NEED FOR ADVANCED SEISMOGENIC FAULT CHARACTERIZATION STUDY AS A BASIS FOR RELIABLE SEISMIC HAZARD

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Abstract

N. Macedonia as a country has a rather long history in the domain of seismic hazard assessment, implementing and testing different hazard models and methodologies, with aim to assure most reliable seismic hazard assessment. Dominantly, previously used seismic hazard models (Mihailov, 1978; Milutinovic et al., 1998; Dojcinovski, 2005; Stamatovska and Koytcheva, 2013; Salic, 2015; Milutinovic et al., 2016) were consist of aerial type or gridded seismicity sources, mostly due to the lack of consistent and reliable seismogenic fault parameters. The purpose of this study is to summarize all up to date available national fault parametrization data (Basic Geological Map 1:100.000; Arsovski and Petkovski, 1975; Janchevski, 1987, Arsovski, 1997; Dumurdzanov et al., 2005; Drogreshka, 2018), draw the gaps and inconsistencies and propose feasible state-of-the-art methodologies to be used for seismogenic fault parametrization. Being aware of the lack of recent and modern geological, tectonic and seismological data, the authors are also taking the possibility to propose the alternative methods for fault characterization and classification based on geodetic strain rates and satellite data. The recommendations from this research aims to contribute in the scientific research domain – seismic hazard analysis, as well as to have direct practical application in the seismic design regulations since N. Macedonia is in a process of adaption of the European design regulation (Eurocodes).

Keywords: Faults, Tectonics, Seismicity, Seismic hazard, N. Macedonia

1. Introduction

N. Macedonia as a part of South Eastern Europe is a country that is characterized with relatively high seismic hazard and risk when compared to Central and Northern European Countries. Reliable seismic fault definition and characterization is one of the key pillar of the reliable seismic hazard assessment. As of today, the most of the available research in the field of tectonics or related fields (Basic Geological Map 1:100.000; Arsovski and Petkovski, 1975; Janchevski, 1987, Arsovski, 1997; Dumurdzanov et al., 2005; Drogreshka, 2018) although containing valuable research information does not provide full comprehensive and harmonized state-of-the-art database related to active seismic faults needed for the reliable seismic hazard assessment. The main aim of this paper is to present the review of available fault databases for the territory of N. Macedonia and identify the present gaps and inconsistencies, as a basis for further research.

The most of the seismic hazard models developed on national scale (Mihailov, 1978; Milutinovic et al., 1998; Dojcinovski, 2005; Stamatovska and Koytcheva, 2013; Salic, 2015; Milutinovic et al., 2016) for the definition of seismicity primarily used the classical areal type sources and recently also gridded seismicity sources (Salic, 2015; Milutinovic et al., 2016). The selection of this type of sources is dominantly forced by an evident luck of reliable seismic fault parametrization data.

N. Macedonia is in the phase of adoption of European design regulation (Eurocodes). For that purpose, several required National Annexes are still in the phase of preparation along with the definition of other nationally defined parameters. The importance of development of new comprehensive and harmonized state-of-the-art database related to active seismic faults is directly needed also for the definition of parameters stated in the EC-8 Part 2 (3.2.2.3) as well as EC-8 Part 5 (11.2.2) where explicitly is required definition of seismically active faults.

2. Seismicity and seismo-tectonic characteristics of the territory of N. Macedonia

The territory of N. Macedonia is located in the central part of Balkan Peninsula (Fig. 1). The overall Balkan region is characterized with high seismic activity which is result of ongoing active tectonic processes in the Eastern Mediterranean region which are dominantly influenced by: (1) Subduction of the Adriatic microplate under the Dinarides; (2) Subduction of the Ionian and Levant micro plains under the Hellenic trench; and, (3) The collision between the Eurasian and the Arabian plates, related to the North Anatolian fault zone (NAFZ) (Burchfiel et al., 2006). As a consequence of these regional processes, the seismicity in the territory of Macedonia is associated with recent tectonic movements along normal faults (Dumurdjanov et al., 2004). The genesis of these faults is related to the South Balkan Extensional Regime (SBER) and the neotectonic vertical differential motions that affected the central Balkan region at the end of the Early Miocene.

