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# 3D MONITORING OF ACTIVE FAULT STRUCTURES IN THE KRUPNIK-KRESNA SEISMIC ZONE, SW BULGARIA

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**ABSTRACT**
The present paper concerns long-term 3D monitoring of active fault structures in the Krupnik-Kresna seismic zone, SW Bulgaria with the use of extensometers TM71. The purpose is to establish the real rates of fault movements in the most seismically active area in Bulgaria. Three points were installed (B6 on Krupnik Fault, and K5 and K12 on Struma Fault), which indicate a recent activity. The fault movements are characteristic with "calm" periods, linear slips, accelerations and sudden displacements. Different regimes of dynamics have been established corresponding to different periods. The greatest dynamics is found at monitoring point B6 along Krupnik Fault: for the whole period of observation the trends are calculated as left lateral slip with 1.88 mm/a and a thrusting with 1.59 mm/a with high correlation coefficients. Co-seismic displacements from local and distant earthquakes were recorded. The significant impact was from M=7.4, 17 August, 1999, Izmit Earthquake, Turkey, showing a shortening of 8.34 mm, a right-lateral slip of 5.09 mm and a thrusting of 0.96 mm. After that, for a short period of time the regime of movement on fault was changed. Movements on the Struma system reveal lower rates. Both points show left-lateral movements, 0.28 mm/a at K5 and 0.09 mm/a at K12, and thrusting with 0.11 mm/a at K5 and 0.72 mm/a at K12.

**KEYWORDS:** 3D monitoring, active faults, co-seismic displacements, Krupnik-Kresna seismic zone, SW Bulgaria

## INTRODUCTION

Struma and Krupnik fault zones are the most prominent tectonic structures in Southwestern Bulgaria. In the Simitli graben, they intersect each other almost perpendicularily. This place is characterized by intense seismicity – the epicenter area of the strongest earthquake in Bulgaria is located here. On 4 April 1904, two strong earthquakes occurred within an interval of 23 minutes – at 10:02 and 10:25 GMT, with reported magnitudes 7.2 for the first one and 7.8 for the second one (Karnik, 1968; Christoskov and Grigorova, 1968). Exactly these structures are connected with the intense dynamics in this part of Bulgaria. Over 50 % of the earthquakes registered annually throughout the country are concentrated just here (Botev and Glavcheva, 2003).

Contemporary dynamics in SW Bulgaria is a subject of discussion, different opinions and hypotheses. This creates high interest in establishing the real values of movements in the region, as well as the relationships between tectonic movements and local and regional seismicity.

Due to this reason, instrumental monitoring of tectonic movements started in 1950's by geodetic observations over a local geodetic network in the Simitli graben and some benchmarks located along the railway trace Sofia-Thessaloniki (Milev et al., 1984). The first results found highly variable vertical velocities reaching at some places up to 3.4 mm/a. Therefore, a project for integrated studies for clarifying the dynamics of this region by means of three-dimensional precise extensometers started in the 1980's. These included installation of three monitoring points in especially selected sites of the two fault structures. In recent years, GPS monitoring of local and regional network has been held. The temporary results confirmed the previous conclusions obtained by Milev et al. (1984). Furthermore, the most intense tectonic movements in Bulgaria have been established just in this area. It is GPS point No 16 showing a rate of 6.9 mm/a, which is the highest one in the country (Dobrev et al., 2005). The latest GPS measurements show uplift of Pirin Horst with 2 mm/a and movements along the western part of Krupnik Fault to North direction at 3 mm/a (Georgiev et al., 2007).

Until now, data concerning the results of measurements referred to different periods of observing the monitoring points have been published (Avramova-Tacheva et al., 1984; Dobrev and Košťák, 2000; Dobrev, 2005; and others). Influences of local and regional seismicity are established at the gauges. They concern both co-seismic effects (Dobrev and Košťák, 2000, and others.) and some pre-seismic effects (Shanov, 1993; Shanov and Dobrev, 1997; Košťák et al., 2007). The latest full results concern different periods – until May 1999 (Dobrev and Košťák, 2000) and until November 2004 (Dobrev, 2005).

Long-term measurements showed that there were influences of earthquakes with epicentres located in NE part of the Simitli graben (around the intersection of Krupnik and Predela Faults) on the movements at point B6 (Dobrev et al., 2003). For example, it was found that during the seismic activity in Predela Fault the movements in point B6 stop or decrease.

