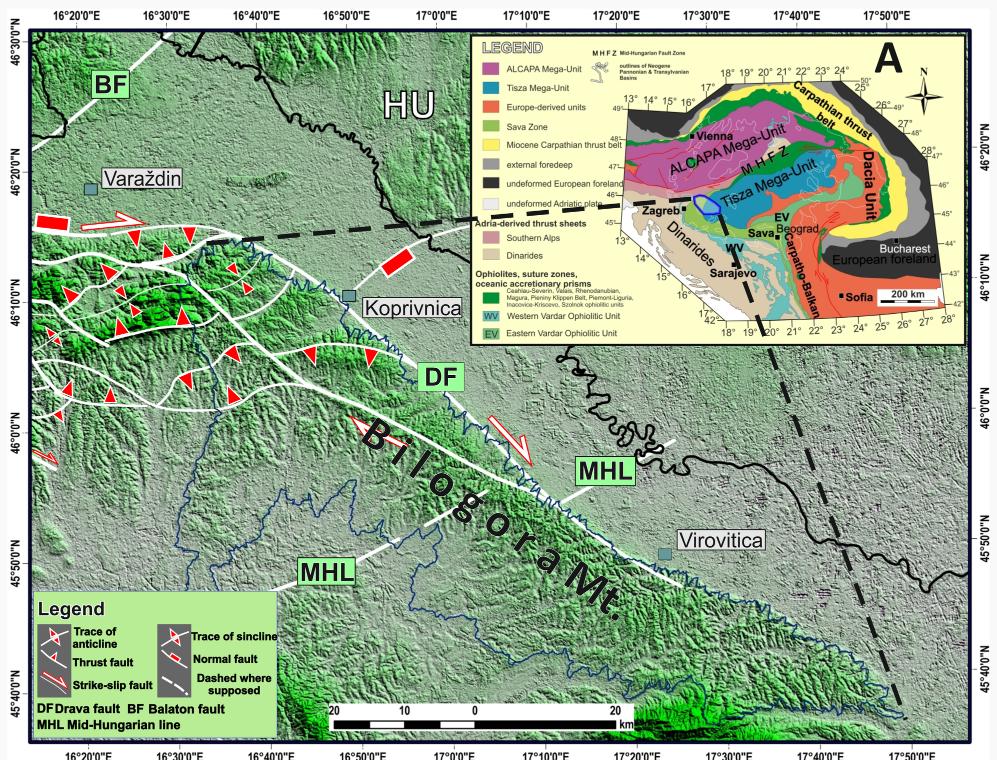

Fig. 2. Major Late Pontian to recent map scale reverse, normal and strike-slip faults and fold in border zone of Dinarides and Panonian Basin (slightly modified after Tomljenović & Csontos,2001) Insert map **A** shows simplified tectonic framework of study area (after Ustaszewski et al., 2009 and Schmid et al., 2008).

III. SEISMICITY

Tectonic activity is documented by historical seismicity reporting several rare and moderate earthquakes (M≥6) with intensity of VI°-VIII° MCS in vicinity of towns Koprivnica, Đurđevac and Virovitica (**Fig. 3**). Greatest horizontal stress direction determined from fault plane solutions of the of instrumentally recorded earthquakes (3.5≤ M_L≤ 5.6) is characterized by NE-SW orientation, indicating steeply NE-dipping, and S-SW dipping seismogenic structures with predominantly strike-slip and reverse motions (Prelogović et al., 1998 & Herak et al., 2009).

