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SOURCE MECHANISM OF THE 1994 SEPTEMBER 1 M_L = 5.2 BITOLA EARTHQUAKE

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A b s t r a c t: The source mechanism of the earthquake occurred on September 1, 1994, with local magnitude M_L = 5.2, in the Bitola region in the south-western part of the Republic of Macedonia, was studied in details. The studies included *P*-nodal planes determination for the earthquake, synthesizing of *P*-wave traces with the two *P*-nodal planes taken separately as fault planes, locating of adjacent earthquakes, as well as a comparison of all the obtained results with the results of the previous macroseismic studies of the earthquake and the neotectonic conditions in the Bitola region. A normal left-lateral fault striking toward WNW was confirmed as a source mechanism of the earthquake. That fault can be associated with the neotectonic Pelister fault, the last being the northern border of the mountain Baba.

Key words: earthquake source mechanism; dislocation model; synthetic seismogram

1. INTRODUCTION

An earthquake occurred in the region of the town of Bitola (south-western part of the Republic of Macedonia) on 1 September 1994, with 16 h 12 min 40.40 s UTC origin time and local magnitude $M_L = 5.2$ [1]. From all the seismographs of the seismological network in the Republic of Macedonia, only the mechanical seismographs CONRAD and MAINKA and the digitally re-cording vertical channel of the short-period electromagnetic Kinemetrics SS-1 seismometer at the seismological station in Skopje (SKO) recorded the ampli-tudes of the ground motion without clipping (Fig. 1). The earthquake caused significant macroseismic effects on the territory of the Republic of Macedonia and neighboring countries [2]. It was a main shock for a sequence of earthquakes (shocks), observed in the Bitola region from September 1, 1994, up to June 18, 1996 [3].

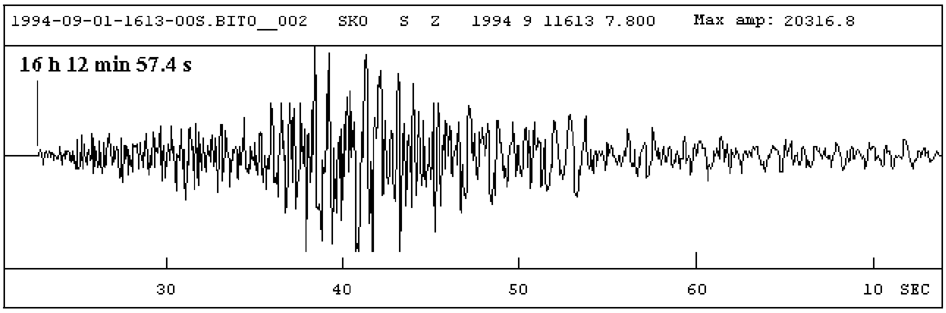

Fig. 1. Digital record of the 1994 September 1 ML 5.2 Bitola earthquake on the vertical channel of the short-period electromagnetic Kinemetrics SS-1 seismometer at the Seismological Observatory in Skopje (SKO)

The hypocentre of the main shock was located with latitude $\varphi = 41.12\ °\mathrm{N}$, longitude $\lambda = 21.25\ °\mathrm{E}$ and depth h = 15 km [1], and that is within the net of faults in the western part of the Bitola region (Figs. 3 and 6). Most of those faults are borders of active neotectonic blocks and thus expected to be seismogenic. As no evidence of a new surface rupturing was reported, instrumental identification of the fault that generated the earthquake was necessary.

As it is known, the orientations of the fault plane and the fault slip (fault walls' relative slip) in the dislocation theory of seismic sources are referred to as a source mechanism, with the fault plane itself and the plane that is perpendicular to the fault slip being the nodal planes of the far-field longitudinal (*P*) seismic motions (*P* nodal planes), [e.g. 4 and 5]. The most prominent method of source mechanism determination uses the polarities of the first far-field *P* seismic motions, since then only one (vertical) component of the seismic records is used, and in that way the determination errors are minimized. However, the method gives a double-valued solution for the source mechanism, because then it is not possible to distinguish the fault-plane between the two *P* nodal planes. Therefore this method is often denoted as *P*-nodal planes determination, and the resolving of the fault-plane ambiguity is usually done with other seismological or non-seismological considerations.

