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ORIGINAL ARTICLE

Seismotectonic model backing the PSHA and seismic zoning of Republic of Macedonia for National Annex to MKS EN 1998-1:2012 Eurocode 8

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Abstract The seismicity in Macedonia is associated with recent tectonic movements along normal faults. The normal fault tectonics is a consequence of extensional processes that started at the end of the Early Miocene, which affected the larger part of the Balkan region and still is present today. These vertical differential faulting processes, distinguished also as neotectonic, divided the terrains into uplifting (horsts) and subsiding blocks (grabens). The movements along some of those faults are active even today, particularly along the superimposed faults stretching east-west (EW) to northeast-southwest (NE-SW), which transversally cross the geological units and tectonic structures, representing areas of dominant seismic activity in Macedonia. The seismic activity of destructive nature, which affects the territory of Macedonia, is modeled by 10 seismotectonic zones with predominant EW and NE-SW orientation. With the proposed new seismotectonic model, we have fundamentally redefined the existing seismicity models of Macedonia. The paper presents and discusses in all necessary details the construction and elements of the seismotectonic model developed and adopted by Milutinovic et al. (2016) for the development of a seismic zoning map of Macedonia for National Annex FN MKC EN 1998-1:2012/NA:2018 to MKS EN 1998-1:2012 Eurocode 8.

Keywords Seismotectonic zoning · Seismic hazard · Active faults · National Annex to Eurocode 8 · Macedonia

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1 Introduction

The territory of the Republic of Macedonia and the bordering countries (by alphabetic order: Albania, Bulgaria, Greece, Serbia-south) are among the most seismically active regions of the Balkan Peninsula. Historically, it has been affected by a number of moderate, strong, and major earthquakes associated with damaging intensities reaching IX to X degrees of MSK-64 seismic intensity scale.

The process of seismic hazard assessment for the territory of Macedonia dates back to the mid of the last century and has evolved along with the seismic zoning maps accompanying seismic design codes (SDC) and related technical rulebooks and regulations in effect and/or based on numerous national and international research projects in the field.

The Skopje earthquake of 1963 pointed to inconsistencies and weaknesses in certain segments of the regulations of 1948, which was the main reason for passing the PTP-GvSP64 rulebook in the 1964 year. Due to the same reasons, following the 1979 Montenegro earthquake, in the 1981 year, the PTP-GvSP64 (1964) was replaced by PIOVS81 (1981) rulebook.

The PTP-GvSP64 (1964) over the entire period of its enforcement and PIOVS81 (1981) until the 1982 year as well, were accompanied by seismologic map of Yugoslavia (Mihailovic 1950). From 1982 to the 1996 year, PIOVS81 (1981) was accompanied by provisional seismic zoning map of Socialistic Federal Republic Yugoslavia, abbreviated in the following by SFRY (Official Gazette of SFRY No. 49/82), based on a statistical analysis of known earthquakes that had struck the territory of Yugoslavia in the past.

In 1996, a set of probabilistic seismic zoning maps in terms of maximum expected MCS intensities were associated with PIOVS81 (1981). Maps, in scale 1:1,000,000, developed for return periods (RP) of 50, 100, 200, 500, 1000, and 10,000 years (RP50 to RP10000), based on the assumption that RP and the time span are the same, thus with 37% of non-exceedance probability, covered the entire territory of SFRY with isolines of seismic intensity drawn with the accuracy of ± 5 km. The RP500 map (Official Gazette of SFRY No. 52/90) was prescribed for the design of buildings classified into II and III categories (all residential and other buildings not classified by PIOVS81 (1981) as essential structures and/or facilities). RP500 crop for Macedonia that is still in effect is presented in Fig. 1a.

Macedonia is presently in the process of adaptation and adoption of the Eurocodes, particularly MKS EN 1998-1:2012 Eurocode 8, which defines the format and the procedure of the definition of seismic design effects upon structures. In that regard, Milutinovic et al. 2016 developed seismic zoning maps that comply with EN 1998-1:2004 requirements in terms of (1) reference peak ground acceleration on type A ground (a_{gR}) and (2) reference return periods (T_{DLR} and T_{NCR}). Subscripts DLR and NCR stand for the seismic action corresponding to damage limitation ($T_{DLR} = 95$ years, or RP95 in the following) and no-collapse ($T_{NCR} = 475$ years, or RP475) requirements, respectively.

The RP475 (or 50 years with $P_{NCR} = 10\%$ probability of exceedance) seismic zoning map of Macedonia adopted for National Annex FN MKC EN 1998-1:2012/NA: 2018 to MKS EN 1998-1:2012 Eurocode 8 is presented in Fig. 1b. It divides Macedonia into five equally spaced a_{gR} seismic zones (Z1 to Z5), ranging from $a_{gR} = 0.1$ g (zone Z1) to $a_{gR} = 0.30$ g (zone Z5), g = 9.81 m/s/s. A separate color presents each seismic zone. The solid black lines in Fig. 1b are acceleration isolines (in g, g = 9.81 ms^{-2}), i.e., the results of seismic hazard calculations mapped on equidistant acceleration step of 0.05 g. Accordingly, the official title of the map presented in Fig. 1b is "seismic zoning of Macedonia with elements of seismic hazard."

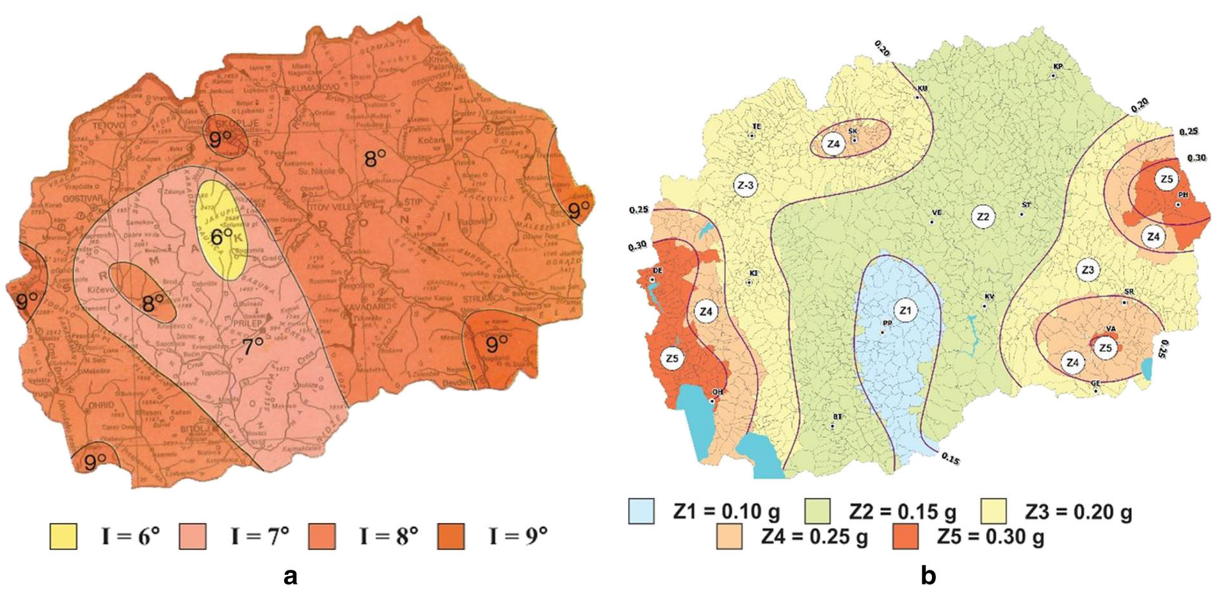

Fig. 1 Seismic zoning maps of Macedonia. **a** 1990 Official RP500 seismic zoning map of Macedonia (Seismological Association of SFR Yugoslavia 1987). **b** RP475 Seismic zoning map of Macedonia, ground-type A, Vs ≥ 800 m/s (Milutinovic et al. 2016). Adopted for National Annex to MKS EN 1998-1:2012 Eurocode 8

The thin lines denote so-called "cadastral municipalities," which divide Macedonia into 1776 land units that comply with historic and current land book records. Such zoning—following the cadastral municipality borders—is in a support of administrative inclusion of location-specific seismic design parameters into document "urbanistic conditions for construction," being issued by municipal urbanistic offices, which, according to law for construction, is a document indispensable for the beginning of any design/construction activities and obligatory for obtaining the construction license.

The seismic zoning map of Fig. 1b is a logic tree combination, with weighting factors of 0.5, of two seismic hazard assessments. The first one is based on the smoothed seismicity model (Kijko and Smit 2012), whereas the second one is based on the seismotectonic model used by Milutinovic et al. (2016) in the development of seismic zoning maps for the National Annex to MKS EN 1998-1:2012 Eurocode 8.

The objective of this paper is to present and discuss in all necessary details the construction and elements of the seismotectonic model adopted by Milutinovic et al. (2016) for development of seismic zoning map of Macedonia for the National Annex FN MKC EN 1998-1:2012/NA:2018 to MKS EN 1998-1:2012 Eurocode 8.

The findings and results of this contribution can contribute to ongoing, e.g., SERA (Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe; http://www.sera-eu.org/home) and/or EFEHR (European Facilities for Earthquake Hazard and Risk; http://www.efehr.org/en/home/), as well as the future seismic hazard studies on the regional level, especially in the domain of definition of active tectonic zones.

2 Seismicity of Macedonia

The territory of the Republic of Macedonia is situated in the central part of southeast Europe, i.e., the Balkan Peninsula. Nowadays, the Balkan Peninsula is in a collision zone between three major plates: Eurasian, African, and Arabian. The active tectonic processes in the eastern Mediterranean are most influenced by the (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 (e.g., Dumurdjanov et al. 2004a, b, c). The genesis of these faults is related to the extension and neotectonic vertical differential motions that affected the Central-Balkan region at the end of the Early Miocene. Some of these faults are active even today and represent active seismic zones. According to the (Burchfiel et al. 2006) available evidence, for the last 2500 years, around 3000 earthquakes with magnitude $M_L = 3.0–7.5$ affected Macedonia (Cejkovska et al. 2016), where the earthquakes before the year of 1900 are historic earthquakes mainly with destructive character.

According to the existing historical records with different reliability and the evidence of earthquake destruction of old towns (Stobi, Skupi, Isar-Marvinci, Heraklea Linkestis, Lychnidos and others), a number of earthquakes of destructive nature and evaluated intensity of IX degrees according to the European Macroseismic Scale (EMS-98) (Grünthal 1998) struck the territory of Macedonia and its adjacent regions prior to 1900 (Table 1, Fig. 2).

In Fig. 2, as well as in Figs. 6, 7, 8, 9, 10, 11, 12, 13, 14, and 15, faults with strong evidence for active displacement (scarps or deflected rivers) and faults with well-developed morphological evidence for recent activity are shown with solid lines, whereas those with weak morphological evidence for recent activity are shown with dashed lines (Dumurdjanov et al. 2004b, c).

Following the installation of the first seismological stations throughout Europe, i.e., after the year 1900, the beginning of the instrumental recording of earthquakes has started. From this period onwards, earthquakes are systematically recorded and cataloged with respect to defined magnitude and intensity scales, with a relatively precise definition of the associated earthquake parameters. In the period after the year 1900, a total number of 13 destructive earthquakes are recorded in the territory of Macedonia and its adjacent areas. The epicenters of most of these earthquakes are located along superimposed faults stretching from EW to NE-SW direction (Table 1, Fig. 2).

Most of the strong earthquakes of Table 1 show normal faulting (e.g., Ritsema 1974; Ranguelov et al. 2008) and are associated by surface coseismic cracking with vertical movements ranging from tens of

Table 1 List of significant earthquakes affecting the territory of Republic of Macedonia and vicinity. (Source: Macedonian earthquake catalog presented in Cejkovska et al. 2016)

Year	Month	Day	M_L	I_0	Epicentral area	Observed and reported effects
Earthquakes before 1900						
−300	-	-	6.05	IX	Valandovo (MK)	
400	-	-	6.05	IX	Gradsko (MK)	
518	-	-	6.05	IX	Skopje (MK)	
527	-	-	6.05	IX	Ohrid (MK)	
896	09	04	6.05	IX	Pehčevo (MK)	
1456	06	16	6.05	IX	Prizren (XK)	
1555	-	-	6.05	IX	Skopje (MK)	
1641	-	-	5.57	IX	Kyustendil (BG)	
1896	02	11	6.33	IX	Korçë (AL)	
Earthquakes after 1900						
1902	07	05	6.50	IX	Assiros (GR)	Destruction, human loss and injury, and ground cracking
1904	04	04	6.70	IX	Kresna (BG)	Massive destructions and surface dislocations
1904	04	04	7.50	X		
1905	10	08	6.10	VIII	Kresna (BG)	-
1906	09	28	6.00	VIII	South of Ohrid lake (AL)	-
1911	02	18	6.70	IX	South of Ohrid lake (AL)	Heavy destruction and human loss and injury
1912	02	13	6.00	VIII	South of Ohrid lake (AL)	-
1921	08	10	6.10	IX	Vitina (XK)	-
1931	03	07	6.00	VIII	Valandovo (MK)	Heavy destruction, human loss and injury, ands ground settlement
1931	03	08	6.70	X		
1942	08	27	6.00	IX	Peshkopi (AL)	-
1960	05	26	6.40	IX-X	Korçë (AL)	Serious damage and loss of life and injury
1963	07	26	6.10	IX	Skopje (MK)	Heavy destruction, human loss and injury, and ground fissures
1967	11	30	6.50	IX	Debar (MK)	Destruction, human loss and injury, and surface faulting
1978	06	20	6.50	VIII+	Thessaloniki (GR)	Extensive damage and loss of life and injury

AL Albania, *BG* Bulgaria, *GR* Greece, *MK* Macedonia, *XK-UN* protectorate Kosovo

centimeters (Thessaloniki earthquake, 1978) up to meters (Kresna-Kroupnik earthquakes, 1904) (Ranguelov et al. 2008).