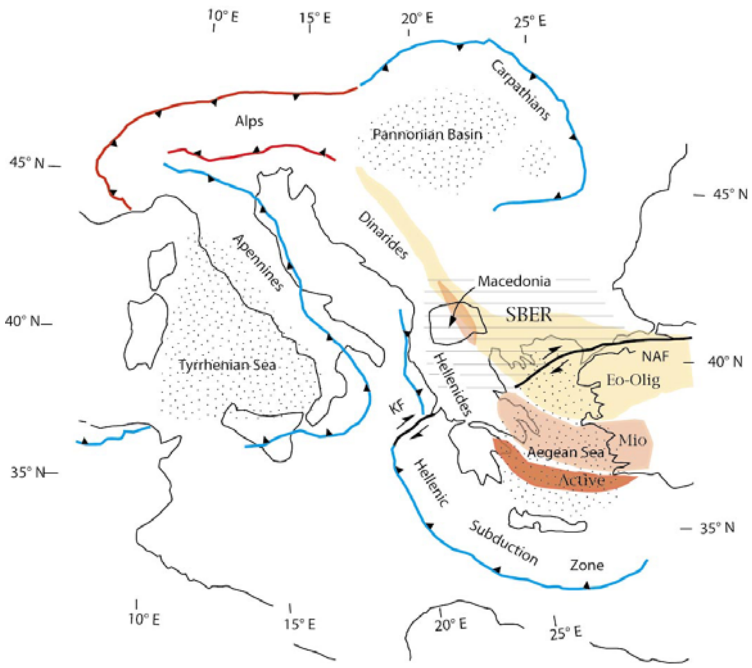
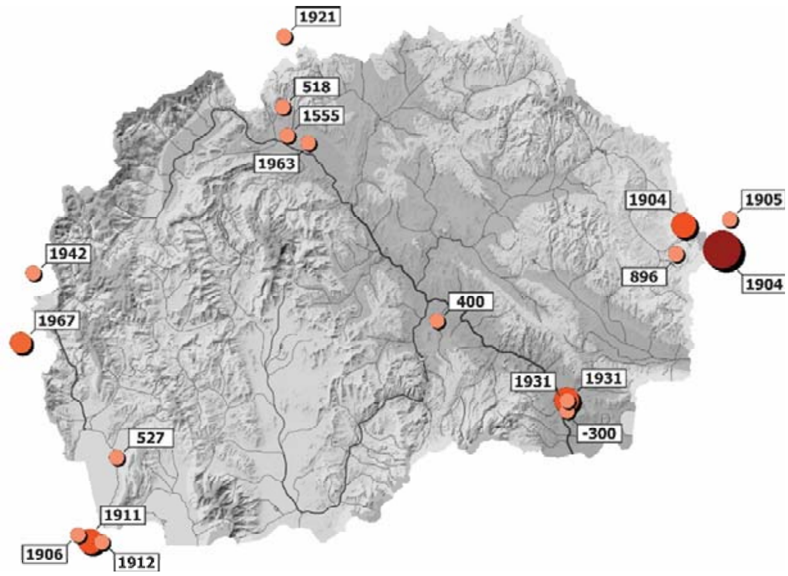


Fig. 1 – Location of the South Balkan extensional regime (SBER) within the eastern European region [according Dumurdzanov et al. (2005)]

The latest published official national earthquake catalogue (Cejkovska et al., 2016) comprises of total 1.756 earthquake events with magnitude M_L (3.0 – 7.5) for the territory bounded with coordinates Lat: 40.60 – 42.40 and Lon: 20.30 – 23.20 related to the period 300 BC – 2014. It is obvious that the strong seismic activity ($M_L \geq 6.0$) is present throughout the history, out of which 12 strong earthquakes happen only in the last century (Fig. 2). According to Dumurdzanov et al. (2016) the epicenters of the most of these earthquakes are located along superimposed faults stretching from E-W to NE-SW direction, as a result of the releasement of the accumulated energy due to the permanent extensional tectonic processes. Two most recognizable earthquakes that affected this territory are the so-called Pehchevo-Kresna earthquake from 1904 (M_L=7.5) and the very well-known Skopje earthquake form 1963 (M_L=6.1).