Several events have happened since mid-1999 onwards, which have been detected by monitoring points in that research area. These are a number of earthquakes occurring in several Balkan countries south and southeast of the research area. One of them is the Izmit Earthquake of 1999 that caused serious displacements at the monitoring gauge. At the same time there is an almost constant weak local seismic activity. All this shows the need for continuing observation and analysis of the new results as well as the accompanying factors influencing on the movements (seismic activity, etc.).

## TECTONICAL AND GEOLOGICAL SETTING

In regional aspect, the research area is located in the eastern part of the Balkan Peninsula, north of the Aegean arch and area of rotation of North Anatolian Fault to Central Greece (Fig. 1). This area is subjected to the extensional regime in the direction of N-S (Mercier, 1981; McClusky et al., 2000; Kotzev et al., 2001, 2006, and others). The tectonic setting in SW Bulgaria and mainly in the area of research has been studied by Zagorchev (1970, 1992, etc.), Moskovski and Georgiev (1970) and others.

According to the tectonic division of the territory of Bulgaria, the research area is situated within the Morava-Rhodope structural zone, in its western part (Dabovski et al., 2002). The monitoring points are located in two interesting tectonic structures – Simitli graben and the flanked from south Kresna Horst (Fig. 2).

Simitli graben is defined by two parallel antithetic structures – Krupnik Fault and Gradevo Fault, forming a common Krupnik-Gradevo fault system with a general orientation of 40°. The main activity is along the Krupnik fault. It surrounds the Simitli graben in the south. It follows a direction from 20-40° to 80-90°. The fault has a clear normal fault mechanism with a slight left-lateral component (determined by the slickensides). Tranos et al. (2006) found a long east-west oriented fault zone giving the name Kochani-Krupnik-Bansko rupture zone. This zone crosses the recent territories of Bulgaria and FYR of Macedonia. Its total length is estimated to exceed 100 km. They connect it with the strong 1904 seismic sequence.

The activation of the Krupnik fault started during the Miocene times (~13 Ma). Basing on geological and morphological data, the slip-rate along the fault for this period is estimated from 0.15 mm/a (Meyer et al., 2002) to 0.35 mm/a (Ganas et al., 2005).

The northern Gradevo fault is unclear on the surface. Due to this reason, its role is incorrectly ignored by many authors, and omitted in some publications (for example, Meyer et al., 2002). However, it is clearly exhumed in an outcrop at 3-4 km E of Simitli Town. Also, it was found in boreholes drilled to search for coal and other mineral resources in the 1960's and 1970's (Dobrev, 1999).

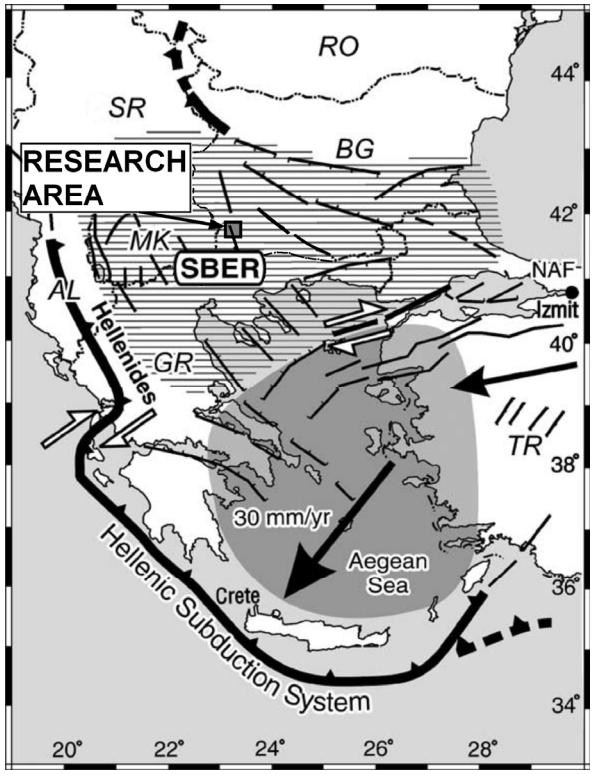


**Fig. 1** Simplified tectonic map of the eastern Mediterranean with research area (adapted from McClusky et al., 2000, and Kotzev et al., 2006 ). Grey quadrangle shows the research area. Arrows show observed direction of motion relative to Eurasia. Hatching shows the South Balkan extensional region (SBER). Shaded area indicates the suprasubduction extensional region. NAF is North Anatolian Fault. Solid lines are normal faults, locally with showed down-throw displacement. Lines with triangles are thrust faults. Relative strike-slip displacement is shown with open arrows. Countries: AL, Albania; BG, Bulgaria; SR, Serbia; GR, Greece; MK, FYR of Macedonia; RO, Romania; TR, Turkey.