3 Main tectonic and neotectonic features

3.1 Main geotectonic units

Throughout the long geological history, a number of geotectonic units were formed as a result of polyphase tectonics, sedimentation, and magmatic-metamorphic processes in the wider Balkan Peninsula. The territory of Macedonia is divided by five geotectonic units: Debar Zone (in Fig. 3 denoted by DZ), West Macedonian Zone (WMZ), Pelagonian Massif (PM), Vardar Zone (VZ), and Serbo-Macedonian Massif (SMM). The Pelagonian massif and the West Macedonian zone are part of the Inner Dinarides. The boundaries between the geotectonic units, as presented in Fig. 3, are outlined based on old, pre-neotectonic faults, of dominantly NW-SE orientation, which presently are not seismic active.

The Serbo-Macedonian and Pelagonian massifs represent the Precambrian crystalline mass composed of high-grade metamorphic rocks of different types of gneisses, kyanite-staurolite-almandine micaschists and amphibolites, and products of two granitic intrusions. Over the Proterozoic complexes of metamorphites, there transgressively lie Riphean-Cambrian low-grade metamorphic schists, metabasic rocks, impure marbles, and marbles. Vardar and Western Macedonian zones primarily were formed in the Early Paleozoic from which the

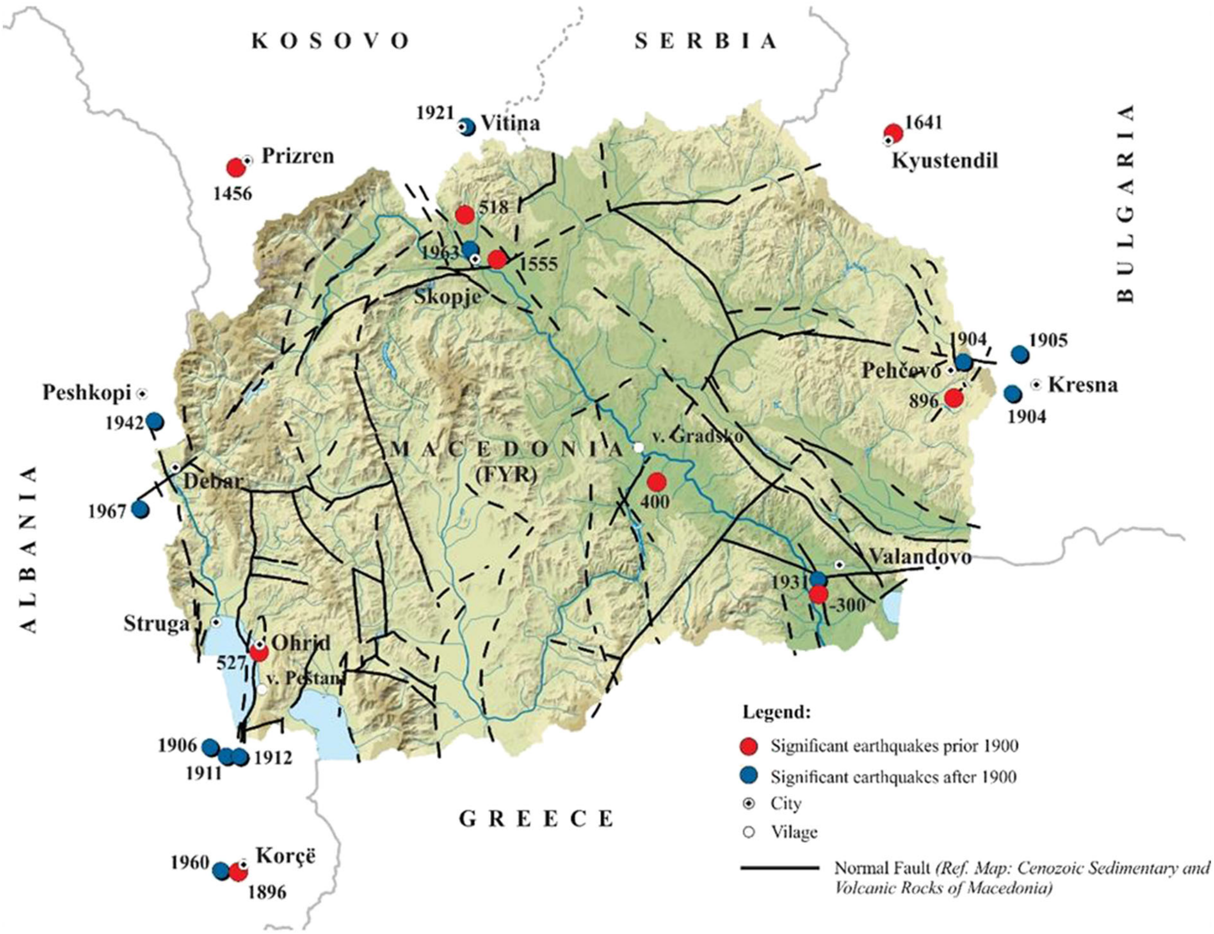

Fig. 2 Location of significant earthquakes in Macedonia and its vicinity (compiled by Salic)

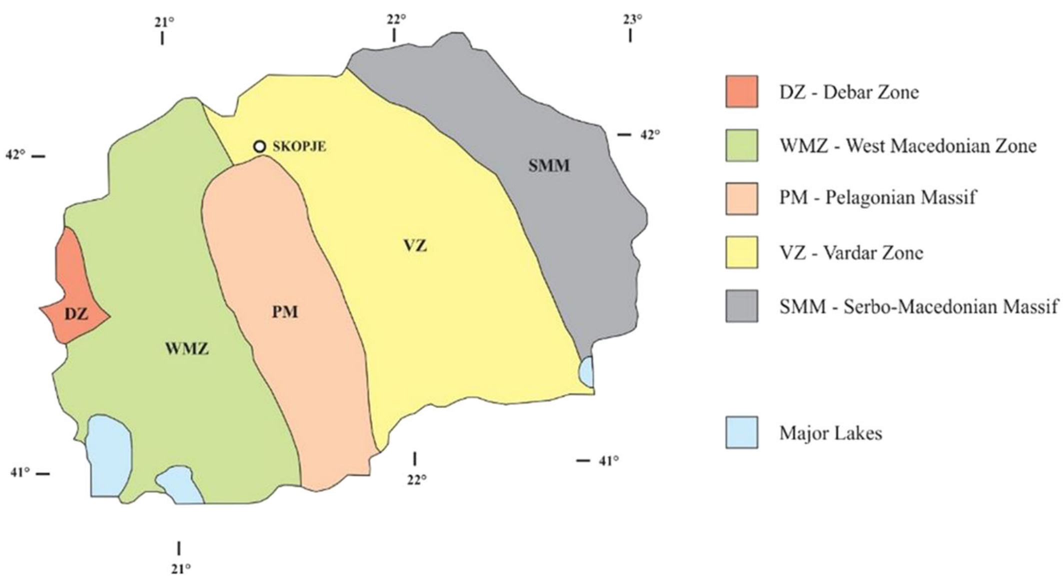

Fig. 3 Schematic representation of geotectonic units in Macedonia (source: Arsovski and Petkovski 1975; Arsovski 1997, reprocessed in color)

Vardar zone in the Early Jurassic was restored as a rift zone. The Debar zone was created by the Laramide compression.

The Serbo-Macedonian massif is composed of high-grade metamorphic rocks (Arsovski and Petkovski 1975; Dumurdjanov 1985-86; Arsovski 1997), i.e., different types of gneiss, micaschist, and amphibolite, which are transgressively overlapped by complex of Riphean-Cambrian low-grade metamorphic terrigenous and basic rocks. The same lithological types are excessively folded and lithologically processed in the later phases of faulting and magmatism, particularly the Hercynian phase and the orogenic granitoids as well as with the more recent Alpine tectonic phases.

In the Pelagonian massif is preserved the primary Proterozoic lithostratigraphic vertical and horizontal zoning as well and its inner tectonic structure (Arsovski and Petkovski 1975; Dumurdjanov 1985-86; Arsovski 1997). In the central part are preserved numerous brachysynclines and domes and brachyanticlines, which consist of the low, homogeneous level of almandine gneisses overlain by the upper level of muscovite and two mica gneiss and migmatite, distene and staurolite micaschists and amphibolite. Over this low gneiss-micaschist complex concordantly lie the Upper Proterozoic complex comprised of a mixed series of albite gneiss, micaschist, and impure marble as well as of marble mass toward the uppermost levels. Intrusions of the Neoproterozoic in metamorphic complex provoked intensive migmatization and feldspatization. The horizontal zoning is characterized by a gradual transition of the metamorphism from the amphibolite facies of the crystalline rocks in the central part to the epidote-amphibolite facies in the peripheral parts of the Pelagonian massif.

The Vardar zone situated between the Serbo-Macedonian massif to the east and the Pelagonian massif to the west was formed in the Early Paleozoic as a primary geotectonic unit. During the Jurassic, it was turned into a rift structure with the development of an oceanic earth crust as remain of the Vardar ocean (Ivanov et al. 1987; Dumurdjanov and Petrov 1992). Today, this geotectonic unit is considered tectonically the most active structure in the Pre-Neotectonic period, i.e., a rift structure of thrusting and overthrusting of reverse faults, of tectonic mélange and so on. In this area, there are preserved tectonic blocks of the Proterozoic age and complexes of the Riphean-Cambrian, Paleozoic, Triassic, Jurassic, Upper Cretaceous, and Upper Eocene-Oligocene age.

The West Macedonian zone is a tectonic element of the Dinarides. It is situated between the Pelagonian massif to the east and Mirdita and Debar zones to the west. The main mass of the zone consists of folded Cambrian-Ordovician low-grade metamorphic complex composed of different schist and metabasite and from Silurian-Devonian anchimetamorphic complex composed of metasandstones, argilloschist, and marbleized limestones, with intrusions of Hercynian granitoid. Considerably less present are transgressive, Triassic terrigenous-carbonate sediments, Jurassic terrigenous-carbonate sediments, and basaltic-gabbroid and ultrabasic rocks.

The Debar zone (Cukali-Krasta zone in Albania) as a tectonic element was created in the Laramide tectonic phase during the Paleocene. In its structure, participate Upper Cretaceous terrigenous and limestone sediments and diapirs of anhydrite-gypsum masses present on Deshat and Stogovo mountains near Debar were overthrusted by Jurassic sediments. In the uppermost parts, there lie relics of transgressive Upper Eocene terrigenous sediments.

During the early tectonic phases of the Alpine orogeny, particularly during the Kimmerian and the Laramide phases, intensive compression in the EW direction took place in the area of the Vardar zone, the Serbo-Macedonian massif, and the West Macedonian zone. During the Upper Cretaceous and Upper Eocene-Oligocene, extension took place in the same direction giving rise to the creation of troughs of Cenomanian-Turonian-Senonian age and trough of Upper Eocene-Oligocene flysch-like and flysch sediments. During the Pyrenean and Savian orogeny phases, compression in the EW direction retook the place.

During these compressions, the contacts between the units and the interior of the units were tectonically considerably active. This is proved by the polyphase intensive folding, reverse faulting, and overthrusting, from E to W, of all existing lithological and tectonic units in the Vardar zone, the Serbo-Macedonian massif, and the West Macedonia zone. Protrusions of tectonic ultrabasites arose between the Vardar zone and the Pelagonian massif and acidic volcanism between the Vardar zone and the Serbo-Macedonian massif as well. As a result of those compressions, all the units of regional and smaller dimensions and regional fault structures are generally oriented in the Dinaride NW-SE direction.

The end of the Savian compression is also the end of the paleotectonic development of the terrains in the central Balkan region. Then, the peneplanation took place and lasted up to the end of the Early Miocene when the Neotectonic phase of development started.

3.2 Neotectonic phase of development

3.2.1 Regional context

The neotectonic movements of the Balkan Peninsula occurred after the last intense thrusting (Early Miocene) and after the Early–Middle Miocene planation (Zagorcev 1992a, b). They were controlled by the extensional collapse of the Late Alpine orogen, and by extension behind the Aegean arc, and were influenced by the complicated vertical and horizontal movements in the Pannonian region. The Balkan mountain and the Dinarian-Hellenic linear neotectonic morphostructure inherited the Alpine orogenic zones and bounded the Central-Balkan neotectonic region. The linear morphostructures were tilted toward the Pannonian and Euxinian basins and the North Aegean trough.

The Central-Balkan neotectonic region has a complicated block structure (horst and graben pattern) dominated by the NNW-SSE Struma and Vardar lineaments and the Middle-Mesta and North Anatolian fault zones. The Struma lineaments consist mainly of normal and right-lateral strike-slip faults. Vertical neotectonic amplitudes along some of the faults reached up to 3–3.5 km, and the thickness of Neogene deposits in the Struma graben complex, up to 1.6 km. Relative to their position in the eastern flank of the Serbo-Macedonian massif, a general tilting of the grabens to the east of about 3 km is recorded (Ranguelov et al. 2008).

The Vardar lineament is located in the western flank of Serbo-Macedonian massif, and accordingly, the orthoplain and the Neogene sediments are dipping west. The thickness of the Neogene sediments in some of the depressions is up to 2–3 km, and the vertical neotectonic amplitudes may be as high as 5 km (Ranguelov et al. 2008). The Vardar and Struma lineaments and Serbo-Macedonian massif form a complicated continental rift structure with maximum subsidence along the lineaments (graben complexes).

Transversal fault zones striking NE-SW are the most important for the development of the Vardar and Struma lineaments and the whole Central-Balkan neotectonic regime. They have been traced at distances of about 100 km. Their intersections with major faults of the Struma and Vardar lineaments are characterized by the most contrasting (3–4 km) vertical neotectonic movements and represent seismotectonic knots of very intense seismicity.