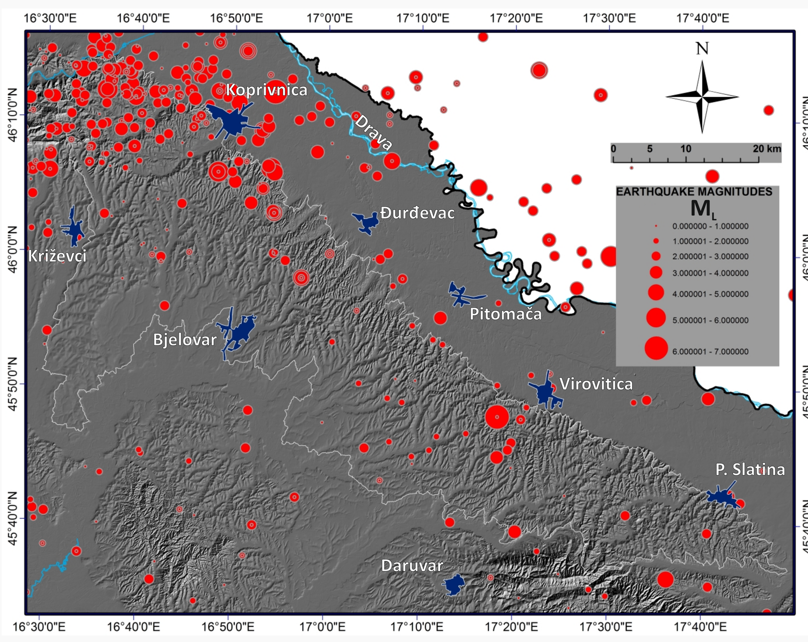

Fig. 3. Epicentres of all earthquake events (576-2012) reported in the Croatian Earthquake Catalogue.

IV. DEM MORPHOMETIC ANALYSIS

Quantitative DEM based morphometric analysis has been widely used in identification areas of ongoing tectonic activity and its surface expression. Landscape features has been analyzed by DEM raster with 10 m cell resolution. Using **ESRI ArcMap 9.x.x.** software package with **CalHypso, Spatial Analyst, ArcHydro 1.1 and StPro extensions** as well as **Matlab software** study area was divided into 130 morphometric units (**Fig. 4)** and analyzed by relative elevation and slope distribution values, hypsommetry, absolute asymmetry ratios and statistical parameters of main longitudinal stream trunk channels (maximum concavity, C_{max} ; position of maximum concavity, Δl/L; concavity factor, C_f; steepness index, k_{sn} and concavity index θ (**Fig. 5, 6 & 7**).

Calculated morphometric parameters have been reclassified, and overlayed as rasters, evaluating on-going tectonic activity (**Fig. 8**).

With convex hypsometric curves, H_i≥0.50 values, AF(abs)≥0.25 values and statistical parameters of main longitudinal streams profiles (C_f≤ 32.16%, C_{max}≤0.265 positioned in upper reach of streams, θ values between 0.73 and 1.01; and avg. k_{sn} values between 10.05 and 12.70) several drainage basins and streams dominantly in NW and central part of Bilogora Mt. (near towns of Koprivnica, Đurđevac and Bjelovar) and few of them on SW slopes in SE part (between towns of Virovitica and Daruvar) are characterized as the most on-going tectonically active areas (**Fig. 8**).

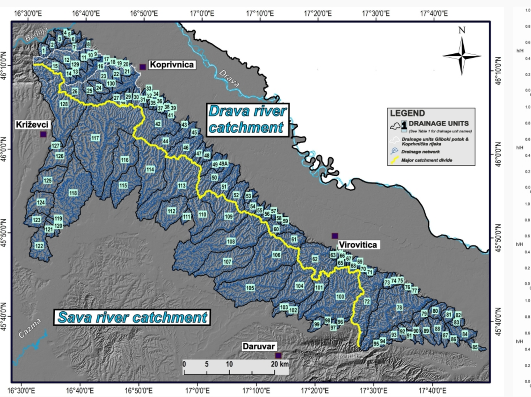

Fig.4. DEM hillshade with delineated morphometric units of Bilogora Mt.

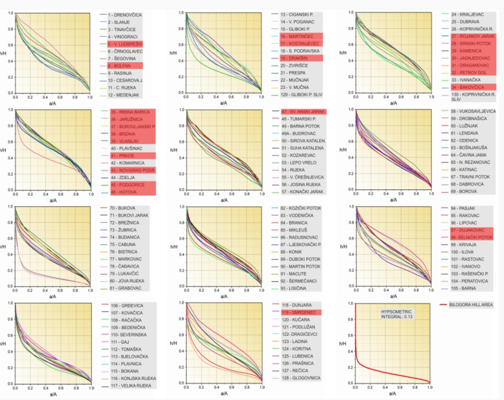

Fig. 5. Hypsometric curves for delineated units of Bilogora Mt. Hypsometric curves have been computed using CalHypso extension (Pérez-Pena et al., 2009).