Year	M_L	I_0
-300	6.10	IX
400	6.10	IX
518	6.10	IX
527	6.10	IX
896	6.10	IX
1555	6.10	IX
1904	6.70	IX
1904	7.50	X
1905	6.10	VIII
1906	6.00	VIII
1911	6.70	IX
1912	6.00	VIII
1921	6.10	IX
1931	6.70	X
1931	6.00	VIII
1942	6.00	IX
1963	6.10	IX
1967	6.50	IX

Fig. 2 – Epicenters of strong earthquakes in N. Macedonia and adjacent regions ($M_L \geq 6.0$)

a) Pehchevo–Kresna (1904), M_L=7.5, I_0=X

b) Skopje (1963), M_L=6.1, I_0=IX

Fig. 3 – Most recognizable earthquakes that affected N. Macedonia

Out of all recognized epicentral areas in N. Macedonia, the most dominant influence on the territory has the epicentral area of Pehchevo-Kresna (border region between Macedonia and Bulgaria). In this epicentral zone in April 1904, an earthquake with the highest up to now observed magnitude (M_L = 7.5) in the continental part of the Balkan Peninsula occurred. This earthquake was largely felt in the Balkan region, accompanied with severe damages as well as secondary earthquake effects such as liquefaction, geysers etc. (Milutinovic, 2017a).

The earthquake, which has the greatest impact, not only as one of the most severe, was the famous Skopje earthquake from July 1963. The earthquake which cause great economic loss to the capital city of Skopje (estimated around 15% of GDP of Yugoslavia for 1962), 1.073 casualties and more than 3.300 heavily injured citizens, trigger awareness of the European and worldwide community for the great importance of prevention and protection of build environment. This earthquake alerted United Nations for the necessity of prioritizing strategies for the disaster risk reduction on global level. Skopje earthquake has put the foundations of European earthquake engineering (Milutinovic, 2017b).

3. Review of available national seismogenic fault databases

On the national level, several available fault databases exist, with inclusion of different sets of seismogenic parameters. Mainly the datasets consists of identification and classification (according to different schemes) parameters, bur very rarely of comprehensive set of parameters related to seismic parametrization. Nowadays, on researchers' disposal are six referent fault databases concerning the territory of N. Macedonia.

3.1. Basic Geological Map (1:100.000)

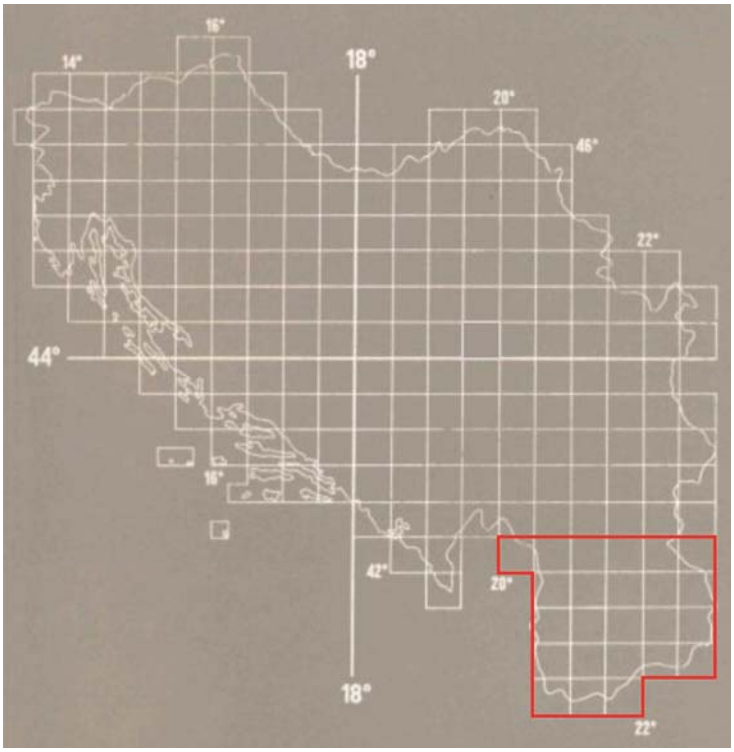


Fig. 4 – Basic Geological Map of Yugoslavia (Federal Geological Bureau, Belgrade) 1:100.000