The Middle-Mesta fault zone (lineaments) is traced at a distance of about 300 km in the west-east direction. It is marked by differentiated neotectonic block movements, most contrasting at the northern and southern slopes of the Belasica horst at the intersection of the Serbo-Macedonian massif. The vertical amplitudes reach up to 2–2.5 km. The Middle-Mesta lineament represented the northern boundary of the Neogene marine ingressions from the North Aegean trough. A right-lateral displacement along some of the faults is inferred from the remote sensing imaginary (Ranguelov et al. 2008).

The Earth's crust of the Balkan Peninsula is highly heterogeneous due to former plate motions and continental collisions. The crust of the Serbo-Macedonian massif and Struma and Vardar lineaments is of intermediate thickness: between 30 and 40 km. Subsided into an imperfect rift structure, this area is situated between areas of thickened crust corresponding to the Pelagonian and Rila-Rhodope massif. The most thickened crustal lens of the Rila-Rhodope massif (40–50 km) coincides with a pronounced isostatic anomaly and the most intense (up to 5 mm/a) recent vertical uplift.

The region appears now mostly under crustal extension and is thought to be the northernmost part of the Aegean stretched domain (e.g., Jackson and McKenzie 1988; Armijo et al. 1996; Burchfiel et al. 2000; Meyer et al. 2002). A number of faults cut across the belts and have an imprint in the regional topography. The faults have sharp traces on the satellite imagery, display typical normal fault morphologies, and bound small hanging wall basins filled with Tertiary sediments. The faults are short, a few tens of kilometers long at most, and segmented. In contrast to the large fault systems in central Greece and western Turkey, and west and east of the Aegean Sea, the faults north of the Aegean are thus smaller and distributed throughout the region. They strike mostly west-northwest (W-NW) to EW in Northern Greece and in the Republic of Macedonia where they cut at right angles across the fabric of the Dinarides-Hellenides belts (Meyer et al. 2002).

The regional structural trends are outlined by the topography and by the courses of large rivers, such as the Vardar, the Struma (Strymon), the Mesta (Nestos), and the Maritsa, all running to the south. The fabric is almost NS in the Dinarides and the Hellenides, rather NW-SE in the Vardar suture zone and the Rhodope, and turns to EW in the Balkan (Meyer et al. 2002). These belts have formed mainly from the late Mesozoic to the early Neogene as the crustal shortening took place between the converging Africa and Eurasia plates (e.g., Dewey et al. 1973).

The Central-Balkan at present is affected by the South Balkan Extensional Regime (SBER) (Fig. 4) dominantly influenced by recent movements of the North Anatolian plate. The direction of these movements is to the southwest with the amplitude of about 20–25 mm year^{-1} (e.g., Burchfiel et al. 2006; Ranguelov et al. 2008). Due to these relatively fast movements, the surface blocks of the Central Balkan crust are moving in the same direction. As a result—the openings (clearly expressed grabens filled by the rivers running to the south—such as Vardar, Struma, Mesta, and Maritza, including all other smaller riverbeds located between Vardar and Maritza) show a clear extension to the north-south direction. The recent GPS measurements show relatively small amplitudes—up to 2 mm year-1, according to Ranguelov et al. (2008) or 2–4 mm year-1 (Kotzev et al. 2008).

The 1996–2000 GPS data and related studies (e.g., Burchfiel et al. 2006; Kotzev et al. 2008) allowed the delineation of the northern boundary of the Aegean extensional province only within the central Bulgaria, which passes through it along an approximately east-west trend separating a northern region with insignificant motion relative to Eurasia from a southwestern region characterized by E-W extensional grabens and increasing southward velocities between 2 and 4 mm/year. Elsewhere, the location and nature of the boundaries of the Aegean extension are poorly defined (Kotzev et al. 2008).

Jouanne et al.'s (2012) work identifies the fault zone forming the boundary between Dinarides and Albanides, as the northern limit of an area, including Albania and western Greece, affected by a clockwise rotation relative to Apulia and also the northern limit of the area (inner Albanides, Macedonia, and Bulgaria) affected by southward motion relative to Apulia and stable Eurasia. Continuous Global Positioning System (CGPS) data also confirm that the external-inner Albanides transition is the western border of the domain (inner Albania, northern Greece, Macedonia, and Bulgaria) affected by southward displacements relative to stable Eurasia and Apulia, whereas the fault zone forming the boundary between Dinarides and Albanides constitutes probably its northern limit.

Underlined by the displacement of the Peshkopia CGPS continuous station in Albania and by stations in Macedonia, Jouanne et al. (2012) localized the northern boundary of SBER between the CGPS Peshkopia and Sarajevo (Bosnia and Herzegovina) stations that respectively show a southward and a northward component in a Eurasian fixed frame and suggested the Scutari (Shkoder)-Peja fault as a good candidate for the western north boundary. The suggestion is in good agreement with the work of Markovic and Djokovic (1995), and others as well, which, based on geologic data, suggests that the northern border of extension probably passes through central Serbia and Montenegro (a bit northern

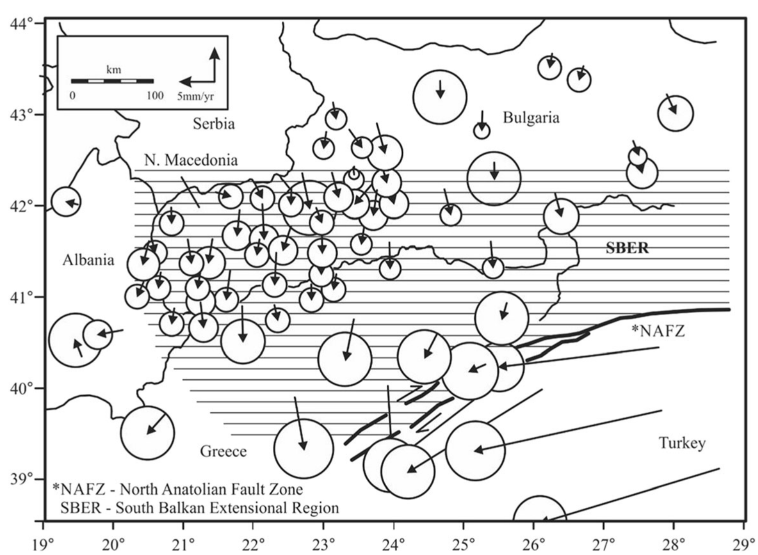

Fig. 4 GPS results for Macedonia and their importance for the South Balkan Extensional Region (SBER) (source: Burchfiel et al. 2006)

than the Scutari-Peja transverse structure) where a series of NE to NS-trending strike-slip faults may be related to grabens formed as pull-apart structures.

Based on a developed FPS database, the BSHAP Project (Mihaljevic et al. 2017) confirms the extensional regime in eastern Albania and Macedonia (Fig. 4) and supports the Jouanne et al. 2012 findings that transverse Scutari-Peja fault zone is a good candidate for a northern, and that external-inner Albanides transition is the western border of the region (inner Albania, northern Greece, Macedonia, and Bulgaria) affected by SBER regime.

3.2.2 National Context

The first research related to the neotectonics of Macedonia was carried out by Arsovski and Petkovski (1975) resulting in the construction of the first neotectonic map of Macedonia. Jancevski (1987) proposed a classification of faults by genesis, age, and morphology. Neotectonic and seismotectonic studies for the territory of Macedonia were also carried out in the frame of different regional and national projects realized by the Institute of Earthquake Engineering and Engineering Seismology (IZIIS) in Skopje. The evolution of the Neogene-Pleistocene basins and Cenozoic tectonics of Macedonia and its relation to the South Balkan Extensional Regime (SBER) have been investigated by Dumurdjanov et al. (2004b, c, 2005).

According to the results from the researches mentioned above, the neotectonic development of the terrains in Macedonia and the central Balkan started at the end of Early Miocene when the region was affected by the extensional regime. These extensional processes were associated with the intensification of the subsidence of the Mediterranean Sea and the formation of the Paratethys Sea in the northern part of the Balkan Peninsula with the EW orientation. This process initiated the change of the geodynamic conditions in the Balkan region. The central Balkan, situated between the Paratethys and the Mediterranean Seas, was affected by intensive extension in a NS direction, i.e., transverse to the general orientation of the earlier geotectonic units.

The results from the GPS measurements in Macedonia (Fig. 4) show that the entire territory is moving toward the S-SE with a speed of 2 to 4 mm year^{-1} (Burchfiel et al. 2006). In the new created geodynamic conditions under the NS extension, the terrains of the Balkan Peninsula between Mediterranean and Paratethys depressions were affected by vertical differential movements. The newly formed normal faults of regional and local character initiated the segmentation of the terrains into uplifting and subsiding blocks. Namely, along some of the faults, the terrains were uplifted, giving rise to horsts, while along the same faults or other normal faults, the terrains subsided and generated grabens that gradually turned into freshwater lakes.

With respect to their location, the newly formed neotectonic regional faults, the horsts, and the grabens are not exclusively related to the area of the existing geotectonic units, but they have superimposed over two or more geotectonic units or at their boundaries as well as within the units themselves.

Neotectonic faults mostly are created as new ruptures along old faults, but due to the NS extensional regime, in the form of superimposed faults with EW to NE-SW orientation that transversally intersects several geotectonic or smaller geological units. The orientation of the neotectonic horsts, grabens, and regional faults in the eastern, central, and part of western Macedonia are dominantly of EW and NE-SW direction, while in the west part of Prespa-Ohrid-Debar, they are NS to NW-SE-oriented, rarely NE-SW and EW.

Different ages of the freshwater sediments in different grabens show that the neotectonic processes were carried out in several phases and with a different intensity. Dumurdjanov et al. (2004a, b, c) distinguish five phases of intensified tectonic motions: (1) Badenian-beginning of the Sarmatian; (2) Upper Sarmatian-Meotian; (3) Upper Meotian-Pontian (Turolian, Pikermian); (4) Pliocene; and, (5) Pleistocene, contributing to the creation of new grabens and extension of the existing ones. During these cycles, 26 basins of the Middle Miocene to Quaternary age were formed (Fig. 5, Dumurdjanov et al. 2004a, b, c).

4 Seismotectonic zoning and characteristic of Seismotectonic zones

The seismotectonic zoning is performed for the area bounded by longitudes (39.80°–43.30°) N and latitudes (19.30°–24.20°) E. It includes territories being at the distance of 100 km from the most eastern/western and northern/southern Macedonian border points bounded within longitudes (40.60°–42.40°) N and latitudes (20.30°–23.20°) E.

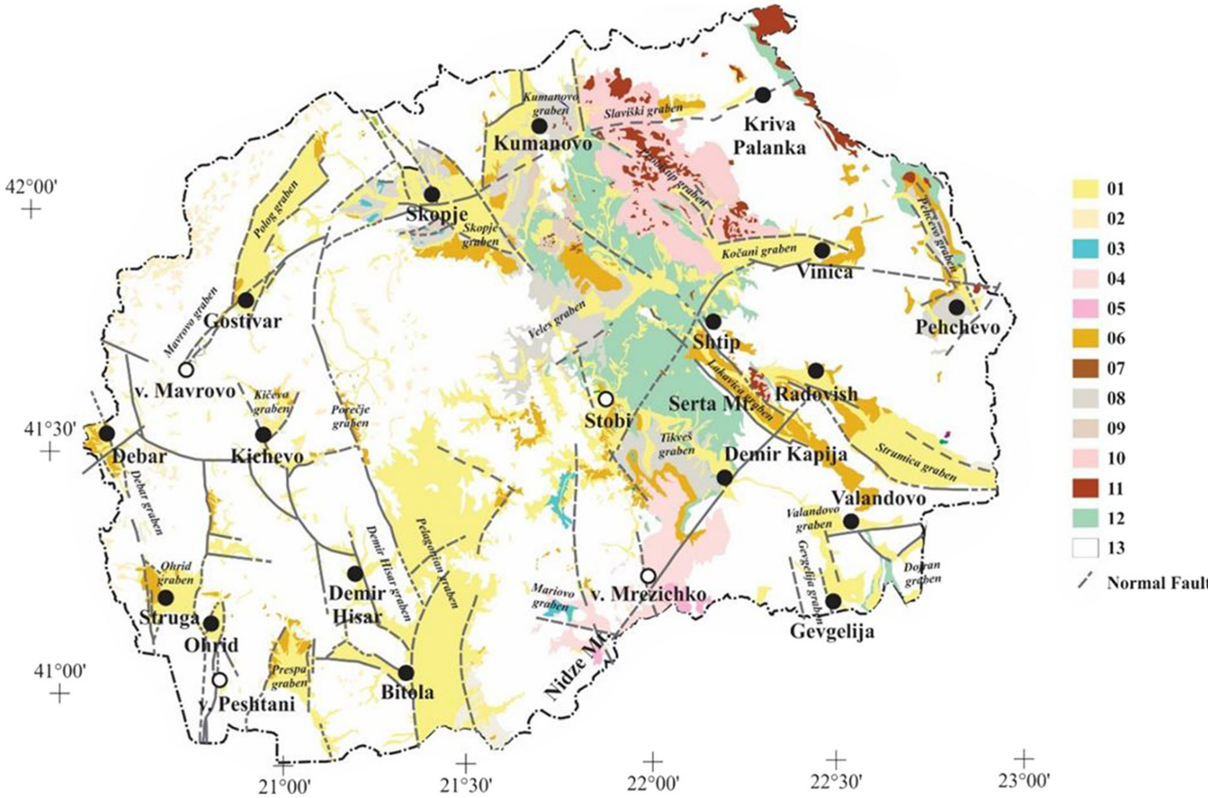

Fig. 5 Map of neotectonic grabens and main active seismic faults in Macedonia (source: Dumurdjanov et al. 2004a, b, c, reprocessed in color). Quaternary: 1-alluvial, proluvial, and limnic sediments, 2-glacial sediments, 3-travertine deposits; Pliocen-Quarternars: 4-aglomerates, tuff, sandstones, and travertine; Pliocene: 5-volcanic rocks (quartz latite, latite, etc.) and 6-continental sediments (gravel, sand, and silt); Miocene-Pliocene: 7-calcalkaline basalt; Miocene: 8-Late Miocene freshwater sediments and 9-Middle Miocene freshwater sediments; Oligocene-Miocene: 10-pyroclastic rocks (breccias, tuff etc.) and 11-volcanic rocks (andesite, latite, quartzlatite, dacite etc.); Late Eocene-Oligocene: 12-flysch-like and flysch sediments and 13-Pre-Eocene complex rocks; Structural symbols: ── normal faults

4.1 Seismotectonic zoning

The locations of the occurred earthquakes in Macedonia are associated with faults of different neotectonic ages that have been active for the last 10,000 years. Such recent motions that are categorized as recent tectonic motions cause a release of accumulated energy in the form of the weak to moderate earthquakes, but also and often, strong ones, most frequently along the superimposed faults intersecting all of the pre-Neogene geological complexes and tectonic structures of Fig. 3.