Struma fault zone is a bundle of parallel faults following direction 150-170°. It is a long structure which starts from the territory of Serbia and can be traced to Halkidiki Peninsula, Greece (Zagorchev, 1992). On the territory of SW Bulgaria it defines the contemporary bed of Struma River. The Struma fault zone intersects the Simitli Graben dividing it into two parts. Going to the South into the Kresna Horst, the Struma zone is forming Kresna Gorge, whose depth

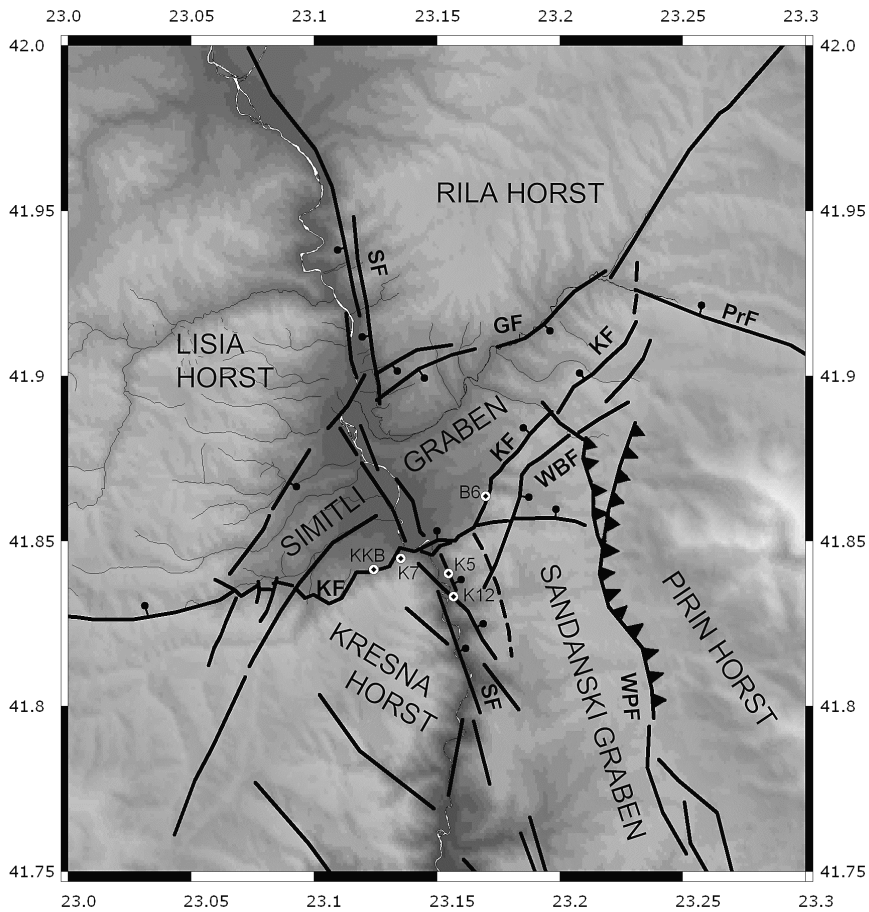


**Fig. 2** Simplified sketch of the research area. The map shows the main tectonic structures, faults and observation points. The main faults are as follows: KF, Krupnik Fault; GF, Gradevo Fault; SF, Struma Fault Zone; WPF, West Pirin Fault (mostly reverse); PrF, Predela Fault; WBF, West Brezhani Fault. Ticks indicate downthrown block, teeth indicate upthown block. The monitoring points localities are shown, KKB is the Seismic Station Krupnik..

exceeds 500 m. The contemporary activity of this fault was recently debated. Most of the researchers have supposed that it was fossilized in late Neogene (personal communication and unpublished data).