The 1:100.000 Geological map developed for the territory of Yugoslavia in 70ties is still used as a referent geological source of data. Out of 209 sheets, 24 are related for the territory of N. Macedonia (Fig. 4) made in the period 1967-1984.

On each Geological map sheet given is the distribution of different types of rock and surficial deposits, as well as locations of geologic structures such as faults and folds with a good satisfactory resolution.

The faults on the Geological map, although seems to be presented in detail, doesn't consists information about the character of the faults, which is stated in the corresponding legends as well. According to this map the faults are classified in four main categories: (1) Determined; (2) Covered; (3) Supposed; and (4) Photo geologically determined. According to this, the fault database related to the Geological map consists only of general identification parameters, without considering the seismic classification and parametrization.

Nevertheless, this Geological map represents and still remains a solid base for fault identification.

Geological Survey of the Republic of N. Macedonia, as in charge national institution, at the moment is in the phase of digitalization, harmonization and upgrade of the current Geological Map.

3.2. Arsovski and Petkovski (1975)

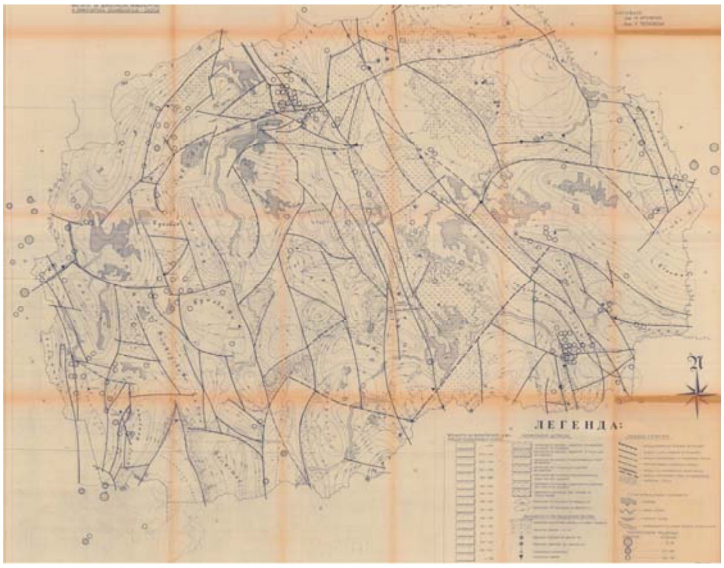


Fig. 5 – Neotectonic Map of Macedonia (Arsovski and Petkovski, 1975) 1:200.000

For the first time, in a comprehensive manner, neotectonic investigations were published by Arsovski and Petkovski in 1975. The publication discusses the geological structure of the region and neotectonic regional aspects. It includes Neotectonic map (1:200.000) (Fig. 5) and Seismotectonic map (1:500.000).

Separate chapter is dedicated to neotectonic fault structures and their seismicity.

The fault structures are classified as: (1) Highly (contrast) expressed in the relief; (2) Weak expressed in the relief; (3) Defined with geophysical methods; (4) Supposed and cover; (5) With horizontal movement; (6) Defined according aero photos; and (7) Transverse Beams.

Although in the text, for some fault structures, it is discussed the historical seismicity, the presented Neotectonic map consists only of general identification parameters, without considering the seismic classification and parametrization. However, this publication should be accepted as referent one, since the forthcoming research presented in Janchevski (1987), Arsovski (1997) and Drogreshka (2018) are based on this study.