The seismicity of Balkans and Macedonia (Macedonia: e.g., Arsovski and Petkovski 1975, Jancevski 1987; Arsovski 1997; Dumurdjanov et al. 2005; Burchfiel et al. 2006; Albania: e.g., Aliaj 1988, 1989; Aliaj et al. 2004; Sulstarova et al. 2000; Ormeni et al. 2017a; and, Bulgaria: e.g., Milev and Vassileva 2007) and Balkan tectonics and geologists relate to seismotectonic (in literature also termed as seismic) zones defined on the base of spatial distribution of seismicity and the expected seismic source zones. Each seismotectonic zone is characterized by its own specific regional tectonic, seismic, and geological context. The seismic source zones, or seismic sources (Fig. 7), are represented by spatio-temporal characteristics of active fault structures comprised by the zone.

The seismotectonic zones were determined from consideration of the present-day SBER tectonic regime of the region, as discussed above, and the subset of the Macedonian earthquake catalog (Cejkovska et al. 2016) which provided the location of epicenters of strong and concentration of weak to moderate earthquakes that cluster along and around a number of active tectonic elements. From these considerations, the regional seismicity of concern to Macedonia, (Milutinovic et al. 2016), is modeled by 10 active seismotectonic zones, as presented in Table 2 and Fig. 6 (zone coordinates are available from authors). Each modeled zone is characterized by the existence of one or more normal faults or "relay" fault structures that, together with local diagonal and/or parallel faults, are carriers of continuous zonal seismic activity, with a potential for generating destructive earthquakes in the future. The adopted seismotectonic zoning includes redefinition of the long-standing hypothesis that the seismicity of central and SE Macedonia is controlled by longitudinal (NS to NW-SE) faulting in the Vardar seismogenic zone, rather than that it is one of the weakest tectonic units with seismicity particularly expressed in the areas of intersection of reactivated old faults stretching in Vardar direction with neotectonic faults that predominantly stretch in a transverse (EW to NE-SW) direction.

The seismotectonic model (Fig. 7) adopted for the probabilistic seismic hazard analysis (PSHA) of Macedonia encompasses three complex seismotectonic zones (zones 1, 2, and 3) and seven (zones 4 to 10) seismotectonic zones that encompass only the seismic sources constituting them.

The adopted seismotectonic zones with minor exceptions are associated with the occurrence of past and future earthquakes of larger magnitudes. The remaining national territory is considered the territory of lower seismic potential, i.e., the background seismotectonic zone. The seismicity potential of zones located in the southwestern part of the country originates from normal faults stretching in NE-SW (Kičevo, zone 4), NW-SE (Ohrid-Struga, zone 7 and Bitola-Prespa-Demir Hisar, zone 5), and NS (Peštani-Korçë, zone 8) directions. In the other four zones (zones 1, 2, 3 and 6) that belong to the northern, the eastern, and the central part of Macedonia and surrounding regions (Zones 9 and 10), the carriers of seismicity are the relayed normal faults and other normal faults stretching exclusively in EW to NE-SW direction.

The seismotectonic zone 1 is of major importance for any PSHA assessment of Macedonia, since its seismicity affects the capital Skopje and several densely populated regions, including towns of Kriva Palanka, Kumanovo, Gostivar, Tetovo, and Debar, altogether counting for about 60% of the Macedonian population.

Please note that for all statements which are not explicitly referenced hereinafter, Milutinovic et al. (2016) shall be assumed.

4.2 Characteristics of seismotectonic zones

This zone (Fig. 8) represents a superimposed fault zone that, from east to west, transversally intersects the

Table 2 Characteristic parameters of adopted seismotectonic zones

Zone	Seismotectonic zone name	Area (km^2)	Orientation	maxMw occurred	maxMadopted
Z1-1	Kyustendil-Kriva Palanka-Kumanovo-Skopje-Gostivar-Mavrovo-Debar-Elbasan-Vlorë	9652.21	EW to NE-SW	6.5	6.9
Z1-2				5.7	6.1
Z1-3				6.1	6.5
Z1-4				5.6	6.1
Z2-1	Kresna-Pehčevo-Vinica-Štip-Gradsko	4369.02	SW-W-E	4.9	5.8
Z2-2				4.6	5.8
Z2-3				7.4	7.4
Z3-1	Valandovo-Gevgelija	2998.12	WNW-E	6.7	6.9
Z3-1				4.8	5.8
Z4	Kičevo	1340.62	ENE-WSW	4.8	5.8
Z5	Bitola-Prespa-Demir Hisar	1480.35	WNW-SE	5.6	6.1
Z6	Nidze-Mrezhichko-Demir Kapija-Serta-Radoviš	3219.34	NE-SW	5.6	6.1
Z7	Ohrid-Struga	1287.14	NW-SE	6.1	6.1
Z8	Peštani-Korçë	1101.15	NS	6.7	6.9
Z9	Prizren	3408.41	NW-SE	6.1	6.3
Z10	Uroševac (Ferizaj)	3284.61	NW-SE	6.1	6.5
Z11	Background, 5 zones	126,802.38	-	5.2–6.3	5.5–6.3
Total		158,943.35	-		

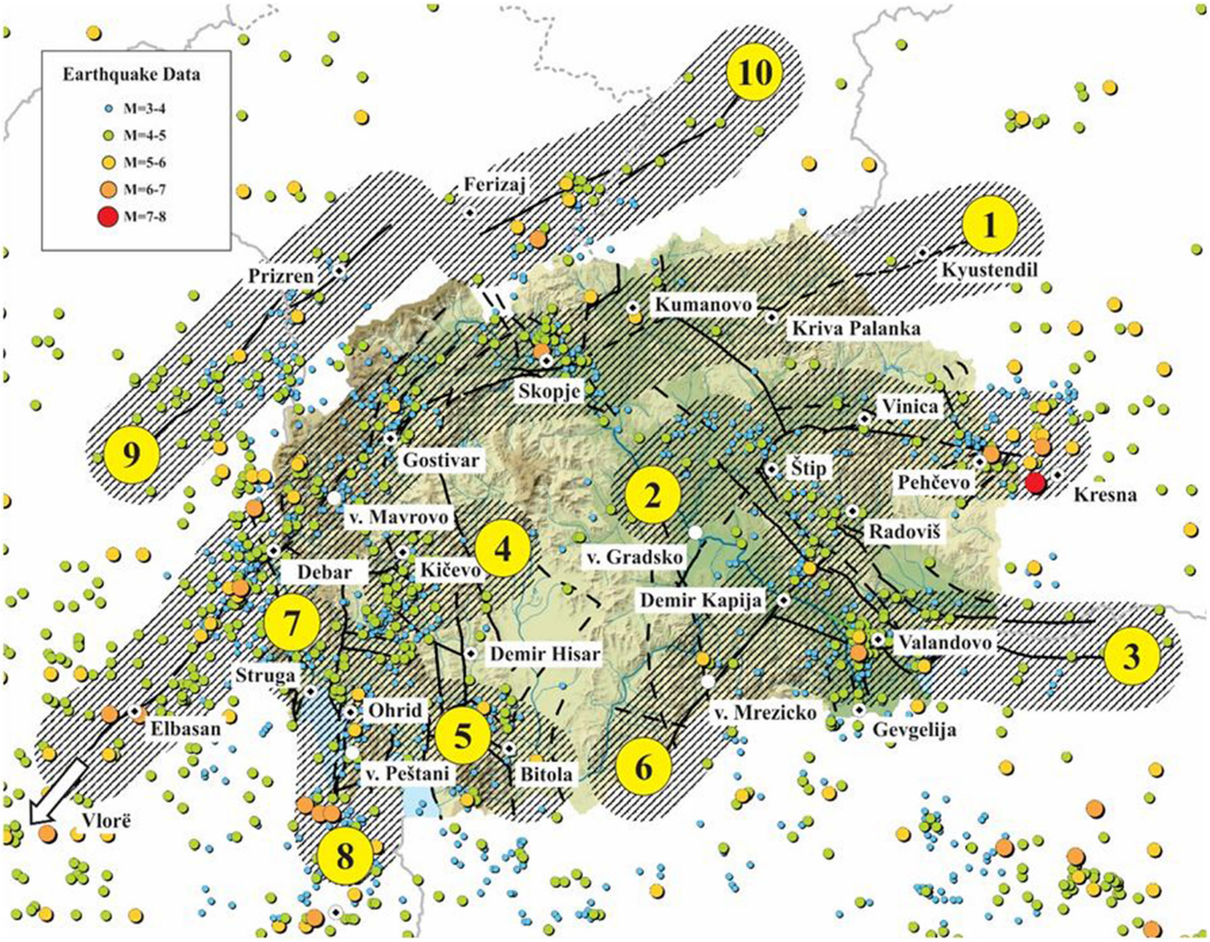

Fig. 6 Seismotectonic map and seismic zones in the Republic of Macedonia (source: Milutinovic et al. 2016, redesigned). —/— — Seismically active faults; ○ Seismological data: earthquake epicenters with magnitude $M = 3–8$; Active seismotectonic zones: (1) Kyustendil-Kriva Palanka-Kumanovo-Skopje-Gostivar-Mavrovo-Debar-Elbasan-Vlorë, (2) Kresna-Pehčevo-Vinica-Štip-Gradsko, (3) Valandovo-Gevgelija, (4) Kičevo, (5) Bitola-Prespa-Demir Hisar, (6) Nidze-Mrezicko-Demir Kapija-Serta-Radoviš, (7) Ohrid-Struga, (8) Peštani-Korçë, (9) Prizren, and (10) Uroševac (Ferizaj)

geotectonic units of the Serbo-Macedonian massif, the Vardar zone, the West Macedonian zone, and the Debar zone (Fig. 3) and continues further toward southwest, to Albania, where it intersects with Cukali-Krasta and Mirdita zones.

4.2.1 Seismotectonic zone 1: Kyustendil-Kriva Palanka-Kumanovo-Skopje-Gostivar-Mavrovo-Debar-Elbasan-Vlorë

The Albanian segment of zone 1 is recognized by Albanian researchers as a SW-NE transverse extensional fault system located in the central part of Albania stretching either from Elbasan (Elbasan-Debar-Tetovo Transversal Fault Zone; Aliaj 1988, 1989; Aliaj et al. 2004, and other works) or Vlora (Fig. 9, Vlora-Lushnja-Elbasan-Debar transversal fault zone; Sulstarova et al. 2000; Ormeni et al. 2017a).

The Vlora-Lushnja-Elbasan-Debar (VLED) transversal fault zone (TFZ) (Fig. 9) is recognized as early as 1969 (Sulstarova and Kociaj 1969) based on the chronological and geographical distribution of epicenters of some strong earthquakes in Albania in the period 1800–1967, the position of their epicenters, and focal-mechanism solutions of some of these earthquakes. The authors also recognized that this seismogenic belt continues for several hundred kilometers northeast beyond the territory of Albania, thus in Macedonia. Current tectonics along the VLED segment of seismotectonic zone 1 is expressed by an alignment of notable historical