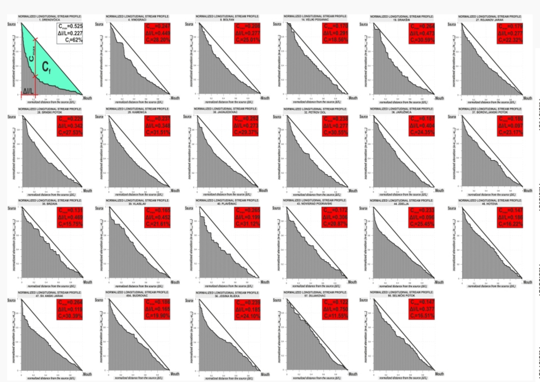

Fig. 6. Normalized longitudinal main stream profiles. Calculated statistical parameters; concavity factor (Cf), maximal concavity (Cmax) and distance from the source (Δl/L).

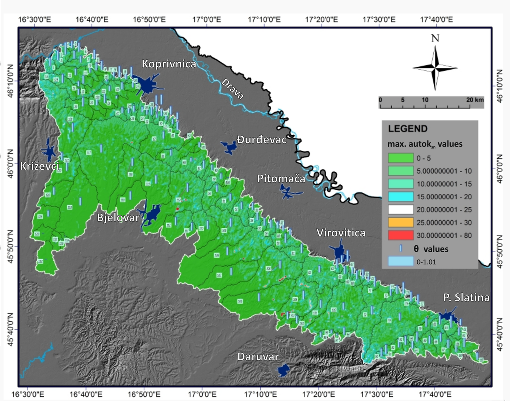

Fig. 7. Spatial distribution of concavity index and max. values of steepness index.

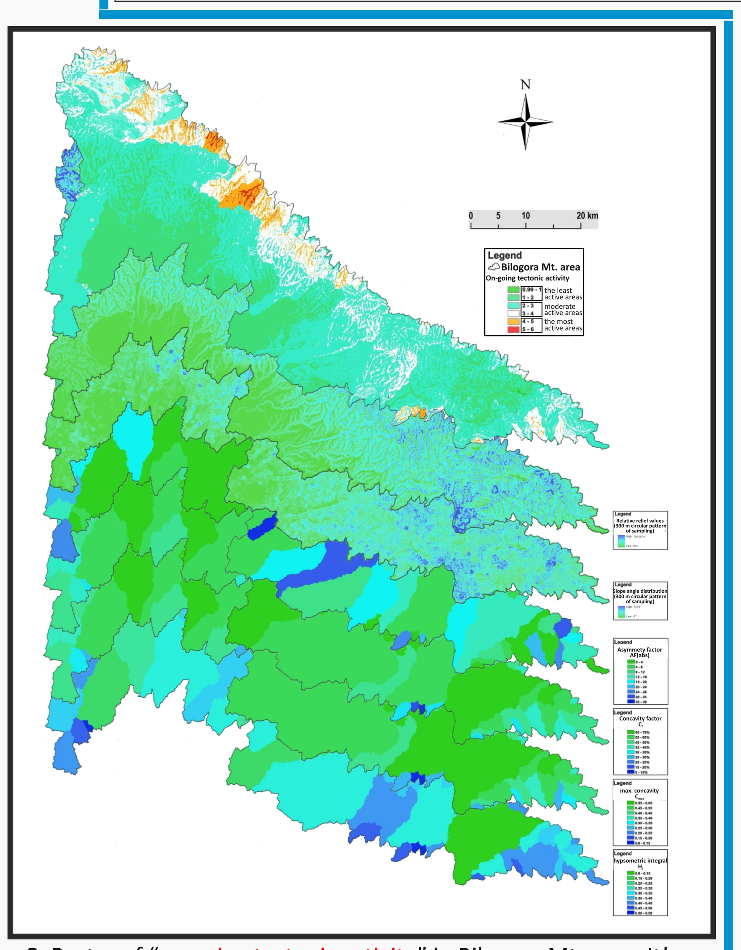

Fig. 8. Raster of "on-going tectonic activity" in Bilogora Mt. area. It's generated by weighted raster overlay of : hypsometric integral, maximal concavity, concavity factor, asymmetry factor, slope angle and relative relief distribution.

