

# 120<sup>TH</sup> ANNIVERSARY OF SEISMOLOGY IN BULGARIA: MILESTONES, DEVELOPMENT AND ACHIEVEMENTS

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**Suggested citation:** Glavcheva, R., and Matova, M. 2014. 120<sup>th</sup> anniversary of seismology in Bulgaria: milestones, development and achievements. *Boletín de Geología*, 36 (2): 125-158.

## ABSTRACT

The territory of Bulgaria is situated in the eastern part of the Balkan Peninsula, South-Eastern Europe, being a part of the Alpo-Himalayan seismic belt. The most important cities in Bulgaria lie in the vicinity of Neogene-Quaternary active faults. Due to these circumstances organized monitoring of earthquakes as well as development of seismological practice started in Bulgaria at the end of 19<sup>th</sup> century. The foundation of seismology in Bulgaria was laid in 1891 by the meteorologist and also the first Bulgarian seismologist Spas Watzof, later honored with academic rank. Spas Watzof founded and organized a well managed service for regular observation of co-seismic and post-seismic effects of earthquakes. Soon after, in 1903, Bulgaria was accepted as a member of the International Seismological Association (the predecessor of the International Association of Seismology and Physics of the Earth's Interior - IASPEI). It should be noted that foreign experts demonstrated scientific interest in cases of strong earthquakes that took place on the territory of Bulgaria in the beginning of 20<sup>th</sup> century (Hörnes, 1904; Grablovitz, 1904; Mihailovich, 1933; Richter, 1958) as well as on using instrumental records made in Bulgaria for their revolutionary discoveries (Reid, 1910; Mohorovicic, 1910). At present Bulgaria participates in international activities in the frames of the European Seismological Commission (ESC) – a regional commission of the IASPEI, the International Federation of Digital Seismograph Networks (FDSN), the Balkan Geophysical Society and the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO). On occasion of the 120<sup>th</sup> anniversary of the seismology in Bulgaria it is reasonable the results of studies covering such a long period and published in international and Bulgarian journals and monographs to be summarized and presented herein. The summary of the milestones, development and achievements in the field of Macroseismology, Instrumental seismology and Geodynamics in Bulgaria is chronologically presented. The paper aims also to spread more effectively the Bulgarian scientific information abroad as well as to popularize some seismic peculiarities and phenomena in the central-eastern Balkan Peninsula.

**Keywords:** Bulgaria, seismotectonics, macroseismology, historical seismology, instrumental seismology, seismic hazard, regional and world geodynamics.

## 120° ANIVERSARIO DE LA SISMOLOGÍA EN BULGARIA: HITOS, DESARROLLO Y LOGROS

### RESUMEN

El territorio de Bulgaria está situado en la parte oriental de la península de los Balcanes, al sureste de Europa, siendo una parte del cinturón sísmico Alpes-Himalaya. Las ciudades más importantes de Bulgaria se encuentran en las inmediaciones de las fallas activas del Neógeno-Cuaternario. Debido a estas circunstancias, el monitoreo organizado de terremotos, así como el desarrollo de la práctica sismológica inició en Bulgaria a finales del siglo XIX. La fundación de la sismología en Bulgaria ocurrió en 1891 por el meteorólogo y también el primer sismólogo búlgaro Spas Watzof, posteriormente honrado con rango académico. Spas Watzof fundó y organizó un servicio bien direccionado para la observación regular de los efectos co-sísmicos y pro-sísmicos de los terremotos. Poco después, en 1903, Bulgaria fue aceptada como miembro de la Asociación Sismológica Internacional - ISA (predecesora de la Asociación Internacional de Sismología y Física del Interior de la Tierra - IASPEI). Es importante anotar que expertos extranjeros demostraron interés científico en casos de fuertes terremotos que tuvieron lugar en el territorio búlgaro a inicios del siglo XX (Hörnes, 1904; Grablovitz, 1904; Mihailovich, 1933; Richter, 1958), así como en el uso de registros instrumentales hechos en Bulgaria por sus descubrimientos revolucionarios (Reid, 1910; Mohorovicic, 1910). Actualmente, Bulgaria participa en actividades internacionales en el marco de la Comisión Sismológica Europea (ESC) – una comisión regional de la IASPEI, la Federación Internacional de Redes Digitales de Sismógrafos (FDSN), La Sociedad Geofísica Balcánica y la Organización Integral de Tratados de Prohibición de Pruebas Nucleares (CTBTO). La sismología en Bulgaria celebra su 120° aniversario y es razonable que los resultados de los estudios realizados en este periodo tan largo y publicado en revistas y monografías internacionales y búlgaras sea resumido y presentados aquí. Se presenta cronológicamente el resumen de hitos, desarrollos y logros en el campo de la Macrosismología, Sismología Instrumental y Geodinámica en Bulgaria. El documento trata también de difundir más efectivamente la información científica búlgara más allá de sus fronteras e igualmente divulgar algunas peculiaridades y fenómenos sísmicos de la parte centro-oriental de la península Balcánica.

**Palabras Clave:** Bulgaria, sismotectónica, macrosismología, sismología histórica, sismología instrumental, amenaza sísmica, geodinámica regional y mundial.

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## INTRODUCTION

The territory of Bulgaria, located in the eastern part of the Balkan Peninsula, is surrounded by lands characterized by high seismic activity and frequent damaging earthquakes that influence the seismic hazard in the country. The Bulgarian territory has originated destructive earthquakes over the centuries. It is remarkable that during the first 30 years of 20<sup>th</sup> century five earthquakes of magnitude  $M_s \geq 7$  ( $M_s$  is the surface-wave magnitude) occurred in this country reaching magnitude 7.8 in southwestern Bulgaria, 7.2 in northeastern Bulgaria, and 7.0 in southern and northern Bulgaria; the cited magnitude assessments are according to Christoskov and Grigorova (1968). Since then few moderate earthquakes with magnitude less than 6.0 have occurred. The earthquakes in Bulgaria have their foci mainly in the upper crust (down to 30-35 km), and only few events are located in the lower crust (down to 50 km in SW Bulgaria).

The seismology in Bulgaria has been developing for more than 120 years. We summarize the milestones, development and achievements in three main fields in it: (1) Macroseismology, the branch of seismology which studies observable effects of earthquakes on people, objects, buildings, and nature. The macroseismic data ensured a basis for development of the historical seismology and seismic hazard assessment, both of great scientific and social importance and they are also reviewed herein; (2) Instrumental seismology, the earthquakes are registered instrumentally and this circumstance allows widening of the set of earthquake's characteristics and development of new approaches to study the Earth; (3) Seismological contribution in the field of regional and world-wide geodynamics. We review and discuss the chronological development of these three aspects as well as the main tasks and problems that were studied and solved. Before starting discussion on these three aspects we present information on present day seismicity of Bulgaria as well as its spatial relation with the regional tectonic setting.

## TECTONIC SETTING AND SEISMOGENIC STRUCTURES

The territory of Bulgaria is situated in the Balkan Peninsula, South-Eastern Europe and represents a segment of the southern periphery of Eurasian plate. The Bulgarian territory has been exposed to the ongoing collisional process due to dynamic pressure caused by the African and the Anatolian plates. The regional tectonic evolution is also associated with the strong influence of the main neighboring structures as the

Mediterranean region from the south, the Carpathian system from the north and the Black Sea from the east. Actually, Bulgaria is in the Eastern European part of the recently active Alpine-Himalayan tectonic belt characterized by expressed seismicity.

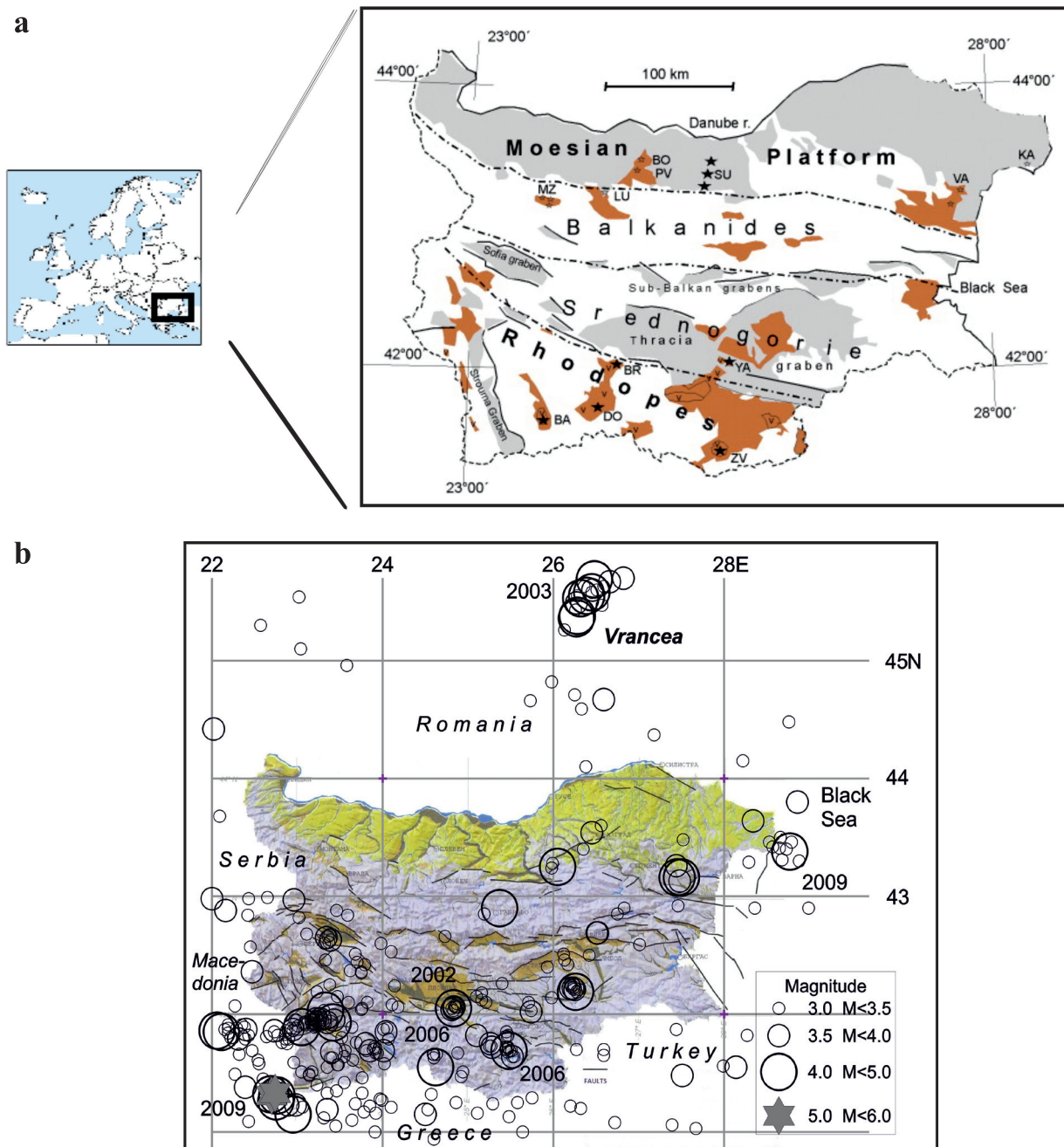
The dynamic evolution of the geological structures in Bulgaria has been the subject of numerous publications (Gočev, 1991; Kotzev *et al.*, 2001; van Hinsbergen *et al.*, 2008, etc.). The Alpine orogenic systems of Balkanides, Srednogorie and Rhodopes (FIGURE 1a) developed gradually in the central and southern parts of the country as result of folding, faulting, vertical and horizontal block displacements in the upper part of the lithosphere. The degree of their mobility depends on their position in the Alpine-Himalayan orogenic belt. The Alpine structural genesis was influenced by the local, regional and planetary geological environment. The structures from the Pre-Alpine stages were totally or partially remade. Their traces are included in the Alpine units. According to Zagorchev (1992), during the Neogene and Quaternary time the tectonic processes in Bulgaria were related to the destruction of Late-Alpine orogen, extensional stress environment and complex interaction of intense vertical and horizontal movements in the region. At present, the territory of the country represents mosaics of Alpine structural units and inherited Pre-Alpine relicts. Cenozoic formed structures like horsts, grabens, depressions and basins are found often across the territory.

In the northern Bulgaria a relatively older and stable structural unit of the Moesian platform is situated (FIGURE 1a). The platform represents an epi-Hercinian formation. Paleomagnetic studies of 800 volcanic and sedimentary samples from 12 localities in the Moesian Platform and Bulgarian part of the Rhodopes show existence of insignificant post-Eocene rotation of these lands with respect to Eurasia. The stability of the studied regions is recently confirmed by van Hinsbergen *et al.* (2008). The stability could be interpreted as a result of the position of the Balkanides, Srednogorie and Rhodopes in the northern periphery of the Alpine-Himalayan belt and its partial overlapping with the Moesian plate.