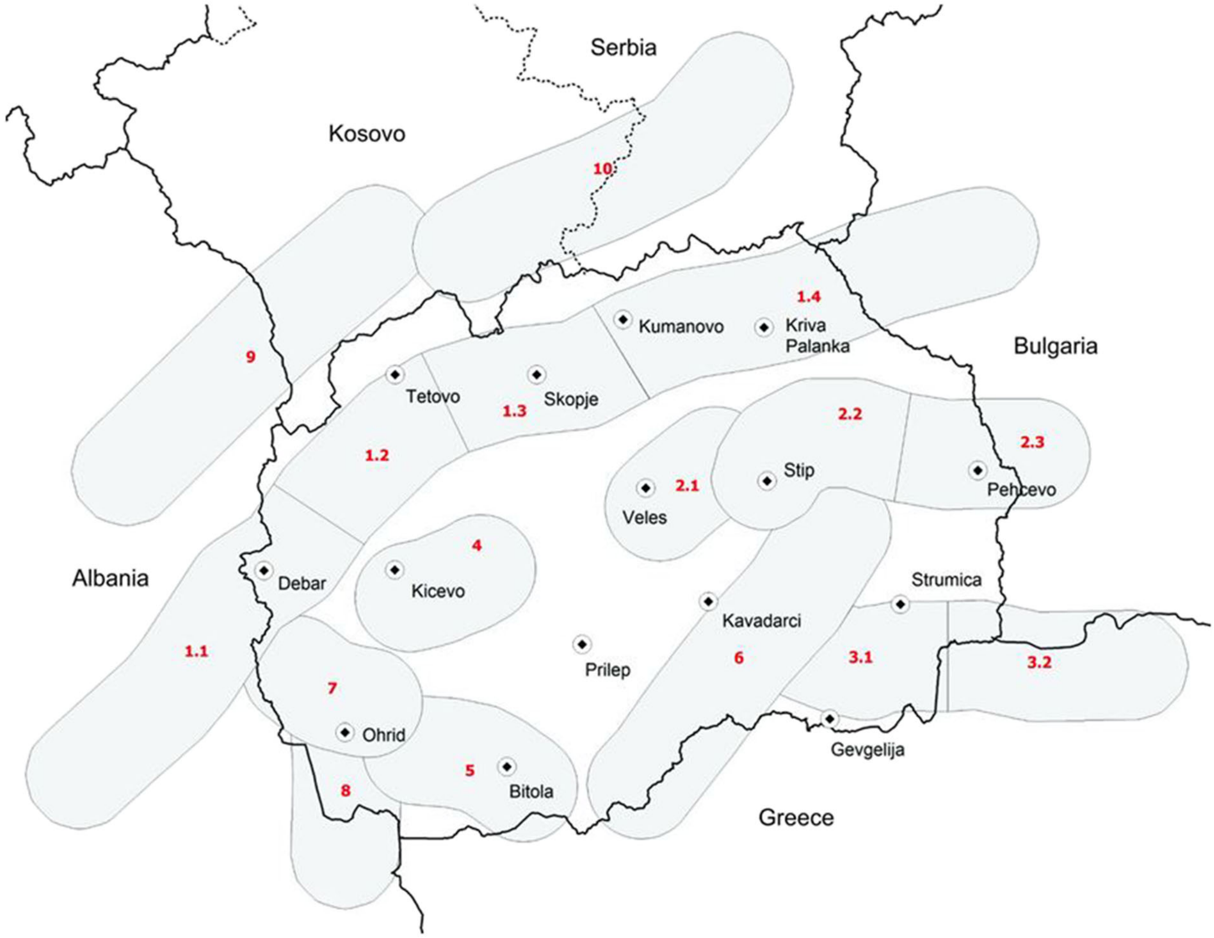

Fig. 7 Segmentation of seismotectonic zones as considered for PSHA (source: Milutinovic et al. 2016, redesigned)

seismicity with 15 (Peshkopi in 1942 and Debar in 1967 events included) historical and instrumental earthquakes with Ms > 6, as well as by the NE-SW alignment of the clusters of the aftershocks following the September 1959,

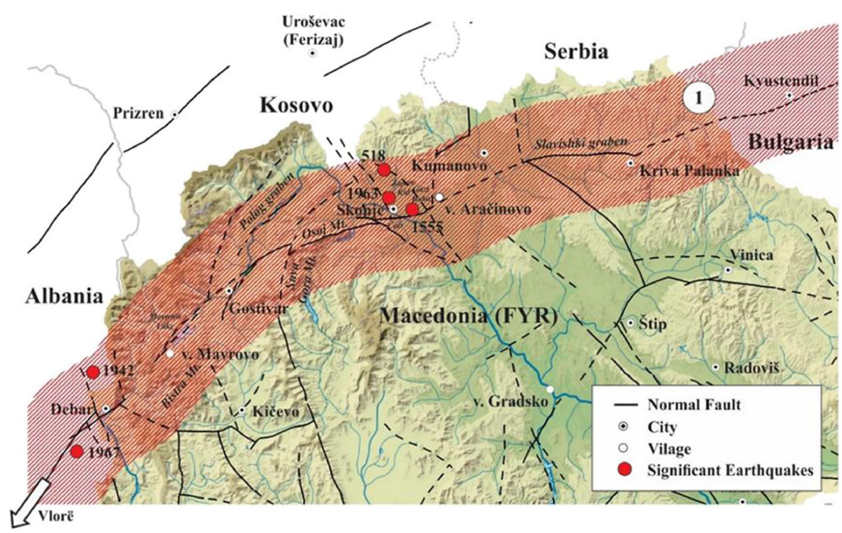

Fig. 8 Kyustendil-Kriva Palanka-Kumanovo-Skopje-Gostivar-Mavrovo-Debar-Elbasan-Vlorë seismotectonic zone (zone 1)

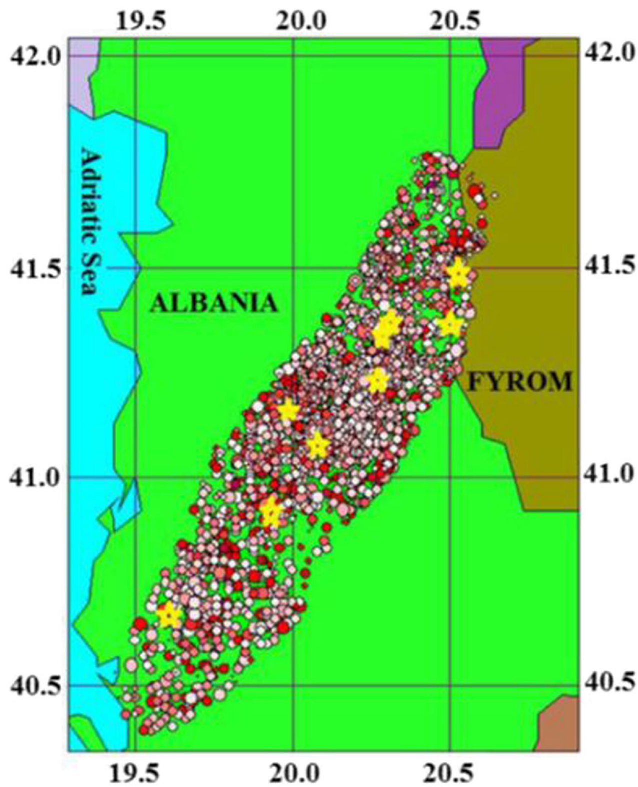

Fig. 9 Epicenter distribution of all earthquakes with Md ≥ 1.7 and depth < 70 km in the VLED TFZ between 1964 and 2015. Stars represent the principal main shocks with Md ≥ 4.5. (Source: Ormeni et al. 2017a)

November 1967, and September 2009 earthquake sequence (Jouanne et al. 2012) located at the southwestern end and the northeastern end of the fault zone (Jouanne et al. 2012).

In the territory of Macedonia, this zone has a length of about 200 km. To the east, it has an ENE-WSW orientation. From Gostivar toward the west and in Albania, it stretches in the SW direction. This zone is represented by several identically oriented "en echelon"-distributed normal faults. At Kyustendil and to the east, there is a distinguished fault. Toward Kriva Palanka, it is not located with certainty; while after that, it limits Slavish Upper Miocene graben on the southeast side with a normal fault distinguished in the relief, with a dip of 75° toward the north.

Further on, it continues to Kumanovo, and then again, the zone is not precisely located. In Skopje and toward the west, i.e., the north slope of Osoj Mountain and Suva Gora toward the Polog graben, are limited by normal, distinguished in the relief, faults of dip 70–75° toward the north. In Skopje, north from the main fault, approximately running through the village Aračinovo-Gazi Baba-Čair-Zajčev Rid stretches seismically very active parallel fault. Along this fault is the epicenter of the 1963 Skopje ($M_L = 6.1$) earthquake and the epicenters of a number of weaker earthquakes as well. Further on, through Bistra Mountain (Mavrovo field-lake), the location of the zone is unclear; while after that, in the Radika river valley, through Debar, it is again manifested by a distinguished fault.

Based on 12 to 24-h GPS measurements performed in 2003, 2006, 2008, and 2009 on Albanian permanent and episodic GPS networks, Jouanne et al. (2012) conclude that the current tectonics of Elbasan-Debar segment of zone 1 is expressed by the extension. Strain rate tensors across this fault zone indicate that this fault is mainly normal which is in the excellent agreement with the extension directions deduced from the strain rate tensor and focal mechanisms of 30 November 1967 Mw6.2 Debar earthquake (Sulstarova and Kociaj 1969) and the 6 September 2009 earthquake sequence (Kiratzi 2011) occurring in the same region (mainshock Mw5.4, located ~ 6 km north of the epicenter of the 30 November 1967).

The continuation of this seismotectonic zone in Macedonia is also marked by a noticeable increase of GPS velocities (Burchfiel et al. 2006) compatible with a significant extension along with the structure, as presented in Fig. 4. While Jouanne et al. (2012) exclude the seismotectonic zone 1 as a possible northern SBER boundary, they suggest that this seismotectonic zone is a major limit in the current deformation of Balkan concluding that the ENE-WSW transverse fault zone in Central Albania and western Macedonia (Diber-Elbasani fault) appears to be mainly affected by a moderate extension.

The last earthquake affecting Skopje (M5.3) from seismotectonic zone 1 occurred on 11 September 2016. Based on observations from MAKPOS GNSS reference stations and the analysis of horizontal Earth's crust displacements, Solarić et al. (2017, 2018) showed that horizontal displacements were possibly only a millimeter, with already recognized tendency of movement (Fig. 4) of the part of the Eurasian plate on which Skopje and its surroundings are located. The study of vertical displacements, although three times inferior to the horizontal ones and therefore uncertain, indicated a slight elevation of the Earth's crust during the earthquake followed by a return to approximately the same level as before it. On this basis, Solarić et al. (2017, 2018) concluded that in this M5.3 event, the geological structures and the Earth's crust in the vicinity of Skopje were stressed vertically.

According to historic records along this zone occurred a number of strong earthquakes, namely, in Skopje (518, $M_L = 6.05$ /$I_0 =$ IX/ 1555, $M_L = 6.05$ /$I_0 =$ IX/ and 1963, $M_L = 6.1$ /$I_0 =$ IX/), Debar (1967, $M_L = 6.50$ /$I_0 =$ IX/), and Peshkopi (Albania) (1942, $M_L = 6.0$ /$I_0 =$ IX/).

To properly consider the differences between a small number of earthquakes on the east and the cluster of earthquakes on the W-SW side of the zone 1, over the territory of Macedonia, it is segmented into four seismic source zones (Fig. 7), and each source zone in PSHA is treated by its own temporal characteristics and adopted magnitudes.

4.2.2 Seismotectonic zone 2: Kresna-Pehčevo-Vinica-Štip-Gradsko

The Kroupnik fault is not expressed in the relief in the Pehčevo area. However, there are a lot of geological indications that it continues to the west as Vinica fault, distinguishing the Kočani Middle Miocene graben from the Plačkovica horst. At Vinica, it is manifested as a traceable normal fault in the relief with EW orientation and dip of 65–70° toward the north. From Vinica toward the west, the fault does not have continuity, and it is manifested by an “en echelon” faulting. First, there is a fault cut with the ENE-WEW orientation, then a fault cut of the EW orientation, and then toward Štip, the fault has continuity and the NE-SW orientation up to the Lakavica graben where it is gone. Again, with a slight distinctiveness, it appears starting from Vardar River downstream the Crna Reka River valley at Gradsko.

While there is a possibility that the earthquake of year 400 ($M_L = 6.05$ and $I_0 =$ IX that destroyed the ancient city of Stobi could be associated with the Stobi fault (Arsovski and Petkovski 1975), the occurrence of this earthquake and the existence of Stobi fault are doubtful. Neither pre-1975 (seismologic map of FNRY, Mihailovic 1950) nor post-1975 (neotectonic map of SFRY in scale 1:1,500,000, IGGR 1967; engineering geological map of SFRY in scale 1:500,000, Cubrilovic et al. 1967; seismic zoning maps of SFRY in scale 1:1,000,000; Dumurdjanov et al. 2004a, b) research and the listed official documents recognized the existence of the Stobi fault or the occurrence of the Stobi earthquake. While not completely excluding it as potential cause of Stobi's destruction, archeological research (ARS 2010) usually attributes it to the Goths and Herulis, who ravaged Balkans in 267/9 AD. Based on listed evidence, the western part of zone 2, from Lakavica graben (Fig. 10), is delineated to follow the seismically active fault with EW orientation that formed the Veles graben, rather than in the direction of the doubtful Stobi fault.

4.2.3 Seismotectonic zone 3: Valandovo-Gevgelija

The zone (Fig. 11) consists of fault systems that enclose the Quaternary Valandovo and Gevgelija grabens and the Upper Miocene Dojran and Strumica grabens. Between the Strumica and Dojran grabens rises the Belasica horst, while among the Dojran, Valandovo, and Gevgelija grabens, there is a triangular horst of the below hills. Distinctive and seismically active faults are Strumica fault with EW orientation that divides the Strumica graben from Belasica horst to the south, then Valandovo fault running in EW direction, the fault along the Vardar river valley at Smokvica with NS orientation, and the fault stretching NE-SW determining the Dojran graben to the north and northwest.