3.3. Janchevski (1987)

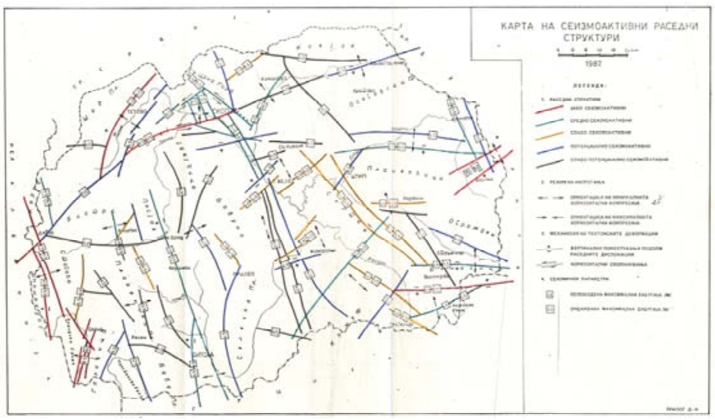


Fig. 6 – Map of Seismic Active Fault Structures (Janchevski, 1987)

Although based on Arsovski and Petkovski (1975), this research without doubt, presents an integral study that focuses on the classification of fault structures by genesis, age and morphology with reference to their seismicity for the territory of N. Macedonia. As for the first time, special attention is dedicated to the classification of faults regarding their seismic potential.

Janchevski (1987) discusses several classifications of seismically active fault structures.

According to the first, based on the specific orientation of the action of the main stress components, seismically active faults are classified into two systems: (1) System with longitudinal stretching direction; and (2) System with transversal and diagonal stretching direction. The accumulation of the seismic energy largely stems from the dominant manifestation of gravitational tectonic processes and less due to the processes of horizontal displacement and reverse slanting, so the seismic faults are classified as gravitational (normal faults) and rarely faults with horizontal displacements (strike slip faults) and reverse faults (Janchevski, 1987).

As one of the most important issue concerning this study is the classification of faults by maximal historic magnitude as well as by an estimation of maximal expected magnitude for each of the identified seismic active faults.

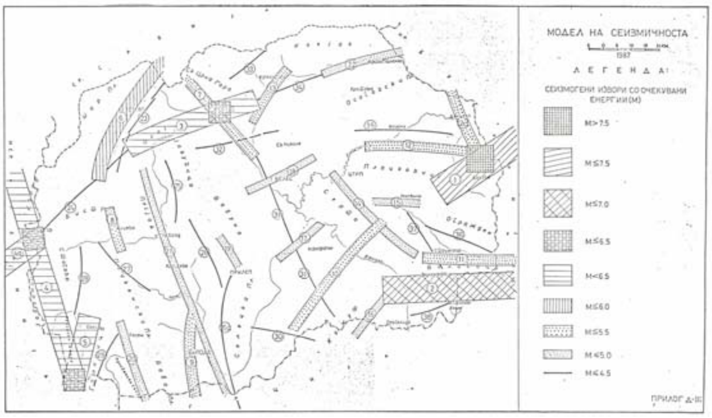


Fig. 7 – Model of Seismicity (Janchevski, 1987)

According to the value of maximal expected magnitude, the fault structures are classified into five categories according their seismogenic potential: (1) Strong (M≥6.0); (2) Medium (M=5.0-6.0); Weak (M=4.5-5.0); Potentially active (M=4.0-4.5) and Potentially weak (M ≤ 4.0) (Fig. 6).

It must be pointed out, that, that for the first time based on the presented fault parameters, the model of seismicity is proposed (Fig. 7).

Summarizing the results of the complete previous research about defining the seismic potential of the territory of N. Macedonia as a seismoactive region, in this model a qualitative and spatial distribution of seismogenic sources is presented resulting from extensive field-cabinet research, past earthquake data, and some general theoretical and practical assumptions. The basic division in categories is made according to the criteria of the importance and the role of fault structures as main carriers of tectonic processes. The seismogenic sources are classified based on the expected energies of the future earthquakes. According to the proposed model of seismicity, we have three respective categories: (1) First order (M>6.0); (2) Second order (M≤6.0) and (3) Third order (M≤5.0). For each defined source (Fig. 7) appointed is the value of maximal expected magnitude.