V. STRUCTURAL INTERPRETATION OF 2D SEISMIC SECTIONS

Possible congrruence between delineated morphometric parameters and on-going tectonic activity was analyzed using **Schlumberger Petrel Seismic to Simulation software (Fig. 9)**. Set of 72 reflection 2D seismic sections were used in construction of structural depth model of Bilogora Mt. area comprising 6 stratigraphic horizons and more than 50 faults active during the Neogene and Quaternary times (**Fig. 10 & 11).**

Spatial correlation between areas delineated as areas with potentially high on-going tectonic activity and structural data proved that delineated units in the NW part of Bilogora Mt. correlate well with subsurface fault-related folds formed during Late Pontian and Quaternary times.

These folds originate in hangingwalls of either normal-inverted or younger reverse faults that cut across the base of Pliocene-Quaternary stratigraphic horizon and propagate towards the surface (**Fig. 12**).Vertical offset along these faults is in range between 20 and 480 m, thus indicating a slip rate of ≤ 0.1mm/year during the Pliocene-Quaternary times (**Table 1**).

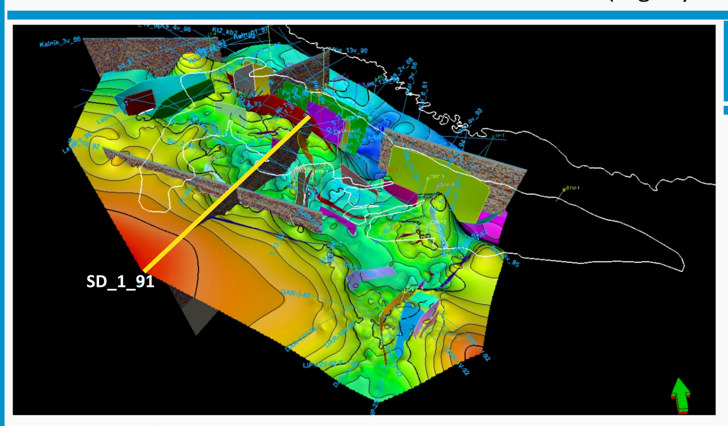

Fig. 9. Petrel database with 2D seismic sections and borehole data.

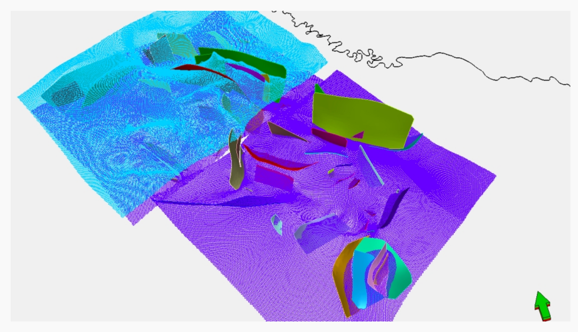

Fig. 10. Petrel 3D «skeleton» & pillar grid modeling.