Numerous Paleogene-Quaternary and Neogene-Quaternary grabens or basins were developed generally in central and Southern Bulgaria. The horsts on the boundaries of the grabens had reached considerable heights (relatively higher rate of vertical displacements), mainly in SW Bulgaria (around 2mm/yr uplifting and to 3mm/yr subsidence). Numerous Tertiary-Quaternary

faults cut the territory of Bulgaria (FIGURE 1b). Numerous geologists and geophysicians have provided information about recent active faults (Boncev and Bakalov, 1928; Mihailovic, 1933a; Gočev *et al.*, 1984; Gočev and Matova, 1989; Matova, 2000, 2003; Botev *et al.*, in Sledzinski /ed./, 2000a; Matova *et al.*,

2003). Prevalable part of the active faults is presented by normal faults, very often with equatorial and subequatorial direction. The reverse faults and napes have more local distribution. More information about geodynamical circumstances in Bulgaria is presented further in this paper.



**FIGURE 1. a.** Main structural and tectonic units in Bulgaria (after van Hinsbergen *et al.*, 2008), **b.** Seismicity of Bulgaria (lower magnitude threshold 3.0, time period 2002-2011) on the background of Quaternary faults and Quaternary deposits (<[http://www.geology.bas.bg/geotech/Kvaternerni\\_razlomi.jpg](http://www.geology.bas.bg/geotech/Kvaternerni_razlomi.jpg)> 2012); the indicated years correspond to earthquakes mentioned in the text (all of them with  $M > 4$ )

Juxtaposition of the tectonic setting to the seismicity pattern over the territory of the country would be of use for recognition which of the faults being considered as active, are also seismogenic at present. To this purpose, earthquakes registered in the national instrumental network during the last decade are extracted from the seismological database. The lower magnitude threshold of the data sample is chosen to be 3.0; the weaker seismic shocks are neglected due to their dispersed occurrence in space. Thus, the resulting dataset consists of 345 earthquakes that occurred from 2002 to 2011 including and are of magnitudes in the range  $3 \leq M_d \leq 5.3$ . Distributed in depth, they occurred down to 20 km in Bulgaria and nearby territories, only the Vrancea seismic source in Romania originated intermediate depth earthquakes (11 shocks) with maximum depth of 160 km. It should be noted that the vertical size of the Vrancea seismogenic volume is of about 80-100 km while its earthquake epicentres form a very compact area.

During the studied decade the territorial distribution of seismicity in the region bound by geographical coordinates 41-45.7°N, 22-29.5°E is irregular (FIGURE 1b). The frequency of seismic generation decreases towards North-East. The highest seismic activity, as usual, is observed in the south-western part of Bulgaria and the close neighbouring territory where the strongest earthquakes ( $M_w$  5.3 and 5.1) occurred in the border area between Bulgaria, Macedonia and Greece. To remember that in the same border region a doublet of earthquakes occurred in March 1931 ( $M_s$  6.0 and 6.7 according to Shebalin *et al.*, 1974). At about 70-80 km to the north the earthquake epicentres form a close to W-E trending strip, where the maximum of seismic frequency over the territory of Bulgaria is observed and where four of all events of magnitude 4 or higher occurred. The strip of epicentres coincides with the strike of young faults in the region that cross the older NNW oriented first order fault system. It should be noted that the above discussed seismicity cluster is situated in the epicentral area of the large doublet of earthquakes that occurred in the beginning of 20<sup>th</sup> century (4 April 1904,  $M_s$  7.1 and 7.8; magnitude evaluation according to Christoskov and Grigorova, 1968). To the west of the noted cluster, outside Bulgaria, the older fault systems that extend to the NNW manifest their seismogenic capability. To the south of the same epicentre concentration, on the territory of Northern Greece, activation is formed along the Middle-Mesta fault system of W-E orientation. And, from the eastern edge of the seismicity strip, continuation of activity is observed in two directions: the first towards ESE into the neighboring Rhodopean

massif, and the second trends SSE along the Pirin Mountain known by its relatively rapid uplifting, then with disintegrating consequences. To preclude with the seismic generation in the south-western region of Bulgaria, it should be noted that the northern board of the mountain massif in this part of Bulgaria is sluggish marked by rare seismic manifestations. Obviously, all the Quaternary faults in SW Bulgaria were seismogenic during the considered period, *i.e.* from 2002 to 2011.

To the North of the above considered territory of Bulgaria, the territory of central West Bulgaria is situated. It is cut by Quaternary faults stretching in ESE-WNW direction. Here, two areas show seismic activation during the considered time period. The first, of SE-NW orientation, is situated to the south of the capital city of Sofia, the second lays in the border region between Bulgaria and Serbia and is of W-E orientation. The maximum observed magnitude in central West Bulgaria for the studied period is less than 4.0.

The central South Bulgaria is the territory wherein two destructive earthquakes ( $M_s$  6.8 and 7.0) occurred in 1928. During the study period the seismogenesis therein was at a very low level. Only the seismic activation in April-May 2002 (mainshock's magnitude  $M_d=4.2$ ) perturbed the seismic pattern of the northern flank of the Rhodopes Mountain that cover the southern part of central Bulgaria. In the eastern Rhodopes a seismic sequence with a mainshock of magnitude  $M_d=4.5$  was observed in 2006. It can be seen in FIGURE 1b that the seismically activated area was along a Quaternary fault of ESE-WNW orientation.

In the south-eastern Bulgaria the seismicity shows a dispersed pattern with exception of the most eastern area where numerous earthquakes have occurred since 2009. It should be noted that a two-year period of similar seismicity characterized by slightly perceptible earthquakes was observed there in the beginning of the 20<sup>th</sup> century (starting in 1907).

The central North Bulgaria is the area where the 1913,  $M_s7$ , earthquake and the 1986 moderate earthquakes ( $M_d$  5.4 and 5.7) took place. However, during the last 10 years it generated few shocks only and comments on the relation with the tectonic setting would be fictional.

The North-East Bulgaria shows scanty seismicity, typical of it. Two seismic sources should be noted therein: (1) the surroundings of Provadia salt mining area with concentration of shallow earthquakes of magnitude less than 4.5 (Dimova *et al.*, 2004; Botev *et*



al., 2005) and (2) the continental slope contacted with the Black Sea known by generating a magnitude Ms7.2 earthquake in the very beginning of the 20<sup>th</sup> century (March 1901). The present-day seismicity of the latter source is low though two seismogenic orientations there are noticeable - WNW-ESE and NNE-SSW. The maximum magnitude during the examined decade was 4.8 on 5 August 2009, hypocentre under the sea, maximum intensity on the land 6 EMS.

Generalizing, at present there exist seismically active Quaternary faults and blocks between them. Most active among them are the structures in SW Bulgaria and the contact lands in Bulgaria, Macedonia and Northern Greece. The degree of seismic activity in the rest of the faults and blocks shows difference even for a 10 years period of instrumental registrations. Nevertheless, some general trends in the territorial seismogenesis can be outlined as follow: W-E (in SW Bulgaria and the neighboring Macedonia, W Bulgaria, N Greece) and quite close to it WNW-ESE (in central South Bulgaria, Rhodopes, NE Bulgaria) on the one hand; almost N-S that coincides with the old structures (in SW Bulgaria: NNE-SSW and NNW-SSE; the neighboring Macedonia NNW-SSE); WNW-ESE (in N Rhodopes) and SE-NW (in W Rhodopes). This seismic activity pattern provides important information about the recent block differentiation.

## MACROSEISMOLOGY AND FIELDS OF USE OF MACROSEISMIC DATA

The seismology in Bulgaria dates back to 1891. Its pioneer and director of the Central Meteorological Station in Sofia was Spas Watzof. He organized a network of correspondents-volunteers for observation of felt earthquakes (shocks detected by people without instruments irrespective of their strength). The observation macroseismic network consisted of meteorological observatories, telegraph-postal services, railway station officials, municipal offices and teachers (FIGURE 2). To unify the collected reports Watzof prepared and spread over the country a special “Instruction and program on the earthquakes observation and documenting” (Watzof, 1902). The Bulgarian seismological service was committed to collect, analyze and archive macroseismic information about affects that accompany and follow felt earthquakes. The telegraphically received information often served to warn local governors about possible aftershocks in the earthquake area. Until 1912 the seismological office had also to collect macroseismic information from Bulgarian lands that remained under Ottoman administration. All the reports coming to the Central Station were systematized and after that included in seismological compilations “Reports on the Earthquakes felt in Bulgaria”.

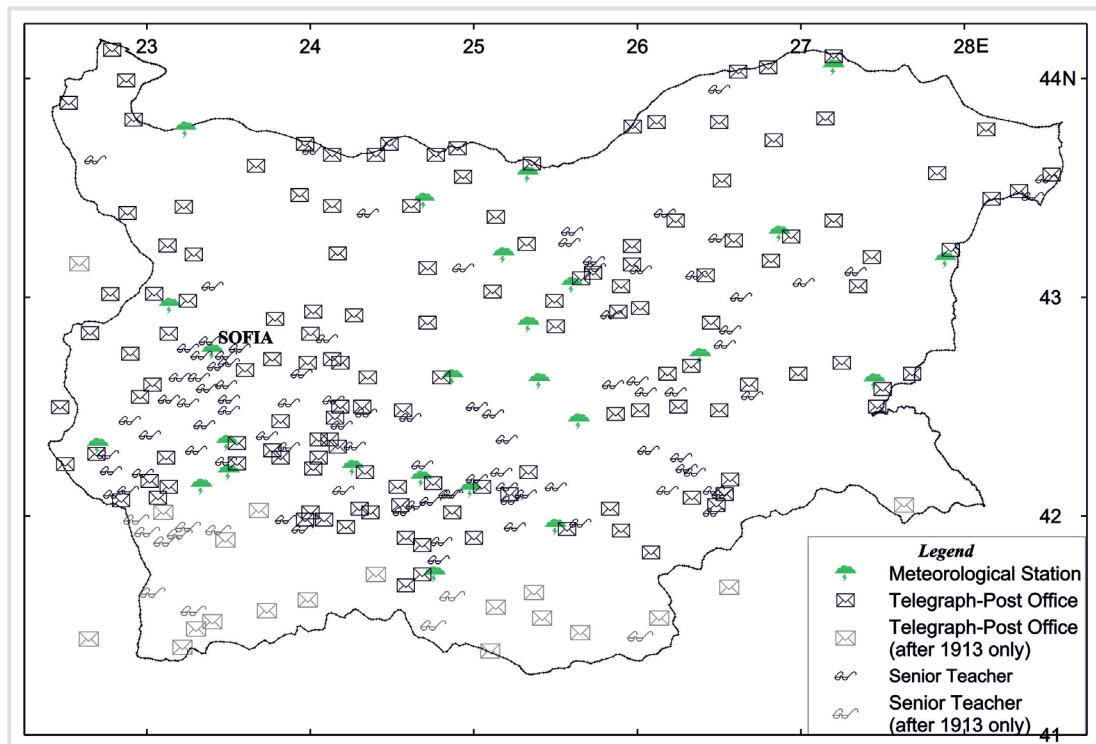


FIGURE 2. Bulgarian network for reports on felt earthquakes (1892-1927); it covers all seismic source zones.

Macroseismology in the pre-instrumental period was concerned chiefly with the observational use, for seismic monitoring and construction of macroseismic bulletins. Except for the correspondents' descriptions, Watzof's "Reports" contain a tabulated systematics of the observed effects being supplemented by reported intensity assessment. Thus, Watzof formed the prototype of a macroseismic bulletin in Bulgaria. This manner of presentation holds to the earthquakes felt in Bulgaria during the period 1892-1927. After Watzof's death in 1928 the employees of the seismological service continued with collecting the macroseismic data. As a result of their efforts, the scientific world received regularly annual reports on earthquake shakings in Bulgaria in the course of 74 years. In addition, the latter information is very important for completing the macroseismic maps at catastrophic earthquakes in Greece (Low Thracia), Turkey (East Thracia and Asia Minor), Romania (the region Vrancea), Macedonia and Serbia. The same macroseismic set of data ensured later the basis for compilation of earthquake catalogs (Grigorova, 1973, in Shebalin *et al.*, 1974; Grigorova *et al.*, 1978; acknowledgments to R. Glavcheva and D. Sokerova /Bulgaria/ "for presentation of important initial data", in Shebalin *et al.*, 1998) and maps of intensity distribution (the macroseismic maps are discussed below).

The last materials presenting eyewitnesses' evidences are those prepared by Watzof just before his death and later edited and published by Kirov (1931). In the following years Kirov preserved only the form of classical macroseismic bulletin skipping detailed eyewitnesses' statements. The strength of shakings began to be assessed by a specialist and not by correspondents-volunteers as previously. This form was adopted and used until the issue of the last macroseismic yearbook (Grigorova and Rizhikova, 1966).