We followed the above described procedure for the earthquake studied.

2. INSTRUMENTAL AND THEORETICAL SEISMOLOGICAL INVESTIGATIONS

Firstly we obtained the *P*-nodal solution for the studied earthquake. We used the programs FPFIT and FPPLOT, [6], on the polarities of 32 first far-field *P* seismic motions for the earthquake [7], on the hypocentre location given above, assuming the Balkan crustal model [8]. The results are given in Table 1 and Fig. 2.

T a b l e 1

The parameters of the obtained P-nodal solution for the 1994 September 1 M_L 5.2 Bitola earthquake

Date: 01. 09. 1994.; Origin time: 16 h 12 min 40.40 s UTC; epicentre: φ= 41.12^{0}N, λ = 21.25^{0}E; hypocentral depth: h = 15 km	Azimuth of the strike ϕ_s (°)	Dip δ (°)	Azimuth of the dip direction ϕ_δ (°)	Vector of the relative slip of the fault walls $\vec{b}$: Azimuth ϕ_b (°)	Dip e_b (°)	Slip angle γ (°)	Component along the dip direction $\sin\gamma$	Component along the strike direction $\cos\gamma$
P-nodal plane I (fault plane I)	70 ENE	55	160 SSE	206 SSW	45	– 120	– 0.866	– 0.500
P-nodal plane II (fault plane II)	295 WNW	45	25 NNE	340 NNW	35	– 54	– 0.809	+ 0.588

Tension axis (*T*)		Pressure axis (*P*)		Null axis (*O*)	
Azimuth ϕ_T (°)	Dip e_T (°)	Azimuth ϕ_P (°)	Dip e_P (°)	Azimuth ϕ_O (°)	Dip e_O (°)
181 SSW	5	284 WNW	65	268 WSW	24

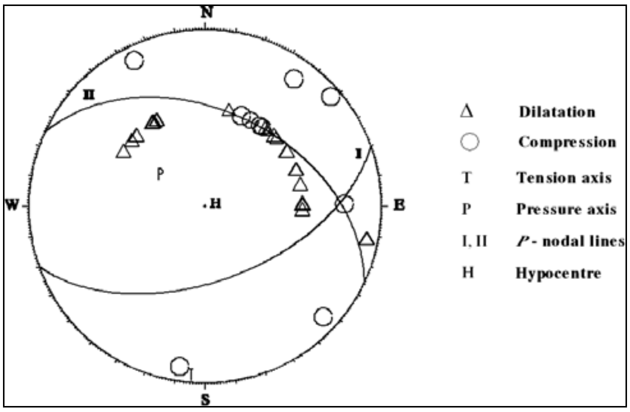

Fig. 2. The zenithal equal-area projection of the hypocentral sphere, obtained with FPFIT and FPPLOT computer programs, for the 1994 September 1 M_L 5.2 Bitola earthquake

As it can be seen, the first *P*-nodal plane, striking the Earth's surface with azimuth $(\phi_s)_I = 70°$ (ENE) and dipping under an angle of $\delta_I = 55°$ toward SSE, defines a normal right-lateral faulting as one possible earthquake source: the azimuth, the dip and the slip angle for the fault walls' relative slip are respectively $(\phi_b)_I = 206°$, $(e_b)_I = 45°$, $\gamma_I = -120°$. The second *P*-nodal plane, striking the Earth's surface with azimuth $(\phi_s)_{II} = 295°$ (WNW) and dipping under an angle of $\delta_{II} = 45°$ toward NNE, defines a normal left-lateral faulting as the second possible earthquake source: the azimuth, the dip and the slip angle for the relative slip are respectively $(\phi_b)_{II} = 340°$, $(e_b)_{II} = 35°$, $\gamma_I = -54°$.

As it is known, the shocks that are adjacent to some main shock have usually a spatial distribution which spreads along the fault that generated the main shock [e.g. 9]. Therefore, in order to chose between the two possible earthquake sources found above, we studied the spatial distribution of selected adjacent shocks for the earthquake under consideration. We selected the only forshock occurred on September 1, 1994, at 16h 02min 33.0s UTC, with $M_L = 3.5$, and the aftershocks occurred during the first 12 hours after the main shock, all with parameters listed in [3]. The first 12 hours after the main shock were chosen in order to eventually avoid aftershocks generated by more significant neighboring faults, that might be activated by the main fault.