The area is relatively well studied in geological terms. The geological structure was clarified because of the many boreholes drilled in the research area in the 1960's – 1980's.

The Simitli graben is filled by Neogene sediments (Maeotian and Pontian-Dacian): mainly slightly lithified sandstones and clayey sands (Marinova and Zagorchev, 1990). The flanked frame is built by Praecambrian metamorphic rocks, mainly gneisses and amphibolites. Kresna Gorge and the southern flanked framework of the graben are built by granite of two types – with Palaeozoic and Upper Cretaceous age.

The graben is characterized by remarkable depth: the drilling data has reached a depth of about 1100 m in the central part, but in the south near the Krupnik fault it is much greater in depth. By geophysical profiling it was found to be more than 1500 m (Dobrev, 1999).

**SEISMICITY**

The research area is situated within the most seismically active area in Bulgaria. Here are the epicenters of many strong earthquakes that occurred in recent centuries. The last strongest events occurred on April 4, 1904, as it was mentioned above. The main shock affected a large region in recent territories of Bulgaria, FYR of Macedonia and Serbia (Dobrev and Petrov, 2007). Insufficient data concerning these two strong events give rise to different interpretations as to their magnitude, seismic surface deformations, fault activation structures, etc. Therefore estimates of their magnitudes and scope of ruptures vary widely (Ranguelov et al., 2000). Despite wide assessments of their characteristics, these earthquakes are among the most impressive of the Balkan Peninsula (Gutenberg

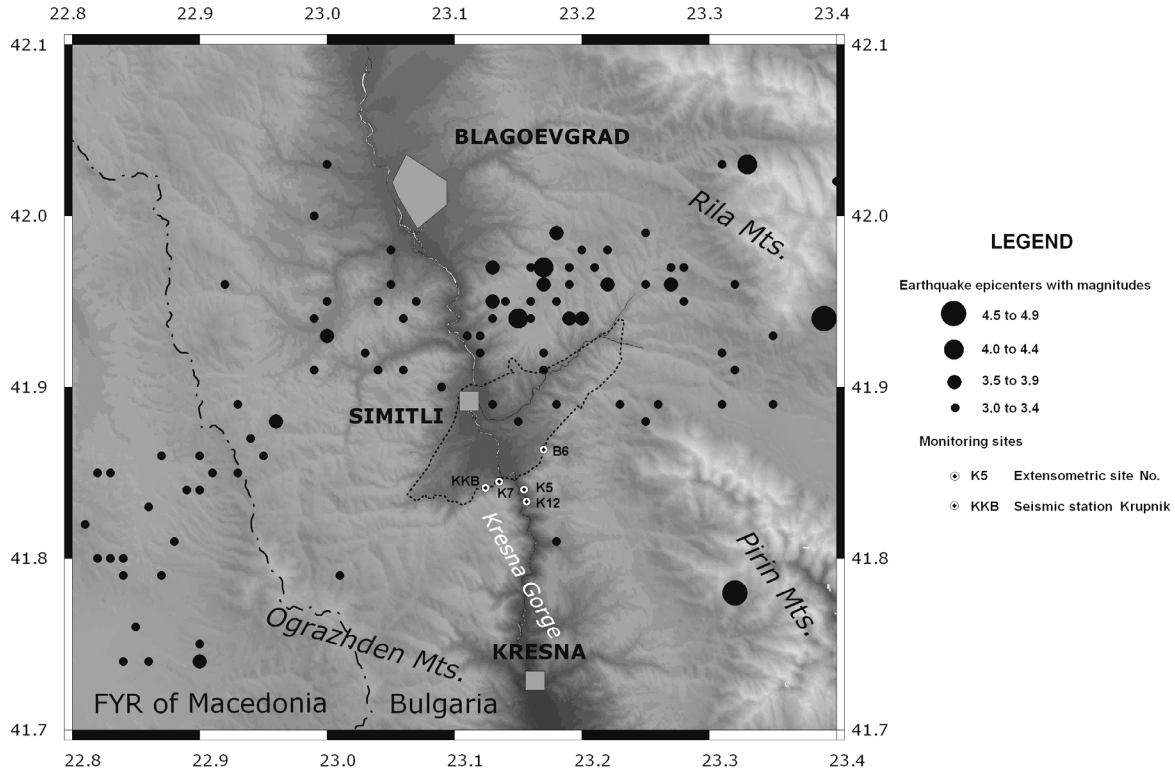


**Fig. 3** Seismicity map of Simitli Graben and adjacent area for period 1982-2010. Black circles show epicenters with magnitudes M≥3. Data is taken from Solakov and Simeonova (1993), Ranguelov et al. (2001) with additions from Geophysical Institute – BAS, and EMCS, Strassbourg.