Over the years, various intensity scales were applied. Intensity value was given by the Rossi-Forel scale - RF (de Rossi, 1883; 1911; the RF scale was published in Bulgaria by Watzof in 1902) till 1912. Further on, the shaking intensity was assessed by Forel-Mercalli 12-degree scale (Mercalli, 1902), it was modified by Cancani (1904) who added two more degrees for catastrophic earthquakes and proposed a peak acceleration value equivalent to each intensity degree. In the course of time modern European intensity scales were adopted successively: the Mercalli-Cancani-Sieberg scale (supplement relying to effects in buildings, Sieberg, 1923) was applied from 1946 to 1960, the Medvedev scale (behavior of different building types,

Medvedev, 1953) and its clarifying-upgrading in the scale of Medvedev-Sponheuer-Karnik (Medvedev *et al.*, 1964) were applied to the earthquakes after 1961 and, finally, the EMS-92 and EMS-98 (Grünthal /ed./, 1993; 1998). Here we would like to recall the conclusion drawn from the comparison of macroseismic intensity scales (Musson *et al.*, 2010, p. 422): "... whatever differences there might apparently be in the wording of the scales, there should be no differences in MSK values and EMS values if the MSK values were correctly assigned".

In cases of important earthquakes (according to the consequences or epicentral position) field investigations of effects are usually undertaken. Special volumes have been dedicated to observational data collected in cases of large shocks in Bulgaria. A very well illustrated book is among the works of great value (Staikoff, 1916). It is devoted to the first Bulgarian field inspection that was conducted by Staikoff in the epicentral area of the Ms7.0 North Bulgarian earthquake in June 1913. The epicentral intensity of this event reached IX MSK (EMS98), the shock damaging many villages completely and two important cities partially. Dineva *et al.* (2002) re-determined the magnitude of this earthquake from a great amount of original records; the result Ms=6.3 is "robust" according to the authors statement and, obviously, much lower than the previous estimate (Ms=7.0 according to Christoskov and Grigorova, 1968).

In April 1928 two catastrophic earthquakes hit a broad area in central South Bulgaria. These two events occurred within a time window of only four days and were of magnitudes Ms 6.8 and Ms 7.0, with epicentral intensity IX and IX-X MSK, respectively; focal depth down to 15 km. These earthquakes were followed by numerous aftershocks during the next four years. The scientific and practical results from field observations undertaken by geologists and construction engineers, with the financial support of local and state governors and especially of the Red Cross, are described in details in DIPOSE (1931). The report was commissioned by the state's government. Its publication was delayed to include the results of the restoration. Jelenko Mihailovic who was in charge of seismology in Belgrad, Serbia, also made a thorough inspection in the suffered area; his conclusions rely predominantly to tectonics and surface geology (Mihailovic, 1933a, 1933b).

The intermediate depth earthquake source Vrancea (from 60 down to 180 km under the earth's surface), which is situated in the neighboring Romania, represents serious threat to the territory of North Bulgaria, especially at

epicentral distances of 150-300 km. The catastrophic earthquake that occurred on 4 March 1977 forced many specialists in tectonics, geology, seismology and earthquake engineers to undertake field surveys of the consequences caused by the event. According to the Romanian Earthquake Catalogue ROMPLUS (2007), the earthquake moment magnitude was  $M_w=7.4$ ; the  $M_w$  value was assessed by the moment magnitude scale (Kanamori, 1977; Hanks and Kanamori, 1979). Results from the thorough field work on the effects of the 1977 destructive earthquake as well as essential seismological information on the Vrancea region seismicity (deep events recurrence, response spectra, intensity attenuation, etc.) were published in the monograph compiled and edited in Bulgarian Academy of Sciences (Brankov /ed./, 1983).

The monitoring application of intensity is of significance for studying currently felt seismic events. The nowadays macroseismic practice in Bulgaria includes the following procedures: phone interviews, internet questionnaires' dissemination and field survey. The field observations carried out immediately after the occurrence of a strong earthquake, not influenced by its aftershocks, give knowledge not only on the earthquake that already occurred but also ensures a basis for developing a scenario for future distribution of the seismic effects. Inspections are accomplished by teams of seismologists, earthquake engineers and specialists in geology. With the local authorities on the spot, the team firstly looks for generalized information concerning the state-of-the-art of the building stock (typical damage and top damages), terrain and soil peculiarities, infrastructure, systems supplying electricity and drinking water, circumstances in the settlements and their surroundings (Glavcheva and Matova, 2009). It is very important to give the people information about the occurred event/-s as well as preliminary advices related to their estate. This ensures psychological support to the population. Public buildings like schools, libraries, cultural and sport buildings, etc., need special attention. After precluding the inspection, the most frequently observed damages and other effects are systematized and assessed. Reports are delivered to The State Agency for Civil Protection and the local governors.

Isoseismal maps in Bulgaria came officially into practice since 1952 (Ileff, 1952). Macroseismic maps for Bulgarian earthquakes of magnitude  $M_s \geq 4$  that occurred till 1970 (77 maps, minimum epicentral intensity of V MSK) are presented in the Balkan Region Atlas assembled and generalized by Shebalin (1974). Most of this material was previously published in

Bulgaria (Grigorova and Grigorov, 1964). Additionally, isoseismal maps of Bulgarian earthquakes can be found in the atlases published by Prochazkova and Karnik (1978), Glavcheva (1993) and in papers devoted to damaging earthquakes in the seismic zones of Bulgaria. For instance, a comprehensive study of the intensity distribution from earthquakes of the same source was provoked by a seismic event of magnitude 5.7 in 1986 (Glavcheva, 1989). Another case of necessity to survey and generalize consequences of earthquakes is in an area with salt mine production in East Bulgaria (Dimova *et al.*, 2004).

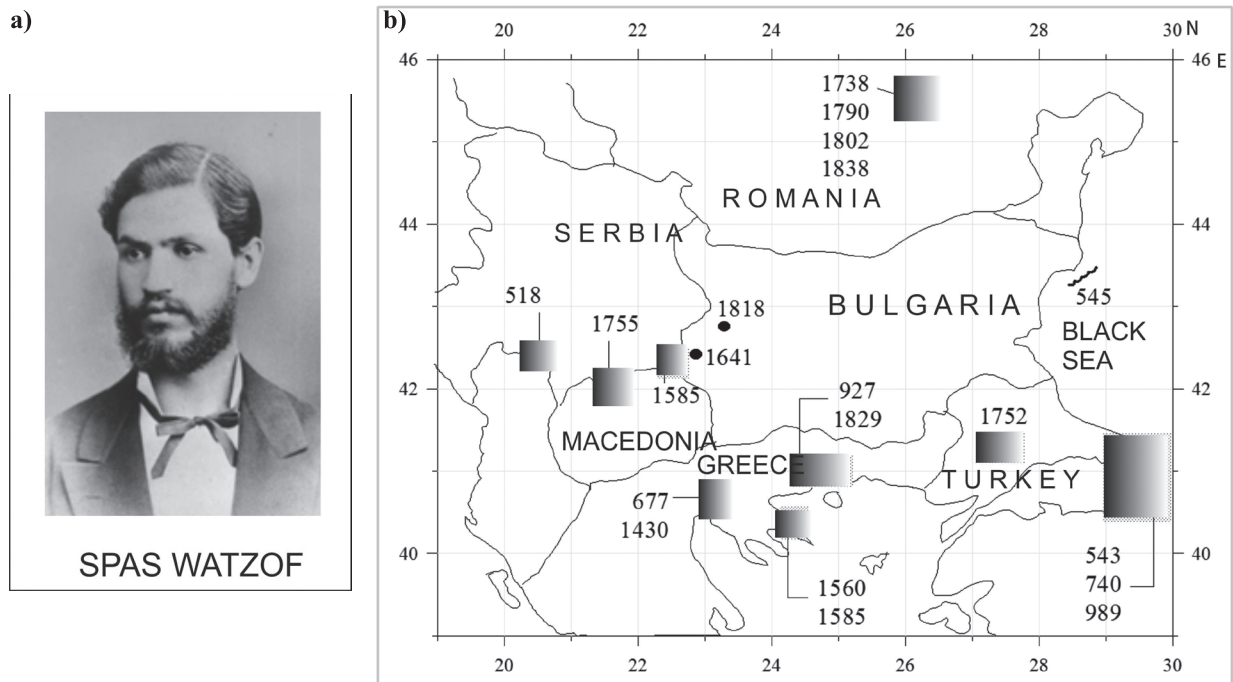
Bulgaria is under the influence of seismic impacts from the neighboring countries too. Especially the intermediate depth earthquakes from Vrancea, Romania, with magnitude higher than 7.0 (37 earthquakes of magnitude  $M_w \geq 7.0$  according to ROMPLUS) usually cause great losses to the territory of North Bulgaria. The 1977 Vrancea earthquake of magnitude  $M_w=7.4$  (evaluation in ROMPLUS) led to partial or complete destruction of about 8500 buildings and killed 125 people in Bulgaria. On this reason, the entire set of intensity maps for Bulgaria in cases of large Vrancea earthquakes was subjected to macroseismic quantitative analysis specifying the intensity attenuation towards the north-west and north-east Bulgaria (Grigorova *et al.*, 1978; Glavcheva, 1983). The isoseismal maps of next destructive Vrancea earthquakes on 30 August 1986 ( $M_w=7.1$  according to ROMPLUS) and 30 May 1990 ( $M_w=6.9$ , ROMPLUS), containing intensity data points, are presented by Evlogiev *et al.* (2010) and Bonjer *et al.* (2010). It should be noted that in the case of November 1940 earthquake ( $M_w=7.7$ , ROMPLUS) Romanian authors have assigned various intensity assessments to one and the same site without reference for the used macroseismic scale; this resulted in several modifications of isoseismals. Thus, the unification of the intensity field in the border areas between Romania and Bulgaria is a necessary task that has to be accomplished in the near future.

### Historical seismology

One of the mandatory requirements for proper assessment of seismic hazard is to conduct a careful and critical evaluation of catalogues that include earthquakes occurred in earlier centuries (the so called historical earthquakes). Development of the historical seismology is impossible without using of macroseismic approaches. The pioneer of historical seismology in Bulgaria was Spas Watzof. He organized intellectuals in Bulgaria to collaborate in searching for information on tremors that occurred in the past. Watzof himself brought

useful information on past earthquakes in Bulgaria and surroundings from sources dating back to the 8<sup>th</sup> century (the Chronographia by Theophanes). Most of the epicentre locations indicated more than a century ago by Watzof (FIGURE 3) were confirmed later and,

only, presented more precisely in a modern way (See ANNEX 1). The comparison with recent catalogues and studies shows that even nowadays sources are not in full agreement in their evaluations of either the magnitude or intensity of excitation.



**FIGURE 3.** a. Spas Watzof, b. Map of epicentral areas of felt earthquakes (areas marked by gray) since antiquity till mid-XIX century according to Watzof's investigations.

The next seismologist who had significant contribution for studying the long-term seismicity was Staikoff. He searched for information about unknown earthquakes through ancient and recent literature, catalogues, periodicals, etc, in Central European libraries. His findings published in (Staikoff, 1930) include 375 earthquakes or clusters that occurred all over the Balkans and in Asia Minor, rarely in Italy, during the time period III c. BC – 1885. His data were used later at the joint compilation of the earthquake catalogue of the Balkan Region (Shebalin *et al.*, 1974).

Almost a century after the pioneering efforts of Watzof, a new search for earthquakes in the past was commenced through different kinds of compilations (historical sources, marginal notes, memoirs, and manuscripts). A thorough work fulfilled by Babachkova and Rizhikova (1993) led mainly to first hand sources. Unknown weak earthquakes in Bulgaria and pieces of data on strong earthquakes in the neighborhood were found.

The earthquake catalogues are advanced expression of seismic inventory. However, very often data from

a given catalogue that are loaded with errors due to both incorrect interpretation and misunderstanding of the source of information are included in subsequent catalogues. For the seismicity of Bulgarian lands two catalogues have been prepared in the last 40 years. The earlier one was a product of the Project on Seismicity of the Balkan Peninsula (Shebalin *et al.*, 1974). For earthquakes in the past it points to the information sources and frequently quotes corresponding descriptions. The second catalogue was created in connection with the seismic zoning of Bulgaria (Grigorova *et al.*, 1978, further marked as GRAL978). In GRAL978, the historical earthquakes are presented as parameterized entries. Unfortunately, this catalogue also inherited some of the above mentioned disadvantages.

The primary sources of information in GRAL978 are the late compilations of two Bulgarian seismologists Watzof (1902, 1908, 1912) and Staikoff (1930); “late” means that they are second-hand sources retelling stories or citing another unoriginal source. These circumstances forced the Bulgarian team as a participant in the NA4 module “Distributed Archive of



Historical Earthquake Data” of the Project “Network of Research Infrastructures for European Seismology” (NERIES, No.026130), Sixth Framework Program of the European Commission, to critically reconsider the way of analyzing and proceeding the collected by Watzof and Staikoff information.

The analysis started from “what was known” and this was the catalogue GRAL978 together with the corresponding information source (ANNEX 2). The bibliographic lists presented in the cited Bulgarian compilations helped for finding out earlier information. The catalogue entry corresponds to the time prior to the Seismological Service establishing and earthquakes of a macroseismic magnitude  $M_{ms} \geq 4.5$  according to the information given by the catalogue GRAL978. The catalogue entry provided by GRAL978 (ANNEX 2: column 1 in Table 2.1) is examined in this study by information sources coeval to the corresponding seismic event (column 3; reference lists of these sources have been added to ANNEXES following this main text). By the above described procedure the identity of corresponding earthquake is verified and the catalogue

macroseismic parameters upgraded. Column 2 of Table 2.1 contains the main critical remark to the established state of affairs together with the resulting entry if determinable.