In this zone, the Valandovo area is a seismically most active part. To the south of Valandovo, there is a quaternary tectonic depression filled with coarse proluvial-alluvial and subsoil material with a thickness of about 70 m. On the south, this graben with EW orientation is

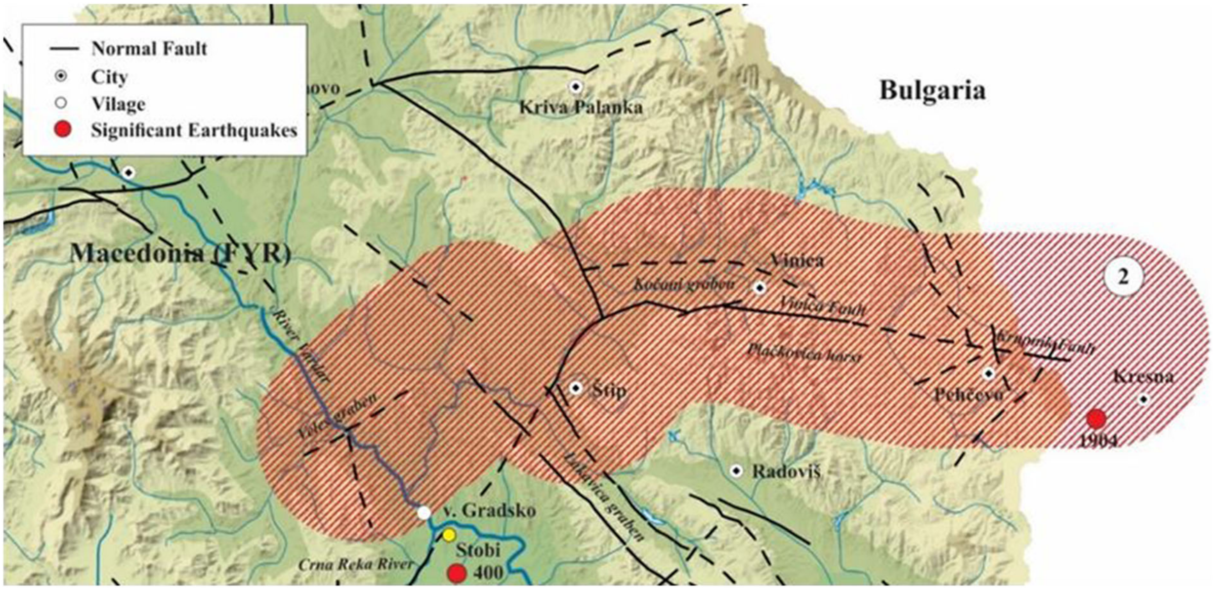

Fig. 10 Kresna-Pehčevo-Vinica-Štip-Gradsko seismotectonic zone (zone 2)

sharply limited by a traceable normal fault with a dip of 65–75° toward the north, stretching from the village of Marvinci toward Brajkovci to Bašibos. Toward the west, at the Vardar river, it is intersected by a fault stretching NS where the epicenters of the two very destructive Valandovo earthquakes that occurred in 1931 (7 March, $M_L = 6.00$, I_0= VIII and 8 March, $M_L = 6.70$, $I_0 = X$) were located. Toward the west, the fault is displaced and continues to W-NW; while toward the east, it continues in the Greek territory. Along this fault, a large number of $M_L \geq 3$ earthquakes were recorded. According to historical records, a destructive earthquake took place along this fault as well, as in the year 300 BC ($M_L = 6.05$ and I_0= IX).

Along the Strumica fault, which is very traceable in the relief and limits the graben from the Belasica horst, occurs rare and weak earthquakes. The Dojran graben has a circular form. Probably its forming has started during the Early Miocene. The most important seismically active structure is the NE-SW fault stretching from

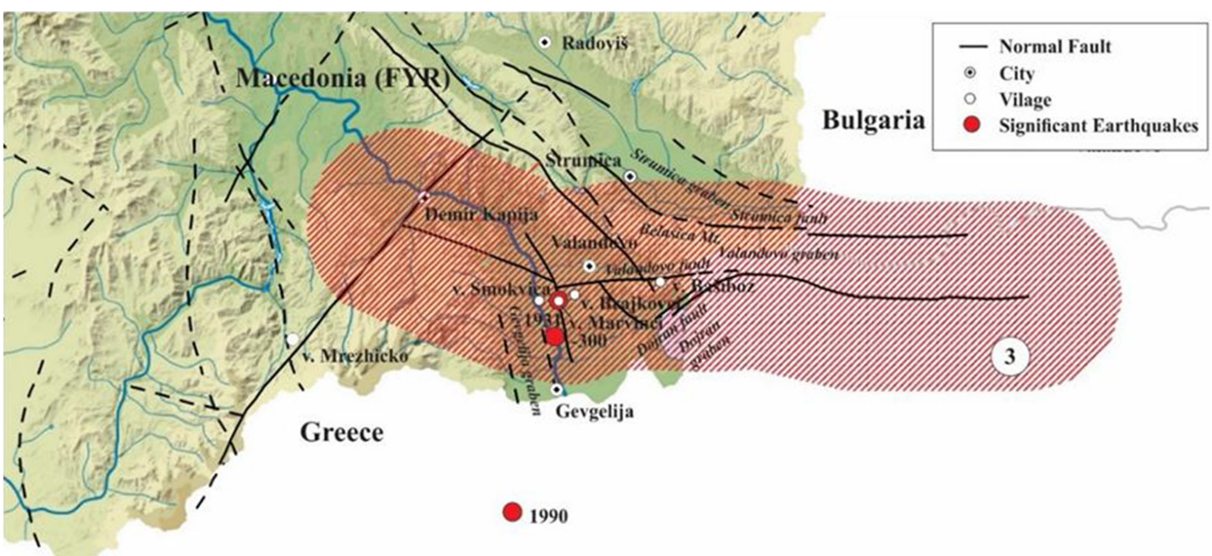

Fig. 11 Valandovo-Gevgelija seismotectonic zone (zone 3)

Belasica through Dojran toward Gevgelija. The Gevgelija graben has an asymmetric form and is slightly elongated in NS direction. This graben is also filled by quaternary fluvial and proluvial deposits with a thickness of about 80 m. Here, seismicity is manifested along the NS fault stretching along the Vardar river valley. The strongest ($M_L = 5.50$, Io = VIII) earthquake of a more recent date that affected Valandovo and Gevgelija took place in 1990.

4.2.4 Seismotectonic zone 4: Kičevo

This seismotectonic zone (Fig. 12), represented by the tectonic knot composed of several normal faults, is defined by the Kičevo graben filled by Upper Sarmatian-Meotian sediments. The main seismically active fault stretches along the Treska river with EW orientation. Active is also the fault in NNW-SSE direction that limits the graben on the west side and the fault stretching NE-SW on the east side. The graben is considerably active, mainly its south part, generating moderate earthquakes with a M_L magnitude between 4 and 5.

Zone 4 is designed to follow the orientation of the fault with strong evidence for active displacement stretching in ENE-WSW direction. The adopted direction is consistent with the assumption that the primary carrier of seismicity is the superimposed transverse fault tectonic of predominantly EW to NE-SW orientation and that recent earthquakes occur at junctions of neotectonic faults with reactivated pre-Early Miocene faults.

4.2.5 Seismotectonic zone 5: Bitola-Prespa-Demir Hisar

In this seismotectonic zone (Fig. 13), the most seismically active is the Pelister transverse fault, which limits Pelister (Baba Mountain) horst on the north side and elongates between the Prespa and Pelagonia valleys. The fault is arch-shaped and stretches in SE to NW. It is very distinctive and morphologically identifiable, with scarps and distortion of the riverbeds. To its north, there are other two parallel faults with developed scarps that are also seismically active. Seismically active is also NS-stretched Bitola fault, which is contrastingly expressed between the Pelagonian graben and the Pelister horst.

Prespa faults that separate the Prespa graben from the Galicica-Petrina horst are seismically active as well. Seismic activity with frequent weak to moderate earthquakes takes place also along several faults with NW-SE orientation that limits Demir Hisar graben.

There is data that the strongest historic earthquake in this zone occurred in 1870.

4.2.6 Seismotectonic zone 6: Nidze-Mrezhichko-Demir Kapija-Serta-Radoviš

Along the route from the south side of Kajmakcalan (Nidze Mountain)—eastern from the Mrezhichko village-Demir Kapija-Serta Mountain-Radoviš—in NE-SW direction extends vertical fault with a length of over

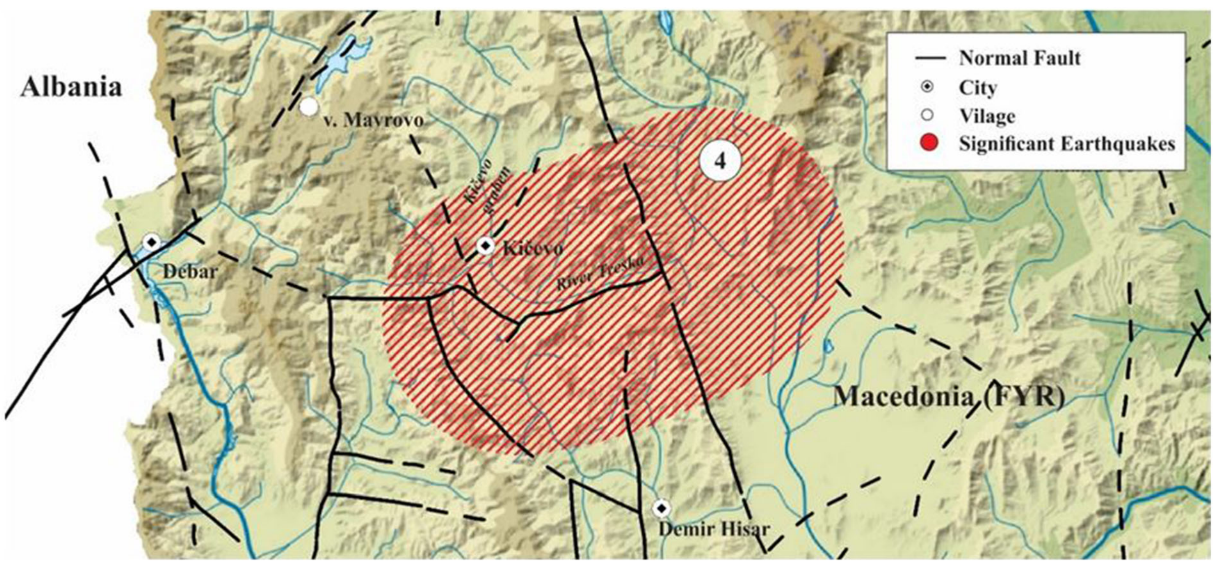

Fig. 12 Kičevo seismotectonic zone (zone 4)

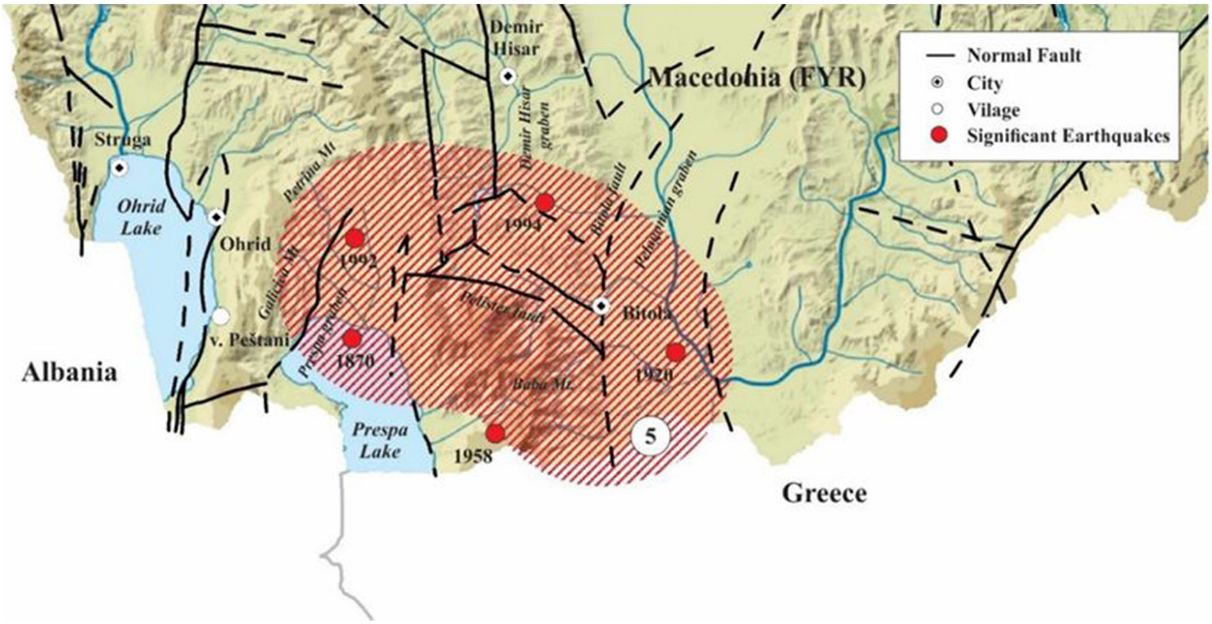

Fig. 13 Bitola-Prespa-Demir Hisar seismotectonic zone (zone 5)

100 km (Fig. 14). This fault creates a cascade in the Vardar riverbed. In 1985, along this fault, an earthquake (M_L = 5.30, I_0= VII) had occurred in Demir Kapija. The earthquake (M_L = 5.50 and Io = VIII) that took place in 1910 in Mrezhichko village (Kavadarci area) most probably was associated with the activity of this fault.