and Richter, 1954; Shebalin et al., 1974; Ambraseys, 2001; Papadimitriou et al., 2006; Tranos et al., 2006, 2008, and others).

There is some historical information about other strong earthquakes before, like the one of 7 January 1895 (M=5.1), on 6 December, 1866 (M>6?), recently proved to have not been in the study area (Glavcheva, 1999, 2004) and the disastrous 4 September, 1896 earthquake (Watzof, 1902; Shebalin et al., 1974). For the period of monitoring in the area of the Simitli graben and its vicinity (1982-2010) over 200 earthquakes with a magnitude M≥3 have been registered (Fig. 3). However, the area was imposed on the influence of neighboring foci, for example from the Mesta graben (30 km East of the research area), from FYR of Macedonia (Valandovo), from Central and Northern Greece and even from Turkey. Only for the last 5 years, in our neighboring countries more than 30 earthquakes with magnitude M≥5 have been registered (according to data of European Mediterranean Seismological Centre, Strasbourg).

In Figure 3 it is obvious that the frequent nowadays seismicity is concentrated N and NW of Simitli graben. A part of these earthquakes is originated in a depth range from 2 to 5 km (acc. to EMSC data) that is difficult to be connected with the Krupnik Fault. It shows presence of other active fault structures, which are located parallel to the Krupnik-Gradevo fault system, northward from the Simitli graben and continuing to the southwest in the territory of FYR of Macedonia.

## INSTRUMENTAL MONITORING

The aim of conducted monitoring is to understand the recent movements along the main structures that are connected with the strongest seismic and tectonic activity in the research area. Establishment of extremely slow movements requires use of highly sensitive equipment, durable to external climatic influences and providing opportunities for long-term monitoring. It is the three-dimensional extensometer TM71 developed in the Czech Republic by Dr. Blahoslav Košťák (Košťák, 1991).

It works on the principle of mechanical interference - moiré, which records displacement as a fringe pattern on superposed optical grids mechanically connected with the opposite walls or crack faces. Due to this principle, which completely avoids any electrical transmissional means, the gauge displays an extremely large long-term stability, and infallible performance under hard outdoor conditions. Practically, it means that values recorded during periods of decades can be well compared. Results will then be provided as displacements on structural planes

**Table 1** Orientation of the spatial axes of monitoring points in SW Bulgaria (after Avramova-Tacheva et al., 1984; Košťák and Avramova-Tacheva, 1988; Dobrev et al., 2003).

| Monitoring point No. | Coordinates | +X horizontal zone extension or shortening | +Y horizontal shear movement along the fault (fissure) direction | +Z vertical movement | local fault direction |
|---|---|---|---|---|---|
| K5 | 23.155° E 41.840° N | SW block to 225° (extension) | SW block to 135° (sinistral slip) | subsidence of the SW block (probably reverse slip) | 150° |
| B6 | 23.170° E 41.864° N | Neogene basin to 290° (extension) | Neogene basin to 200° (sinistral slip) | subsidence of the Neogene basin (normal slip) | 20° |
| K7 | 23.135° E 41.845° N | The northern block to 350° | The northern block to 260° | subsidence of the northern block | 260° |
| K12 | 23.157° E 41.833° N | SW block to 240° (extension) | SW block to 150° (dextral slip) | reverse movements (or subsidence of the SW block) | 150° |

in mm, and time trends derived as rates in mm per year under hard field conditions in a prolonged operation. The accuracy of instrument is 0.05-0.0125 mm in all three space co-ordinates and 3.2 x $10^{-4}$ rad in angular deviations. Temperature effects in the system including holders are eliminated numerically, while such effects upon the rock are not eliminated in the data and are observable in climatic cyclic variations.