It is worth to be mentioned that in terms of their importance and size Janchevski (1987) categorizes the fault structures in three categories: first, second and third order category. There is a classification based on the age of the faults and also for certain seismically active fault structures in this database is given an estimation of the angle of the fault plane (Dip), indication for direction of movement, their exposition in the relief (where most of the faults along the entire length are highly expressed-contrasted in the relief, a smaller proportion are moderately expressed and there are also faults that are poorly expressed in the relief), and information about certain faults as a supply channels of volcanic activity or supply channels of thermos-mineral springs, etc.

From the standpoint of the authors of this paper, not enough attention is dedicated to this research by other researchers, more because Janchevski (1987) presents unique and systematic set of fault parameters, especially related to their seismogenic characteristics.

3.4. Arsovski (1997)

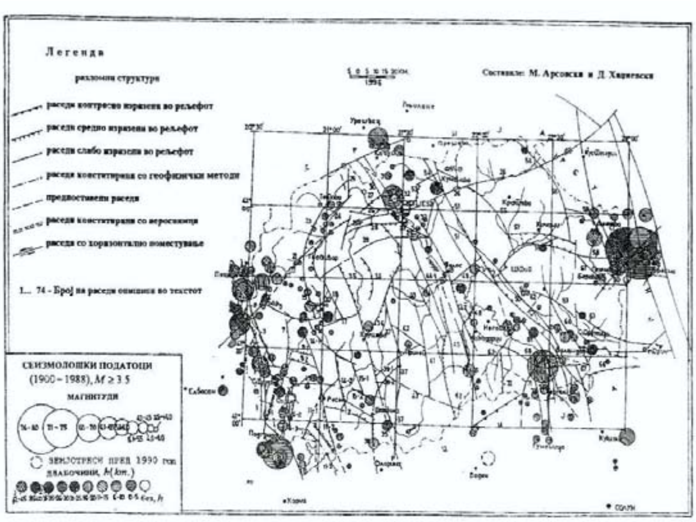


Fig. 8 – Seismotectonic Map of Macedonia (Arsovski and Hadzievski, 1996)

This research published as a book, although the most cited, in the domain of characterization of fault structures is completely based on the research presented in Arsovski and Petkovski (1975). No any major differences or upgrade was made.

The fault structures are classified very similarly as in Arsovski and Petkovski (1975) as: (1) Highly (contrast) expressed in the relief; (2) Medium expressed in the relief (3) Weak expressed in the relief; (4) Defined with geophysical methods; (5) Supposed; (6) With horizontal movement; and (7) Defined according aero photos.

No any seismic classification and parametrization is proposed.

So, in terms of seismicity, presented data are limited and mainly descriptive. In the presented seismotectonic map given in Arsovski (1997) (Fig.8) the spatial distribution of earthquake epicenters is given together with the important seismogenic faults where information about larger historical earthquakes and their magnitude, hypocenter depth and intensity are discussed in the text as part of the explanation given for each epicentral zone.