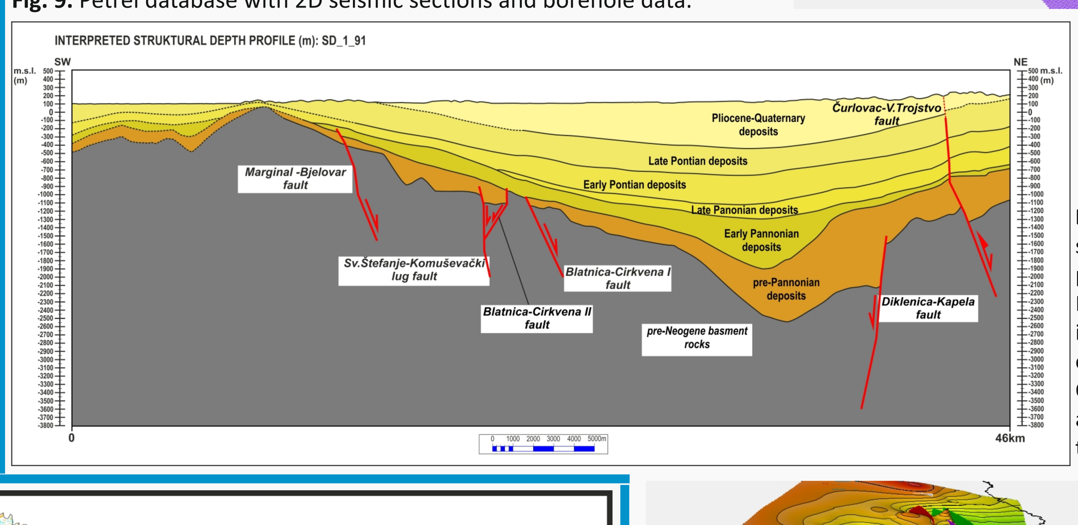

Fig. 12. Interpreted structural depth profile SD_1_91. Notice normal-inverted fault that cut base of Pliocene-Quaternary horizon and propagate towards the surface.

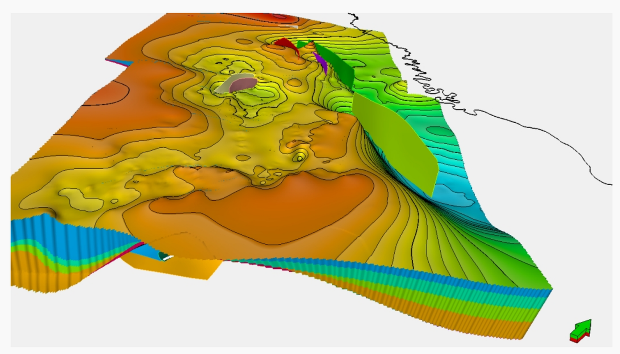

Fig. 11. Petrel 3D stuctural depth model of Bilogora Mt.

	Pliocene-Quaternary active faults	Rupture area (RA,km^2)	Magnitude M	Max. displacement MD (m)	Pliocene-Quaternary faults, total vertical offset (m)	Slip rate mm/yr
1	Čurlovac-Veliko Trojstvo	81,10	5,94	0,26	—	—
2	Kašljevac-Polum	42,50	5,67	0,15	85,00	0,02
3	Bačkovica-Cremušina	26,70	5,47	0,11	20,00	0,00
4	Dugački Gaj-Tomaš	39,30	5,63	0,14	250.00 ?	0,05
5	Nevinac-Velika Ciglena	14,60	5,21	0,07	200.00 ?	0,04
6	Selanec-Podvinje	16,10	5,25	0,07	40,00	0,01
7	S.Podravska-K.Ivanec	52,40	5,75	0,18	110,00	0,02
8	Jankovec-Kunovec Breg	20,40	5,35	0,09	?	?
9	Salamunovec-V.	61,60	5,82	0,21	?	?
10	Kolarec-V.Poganac	134,00	6,15	0,39	25 ?	0,00
11	Glogovac-Kalinovac	147,00	6,19	0,42	480,00	0,09
12	Glogovac-Plavšinac	33,80	5,57	0,13	60,00	0,01
13	Prkos-Paulovac	704,00	6,86	1,46	140,00	0,03
14	Javorovac-Čepelovac	46,80	5,71	0,17	20,00	0,00
15	Virje-Čepelovac	37,90	5,62	0,14	21,00	0,00
16	M.Črešnjevica-Taborište	106,00	6,05	0,32	85,00	0,02
17	Kladare-Pitomača	25,20	5,44	0,10	145,00	0,03
18	Dežanovac	102,00	6,04	0,31	120,00	0,02
19	Gornji Daruvar-	23,40	5,41	0,09	—	—
	min. value	14,60	5,21	0,07	20,00	0,00
	max. value	704,00	6,86	1,46	480,00	0,09
	avg.value	90,76	5,73	0,25	110,50	0,02

Table 1. Numbered Pliocene-Quaternary active fault with calculated magnitudes, max. displacement, total vertical offset and slip rate values.