The distribution of the epicentres of the adjacent shocks studied here had its maximal linear dimension *L* = 13 km along the direction ESE-WNW (Fig. 3). This suggested the second of the two possible earthquake sources.

Synthetic far-field seismograms for the studied earthquake has been previously generated in [10], for different proposed earthquake sources. We generated here synthetic far-field *P*-wave traces for the two possible earthquake sources suggested by the obtained *P*-nodal solution and for the seismological station in Skopje (SKO) as an observational point. For both possible earthquake sources, the Haskell model of an unilateral shear dislocation on a rectangle and with a rump source-time function [11] was used (Fig. 4). In implementing the expressions for the far-field *P*-wave displacements in an isotropic homogeneous medium that are given in [11], we valued the rupturing velocity with $v_L = 2.7\,\mathrm{km/s}$ and the final dislocation in the rump source-time function with unit (a^1 = 1) for both possible earthquake sources. Further, in both cases the dislocation rectangle's final width was valued with unit ($W = 1$), its final length with $L = 13$ km, the last being the above obtained maximal linear dimension of the distribution of the adjacent shocks' epicentres. The dislocation rise time (t_a) was taken with values 2.92 s and 2.49 s respectively for the first and the second possible earthquake source. For accounting the effects of the *P*-waves' propagation in heterogeneous medium from the source up to the seismological station in Skopje, the reflectivity method [e.g. 12] was used on the Balkan crustal model from [8].

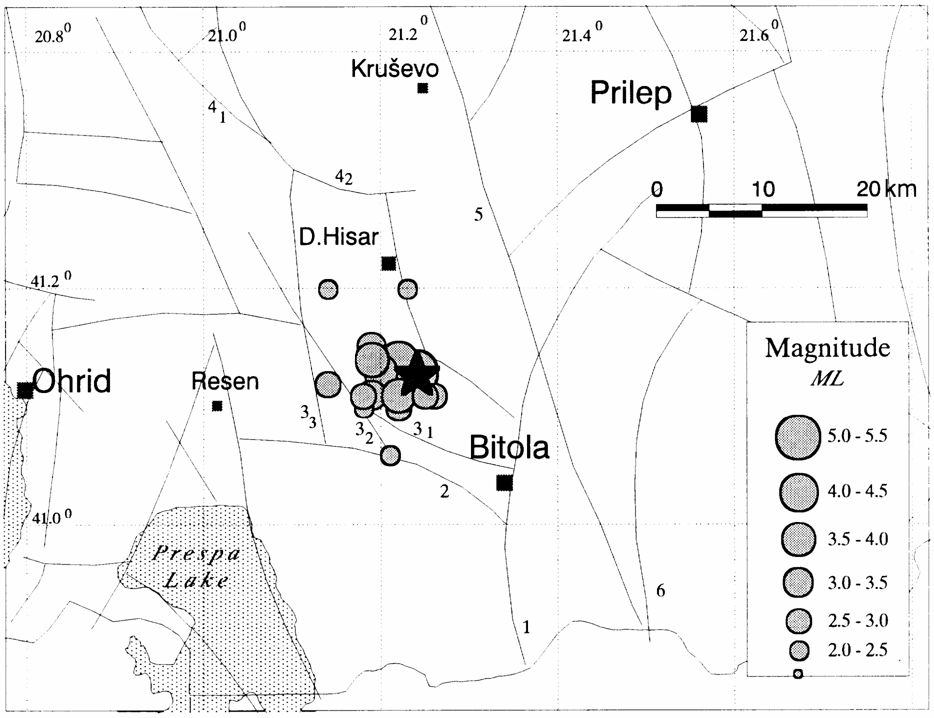

Fig. 3. Distribution of epicentres of the studied adjacent earthquakes for the 1994 September 1 M_L 5.2 Bitola earthquake (one forshock and several aftershocks occurred during the first 12 hours after the main shock). The star symbol is for the epicentre of the main shock. N°1 - N°6 - faults bordering the neotectonic structures in the Bitola region (see also the legend in Fig. 6)