3.5. Dumurdzanov et al. (2005)

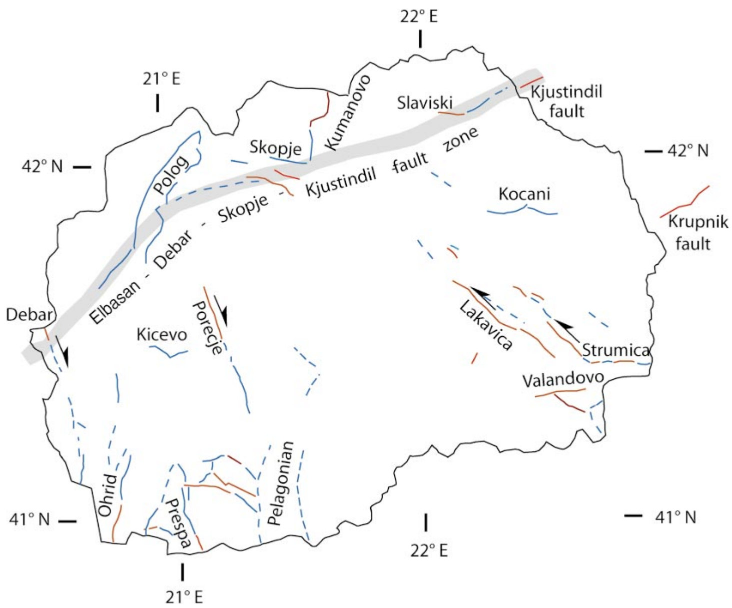


Fig. 9 – Active and young (late Pleistocene) faults of Macedonia (Dumurdzanov et al., 2005)

The research presented in Dumurdzanov et al. (2005) is the contemporary work related to the Cenozoic tectonics of Macedonia and its relation to the South Balkan extensional regime. The authors in separate section discussed active and young (quaternary) faults.

Active faults are classified in three categories: (1) Faults with evidence for active displacement (scarps or deflected rivers); (2) Faults with well-developed morphological evidence for recent activity; and (3) Faults with weak morphological evidence for recent activity (Fig. 9).

The location of active faults is based on studies related to slow slip rates on faults (<1 to ~2 mm/year) as determined from GPS studies, low seismicity and long recurrence intervals (Dumurdzanov et al., 2005).

The location of active faults is also marked by seismic activity, although the location of earthquakes relative to known faults is not always clearly established, and much more detailed studies of the seismicity was recommended. This study for certain identified faults discusses also other parameters such as type of fault, dipping angle, and maximum occurred magnitude.

The importance of this study, as well as related studies by Burchfiel et al. (2006) and Burchfiel et al. (2008), focus the attention on the seismicity of faults dominantly influenced by the SBER (South Balkan Extensional Regime) as the main carriers of the strong seismicity in N. Macedonia.

3.6. Drogreshka (2018)

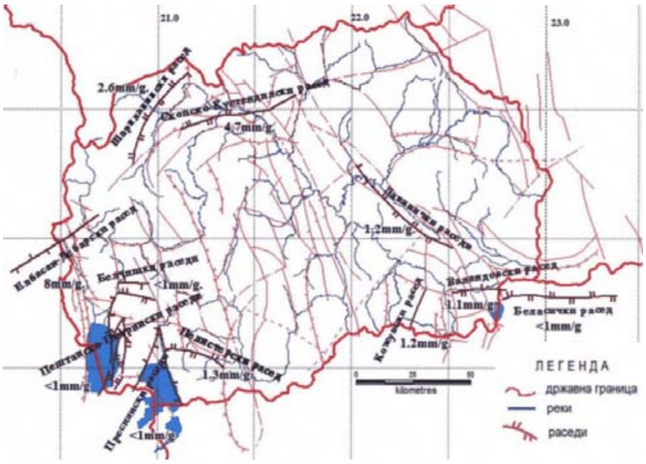


Fig. 10 – Average velocities of some active faults in N. Macedonia (Drogreshka, 2018)

The latest study by Drogreshka (2018) is related to application od dislocation theory in the definition of epicentral areas and tectonic conditions in the territory of N. Macedonia.

Considerable contribution made by this research is the creation of the FPS (Fault Plane Solution) database that consists of 57 mechanisms related to earthquakes with $M_L \geq 4.0$ for the period 1960-2010, as a solid base for typological classification of active faults. The focal mechanisms are determined using the signs method of the P wave which depends only on the first appearance of the seismogram in the far field.

In the final step of this study, the average velocity of the tectonic relative displacement (slip velocity) of the faults is determined.

This is done for eleven of the most active faults in the territory of N. Macedonia that have manifested considerable seismic activity in the last 50 years (1960-2010), using the Brune method that uses the sum of seismic moments of a sufficiently large number of earthquakes (from weak to strong) in a given period of time and their fault surfaces. The average slip velocity for determined faults is shown in the range of <1 – 8mm/year (Fig. 10).