VI. ASSESSMENT OF ACTIVE FAULTS SEISMOGENIC POTENTIAL

In estimation of seismogenic potential (1) and possible max. displacement-MD (2) of Pliocene-Quaternary active faults we used published rupture area (RA in km^2) geometrical fault propreties-magnitude scaling relationships proppsed by Wells and Coppersmith (1994):

$$M=4.07+0.98*\log(RA) \quad (1)$$

$$\log(MD)=-5.46+0.82*M \quad (2)$$

Results show that Pliocene-Quaternary active faults are capable to generate earthquakes with magnitudes up to 6.86 which are significantly greater than historically reported magnitudes in Croatian Earthquake Catalogue. In addition, calculated values of possible maximum vertical surface displacement for those faults are in the range 0.07-1.46 m (**Table 1**).

VII. CONCLUSION

1. Possible on-going tectonic activity in Bilogora Mt. is recognized for following drainage basins:
   - NW part - **No. 4-5, 7-8, 17-19, 29-32, 36-39 and 41**
   - Central part - **No. 44-49, 52 and 56**
   - SE part - **No. 89, 95, 97-99**
2. Tectonically active areas correlate well with subsurface fault-related folds formed in hangingwalls of either normal-inverted or younger reverse faults that cut across the base Pliocene-Quaternary horizon and propagate towards the surface.
3. Calculated vertical offset along these faults indicate **slip rates of 0.1mm/year** during the Pliocene-Quaternary times.
4. Pliocene-Quaternary active faults are capable to generate earthquakes **with magnitudes up to 6.86. Possible maximum vertical surface displacement** for those faults are in range **between 0.07 and 1.46 m.**

Acknowledgements

This study was financed by the Ministry of Science, Education and Sports of the Republic of Croatia, through Projects Nos. 195-1951293-3155; 119-1193086-1314, and 119-1193086-1315. All support is gratefully acknowledged.

References

Hećimović, I ., Prelogović, E. (1987): Basic geological map 1:100 000. Sheet Podravska Slatina, explanatory notes. Federal geological institute, Beograd, 39 p. | **Herak, D., Herak, M., Tomljenović, B. (2009)**: Seismicity and earthquake focal mechanisms in North-Western Croatia. Tectonophysics 465, 212-220 p. | **Pérez-Peña, J.V., Azor, A., Azañón, J.M., Keller, E.A. (2010)**: Active tectonics in the Sierra Nevada (Betic Cordillera, SE Spain): Insights from geomorphic indexes and drainage pattern Analysis. Geomorphology, 119, 74-87. | **Prelogović, E., Saftić, B., Kuk, V., Velić, J., Dragaš, M., Lučić, D. (1998)**: Tectonic activity in the Croatian part of the Pannonian basin. Tectonophysics 297, 283-293 p. | **Saftić, B., Velić, J., Sztanó, O., Juhász, G., Ivković, Ž. (2003)**: Tertiary Subsurface Facies, Source Rocks and Hydrocrbon Resevoirs in the SW Part of the Pannonian Basin (Northern Croatia and South-Western Hungary). Geologia Croatica 56/1, Zagreb, 101-122 p. | **Schmid, S.M., Bernoulli, D., Fügenschuh, B., Matenco, L., Schefer, S., Schuster, R., Tischler, M., Ustaszewski, K. (2008):** The Alpine-Carpathian-Dinaridic orogenic system: correlation and evolution of tectonic units. Swiss Journal of Geosciences 101, 1, 139-183. | **Tomljenović, B., Csontos, L. (2001):** Neogene-Quaternary structures in the border zone between Alps, Dinarides and Pannonian Basin (Hrvatsko zagorje and Karlovac Basin, Croatia). International Journal of Earth Sciences (Geologische Rundschau), 90, 560-578.| **Ustaszewski, K., Schmid, S.M., Lugović, B., Schuster, R., Schaltegger, U., Bernoulli, D., Hottinger, L., Kounov, A., Fügenschuh, B., Schefer, S. (2009):** Late Cretaceous intra-oceanic magmatism in the internal Dinarides (northern Bosnia and Herzegovina): Implication for the collision of the Adriatic and European plates. Lithos, 108, 106-125 p. | **Wells, D.L., Coppersmith K.J. (1994):** New Empirical Relationships among Magnitude, Rupture Length, Rupture Width, Rupture Area, and Surface Displacement. Bulletin of the Seismological Society of America, Vol. 84, No. 4., 974-1002 p.