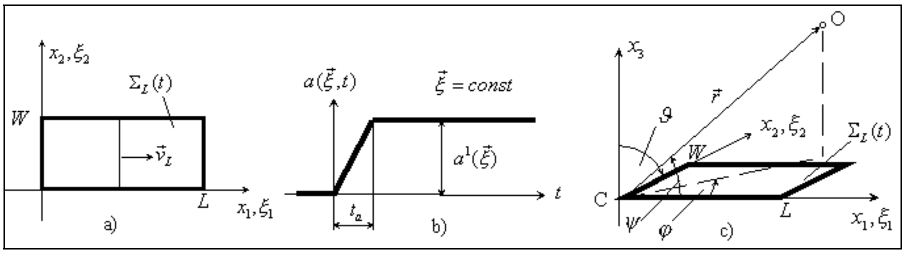

Fig. 4. The Haskell dislocation model, used in this study for synthetizing seismic far-field *P*-wave traces: **a)** rectangle of shear dislocation with legnth *L*, width *W* and surface $\Sigma_L(t)$ increasing in time (t) with rupturing velocity v_L along the x_1 direction; $\vec{\xi}(\xi_1, \xi_2)$ are the points of $\Sigma_L(t)$; **b)** development in time of the shear dislocation $a(\vec{\xi}, t)$, from zero value up to the final value $a^1(\vec{\xi})$; t_a is the dislocation rise time; **c)** the spherical polar coordinates (r, ϑ, φ) used to determine the position of the surface $\Sigma_L(t)$ with respect to the observer at location $O(\vec{r})$. (Modified from [5] and [11].).

We compared the obtained synthetic far-field *P*-wave traces with the *P*-wave traces on the records from the mechanical seismograph MAINKA at the seismological station in Skopje. It was found out that the synthetic far-field *P*-wave trace for the second possible earthquake source (normal left-lateral and WNW striking fault) was more similar to the observed *P*-trace (Fig. 5).

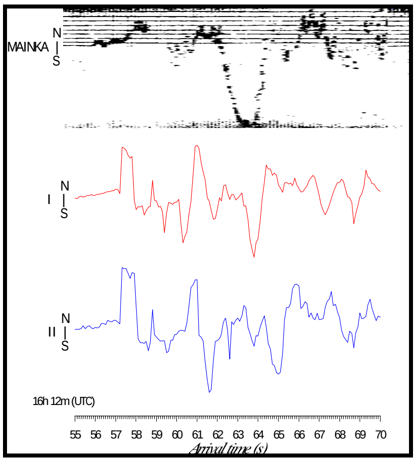

Fig. 5. Synthetic seismograms for the two possible sources of the 1994 September 1 M_L 5.2 Bitola earthquake in comparison with the earthquake record on the mechanical seismograph MAINKA, NS component, at the Seismological Observatory in Skopje

3. COMPARISON WITH THE RESULTS OF THE MACROSEISMIC INVESTIGATIONS

As it is known from the macroseismic studies, the maximal intensity isoseimal for an earthquake is that one which mostly reflects the earthquake source mechanism [e.g. 13 and 14]. We used it in order to check the choice between the two possible sources for the 1994 September 1 Bitola earthquake that was made in the above instrumental and theoretical seismological investigations.

The maximal intensity of the earthquake studied had been previously evaluated by VII-VIII MSK-64 at the villages NW near Bitola [2]. An elliptical VII MSK-64 isoseismal, with a principal axis along the direction SE-NW, was also contoured in [2]. The presentation of this principal axis on the Earth's surface, together with the fault strike directions and fault walls' lateral movements that correspond to the two possible earthquake sources from the above obtained P-nodal solution is given in Fig. 6. Neotectonic faults in the Bitola region are also shown in the presentation. As it can be seen, the orientation of the VII MSK-64 isoseismal's principal axis is closer to the fault strike direction for the second possible earthquake source (a normal left-lateral and WNW striking fault).