4. Identified gaps and inconsistencies

Detailed analysis of the available national fault databases as presented in Chapter 3, shows that none of them comprises of all relevant state-of-the-art seismicity parameters, needed for reliable seismic hazard definition. The most comprehensive database as of now is the one given by Janchevski (1987) (Chapter 3.3). The databases presented in the Basic Geological Map (1:100.000) (Chapter 3.1), Arsovski and Petkovski (1975) (Chapter 3.2) and Arsovski (1997) (Chapter 3.4) although containing valuable geological and tectonic information, does not offer a consistent and harmonized set of seismic fault parameters. The latest research presented in Drogreshka (2018) should be considered as valuable in the domain of fault classification and slip rate determination.

Regarding the latest European research, the fault database (EDSF) developed in the frame of FP7 EC Project SHARE (2013) presented in Basili et al. (2013) contains only faults that are deemed to be capable of generating earthquakes of magnitude equal to or larger than 5.5 and aims at ensuring a homogeneous input for use in ground-shaking hazard assessment in the Euro-Mediterranean area. Although N. Macedonia wasn't SHARE project partner, for the territory of N. Macedonia are assigned certain number of seismogenic faults with all the corresponding state-of-the–art seismicity parameters. Although comprehensive by its structure and content, this database is created with larger regional resolution and contains information only to seismogenic faults that may be capable of generating earthquakes with magnitude ≥ 5.5, which limits the overall fault modeling excluding the faults that are capable of generating the earthquakes with magnitude 4.0 – 5.5. Nevertheless, this database should be considered as a recent European effort in the field of fault parametrization and should be taken into account in the further research.

Schematically presented, identified gaps and inconsistences are systemized in Table 1.

Table 1 – Available active faults database properties

Database:		**(3.1)**	**(3.2)**	**(3.3)**	**(3.4)**	**(3.5)**	**(3.6)**	**SHARE**
General Identification		●	●	●	●	●	●	●
General Classification		●	●	●	●	●	●	●
Parametrization	Length	●	●	●	●	●	●	●
	Width			○				●
	Strike	●	●	●	●	●	●	●
	Dip			○		○		●
	Rake							●
	Slip rate						○	●
	Mmax			●				●
● Information for all faults in the database ○ Information for selected faults in the database								

5. Conclusions and recommendations for future research

It is of outmost importance, for the territory of N. Macedonia, to be compiled and proposed state-of-the-art comprehensive fault database composed of all potentially seismic active faults capable of generating magnitudes $M_L \geq 4.0$. The database should be based on contemporary standards for definition and characterization of active faults. Special attention should be devoted to Quality Assurance and the characterization of uncertainties and of multiple interpretations, to ensure a homogenous input for use in hazard assessment. This implies that the research to be done will have a key role in the scientific research domain especially in the field of the seismic hazard analysis including both probabilistic and deterministic, since both at the very beginning require characterization and parametrization of all potentially active seismic sources. The research will also have a practical direct application in the frame of new seismic design regulations (codes), since N. Macedonia is in a process of implementation of the European design regulation (Eurocodes) where the data on seismic fault parameters (location, expected magnitude, slip rate activity) are clearly needed for generation of National Annexes related to EC-8 Part 2 (3.2.2.3) and EC-8 Part 5 (11.2.2).

Some of the required data needed for the development of the contemporary comprehensive fault database includes: extensive study on historical seismicity, available geological data, tectonic regime data, modern geological data, reliable seismological data, topographic data, morphological characteristics, fault plane solution and focal mechanism databases, stress data and stress components orientation, field research and surveys, geological surveys, in-depth geophysical research, stratigraphic surveys, geodetic deformation rates, etc. In the case of limited fundamental geological and geophysical investigations, it is of outmost importance that also the alternative novel techniques and methodologies should be taken into consideration, such as using of GPS, GNSS, satellite imagery data etc.

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