As a result of the analysis of information sources (*e.g.* historic, diplomatic, ethnographic, travel literature, and newspapers issued in the second half of the 19<sup>th</sup> century) coeval as much as possible to each of the considered earthquakes, 25 events in the period 15<sup>th</sup> century-1891 have been revised. Some of them are proved to be fake (1450), some are erroneously localized on the territory of Bulgaria (1444, 1660, 1759, 1832 and 18 Dec. 1866), one new event is added (1618), two events are unified (1704 and 1749), others have received corrections of dating, or epicentre determination or, most often, intensity value (FIGURE 4). Corrections are owed presumably to careless reading of information (ANNEX 2). The critical re-evaluation of the macroseismic archive of earthquakes felt in Bulgaria can be considered as an improvement of the knowledge on historical seismicity.

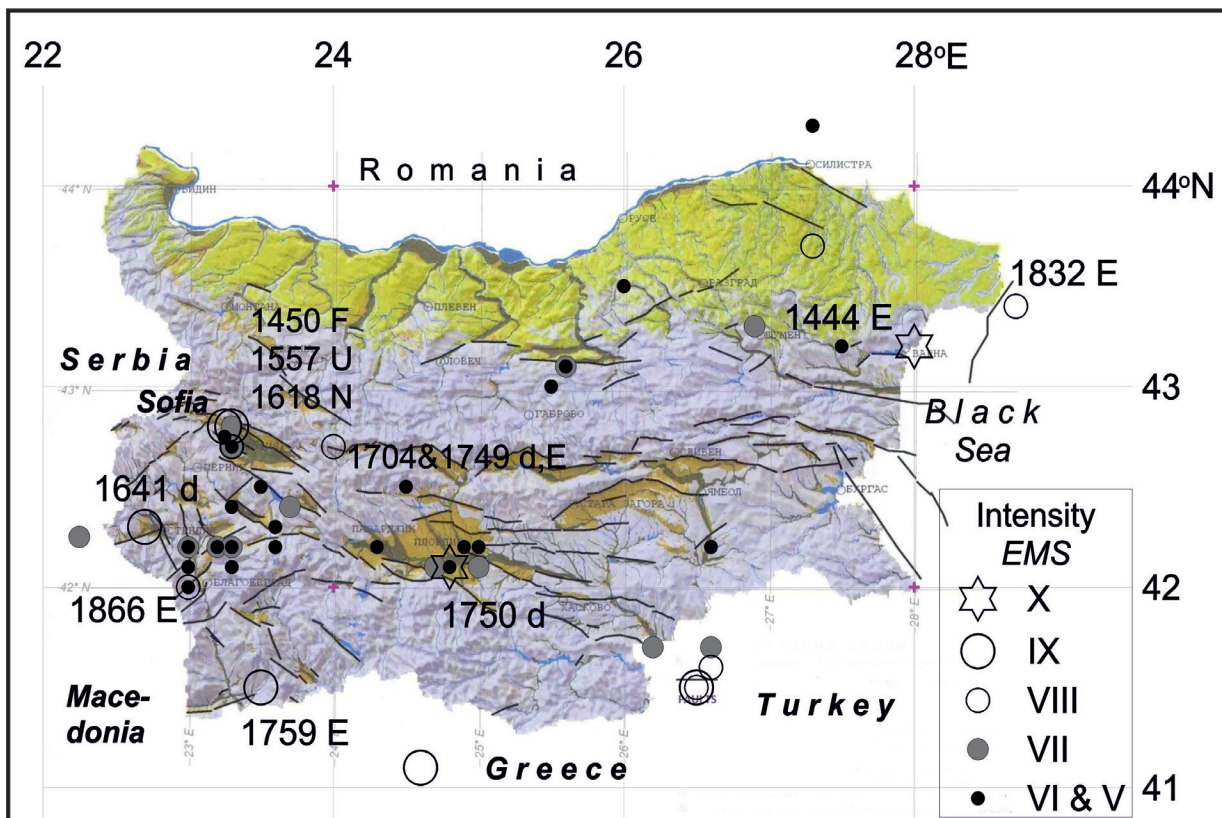


FIGURE 4. Comments to the catalogue of historical earthquakes: Years marked in cases of documented/reported intensity  $\geq VIII$  EMS; The abbreviations used as follows: E= epicentre changed; F= false entry; d= dating revision; N= new event; U= uncertain event

## Studies on seismic hazard

The seismic intensity is also used at present in a predictive way for seismic hazard and risk studies, where damage and loss estimates can be inferred from expected intensity values. The assessment of seismic hazard and generation of earthquake scenarios is the first step in the evaluation of seismic risk.

The irregular macroseismic effects of the Vrancea intermediate depth earthquakes (depth interval from 60 to about 180 km) are directly included in the seismic hazard calculations for Bulgaria and adjacent territories framed between 41-45°N, 22-30°E (Simeonova *et al.*, 2006). The probabilistic seismic hazard assessment in terms of intensities (probability that various levels of intensity will be exceeded during a certain period at a given site) is performed following Cornell (1968) with the program EQRISK (McGuire, 1976). Two factors suggested the use of macroseismic intensity instead of peak ground acceleration or spectral acceleration: the direct correspondence between intensity of shaking and the degree of damage, and the intensity as being the original parameter of historical earthquakes. The intensity-frequency relations and the site intensities are computed as a function of observed MSK epicentral intensities based on a catalogue for the whole area (Shebalin *et al.*, 1998).

The seismic hazard maps have been later updated by Leydecker *et al.* (2008) dealing separately with the shallow earthquakes over the whole study territory and the intermediate depth's earthquakes from Vrancea. The seismic hazard evaluation has been obtained following the same methodology for the entire territory of both, Bulgaria and Romania, and according to the requirements of the European earthquake building code EUROCODE 8 (EC 8). Calculations are done for recurrence periods of 475 years (probability of exceedance of 10% in 50 years) for the design earthquake and 95 years (probability of exceedance of 10% in 10 years) in order to limit the damage of buildings and the financial loss in case of weaker earthquakes with higher frequency of occurrence.

It is worth noting that earlier studies on the seismic hazard in Bulgaria (Bonchev *et al.*, 1981, 1982; Orozova-Stanishkova and Slejko, 1994; van Eck and Stoyanov, 1996; Solakov *et al.*, 2001b) used the magnitude-frequency relations and the epicentral or site intensities proceeding from magnitudes. However, the magnitude has been loaded with great uncertainty almost till the 60-ties of the 20<sup>th</sup> century as a value resulting from intensity. One more remark: only Bonchev *et al.* (1982)

have performed hazard analysis for the whole territory of Bulgaria for different probabilities of exceedance, but not for a 475 years return period as EC8 recommends.

Based on earthquake catalogues, regional seismotectonics and geotechnical zonation, earthquake scenarios (ground motion hazard maps by both approaches: deterministic and probabilistic) for important urban areas in Bulgaria are presented by Solakov *et al.* (2009). For the capital city Sofia ground shaking accelerations in terms of peak ground acceleration (PGA) and response spectral accelerations in the frequency interval 0.5 – 3.3 Hz were evaluated by a deterministic approach; thus, in the case of local earthquake of magnitude 6.3 the estimated PGA values are in the range 0.05÷0.3 g, and the maximum spectral amplitude is 0.75g at frequency of 3.3 Hz. The probabilistic approach that gives an idea of the pattern of ground motions for future earthquakes was estimated according to the technique accepted in the frames of the European project Risk-EU (2001-2004). Following this technique, the obtained for the capital city Sofia PGA value was in the interval 0.15÷0.28g for bedrock (Solakov and Simeonova, 2006). In practice, similar scenarios are intended as a basic input for developing detailed earthquake damage scenarios for the cities. They can be used in the urban and infrastructure planning.

To generate earthquake damage scenarios for earthquakes of magnitude between 4.1 and 8.0 centered in an arbitrary point in Bulgaria and adjacent territories, the software package Automated System for Assessment of Earthquake Consequences (ASEC) was created and used in Bulgaria (Solakov *et al.*, 2001a). It includes also a previously developed approach for estimation of the possible human losses in case of strong earthquakes (Christoskov, Samardjieva, 1984; Christoskov *et al.*, 1990). The ASEC estimates the statistical mean values of human casualties, building damages and the cost for covering losses. Such estimations are especially helpful for rescue teams after a strong earthquake has struck Bulgaria.

An Advanced Research Workshop “Earthquake monitoring and seismic hazard mitigation in Balkan countries “, financed by the program “The NATO Science for Peace and Security” was hold in Borovetz, Bulgaria 11 – 17 Sep. 2005. Forty two scientists from 22 countries took part in the workshop, including representatives of international organizations like IRIS, ORFEUS, EMSC, MEDNET, CTBTO. The main topics of the meeting included: geology, tectonics of lithospheric plates, tomography of the crust and mantle

seismicity, seismic risk and hazard, seismic networks and activities - global, regional and national; operations of global and regional seismic networks. The organizing, managing and implement of the workshop as well as the publishing of the presented lectures (Husebye and Christova eds., 2005) were carried out mainly by the efforts of Bulgarian workshop sci director and the local organizing committee.

## **INSTRUMENTAL SEISMOLOGY IN BULGARIA: EQUIPMENT AND MAIN RESULTS FROM INSTRUMENTAL MONITORING**

The instrumental seismic monitoring in Bulgaria started after a couple of devastating earthquakes (Ms7.1 and Ms7.8 according to determinations by Christoskov and Grigorova, 1968) that occurred on 4 April 1904 in the south-western part of nowadays Bulgaria. The first seismological station in Bulgaria was opened in Sofia in 1905 where two horizontal components of the mechanical Omori-Bosh seismograph were installed by the young seismologist Staikoff. These undamped pendulums began operating as follows: since 16 April 1905 the EW component, and since 1 June 1905 the NS component. In 1934 two horizontal Wiechert seismographs (eigen period  $T_0=9-11$  sec; magnification around 200; with air damping) began operating in the capital city. They were in operation along with the electromagnetic type of seismographs till 1980 when the national seismological service of Bulgaria was expanded. The development of the instrumental network in Bulgaria during the 20<sup>th</sup> century can be traced in ANNEX 3 (data borrowed from Christoskov, 1992).

The actual start of the instrumental seismology in Bulgaria is associated also with the creation and issuing of instrumental bulletins which cover the earthquake records from the following periods: 1905-1911 (Watzof, 1907, ..., 1921), 1935-1946 (distributed only in mimeograph), 1947-1956 (Kirov and Grigorova, 1957, 1958) and finally from 1960 until 1965 (Grigorova *et al.*, 1962; Grigorova and Rijikova, 1963; Rizhikova, 1970). It is noteworthy that the records of Sofia seismic station were used in studying the awful 1906 San Andreas, California, earthquake (Reid, 1910) as well as in the examinations on the thickness of the crust by Mohorovicic (1910).

The deployment of instrumental registration in Bulgaria led to development, adaptation and application of new methodological approaches as listed chronologically below:

- Attempts were made to create a local magnitude classification (Grigorova and Grigorov, 1962; Christoskov, 1962);
- The microseismic noise at Sofia station was measured (Christoskov and Holub, 1963);
- A comprehensive microseismic zoning with the participation of professor Medvedev was accomplished to support a dam safety (Medvedev *et al.*, 1963);
- A normalized magnitude scale for near and distant earthquakes was completed (Christoskov, 1964);
- Propagation velocities of surface waves across the Aegean Sea were investigated (Rizhikova, 1966);
- Results on body waves propagation velocities and the Earth's crust structure in Bulgaria were reported (Grigorova and Sokerova, 1967);
- An approach to generalization for the weak earthquakes in Bulgaria was suggested (Rizhikova and Glavcheva, 1974);
- Bulgaria collaborated to compiling the first united earthquake catalogue for the Balkan Region (Grigorova, 1973, in Shebalin *et al.*, 1974);
- P-wave travel time residuals in the Balkan region were investigated (Sokerova, 1974);
- Maps of seismic activity within Bulgaria were constructed (Grigorova and Glavtcheva, 1976);
- Induced seismic activity was proved in the Iskar Dam surrounding (Grigorova *et al.*, 1976);
- Experimental telemetric transmission of analog seismological information between a mountain in surrounding and the building of the Geophysical Institute in Sofia was carried out via ultra short waves in 1978;
- Prognostic seismic zoning of Bulgaria, that became the fundament of the Bulgarian Code for design of structures in seismic regions (1987), was committed and completed by a wide range of specialists in the earth sciences (Bonchev *et al.*, 1981, 1982); many years ago, the first seismic regionalization of Bulgaria was approached by Kirov and Grigorova (1957) based only on seismological background;
- Focal mechanisms for two earthquakes of a medium strength (magnitude up to 5) that occurred in SW Bulgaria were constructed and examined (Georgiev and Ichikava, 1976).