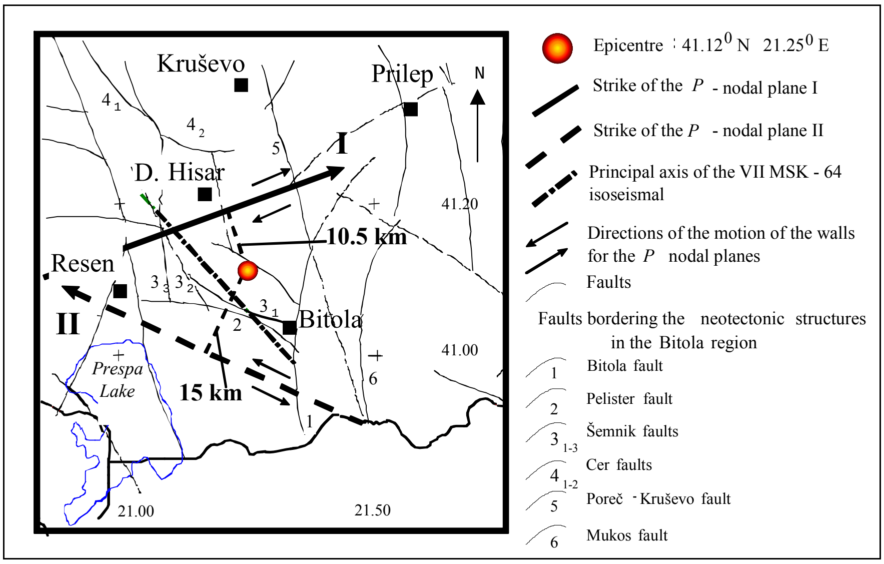

Fig. 6. Presentation on the Earth's surface of the obtained P-nodal solution for the 1994 September 1 M_L 5.2 Bitola earthquake and its comparison with the corresponding macroseismic and neotectonic data

Figure 7 presents the *P*-nodal plane II from Table 1 in the vertical plane that is perpendicular to the *P*-nodal plane II itself. As it can be seen, of Bitola and the area the strongest macroseismic observed, effects were located on the hanging fault wall, which exhibited lateral movement toward NNW and downward movement along the fault dip direction.

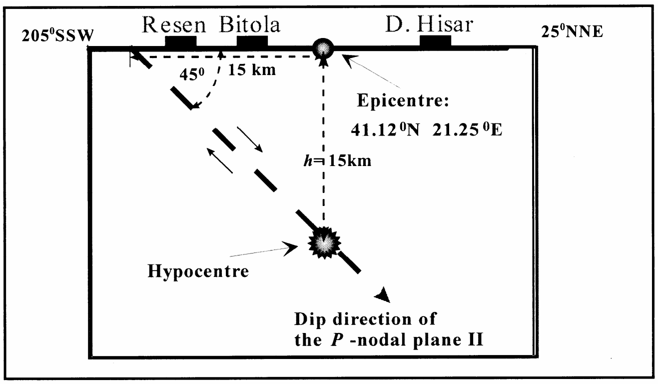

Fig. 7. Presentations of the epicentre, the hypocentre and the P-nodal plane II for the 1994 September 1 M_L 5.2 Bitola earthquake in the vertical plane perpendicular to the P-nodal plane II itself

4. CONSIDERATION OF THE NEOTECTONIC CONDITIONS

As it is known from previous tectonic investigations [e.g. 15], the neotectonic activity in the Bitola region has been manifesting differential horizontal and vertical movements of several structures. The vertical movement are more expressed, since the Pelagonian depression, having an eastern (bigger) and a western (smaller) branch (Fig. 8), with the town of Bitola located at their intersection, has been characterized by a strong tendency to subsidence since Pliocene. In the eastern part of the Bitola region, the depression is bordered by the Selek block, which is a structure with a uniform Pliocene-Quaternary uplifting. In the western part of the Bitola region, the depression is bordered by Pelister (Baba Mountain), Ilin, Šemnik and Luben blocks, all being Pliocene-Quaternary uplifting structures. The total neotectonic uplift of the Pelister block is about 2200 m. The uplifting of the Ilin block is less intensive (1800 m since Pliocene), but still more intensive than the uplifting of the Luben block (1600 m since Pliocene) and of the Šemnik block (1000 m since Pliocene).