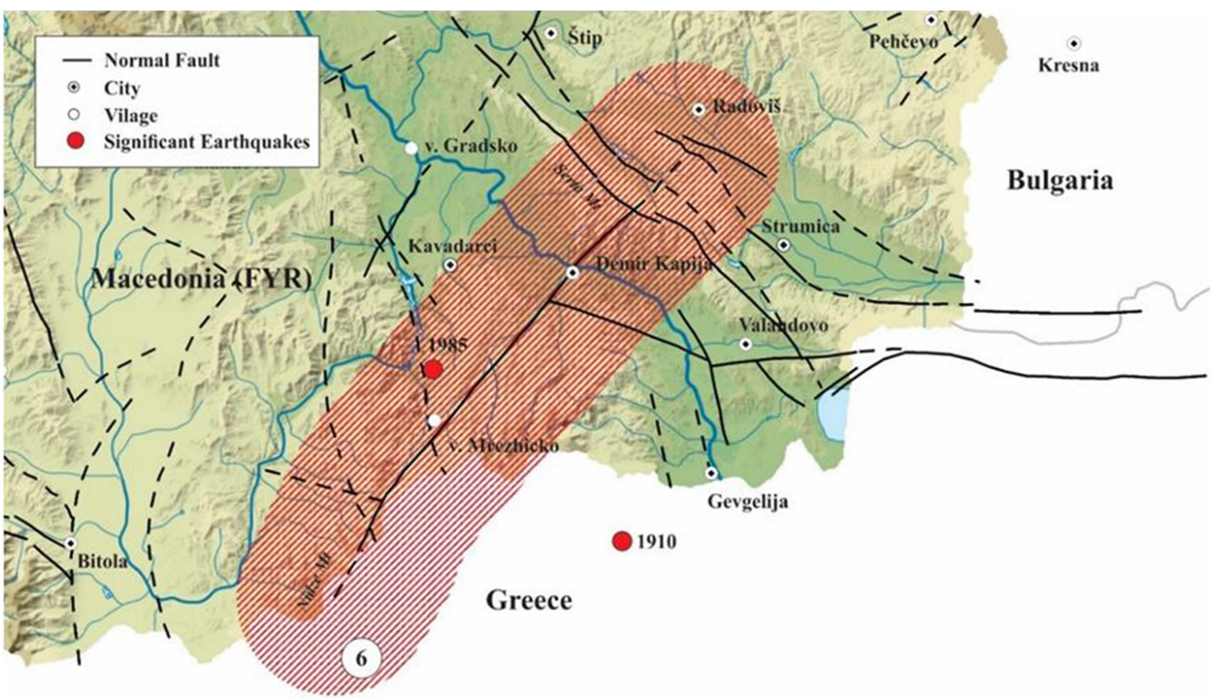

Fig. 14 Nidze-Mrezhichko-Demir Kapija-Serta-Radoviš seismotectonic zone (zone 6)

4.2.7 Seismotectonic zones 7 and 8: Ohrid-Struga (7) and Peštani-Korçë (8)

Seismotectonic zones 7 and 8 (Fig. 15) are represented by the area of the Upper Miocene Ohrid graben and its boundary parts at Galichica-Petrina horst to the east and Jablanica horst to the west.

The normal faults that limit the Ohrid graben in a cascade manner have a steep dip and are contrasted in the relief. They stretch in NS direction toward Petrina-Galicica horst to the east and Jablanica to the west.

The Ohrid-Struga zone is characterized by a moderate to high seismicity. According to historical evidence, a moderate to strong earthquake of $M_L = 6.05$, $I_0 = IX$ has stricken the area in the year of 527 AC. Another considerable earthquake ($M_L = 5.57$, $I_0 = VIII$) in this zone is the moderate magnitude earthquake of 1893. Strong seismic activity was also recorded in the southern part of the Peštani-Korçë zone, i.e., 1906 ($M_L = 6.00$, Io = VIII), 1911 ($M_L = 6.70$, Io = IX), and 1912 ($M_L = 6.00$, Io = VIII). The earthquakes with higher magnitudes are related to faults stretching WNW-ESE to EW.

The source zones 7 and 8 are delineated as separate zones to primarily underline the difference between the large magnitude events on the south and small-to-moderate magnitude events on the north, but also due to differences in the earthquake rates. For the southern part of the source zone 8, there is strong geological evidence on features of active fault movement, whereas for zone 7, there is only weak morphological evidence for recent activity.

Source zones 5 and 7 are both extending in approximately the same S-SW direction, even though they are not aggregated in the single zone since fragmentary S-SW-striking normal faults encompassed by source zone 5 are with strong geological evidence for recent activity. Weak seismicity studies are needed for further clarification of the relation of source zone 7 with zones 5 and 8.

4.2.8 Seismotectonic zones 9 and 10: Prizren (9) and Uroševac (10)

Along with the NE-SW superimposed fault structure Skadar-Peje (Scutari-Pec) in the same direction, but

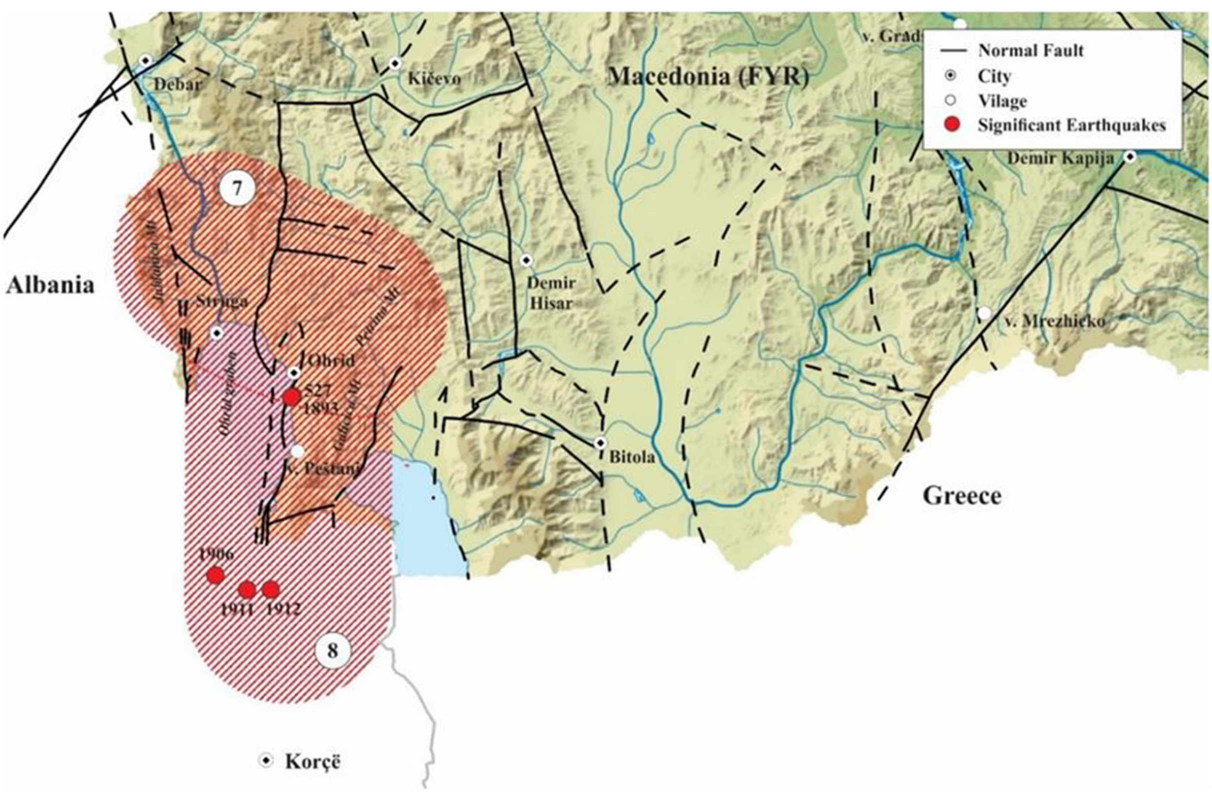

Fig. 15 Ohrid-Struga (zone 7) and Peštani-Korçë (8) seismotectonic zones

southern, is located the so-called Prizren seismotectonic zone (Fig. 16). Several relay normal faults represent the zone. The destructive earthquake of 1456 (Mw = 5.96, I_0 = IX) is associated with those faults.

Uroševac (Ferizaj) zone (Fig. 16) is located northeast of the Prizren zone. Seismic activity along this zone is connected with relay normal faults as well. The strongest earthquake (Mw = 6.01, I_0 = IX) associated with this zone is the earthquake of 1921.

5 Discussion and conclusions

The process of seismic hazard assessment for the territory of Macedonia dates back to the mid of the last century (Mihailov 1978; Milutinovic et al. 1998; Dojcinovski 2005; Stamatovska and Paskaleva-Koytcheva 2013, and other). The common denominator of all studies is the implementation of seismotectonic zoning with NS or NW-SE orientation. Consequently, the implemented seismic hazard models used either area (Mihailov 1978: Stamatovska and Paskaleva-Koytcheva 2013) or line (Dojcinovski 2005) sources of the NS and NW-SE orientation.

Accepting conceptually the same principles of seismotectonic zoning, Milutinovic et al. (1998) and later Salic (2015) conducted seismic hazard assessments by implementing area sources arranged in NW-SW direction to (1) strengthen the transverse seismicity and (2) to a certain degree, neutralize the effect of the long-standing hypothesis that the seismicity of Macedonia is controlled by tectonic elements stretching exclusively in NS and NW direction, with particular emphasis on the Vardar seismic zone as a primary carrier of the seismicity of Macedonia.

Prior to GPS evidence that Macedonia, including eastern part of Albania, south Serbia and south Bulgaria, since the Early Miocene are subjected to South Balkan Extensional Regime; Albanian seismic hazard analysts seriously considered the existence of three transverse seismotectonic zones: (1) the SW-NE trending Skadar-Tropoja normal fault zone; (2) the SW-NE trending Elbasani-Debar normal fault zone; and (3) the NW-SE trending Vlora-Tepelena transverse fault zone

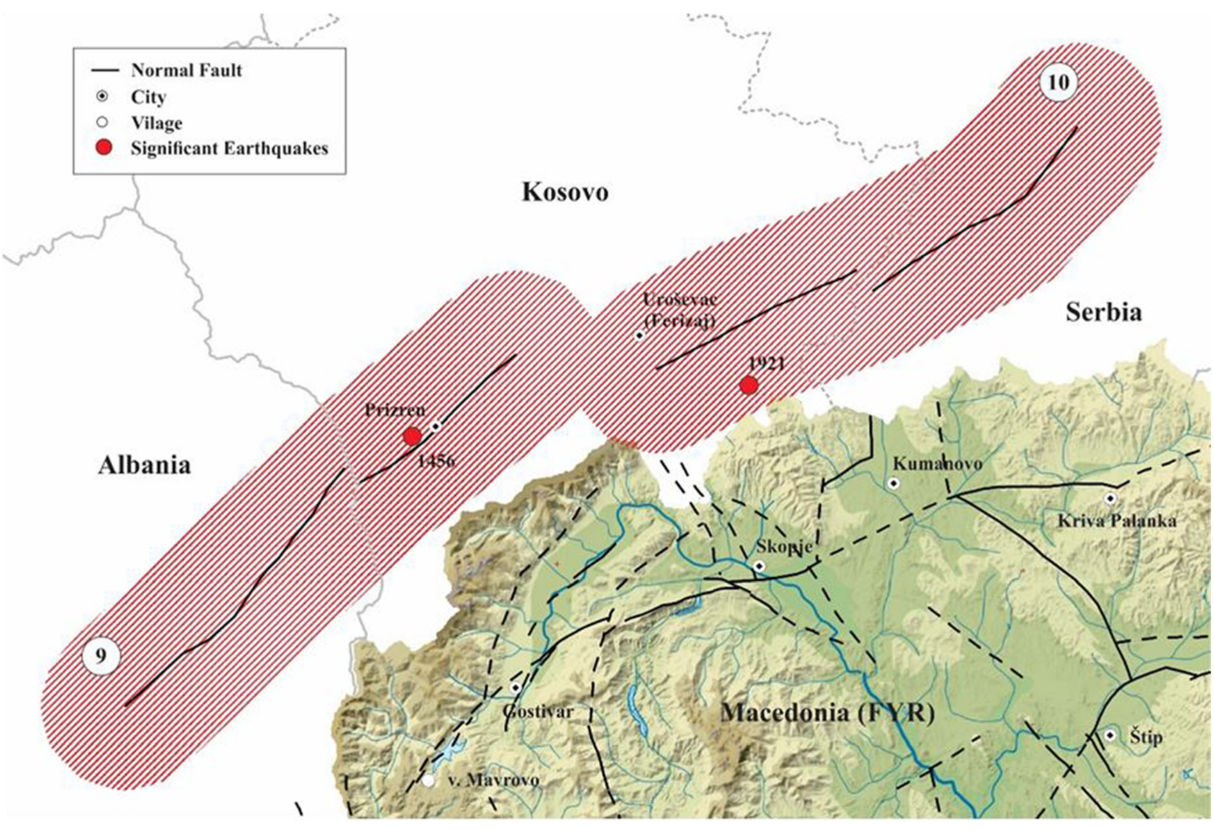

Fig. 16 Prizren (zone 9) and Uroševac (Ferizaj) seismotectonic zone (10)

(Sulstarova et al. 2000; Aliaj et al. 2004, 2010; Muco 2013; Ormeni et al. 2017b).

While the Kyustendil-Kriva Palanka-Skopje-Debar-Elbasan fault zone of tectonic activity was postulated for many decades by Macedonian geologists (Arsovski and Petkovski 1975, Jancevski 1987; Arsovski 1997; Dumurdjanov et al. 2005; Burchfiel et al. 2006), the postulate did not have any serious reflection on the seismic hazard assessments of Macedonia.

The seismotectonic zoning model presented (Milutinovic et al. 2016) is used for seismic hazard assessment of Macedonia and the development of seismic zoning maps compatible with MKS EN 1998-1:2012 Eurocode 8 requirements. The adopted seismotectonic zoning:

– is physically consistent with SBER geodynamic regime (Fig. 4) presently affecting the territory of Macedonia and neighboring areas in western Albania, south Serbia, south Bulgaria, and Greece (Radovanovic 2003; Dumurdjanov et al. 2004a, b, c, 2005; Burchfiel et al. 2006; Kotzev et al. 2008);
– associates the seismicity in Macedonia with transverse seismotectonics, i.e., superimposed normal faults stretching EW to NE-SW and transversally cross the geological units and tectonic provinces (Fig. 3) of Macedonia;
– assumes that most of the strong and damaging earthquakes of the twentieth century (Table 1) are related to normal faulting (e.g., Ranguelov et al. 2008; Dumurdjanov et al. 2016); and,
– redefines the obsolete and physically inconsistent modeling of the seismicity in Macedonia, postulating that NS to NW SE-oriented tectonics is the primary carrier of seismicity, by the paradigm that the primary carrier of seismicity in Macedonia is the superimposed transverse faulting tectonics of predominantly EW to NE-SW orientation.