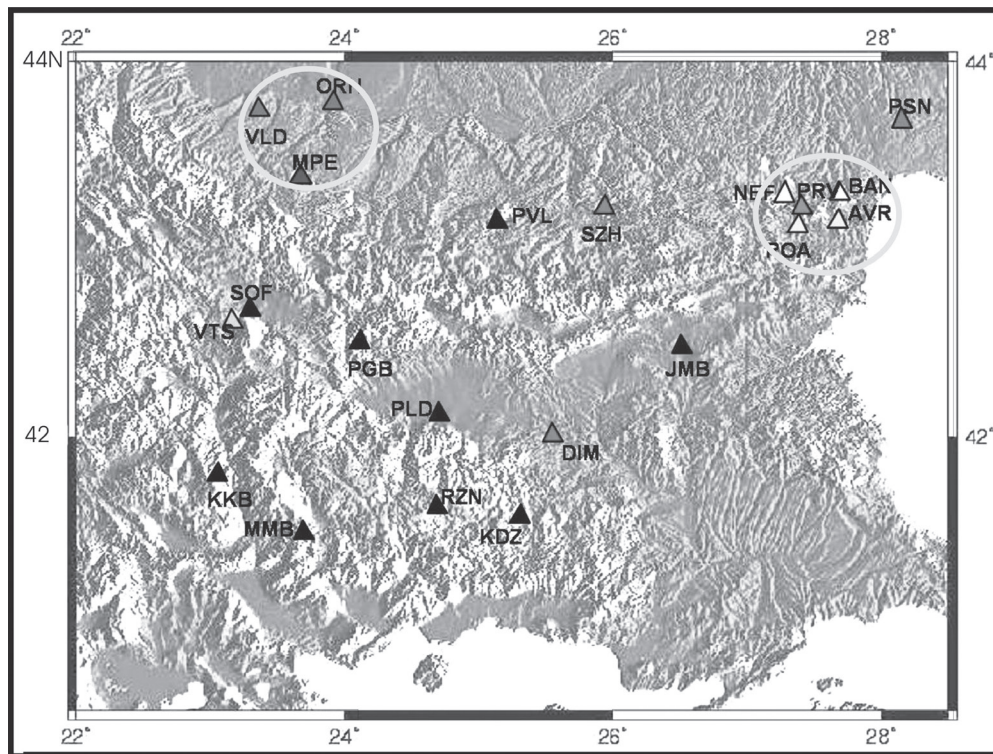
Most of the problems listed above have become later a permanent objective for further studies and development.

Since March 1980, for about a year, the National Telemetric Seismological System for Information (NOTSSI) was established; inquiry about the network development is available in TABLE 3.1 and FIGURE



3.1, in ANNEX 3. The NOTSSI stations were equipped by Teledyne Geotech with short-period seismographs S-13, with a frequency band 1.25-10 Hz (0.1-0.8 sec). By simultaneous operation of low and high gain channels, a station dynamic range of 80 dB was achieved (Samardjiev *et al.*, 1980). In the course of time the telemetry network has been expanded to 14 basic registration sites (all of them with vertical S-13) with real

time signal transmission to the Geophysical Institute, Sofia, ensuring continuous monitoring. Additionally, two networks for local monitoring of seismicity started operating in the mid-1990 in connection with the seismicity observation around a NPP site in NW Bulgaria (since 1993) and a salt deposit exploitation site in NE Bulgaria (FIGURE 5).



**FIGURE 5.** Bulgarian instrumental network: the seismic stations are indicated by triangles and the corresponding station code; the local networks sites are marked by ellipses.

Naturally, a number of studies were carried out on the capabilities of the new registration system: finding out the optimum equipment magnifications for detecting first motion of P body waves from short distance earthquakes in Bulgaria and some other related problems (Rangelov and Christoskov, 1980; Danev, 1982), determination of station corrections in a network of standard seismic stations (Christoskov and Venedikov, 1986), development of a classification for express magnitude evaluation by the short period seismographs S-13 (Samardjieva, 1991), identification of natural and artificial sources (Christoskov *et al.*, 1986; Riznichenko *et al.*, 1987; Milev and Christoskov, 1988), etc.

The presence of well arranged network (Solakov, 1991; Glavcheva *et al.*, 2003; Botev and Glavcheva 2003) ensuring qualitative instrumental records resulted in gradual liquidation of non-uniform parameterization of

earthquakes. Based on the methodological principles and practical results developed by Chalturin and Christoskov (1974), Karnik and Christoskov (1977), Christoskov *et al.* (1978, 1985), Christoskov achieved unification of the magnitude determinations from various types of seismic waves for Bulgaria making them compatible with the standard surface wave teleseismic magnitudes. Thus, he constructed calibrating curves for P, S and L waves for shallow events at a depth down to 60 km at short epicentral distances ( $<10^\circ$ ) for the short and medium period seismographs (Christoskov, 1994). These new calibrating functions turned out especially necessary after installing the short-period Teledyne Geotech devices in Bulgaria.

The high sensitivity of recording in the NOTSSI stations as well as the very broad-band characteristics of the MEDNET station VTS ensured a basis for further



examination of the seismic behaviour in various seismic zones and studies on the Earth's structure. Numerous problems became possible to be studied and successfully solved, moreover at a higher level as the following:

- Regular compilation and dissemination of reports on current seismicity observed in Bulgaria and nearby territories (Botev *et al.*, 1991, ..., 2010; Botev *et al.*, 2006b);
- Specification of aftershock manifestations in time after remarkable events according to the modified Omori formula and maximum likelihood method (Simeonova *et al.*, 1988; Simeonova and Solakov, 1999);
- Development and yielding practical results of a dislocation model for determining some basic geometrical parameters of extended earthquake sources by the body-waves time difference between the amplitude maxima and the starting points of the records (Christoskov *et al.*, 1990);
- Solving of earthquake focal mechanisms for particular seismic zones – for instance, Dineva *et al.* (in Sledzinski /ed./, 2000b) obtained fault plane solutions for numerous small and moderate shocks that occurred during 1972-1993 in SW Bulgaria and its surroundings (40.8°N÷42.4°N and 22.0°E÷24.2°E); the results may be summarized as follows: 60 % of the solution type is the normal type, around one third of solutions are of reverse type and only 5% of the events are with horizontal movement along the fault. The authors suggested concordance with the regional sub-horizontal tensional stress;
- Discussing the stress distribution over the entire territory of Bulgaria and geodynamical knowledge: Analysis of a homogenized set (unified presentation after checking and/or a re-calculating) of focal mechanisms for 158 earthquakes of magnitude  $M > 3$  that occurred during 1980-2000 in Bulgaria yielded to the following results (Botev *et al.*, 2006a): concerning the territorial distribution, the relative share of the dominant focal solutions, namely of those ones of a normal type, decreases from SW towards NE (the rest of the contributions refers to the geodynamics and are discussed further);
- Obtaining of spectral characteristics of seismic waves directed to outline the site specificity of seismic danger (Deneva, 1985);
- An anisotropic layer at depths of 30–45 km was identified in southeastern Europe based on the records of very broadband seismometers and the dispersion properties of Rayleigh and Love surface waves (Raykova and Nikolova, 2003); frequency-time analysis and the Backus–Gilbert inversion method (1968, 1970) were applied;
- The heterogeneity of the crust and upper mantle for the territory of Bulgaria was proved according to seismic data (Botev and Vinnik, 1984; Botev *et al.*, 1987; Spassov and Botev, 1987, 1989)
- Ideas on interaction between neighboring seismic zones (sources of trigger effects) were examined on the purpose to understand the tectono-physical mechanism of the earthquake generation (Gospodinov and Rotondi, 2006; Papadimitriou *et al.*, 2007);
- Searching for earthquake precursors, like: changes of the properties of the earth's medium based on the examination of body waves particle velocity (Yelenkov and Stoyanov, 1986); anomalies in the ionosphere by land measurements (Nestorov, 1979; Ralchovski and Komarov, 1987, 1989); anomalies in the ionosphere by satellite monitoring (e.g., Gousheva *et al.*, 2008); anomalies based on geomagnetic monitoring (Botev *et al.*, 2007), and on seismological features in earthquake zones.

Bulgaria has gained extensive experience throughout participation in accomplishment of international initiatives on testing advanced methods and techniques for data acquisition and processing, most often on a multidisciplinary basis – it comes to European and bilateral projects as well as other joint activities: “Genesis and Impact of Tsunami on European Coast” (GITEC, 1993-1995), “Assessment of seismic potential in European large earthquake area” (ASPELEA, Oct. 1997-June 2000), “An advanced approach to earthquake risk scenarios, with applications to different European cities” (RISK-UE, 2001-2004; subcontract “Seismic hazard assessment and ground motion scenarios for the city of Sofia”), “Developing existing earthquake data infrastructures towards a Mediterranean-European Rapid Earthquake Data Information and Archiving Network” (MEREDIAN and Amendment to MEREDIAN, 2000-2006), Field Investigation Team for severe earthquakes in Europe and the Mediterranean basin with European Seismological Commission (FITESC, since 2002), “Natural and Environmental Disaster Information Exchange System” (NEDIES, a project conducted by the Protection and Security of the Citizen, IPSC, of the EC Joint Research Centre, JRC, 2006), “Network of Research Infrastructures for European Seismology” (NERIES, 2006-2010; subcontract), “Seismotectonics and properties of the strong earthquake sources” and “Analysis of the tectonic and the seismicity of strong earthquakes focal zones” (bilateral with Pacific geographical institute, Russian Academy of Sciences

– The Far East Division, 2002-2004 and 2006), “Seismogenesis and interactions between earthquake sources in the Southern Balkans” (bilateral Bulgaria-Greece, 2005-2008), “Seismic hydrogeological vulnerability of the environment and the society in the Balkan region” (Balkan Project, UNESCO-Bulg. Acad. Sci., 2004-2012; see Matova, 2004), and others.

### **The modern instrumental seismological equipment in Bulgaria**

The upgrading of the National Seismological Network (NSN) started in 1996 when a station close to Sofia was equipped with STS-1 and Quanterra 380. Two more stations in South Bulgaria were supplied with Quanterra 330 data loggers and Guralp CMG-40T broad-band sensors in 2003. The participation of Bulgaria in the European project MEREDIAN-2 involved NSN into the broadband European network. Thus, since 2004 the real-time data transmission from the above three stations became available via digital telephone lines.

In 2005 the modernization of the NSN by means of digital technology was completed. Nowadays the upgraded NSN consists of 13 stations equipped with REF TEK High Resolution Broadband Seismic Recorders (DAS 130-01/3) and one station with Quanterra 680 recorder; the sensors are of different type – VBB STS1, STS2, KS2000; BB CMG 40T and CMG 3ESPC; SP S-13; accelerometers REF TEK 131/03 (Solakov *et al.*, 2011). The peripheral stations transmit seismic data continuously to the National Data Centre (NDC) for analysis and archiving (Dimitrova *et al.*, 2006). The real-time data flow transfer is performed via the network of the Bulgarian Telecommunication Company (BTC), using optical line from the BTC centre to the central seismological site in Sofia. Additional advantages of the real-time acquisition and processing are avoiding loss of data as well as interfering of a station noise; details are expressed by Solakov *et al.* (2011).

Data from the Quanterra recorder and foreign stations are collected and simultaneously transferred to MEDNET and NEIC in real time using the SeisComp/ SeedLink software. Regional real-time data exchange between Bulgaria and Romania, Macedonia, Serbia and Greece is continuously going; it complements the data set for localization of seismic events. The source parameters that are provided automatically may be reviewed by the seismologist on duty thanks to the possibility to accomplish express manual relocation operating with the wave forms. However, the magnitude estimation algorithm needs further tuning. Thus, in the latest 2005 the NSN switched from analogue, short period

one component recording to 3-component, broad-band on-site digital recording, automatic processing and digital data analyses. At present the NSN is a reliable broad-band digital network which accomplishes real-time seismic monitoring and disseminates earthquake solutions via internet <http://ndc.geophys.bas.bg/>, under the management of eng. Stoyanov.

The National seismological Data Center /NDC/ is the only unit in Bulgaria authorized for acquisition of seismological information. In cases of earthquakes felt on the territory of Bulgaria, the information is transmitted to the government authority, mass media and population. Information on strong felt earthquakes is directed also to the Field Investigation Team of European Seismological Commission.

### **SEISMOLOGICAL CONTRIBUTIONS IN THE FIELD OF REGIONAL AND WORLD-WIDE GEODYNAMICS**

Immediately after the 1928 mainshocks (Ms 6.8 and 7.0 according to Christoskov and Grigorova, 1968) presence of coseismic ruptures of 105 km total length on the earth surface was reported. This information can be found in the monographs (DIPOSE, 1931; Mihailovic, 1933a, 1933b). The earthquakes also produced a large subsiding area in the Maritza valley, South Bulgaria, with the formation of several temporary lakes and landslides. Before (1923-1927), by chance, and after (1929-1930) the 1928 large earthquakes the National leveling network conducted leveling service providing very important information about elevation changes related to the destructive earthquakes. The accuracy of the collected leveling data was estimated as better than 1cm by Mirkov (1932). These data, after appropriate analysis, contributed for clarifying the geodynamical factors in the Upper Thracia, South Bulgaria, even during the next tens of years (Jankow, 1938; Dimitrov and Ruegg, 1995). Fault plane solutions published for the greater 1928 mainshock (Ms7.0) from Glavcheva (1984), VanEck and Stoyanov (1996), Dimitrov and Ruegg (1995) indicated a WNW–ESE oriented normal fault with a dextral strike-slip component.