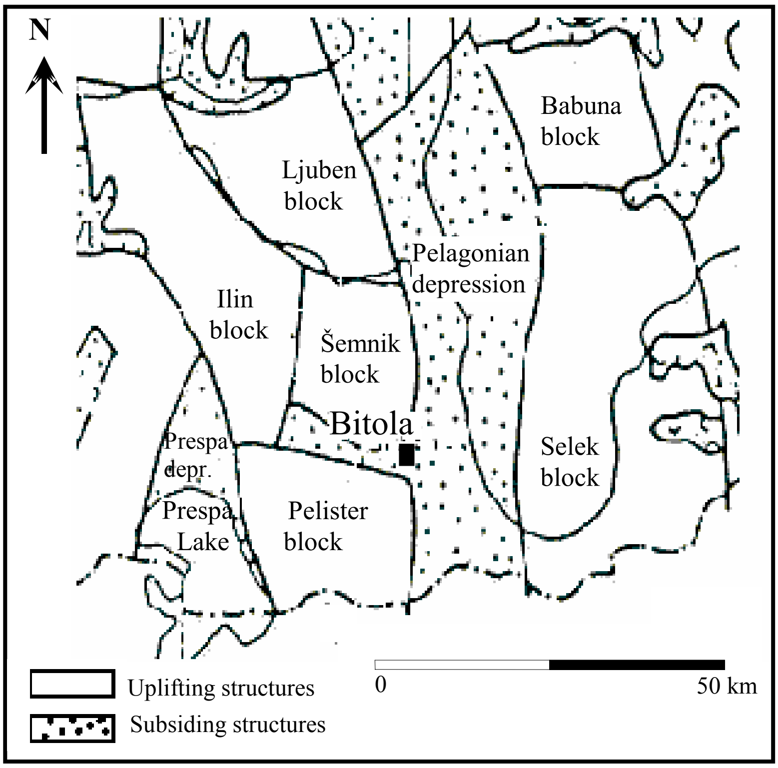

Fig. 8. Neotectonic structures in the Bitola region (Modified from [15])

All this suggests that the stronger earthquakes in the Bitola region should be generated along the faults which are borders of these neotectonic structures (the inside faults should be expected to produce smaller earthquakes). From all those bordering faults, only the Pelister fault (N^{o}2 in Fig. 6), striking toward WNW and dipping toward NNE, fits the normal left-lateral and WNW striking fault confirmed as a source for the 1994 September 1 Bitola earthquake from our instrumental and macroseismic investigations.

5. CONCLUSIONS

The comparison of the synthetic far-field seismograms for the two *P*-nodal planes as possible fault planes with the empirical far-field seismograms was enough to strictly determine the source mechanism for the 1994 September 1 M_L 5.2 Bitola earthquake. The comparisons of the *P*-nodal solution with the observed aftershocks epicentres distribution and macroseismic data brought separately the same result.

The seismologically confirmed source mechanism is a normal left-lateral faulting, which is striking toward WNW (dipping toward NNE). It was found that this faulting is associated with the neotectonic Pelister fault, which is a contact between the uplifting Pelister block (Baba Mountain) and the western branch of the subsiding Pelagonian depression.

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Р е з и м е

МЕХАНИЗМОТ НА ЖАРИШТЕТО НА БИТОЛСКИОТ ЗЕМЈОТРЕС ОД 1 СЕПТЕМВРИ 1994 ГОДИНА, СО ЛОКАЛНА МАГНИТУДА $M_L = 5.2$

Направени се детални студии на механизмот на жариштето на битолскиот земјотрес од 1 септември 1994 година, со локална магнитуда M_L = 5,2. Во студиите се вклучени: одредување на двете нодални рамнини на лонгитудиналните (*P*) сеизмички поместувања од далечното поле; синтетизирање на трагите на овие бранови со двете *P*-нодални рамнини земени поединечно како жаришта; лоцирање на соодветни придружни земјотреси; споредба на добиените резултати со резултатите од претходните макросеизмички истражувања на анализираниот земјотрес и со неотектонските услови во битолското подрачје. Како механизам на жариштето на анализираниот земјотрес се утврдува нормално лево раседување, со раседна линија насочена кон WNW. Ова раседување може да му се придружи на неотектонскиот Пелистерски расед, кој е северен раб на планината Баба.

Клучи зборови: механизам на земјотресно жариште; дислокациски модел; синтетички сеизмограм

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