The most straight implication of Milutinovic et al. (2016) seismotectonic modeling is the redefinition of the long-standing postulate that the seismicity of central and SE Macedonia is controlled by longitudinal (NS to NW-SE) faulting in Vardar seismogenic zone, rather than "presently, the Vardar seismogenic zone is one of the weakest tectonic units with seismicity particularly expressed in the areas of intersection (tectonic knots) of reactivated pre-Early Miocene faults stretching in Vardar direction (NW-SE) with neotectonic faults of predominant stretch in a transverse (EW to NE-SW) direction."

Macedonia and adjacent Albania and Bulgaria have been the locations of large and destructive earthquakes during the last century. The maintenance and improvement of the presented seismotectonic model are needed, which will require continued GPS measurements within the region to reduce the uncertainty in the calculated crustal velocities and continued geological studies to understand the history of active faults better.

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References

Aliaj Sh (1988) The neotectonics and Seimotectonics of Albania. D.Sc. Thesis, Seismological Institute, Tirana, Albania (in Albanian)

Aliaj Sh (1989) Present geodynamic location of the convergance between the Albanides orogen and the Adriatic Plate. In: Seismological studies, III, No. 10. Seismological Centre, Academy of Scieneces, Tirana, pp 15–38 (in Albanian)

Aliaj SH, Adams J, Halchuk S, Sulstarova E, Peci V, Muco B (2004) Probabilistic seismic hazard maps for Albania. 13WCEE, Vancouver, B.C., Canada, August 1–6, 2004. Paper No. 2469

Aliaj S, Kociaj S, Muco B, Sulstarova E (2010) Seismicity, seismotectonics and seismic hazard assessment in Albania. Academy of Sciences of Albania, Tirana

Armijo R, Meyer B, King GCP, Rigo A, Papanastassiou D (1996) Quaternary evolution of the Corinth Rift and its implications for the Late Cenozoic evolution of the Aegean. Geophys J Int 126:11–53

ARS (2010) online (web of the Archaeological Site Stobi). http://www.stobi.mk/Templates/Pages/StandardPage.aspx?page=187

Arsovski M (1997) Tectonic of Macedonia. Faculty of Geology and Mining, Stip 306 pp. (in Macedonian)

Arsovski M, Petkovski R (1975) Neotectonics of SR Macedonia, publication no. 49. IZIIS, Skopje (in Macedonian)

Burchfiel CB, Nakov R, Tzankov T, Royden LH (2000) Cenozoic extension in Bulgaria and northern Greece: the northern part of the Aegean extensional regime. In: Bozkvet E, Winchester JA, Piper JDA (eds) Tectonics and magmatism in Turkey and the surrounding area, Special Publications, 173. Geological Society, London, pp 325–352

Burchfiel BC, Todosov A, King RW, Kotzev V, Dumurdjanov N, Serafimovski T, Nurce B (2006) GPS results for Macedonia and its importance for the tectonics of the Southern Balkan extensional regime. Tectonophysics 413:239–248

Cejkovska V, Pekevski L, Drogreska K, Najdovska J (2016) Report per the project of the standardization Institute of the Republic of Macedonia entitled National Annexes for Eurocodes. Faculty of Natural Sciences and Mathematics, seismological observatory, Ss. Cyril and Methodius University, Skopje February 2016 (in Macedonian)

Cubrilovic P, Palavestric LJ, Nikolic T, Ciric B (1967). Engineering-geological map of SFR of Yugoslavia in scale 1:500,000. Institute for Geological and Geophysical Research (IGGR), Belgrade, 1967

Dewey JF, Pitmann WC, Ryan WBF, Bonnin J (1973) Plate tectonics and the evolution of the Alpine system. Geol Soc Am Bull 84:3137–3180

Dojcinovski D (2005). Contribution to analysis of global damage and functioning of road systems in earthquake conditions. Institute of Earthquake Engineering and Engineering Seismology (UKIM-IZIIS), Ss. Cyril and Methodius University in Skopje, Doctoral dissertation. Skopje, R. Macedonia, 2005 (in Macedonian)

Dumurdjanov N (1985-86). Petrogenetic characteristics of the high metamorphic and magmatic rocks of the Selecka mountain, SR Macedonia, Yugoslavia. Geologica Macedonica, T. II, Fasc. 1, T2 no. 2, Stip

Dumurdjanov N, Petrov G (1992) Lithostratigraphic characteristics of the ophiolite complex Demir Kapija-Gevgelija (Macedonia). Geologica Macedonica, T 6. No 1, pp 49–60. Stip

Dumurdjanov N, Serafimovski T, Burchfiel CB (2004a) Map: Cenozoic sedimentary and volcanic rocks of Macedonia. https://doi.org/10.1130/2004-Dumurdjanov-Macedonia

Dumurdjanov N, Serafimovski T, Burchfiel CB (2004b) Evolution of the Neogene-Pleistocene basins of Macedonia. Geological Soc. of America, DMC001, p.1-XX

Dumurdjanov N, Serafimovski T, Burchfiel CB (2004c) Evolution of the Neogene-Pleistocene basins of Macedonia: Geological Society of America Digital Map and Chart Series 1 (accompanying notes), 20 pp.

Dumurdjanov N, Serafimovski T, Burchfiel CB (2005) Cenozoic tectonics of Macedonia and its relation to the South Balkan extensional regime. Geosphere 1:1–22. https://doi.org/10.1130/GES00006.1

Dumurdjanov N, Milutinovic Z, Salic R (2016). Seismotectonic zones and seismic hazard of Republic of Macedonia. Third Congress of Geologists of Republic of Macedonia, 30.09–02.10.2016, Struga, Macedonia (in Macedonian)

Grünthal G (ed) (1998) European Macroseismic Scale 1998 (EMS-98). Cahiers du Centre Européen de Géodynamique et de Séismologie 15. Centre Européen de Géodynamique et de Séismologie, Luxembourg, 99 pp.

IGGR (1967) Neotectonic map of SFR of Yugoslavia (scale 1:1 500 000). Institute for Geological and Geophysical Research (IGGR), Belgrade 1967

Ivanov T, Misar Z, Bowes DR, Dudek A, Dumurdjanov N, Jaros J, Jelinek E, Pacesova M (1987) The Demir Kapija – Gevgelija ophiolite. Macedonia, Yugoslavia. Ofioliti Bologna, Italia

Jackson JA, McKenzie DP (1988) The relationship between plate motions and seismic tensors, and the rate of active deformation in the Mediterranean and Middle East. Geophys J Int 93: 45–73

Jancevski J (1987) Classification of fault structures according to genesis, age and morphology, with review to their seismicity on the territory of Macedonia. Institute of Earthquake Engineering and Engineering Seismology (UKIM-IZIIS), Ss. Cyril and Methodius University in Skopje, Doctoral dissertation. Skopje, R. Macedonia, 247 p. (in Macedonian)

Jouanne F, Mugnier JL, Koci R, Bushati S, Matev K, Kuka N, Shinko I, Kociu S, Duni L (2012) GPS constraints on current tectonics of Albania. Tectonophysics 554–557(2012):50–62. https://doi.org/10.1016/j.tecto.2012.06.008

Kijko A, Smit A (2012) Extension of the B-value estimator for incomplete catalogs. Bull Seismol Soc Am 102(3):1283–1287. https://doi.org/10.1785/0120110226

Kiratzi AA (2011) The 6 September 2009 Mw5.4 earthquake in eastern Albania – FYROM border: focal mechanisms, slip model, ShakeMap. Turk J Earth Sci 20:475–488. https://doi.org/10.3906/yer-1001-7

Kotzev V, King RW, Burchfiel BC, Todosov A, Nurce B, Nakov R (2008) Crustal motion and strain accumulation in the South Balkan Region inferred from GPS measurements. In: Husebye E (ed) Earthquake monitoring and seismic hazard mitigation in Balkan countries: Proceedings of the NATO advanced research workshop on earthquake monitoring and seismic hazard mitigation in Balkan countries, Borovetz, Bulgaria, 11–18 September 2005, NATO Science Series IV: Earth and Environmental Sciences, vol 81, pp 19–43

Markovic M, Djokovic I (1995) Neotectonic activity of the Scutari-Pec general area. Ann Geol Penins Balkans 59:23–43

Meyer B, Armijo R, Dimitrov D (2002) Active faulting in SNJ Bulgaria: possible surface rupture of the 1904 Struma earthquakes. Geophys J Int 148:246–255

Mihailov V (1978) Contribution to stochastic modeling of seismicity. Doctoral dissertation, Zagreb, R. Croatia, 1978

Mihailovic J (1950) Seizmološka karta Yugoslavije (seismologic map of Yugoslavia), Radovi seizmoloskog zavoda FNRJ u Beogradu, 110 pp., 1950

Mihaljevic J, Zupancic P, Kuka N, Kaludjerovic N, Koci R, Markusic S, Salic R, Dushi E, Begu E, Duni LL, Zivcic M, Kovacevic S, Ivancic I, Kovacevic V, Milutinovic Z, Vakilinezhad M, Fikret T, Gulerce Z (2017) BSHAP seismic source characterization models for the Western Balkan region. Bull Earthq Eng 15(10):3963–3985. https://doi.org/10.1007/s10518-017-0143-5

Milev G, Vassileva K (2007) Geodynamics of the Balkan Peninsula and Bulgaria. International Symposium on Strong Vrancea Earthquakes and Risk Mitigation, Oct. 4–6, 2007, Bucharest, Romania

Milutinovic Z, Mihailov V, Talaganov K, Trendafiloski G, Olumceva T, Sesov V (1998) Spatial plan of republic of Macedonia-conditions for occurrence and protection against seismic disasters. IZIIS Rep:98–29

Milutinovic Z, Salic R, Tomic D (2016) Seismic zoning map of the Republic of Macedonia according to the requirements of MKC EN 1998-1:2004 – Eurocode 8 (map reading guide), report IZIIS 2016-26, August 2016 (in Macedonian)

MKS EN 1998-1 (2012) Eurocode 8: design of structures for earthquake resistance – part-1: general rules, seismic actions and rules for buildings, December 2012

Muco B (2013) Probabilistic seismic hazard assessment in Albania. Ital J Geosci (Boll Soc Geol It) 132(2). https://doi.org/10.3301/IJG.2012.25

Ormeni R, Özturk S, Fundo A, Celik K (2017a) Spatial and temporal analysis of recent seismicity in different parts of the Vlora-Lushnja-Elbasani-Dibra Transversal Fault Zone, Albania. Austrian J Earth Sci 110(2). https://doi.org/10.17738/ajes.2017.0015

Ormeni RR, Ozturk S, Olgert GJ (2017b) A statistical assessment of the earthquake activity in the Vlora-Lushnja-Elbasani-Dibra transversal fault zone, Albania. J Nat Tech Sci (JNTS) XXII(44)

PIOVS81 (1981) Rulebook on technical norms for construction of high-rises in seismic areas. Official Gazette of SFRY No. 31/81 (including the modifications and amendments 49/82, 29/83, 21/88 and 52/90)

PTP-GvSP64 (1964) Rulebook on technical regulations for construction in seismic areas (Official Register of SFRY No. 39/6)

Radovanovic S (2003) Seismic hazard mMaps and spectra: catalogue preparation, seismotectonic modeling and site class definition. CD proceedings of First International Conference Science and Technology for Safe Development of lifeline systems natural risks: developments, tools and techniques in the CEI area. Sofia, Bulgaria (2003)

Ranguelov B, Mardirosian G, Velkosky S (2008) Seismicity and geodynamics of Macedonia and surroundings. Proceedings of BALWOIS 2008. Republic of Macedonia, Ohrid

Ritsema A (1974) The earthquake mechanisms of the Balkan region. UNDP/UNESCO project REM/70/172, UNESCO, 76 pp.

Salic R (2015) Advanced approach to seismic hazard assessment in the republic of Macedonia, Institute of Earthquake Engineering and Engineering Seismology (UKIM-IZIIS), Ss. Cyril and Methodius University in Skopje, doctoral dissertation. Skopje, R. Macedonia, march 2015. (in Macedonian)

Seismological Association of SFR Yugoslavia (1987) Seismic zoning maps of SFRY (1:1,000,000) for return periods of 50, 100, 200, 500, 1000 and 10000 years, Official Gazette No. 52/90: Article 6: Map for Return Period of 500 years is adopted for the design of buildings of II and III category

Solarić M, Solarić N, Bogadovski Z, Dimeski S (2017) Određivanje pomicanja Zemljine kore u okolici Skopja s pomoću MAKPOS-ovih referentnih GNSS-postaja (Determination of shifts of the earth crust in the surroundings of Skopje by MAKPOS's Reference GNSS Stations), Geodetski list, 71 (94), 4, pp. 277–290. (In Croatian)

Solarić N, Solarić M, Bogdanovski D (2018) Three days before the earthquake in Skopje there was a compression of the Earth's crust. Geodetski list 72(95), 1):15–35

Stamatovska SG, Paskaleva-Koytcheva IZ (2013) Seismic hazard assessment for life-line systems passing through Macedonian-Bulgarian border, 50SE-EEE, Skopje, Republic of Macedonia, 2013

Sulstarova E, Kociaj S (1969) Tërmeti i 30 Nëntorit 1967 dhe brezi sizmogjen Vlorë-Dibër. Bul Univ Tiranes, Ser Shkencat Nat 2:85–95 (in Albanian, with French abstract)

Sulstarova E, Peci V, Shuteriqi P (2000) Vlora-Elbasani-Dibra (Albania) transversal fault zone and its seismic activity. J Seismol 117-131:2000

Zagorcev IS (1992a) Neotectonics of the central parts of the Balkan Peninsula: basic features and concepts. Geol Rundsch 81/3:635–654 Stuttgart

Zagorcev IS (1992b) Neotectonic development of the Struma (Kraistid) lineament, Southwest Bulgaria and northern Greece. Geol Mag 129:197–222

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