It should be noted that Charles Richter in his Elementary seismology (1958) especially emphasizes the geodetic procedure connected with the 1928 Bulgarian earthquakes and recommends the used approach for further data acquisition and processing.

Recently, a monograph devoted to the 1928 South Bulgarian earthquakes was compiled by

a multidisciplinary team of Bulgarian scientists (Sledzinski /ed./, 2000a). The basic problems included in the monograph are related to: seismological, geological and geodetic investigations; complex interpreting; protective measures. The problems solved in the field of seismology related to geodynamics are as follows:

- Evaluation of the source size, released elastic energy, seismic moment, and relative displacement for each of the two 1928 strong earthquakes. On the basis of author's relations and worldwide data generalization, Christoskov (Sledzinski /ed./, 2000a) estimated the above mentioned source parameters as follows: 56 x 18.6 km and 77 x 24.5 km for the Ms6.8 and Ms7.0, respectively;  $7.1 \cdot 10^{14}$  and  $2.7 \cdot 10^{15}$  Joules;  $1.9 \cdot 10^{19}$  and  $5.8 \cdot 10^{19}$  Nm; and 93 and 157 cm.
- Evaluation of the peak ground acceleration in the epicentral regions separately for the two events. Using the root mean square acceleration, Paskaleva (Sledzinski /ed./, 2000a) obtained maximum horizontal acceleration over  $550 \text{ cm/sec}^2$  and more than  $650 \text{ cm/sec}^2$  for M6.8 and M7.0 respectively; maximum vertical acceleration  $\sim 300 \text{ cm/sec}^2$  and  $\sim 350 \text{ cm/sec}^2$ .
- Searching for seismic precursors by analysis of the space-time behaviour of seismicity during the last four decades. Most important findings referring to earthquakes of magnitude  $M_{ms} \geq 4.5$  ( $M_{ms}$  is the macroseismic magnitude) were that they stopped occurring as follow: about 26 years prior the two main events in the activated by them area; for some 13 years in an area 4 times greater than the size of the future aftershock area; and no one shock was documented in the Ms6.8 source volume for the preceding six years (Glavcheva *et al.*, in Sledzinski /ed./, 2000a).

A bit later, a monograph on the couple of devastating earthquakes (Ms7.1 and Ms7.8, according to Christoskov and Grigorova, 1968) that occurred in April 1904 in the Krupnik-Kresna region, south-western Bulgaria, was compiled (Sledzinski /ed./, 2000b). Several important seismological results can be highlighted as follow.

- The energy-time distribution of the shocks of  $M_s \geq 4.5$  during the first 100 minutes that occurred after the Ms7.1 earthquake showed that the 23 minutes time interval in-between the Ms7.1 and Ms7.8 earthquakes should be divided into two sub-intervals characterized by different energy

release: the energy released during the first time interval (11 min) equals the maximum energy released within the whole considered time period of 100 min, while during the second one (12 min) earthquakes of  $M_s \geq 4.5$  were not observed, *i.e.*, the second period indicates for presence of seismic quiescence. Another characteristic feature of the energy-time distribution is that after the second large shock of Ms7.8 earthquakes occurred rather rarely (Glavcheva, in Sledzinski /ed./, 2000b).

- Another problem concerning the two very strong earthquakes in April 1904 in the Krupnik-Kresna region is related to their dynamic characteristic, the magnitude. As mentioned above, according to Christoskov and Grigorova (1968) the magnitudes  $M_s$  of the two devastating shocks are 7.1 and 7.8. Ranguelov *et al.* (in Sledzinski, 2000) suggest the magnitude value either  $\sim 7.8$  evaluated from macroseismics, instrumental data and seismic source dimensions, or 6.4-6.7 according to the recurrence graph, neotectonics, geodetic data, stress field inversion; the coseismic deformations and duration of the aftershock sequence give wavering results. Later, the reappraisal of instrumental data resulted in significantly lower magnitude estimates:  $M_s=6.8$ ,  $M_s = 7.2$  (Ambraseys, 2001) and  $M_w=6.8$ ,  $M_s = 7.2$  according to Dineva *et al.* (2002), instead of the former ones  $M_s=7.1$  and  $M_s=7.8$ .
- Because the Krupnik-Kresna earthquake zone in southwestern Bulgaria shows the highest seismic activity in the country, deserved attention is paid in the monograph to now existing low seismicity, once the aftershock realization has passed. For instance, Dineva *et al.* (in Sledzinski /ed./, 2000b) studied the seismicity in a large area around the Krupnik-Kresna zone situated between geographical coordinates  $40.8^\circ\text{N} \div 42.4^\circ\text{N}$  and  $22.0^\circ\text{E} \div 24.2^\circ\text{E}$  for the period 1985-1993. From a dataset consisting of 3705 earthquakes of magnitude less than 5.1 the authors found out that the seismicity in the region is characterized by clusters related to boundaries between subsiding and uplifting areas.

Aiming to study the seismic sequences of two moderate earthquakes ( $M_L 5.4$  and  $M_L 5.7$ ) that occurred in central North Bulgaria at the southern edge of the Moesian Platform in 1986, a combined seismic data set from the Bulgarian and Romanian telemetric networks was used (Oncescu *et al.*, 1990). A joint hypocenter determination, composite focal mechanism and regional stress tensor inversion were carried out as well as the source areas and

fault dislocations were estimated. The results show that the two seismic sequences took place at the intersection of two E-W trending faults (one of them being the Pre-Balkan Fault) with a secondary fault of SSE-NNW trend. In the two sequences, the main shocks originated from unilateral downward faulting on the secondary fault and on the Pre-Balkan Fault, respectively.

The results obtained are supported by tectonic models of the region (*e.g.*, Bonchev *et al.*, 1982) and indicate that in 1986 the southern part of the Moesian Platform slipped with about 15cm oblique downward.

For the territory framed in South Bulgaria and northern Greece an international team with Bulgarian participation suggested that the east–west trending faults show evidence for dip–slip movement only and there is little field data to support strike–slip displacement on most of the faults. And some faults of north–eastern and north–western strike show evidence for strike–slip (Burchfiel *et al.*, 2000). An example for presence of a NW-SE strike-slip movement was documented as a co-seismic effect in the epicentral area of the M7.0 South-Bulgarian earthquake in 1928: a water-fall formed by normal faulting with a dextral strike-slip component appeared through Tcherkezitsa River, a tributary of the great Maritza River (Petrov and Glavcheva, 2007, after a photography in DIPOZE, 1931). Similar results were obtained by Dineva *et al.* (in Sledzinski /ed./, 2000b) for the south-west Bulgaria and contact areas in Macedonia and Greece. These researchers concluded on the basis of focal mechanism solutions that the predominant quantity of seismic shocks being of a normal type (60% of the whole set) were originated by the fault units oriented in almost W-E direction while a very small quantity of the events (only 5% of 178 earthquakes) were associated with faults oriented NNW-SSE. Explanation for such a spatial distribution of the focal mechanisms the authors found in the existence of a regional sub-horizontal tension stress (normal type of mechanisms) and, at weaker earthquakes, the influence of local stresses (the reverse type solutions and those cases with a strike-slip component).

In geodynamical aspect, a special attention was paid to the seismically obtained stress field that created the discussed focal mechanisms of 158 earthquakes spread over the territory of Bulgaria and nearby areas. In result of modelling of the regional stresses and strains compared to the obtained fault plane solutions, the suggestion of Botev *et al.* (2006) is: in each of the seismic zones extensional sub-horizontal stresses dominate, *i.e.* there are situation of normal focal mechanisms; indirectly, it

is estimated that the magnitude of the principal stresses in the individual zones vary significantly - an indication of inhomogeneity of the Earth's crust; the maximum tension is close to horizontal and towards the NNE or NE (NNW in central North Bulgaria), and maximum compression is almost vertical and of various orientation (E-W in central North BG, ESE in NE Bulgaria, NE in South Bulgaria); differently, the compressional stresses in Krupnik-Kresna zone and surroundings are obtained of ENE orientation but significantly oblique and in the Rhodopes Mountain they seem to be horizontal with a strike E-W extracting from a very small amount of solutions. A mismatch is found between the major axes of the stress and the respective major axes of the strain. According to the authors, such disagreement is characteristic for lands of long-term active tectonics with presence of weakened structures in consequence.

Studies on the present-day geodynamics in world-wide Wadati-Benioff zones (WBZ) are carried out to examine their contemporary geodynamics. The stress distribution in the Wadati-Benioff zones pre-determines all the structural processes in the zones of subduction that are especially remarkable with their seismic activity and tsunami generation along the Pacific ring. The milestones prompting these studies are as follow: the continuous updating of the world-wide earthquake database through improvements in location techniques (*e.g.* Engdahl *et al.*, 1998), the global homogeneous centroid-moment tensor data set (Harvard CMT) (Dzevonski *et al.*, 1983), and the development of appropriate inverse techniques for evaluating the regional or local stress regime from earthquake focal mechanisms (*e.g.*, Gephart and Forsyth, 1984). The investigations aims are as follow: (i) to obtain new and more quantitative information about the contemporary subduction dynamics of the studied regions; (ii) to test the validity of some existing theoretical models and hypotheses; (iii) to outline structures which play specific role in the subduction processes in the studied regions.

The studied Wadati-Benioff zones are as follows: the Aegean (Christova and Nikolova, 1998; Vanek *et al.*, 1987), Tyrhenian (Christova, 1998), Kamchatka (Christova, 2001), Hokkaido and North Honshu (Christova and Tsapanos, 2000; Christova *et al.*, 2006), Ryukyu-Kyushu (Christova, 2004), Izu-Bonin (Christova, 2005), Vanuatu-New Hebrides (Christova and Scholz, 2003; Christova *et al.*, 2004), and Tonga (Bonnardot *et al.*, 2007, 2009). The obtained results allowed assessing the main forces involved in the contemporary dynamics of the studied subduction



zones: the plate convergence, trench suction, slab pull, slab anchor force, mantle viscous resistance. The results confirmed the validity of the basic in the plate-tectonics theory hypotheses that the subducting slabs act as stress guides (Isacks and Molnar, 1971).

The hypothesis by Savage (1969) that the intermediate depth WBZ earthquakes occur on preexisting faults was not confirmed for Vanuatu; the slab-anchor force model by Scholz and Campos (1995) is valid for Vanuatu and Ryukyu-Kyushu but not for Izu-Bonin subduction zone.

Another important contribution of these studies is the outlining of unrecognized before structures that play specific role in the subduction processes in several of the studied regions: *e.g.*, the two-flanked subduction in the Aegean region characterized by different seismogenic properties, stress field, velocity structure and evolution history; the Tokara “channel” in the Ryukyu-Kyushu region dividing the subduction into two parts of different stress regime at depth below 100 km; a ‘deformation’ zone beneath central Hokkaido indicating for possible vertical tear of the slab; slab detachments in the Izu-Bonin and Tonga; a double subduction zone in north Tonga and Kamchatka.

## DISCUSSION AND CONCLUSIONS

During the Neogene and Quaternary time the tectonic processes in Bulgaria were related to the destruction of Late-Alpine orogen, extensional stress environment contributing for disintegration of the Earth’s crust and complex interaction of intense vertical and horizontal movements (Zagorchev, 1992). The complex tectonic and geodynamic environment resulted in the observed alignment of seismicity along and in-between the faults, in contact areas of the horsts, grabens, depressions and basins. The seismicity pattern shows that most seismically active are the Quaternary faults and blocks between them in SW Bulgaria and surrounding. The analysis of 10-year seismicity in Bulgaria and the southern neighbourhood outlines the following general trends in the territorial seismogenesis: W-E and quite close to it WNW-ESE trends of seismicity are observed practically across the entire territory; almost N-S trending seismic lineaments that coincide with the old structures in SW Bulgaria and Macedonia, the same as in W Rhodopes. Generalization of the focal mechanism solutions shows that extensional sub-horizontal stresses dominate in most of the seismic zones, *i.e.* the prevailing earthquake focal mechanisms are of a normal type. The same situation is found in the neighbouring countries to the south of Bulgaria.

In this review dedicated to the 120<sup>th</sup> year development of seismology in Bulgaria, three main fields are presented: macroseismology, together with two branches that use data of macroseismology; instrumental equipment and related study problems; Bulgarian contribution to regional and world geodynamics. Steps and achievements in each of these fields are summarized and chronologically presented. All these fields have generated or applied modern approaches so as to achieve results at a high level and to be beneficial for people.

## The Macroseismology

The observation macroseismic network founded and organized by Spas Watzof was of a remarkable density (FIGURE 2). Hence, annual macroseismic reports published by Meteorological Institute in Sofia in the course of 74 years were of high quality and are of wide use even today. More than 150 isoseismal maps or maps with intensity data points compiled in Bulgaria were published in atlases and studies. Bulgarian monographs are discussed in this study because they provide lessons learnt from experienced strong earthquakes (Ms 7, 1913 and 1986, Md 5.7, 5.4 in central North Bulgaria; Ms 6.8 and 7.0, 1928 in South Bulgaria; the 1977 Vrancea earthquake of magnitude Mw=7.4); two recent monographs are devoted to the 1904 (Ms 7.1, 7.8) and 1928 (Ms 6.8, 7.0) large earthquakes in Bulgaria.

Two important scientific fields use macroseismic data: historical seismology and seismic hazard. Both of them are well developed in Bulgaria.

## Historical seismology

Watzof and Staikoff were the first ones who paid attention to the long-term seismicity. Their findings were the starting point for the compilation of the two catalogues of historical earthquakes in Bulgaria and close surroundings. The nowadays solutions of the same events in comparison with the data extracted by Watzof almost a century ago differ only in the parametric manner of presentation (ANNEX 1). Comments on some Staikoff’s findings may be found in Table 2.1 (ANNEX 2) where 36% of the Bulgarian catalogue solutions are based on his compilation. This table shows, for the first time, to what extent we have improved the earthquake background using contemporary information, differently of the previous studies, for 25 historical events.

## Seismic hazard

An approach was developed for successful use of macroseismic intensity information for compilation of a seismic hazard map for Bulgaria and a part of Romania according to the EUROCODE 8 requirements

(2008). Two factors suggested the preferable use of macroseismic intensity instead of acceleration in construction of seismic hazard maps: the direct correspondence between intensity of shaking and the degree of damage, and the intensity as being the original known parameter of historical earthquakes.

### **The instrumental seismology**

This study traces the development of the capability of the network (ANNEX 3) approaching to the present-day digitalization which was accomplished in the latest 2005. At present Bulgaria participates actively in the international exchange of seismic data. The deployment of instrumental registration in Bulgaria led to development, adaptation and application of new methodological approaches that are thoroughly noted in this paper.

Until 1980, the instrumental interpretation and analysis of seismic records in Bulgaria urgently needed precise determination of the earthquake parameters. For accomplishing this goal, a normalized magnitude scale was developed for near and distant earthquakes in the 60-ies of 20<sup>th</sup> century. The instrumental seismology at that time was concerned in applying different approaches for solving scientific problems like: station noise analysis, microseismic zoning, study the regional Earth's crust and upper mantle structure, investigation of induced seismic activity, etc. Also, a long-time catalogue was compiled around 1978 for accomplishing the first prognostic seismic zoning of Bulgaria.

After modernizing the instrumental equipment in 1980 and establishing of telemetric transfer of seismological data from the periphery to the central point in the Geophysical Institute, Sofia, the scientific community was provided with regularly issued reports on current seismicity; this is still continuing today. The instrumental seismology achieved at this stage new important results: specification of the time distribution of aftershock sequences according to seismic zones (during the late 80-ies and the 90-ies of previous century), evaluation of geometrical parameters of extended earthquake sources of strong earthquakes based on a time difference in the P wave train (in 1990), establishment of an anisotropic layer at depths of 30–45 km in southeastern Europe based on surface waves analysis (in 2003), affirmation of the prevalence of a normal type focal solutions in Bulgaria (2000-2006). Ideas on interaction between seismic zones have been examined (2006 - 2007); searching for earthquake precursors of seismic, geomagnetic, and electromagnetic type started.

### **Geodynamics**

Geodynamical studies of the territory of Southern Bulgaria-Northern Greece suggested that the east–west trending faults show evidence for dip–slip movement only and there is little field data to support strike–slip displacement on most of the faults (2000). A disagreement has been established between the major stress and strain axes in a big set of focal plane solutions in Bulgaria which is characteristic for lands of long-term active tectonics according to the authors (2006).

Bulgaria is in line with the advanced studies on world geodynamics. Studies on space distribution of stresses in world-wide Wadati-Benioff zones (WBZ) were carried out to examine the contemporary geodynamics of active subduction zones and validity of some theoretical hypotheses and models. The results obtained showed that the hypothesis by Savage (1969) that the intermediate depth WBZ earthquakes occur on preexisting faults was not confirmed for Vanuatu; the slab-anchor force model by Scholz and Campos (1995) is valid for Vanuatu and Ryukyu-Kyushu but not for Izu-Bonin subduction zone. Some unrecognized before structures that play specific role in the subduction processes were outlined: the two-flanked subduction in the Aegean region; the Tokara “channel” in the Ryukyu-Kyushu region dividing the subduction into two parts; a ‘deformation’ zone beneath central Hokkaido; slab detachments in the Izu-Bonin and Tonga; a double subduction zone in north Tonga and Kamchatka.

In this paper we systematize and review more than 160 seismological studies with the aim to spread more effectively the scientific information achieved through 120<sup>th</sup> year development of seismology in Bulgaria. Most important aspects of the seismology in Bulgaria like monitoring and analysis of the seismicity, physics of seismic waves and earthquake sources, study of the Earth's crust and upper mantle structure in tectonically active regions, seismic hazard, searching for earthquake precursors, etc. are developing based on instrumental and macroseismic data. The nowadays seismological activities are continuation and upgrading of earlier started activities.

### **ACKNOWLEDGEMENTS**

The present paper has been produced thanks to the longstanding efforts, collaboration and support of all members of the Seismological Department of the Geophysical Institute and the Department of Seismotectonics of the Geological Institute of the Bulgarian Academy of Sciences. The authors are grateful especially to Prof. Dr. Cenka Christova (Geophysical

Institute) for the very useful discussions. Many thanks R. Glavcheva owes to Dr. Paola Albini, Dr. Massimiliano Stucchi and all the colleagues who worked in European 6<sup>th</sup> FP Project NERIES, module NA4, for the lessons on dealing with historical earthquakes. The paper has been greatly benefited by the revision of Dr. Antoine Mocquet and Alejandra Leal Guzmán and the editorial assistance of Prof. Franck Audemard.

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Received: 7 March 2012

Accepted: 30 May 2014

**ANNEX 1.**

Watzof's investigations on historical earthquakes and the present-day knowledge  
 It is worth to compare the findings of Watzof with the latest solutions in catalogues and studies on historical earthquakes. The results confirm once again the merits of Bulgarian seismologist Spas Watzof.

**TABLE 1.1.** Initial data on historical earthquakes in Bulgaria and its surrounding (Watzof's findings) and their nowadays expression

Watzof's findings		Nowadays solution (Balkan Region Catalogue, Shebalin <i>et al.</i> , 1974 and the last product: SHEEC or studies)						
Ye MoDa h	Area	Background information source <sup>1</sup>	Balkan Region Catalogue (Shebalin <i>et al.</i> , 1974)	Background information source(s)	Catalogue solutions in SHEEC <sup>2</sup> and other recent studies	Sources of information		
			Ye MoDa h	'N °E	$I_0 / I_1 / I_2$ (MSK)			
518 WS06	S Serbia and N Macedonia	Marcellinus Comes (5-6 <sup>th</sup> c), indirectly	518	42.1 21.4	$I_0=10$	Hadzievski /ed/	518 according to Papazachos <i>et al.</i> (2000)= PAP00 Ambraseys (2009) = AMB009. Revisited in Skopje (in Skopje)	Marcellinus Comes
542.08:16 WS08	Constantinople (C-ple)	Theophanes (8-9 <sup>th</sup> c), translation	543	40.5 28	$I_0=10-11$	Staikoff (1930); Galanopoulos (1960)= GG <sup>4</sup> ; Drakopoulos (1972)= DD	IX=8 MSK/EMS Constantinople according (acc.) to Guidoboni (1994)=GU194	Theophanes, 8-9 <sup>th</sup> c.
545 WS08	Black Sea tsunami (3p**)	Theophanes	Missing	Missing			544:545 tsunami on BlackSea coast (3 p) acc. to GU194	Malalas and Theophanes
677 WS08	Thessaloniki devastiating	Schmidt (1875)	667	40 ¼ 23 ¼	$I_0=8?$	GG, DD	667 acc. to PAP00 AMB009: a spurious earthquake (eq)	-
740.10:28 WS08	C-ple, Izmit, Iznik	Theophanes	740.10:26	41 29.5	$I_0=8$	EGU (1967), KO (1971), ONA (1972)	740.10:26; C-ple, Izmit, Iznik acc. to GU194; AMB009: a destructive eq, East Marmara Sea	Theophanes, Niceforus Patr., G. Monachus
927 WS08	Thrace	Sym. Logothete (10-11 <sup>th</sup> c), translatt.	Missing	Missing			926:927 Thrace acc. to GU194	Joannes Scylitzes, 11c.
989 WS08	Greece,Thrace, Byzantia	Mushketov, Orlov (1893)	986 Rem [RG]: dating by Scylitzes, 11 <sup>th</sup> c	(41 29)	$I_0=8$	EGU (1967), KO (1971), ONA (1972)	986 acc. to GU194 C-ple, Izmit, GU194	Leo Diaconus, 10 <sup>th</sup> c, in Asia Minor
1430.02:26 night WS08	Thessaloniki	Von Hammer (1835)	1430.02:26	40 ¼ 23 ¼	$I_0=8$	GG, DD, MF	1430.02:26 near Thessaloniki, strong acc. to AMB009	Cananus (ed. 1866) contemporary
1560.02:08 WS08	Greece	Stojanovic (1902)	Missing	Missing			1560.02:08 Mount Athos, no damage acc. to AMB009	Stojanovic (1902)
1585 WS08	N Macedonia	Ivanov (1906)	Missing	Missing			1585 acc. to AMB009 1585.06:28 acc. to Babachkova and Rizhikova (1993), SHEEC <sup>2</sup>	WS08, Ivanov (1906)
1585.07 WS08	Athos	Stojanovic (1902)	1585.06	40 ¼ 24 ¼	$I_0=8$	GG, DD, MF	1585.06:28 acc. to AMB009, problematic SHEEC <sup>2</sup>	Papazachos and Papazachou (2003) = PAP03
1641 WS04	Bulgaria-Macedonia	1904 journal	1641	42.3 22.7	$I_0=9$	GEB, MF	1641.05 SHEEC <sup>2</sup>	PAP03 Mw6.7
1738 WS03	2 historical reports	2 historical reports	1738.06	45.7 26.6	$I_0=8-9$	RCR, RA	1738.06:11.10 SHEEC <sup>2</sup>	Onescu <i>et al.</i> (1999)
1752.07:18/29 WS08	Die Erdbebenwarte	Die Erdbebenwarte	1752.07:18	40.8 26.3	$I_0=8$	Staikoff (1930)	1752.07:29 SHEEC <sup>2</sup>	PAP03 I0=8 Mw7.4
1755.02:15 WS08	N Macedonia	Stojanovic (1903)	1755.02:26	42.5 21.9	$I_0=9?$	MF	1755.02:26 SHEEC <sup>2</sup>	Shebalin <i>et al.</i> (1998)
1790.04:06-19:30 WS08	Russia-Romania-Bulgaria	Mushketov and Orlov (1893)	1790.04:06	45.7 26.6	$I_0=8$	RCR, Staikoff (1930)	1790.04:06 SHEEC <sup>2</sup>	Onescu <i>et al.</i> (1999)
1802 WS02	Transilvania	A description	1802.10:26	45.7 26.6	$I_0=9$	MF, RCR, EGU, Staikoff (1930)	1802.10:26 SHEEC <sup>2</sup>	Onescu <i>et al.</i> (1999)
1818.04:04 WS02, WS08	Sofia	Sprostanov (1900)	1818.04:23	(42.8 23.3)	$I_0=9?$	GEB	1818.04:23 SHEEC <sup>2</sup>	PAP03 I0=8 Mw7.2
1838.01:23 WS02, WS12	Romania-Hungary-Bulgaria	A chronicle	1838.01:26	45.7 26.6	$I_0=8$	Staikoff (1930), MF, RCR, GEB	1838.01:23 SHEEC <sup>2</sup>	Onescu <i>et al.</i> (1999)

<sup>1</sup> The sources noted are bibliographically listed in the References specific to Annex 1

<sup>2</sup> European Earthquake Catalogue 1000-1899 (Stucchi *et al.*, 2013)

<sup>3</sup> I notes epicentral intensity;  $I_0$  is the maximum observed intensity;  $I_1$  is intensity in a given settlement; the EMS intensity value coincides with MSK intensity value, only intermediate values like "9-10" MSK should be considered downwards to the integer value, here 9 EMS

\* Abbreviations according to the Balkan Region Catalogue (Shebalin *et al.*, 1974)

\*\* (3 p) means that the available information is from 3 points (settlements)

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# ANNEX 2

## Evolution of the historical earthquake catalogue of Bulgaria

This investigation is presented chronologically, and differently from previous studies, it deals with information coming from contemporary sources.

**TABLE 2.1.** Initial entries (macroseismic magnitude  $M \geq 4.5$ ) and results extracted from contemporary sources on earthquakes prior to Seismological Service establishing

GRAL978 (Grigorieva <i>et al.</i> , 1978)		Criticism and Upgraded product		NERIES NA-4 work		Epicentral area		Number of macro-seismic points		Io*/Ix* (MSK*)	
Ye	MoDa h	*N	*E	*N	*E	I <sub>1</sub> /I <sub>2</sub> /I <sub>3</sub>	I <sub>1</sub> /I <sub>2</sub> /I <sub>3</sub>				
1444	11:01:00	43.2	28.0	10				4	5	6	7
Carelessly considered information											
Fake Eq ** but connected to a true one distant in space											
1450	42.7.23.3	8						Not in Bulgaria (BG)	-	-	-
2nd hand info - wrong dating											
Fake Eq - erroneous century											
1557	12:01:00	42.7	23.3	7.5				False signal	-	-	-
One fake report; not a disastrous eq *											
To be completed											
1585	July	42	1/2, 22	1/4, 7-8				Sofia	1	1	< 8
Disagreement with (Ambraseys, 2009)											
Missing in GRAL978											
Missing											
1618 New eq											
1641	05:01:00	42.3	22.7	9				Ossogovo Mint	1 and RS-30 km	1	7-8
"May" from the info-lettre's date, uncertain											
1641 spring 42.3(+/-0.5°) 22.7 I <sub>1</sub> = 8											
1660	11:30:09	43.1	23.6	7				Sofia	1	1	8
Trrava in Slovakia (Upper Hungary)											
1704	03:11:23	42.7	24	8.5				Not in BG			
Two events united; defined a common date:											
1717/1718 03:22 42.7 24.0 I <sub>1</sub> ** 8											
1749	06:11:23	42.7	24.2	5.5				Etropole	2	2	8
3 IDPs in Bulgaria added:											
Arbanassi I, 5/6; Pleven I, 6; Svishtov I, 8											
1750	10:01:00	42.1	24.8	9				Not in BG	3	3	8
Date borrowed from the report's issue (Och)											
1750 Date unknown 42.1 24.8 I <sub>1</sub> = 8/9											
(Ambraseys, 2009): 6 Aug											
1759	06:22:26	According to Staiakoff (1930)						Plovdiv	1 and epicentral area	1	8 to 9
Thessaloniki and BG [?] two epicenters under question											
Two epicenters determined: Thessaloniki and Philippi											
1818	04:23:00	42.8	23.3	8.5				Not in BG			
Date clarified											
1818	09:18:00	42.8	23.3	7				Sofia	2	2	8-9
The report relates to Vrancea-1838 eq:											
1838 01:23; 5 IDPs available in Bulgaria											
1832	43.4	28.7	8.5					Sofia, aftershock	1	1	(7)
Intensity map drawn											
1858	09:30:00	42.8	23.25	8				Not in BG	5	5	7
Erroneous epicenter; overestimated intensity											
1858 09:30:10 42.6 23.3 (±0.1°) I <sub>0</sub> = 9											
Intensity map drawn											
1859	07:25:00	42.1	24.7	7.5				Sofia	16	10	9
Erroneous epicenter; overestimated intensity											
1859 07:25 42.6 23.3 I <sub>0</sub> = 6											
1859	08:31:16:30	42.7	23.3	7				Sofia	1	1	7
No changes											
1866	11:06:15	42.7	23.3	6.5				Sofia	2	2	7
Overestimated intensity											
1866	11:15:03:00	42.1	23	6.5				Rila Mint	1	1	4-5
Overestimated intensity											
1866	11:14:03:00	42.3	23.55	6				Sofia	2	2	6
No changes											
1866	12:18:16:25	42	23	8				Not in BG			
It is in GRAL978 by mistake											
Mixed with a seismic event outside BG											
1866	12:19	42.75	3.25	7				Sofia	2	2	6
Overestimated intensity											
1875	02:26:01	43.3	26.9	7.5				Sofia	2	2	6
Overestimated intensity											
1875	02:26:00:00	43.2	26.7	7				Sofia	2	2	6
No significant changes; intensity map drawn											
1890	06:07:06:15	42.4	23.7	7.5				Shumen	11	7	7
Overestimated intensity; intensity map drawn											
1890 06:07 06:15 42.5 23.7 ±0.2° I <sub>1</sub> = 6-7											

1 The sources noted are bibliographically listed in the References specific to Annex 2

\* I<sub>1</sub> notes epicentral intensity; I<sub>2</sub> is maximum observed intensity; I<sub>3</sub> is intensity in a given settlement; the MSK intensity value coincides with EMS intensity value, only intermediate values like "6-7" MSK should be considered downwards to the integer value, 6 EMS in this case

\*\* "Eq" or "eq" means earthquake

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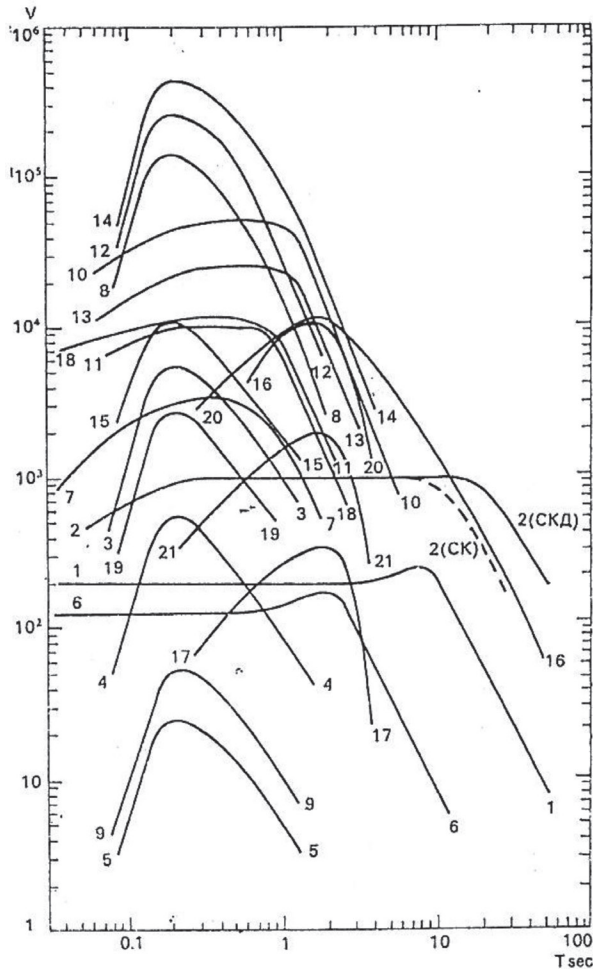
### ANNEX 3

Development of the instrumental network in Bulgaria during the 20<sup>th</sup> century

**TABLE 3.1.** Data on seismic stations in Bulgaria prior to introduction of digital system, according to Christoskov (1992)

Station Code	Starting date	Coordinates °N °E	Elevation [m]	Type of seismometer / accelerometer	Components	Magnification, V	Frequency Characteristics in Fig. III.1	Remark
SOF	1905-04-16	42°42' 23°20'	540	Omori-Bosh	E, N	10	-	Registration closed in 1937
	1934-10-01			Wiechert	E, N	200		
	1937-09-05	42°41'07" 23°20'03"	546	Wiechert	E, N	200	1	Registration closed in 80-ies SKD since 1964
	1960-09-10			SK-3 (SKD)	E, N, Z	1000	1	
	1972-12-01			SMA-1(½ g)	E, N, Z	36 mm/g	2	
1980-03-15	42°40'35" 23°22'10"	502	S-13	Z <sub>1</sub> , Z <sub>2</sub> , Z <sub>3</sub>	1000	-	*TC, **VR in Geophys. Inst.	
1983-03			SMA-1	E, N, Z	18 mm/g	3, 4, 5		
DIM	1961-11-01	42°02'20" 25°34'40"	135	Krumbach	ES, NW	120	6	TC and VR in Geophys.Inst.
	1963-12-21			Kharin	E, N, Z	3500	7	
	1972-12-01			SMA-1(½ g)	E, N, Z	36 mm/g	-	
	1981-02-25			S-13	Z <sub>1</sub> , Z <sub>2</sub>	20 000	8, 9	
PVL	1965-12-20	43°07'17" 25°10'24"	190	SKM-3	E, N, Z	50 000	10	In underground gallery
	1973-09-15			VEGIK	E, N, Z	10 000	11	
				SMA-1(½ g)	E, N, Z	36 mm/g	-	
				1981-03-19	S-13	Z <sub>1</sub> , Z <sub>2</sub>	40 000	
KDZ	1968-07-20	41°38'07" 25°20'26"	330	SKM-3	E, N, Z	25 000	13	TC and VR in Geophys.Inst.
	1973-09-20			VEGIK	E, N, Z	10 000	11	
				SMA-1(½ g)	E, N, Z	36 mm/g	-	
				1980-10-28	S-13	Z <sub>1</sub> , Z <sub>2</sub>	40 000	
VTS	1971-10-01	42°37'05" 23°14'16"	1420	VEGIK	E, N, Z	10 000	11	In tunnel, new building
	1974-12-25			SKM-3	E, N, Z	50 000	10	
	1979-03-09			SKD	E, N, Z	1 000	2	
	1981-05-14			S-13	Z <sub>1</sub> , Z <sub>2</sub>	100 000	14, 15	
				SL-220, -210	E, N, Z	10 000	16	
				SM-3	E, N, Z	350	17	
	1983-03			SMA-1	E, N, Z	18 mm/g	-	
PLD	1977-12-01	42°08'41" 24°45'07"	160	SM-2M	E, N, Z	12 500	18	temporary; VR
	1981-03-19			S-13	Z <sub>1</sub> , Z <sub>2</sub>	40 000	12, 3	
	1983-03			SMA-1	E, N, Z	18 mm/g	-	
MMB	1978-07-03	41°32'47" 23°45'10"	605	SKM-3	E, N, Z	50 000	10	TC and VR in Geoph.Inst.
	1980-04-24			S-13	Z <sub>1</sub> , Z <sub>2</sub>	100 000	14, 15	
	1983-03			SMA-1(½ g)	E, N, Z	36 mm/g	-	
PSN	1979-05-05	43°38'11" 28°08'09"	180	SKM-3	E, N, Z	25 000	13	TC and VR in Geophys.Inst.
	1980-06-01			S-13	Z <sub>1</sub> , Z <sub>2</sub>	20 000	8, 19	
	1983-03			SMA-1	E, N, Z	18 mm/g	-	
RZN	1980-09-18	41°40'38" 24°44'11"	1440	S-13	Z	100 000	14	TC and VR in Geophys.Inst.
	1982-06			SM-3	E, N, Z	12 000	20	
JMB	1982-11-10	42°29'30" 26°31'34"	227	SM-3	E, N, Z	2 000	21	VR
	1982-12-02			S-13	Z <sub>1</sub> , Z <sub>2</sub>	40 000	12, 3	
	1983-03			SMA-1	E, N, Z	18 mm/g	-	
PGB	1983-11-10	42°30'47" 24°10'25"	560	S-13	Z <sub>1</sub> , Z <sub>2</sub>	40 000	12, 3	TC
KKB	1983-04	41°50'32" 23°07'52"	400	SMA-1	E, N, Z	18 mm/g	-	TC
				S-13	Z <sub>1</sub> , Z <sub>2</sub>	100 000	14, 15	
SZH	1986-02-21	43°16' 25°36'	310	S-13	Z	10 000	-	Temporary VR on RV-320
	1987-10-12			SMA-1	E, N, Z	36 mm/g	-	
				S-13	Z	20 000	8	Registration closed in 1988

\*TC – telemetry channel; \*\*VR – visible registration in Geophysical Institute, Sofia



**FIGURE 3.1.** Characteristics of seismographs and seismograph-systems in Bulgaria since 1937 (s. also Table 3.1): 1 – seismograph Wiechert in station SOF; 2 – SK (SKD) in station SOF and SKD, station VTS; 2 – S-13 (high gain), SOF (NOTSSI) and S-13 (low gain), stations PVL, KDZ, PLD, JMB, PGB; 4,5 – S-13 (low gain), SOF (NOTSSI); 6 – Krumbach, DIM; 7 – Kharin, DIM; 8 – S-13 (high gain), DIM, PSN, SHZ; 9 – S-13 (low gain), DIM; 10 – SKM-3, PVL, VTS, MMB; 11 – VEGIK, PVL, KDZ, VTS; 12 – S-13 (high gain) PVL, KDZ, PLD, JMB, PGB; 13 – SKM-3, KDZ, PSN; 14 – S-13 (high gain), VTS, MMB, RZN, KKB; 15 – S-13 (low gain), VTS, MMB, KKB; 16 – SL-220 and SL-210, VTS; 17 – SM-3, VTS; 18 – SM-2M, PLD; 19 – S-13 (low gain), PSN; 20 – SM-3, RZN; 21 – SM-3, JMB.

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