The data are obtained in three Cartesian coordinates, calculated from recorded interference patterns. They represent differential movements according to Table 1. It is always: X - horizontal, across the contact, Y - horizontal slip, and Z - vertical displacement. The movements are relative between the two sides, presented in graphs as displacements of the lower block on the slope to the opposite one, although the interpolation must consider the movement at both sides. The gauge is used for regular monitoring of slow displacements along active faults, landslide fissures and rock deformations.

In 1982-1983, three extensometers for three-dimensional monitoring of fault movements were installed in SW Bulgaria: these are K5 (in Struma Fault inside the Kresna Gorge), B6 (Krupnik fault near Brezhani Village), and K7 (near Krupnik Village - in seismogravitational cracked slope deformation). The last point K12 (in Struma Fault inside the Kresna Gorge) was installed in 2003. Avramova-Tacheva et al. (1984) and Dobrev and Košťák (2000) have already described the present situation of the monitoring points in detail. The frequency of observation is once monthly or bimonthly, as well as after any stronger earthquake or other event that occurred in the area of study. The orientations of spatial axes at all monitoring points are given in Table 1.

The monitoring point K5 (No. 5 in Bulgaria) is installed in a single tectonic structure connected with the Struma fault zone which is oriented N-S (Table 1). At this locality, the fault represents a zone 2.5 m wide filled by broken and crushed granite material. This fault can be traced on southwards where it is evident. The last field studies established that the fault at this site is dipped to NEE, i.e. the meaning of vertical movements should be changed as it is given in Table 1 (see Z-axis).

The next monitoring point (No. 6, B6 or Brezhani 6) was arranged at the Krupnik fault. The measuring system bridges the contact between the Praecambrian amphibolites and the Neogene coarse-grained sediments. A special trench exposes the contact of fault zone, whose width is 3.4 m at that point (Avramova-Tacheva et al., 1984; Avramova-Tacheva and Košťák, 1995).

Monitoring point K7 (No.7 or Kroupnik 7) was installed on a fissure that appeared during the strong earthquakes of 1904 and located on the steep slope 700 m SE from the village of Kroupnik. The extensometer operated till the beginning of 1994. The full results were published by Dobrev and Košťák (2000).

**Table 2** Data for measured seasonal amplitudes and average temperatures at monitoring points.

| Point No. | Average yearly temperature | Average seasonal amplitudes | | | | Full length of holders |
|---|---|---|---|---|---|---|
| | $t_{mean}$ °C | t °C | X mm | Y mm | Z mm | L m |
| K5 | 17.0 | 34.5 | 1.0-1.2 | 0.4-0.5 | 0.7 | 2.52 |
| K12 | 14.2 | 27.8 | 0.30-0.35 | 0.30 | <0.1 | 0.73 |
| B6 | 12.6 | 22.5 | ≥2 | ~0 | ~0 | 2.02 |

The last point K12 (No.12 or Kresna 12) for 3D monitoring was installed in November 2003. The selected fault is an element of Struma Fault zone and it is located inside the Kresna Gorge. Until present, only initial reports have been published concerning the period 2003-2004 (Dobrev, 2005; Dobrev and Avramova-Tacheva, 2007).

## RESULTS

### *MONIRORING POINT B6, BREZHANI VILLAGE, KRUPNIK FAULT*

Until present, several interpretations have been made on the movements along this fault at point B6.

The amplitudes are obvious for the X axis - they are about 2-4 mm and vary due to the big length of holders (Table 2). It is difficult to determine the real amplitude value because of the dynamics of movement. In the other two directions (Y and Z), the amplitudes tend to 0.

For the whole period of observation (1982-2010), it is established that the general movements are as follows: extension 1.15 mm/a (correlation $R^2$=0.76), left-lateral slip of 1.88 mm/a ($R^2$=0.94), and a reverse slip of –1.59 mm/a ($R^2$=0.95). Concerning horizontal movements, varying periods of shortening and extension at fault are established. The deformation accumulated so far is impressive. The amount of total displacement is 86.81 mm at the end of 2010. It is well expressed in Figure 4. In the short term periods, there are several months' periods with variable velocities. These are cycles of acceleration and reduction of movements, sometimes changing of the movement direction, and sharp displacements (Fig. 5). Some of the sharp movements have a co-seismic origin, however anomalies in movements have been established before earthquakes located to the South of the research area, i.e. in Greece (Shanov, 1993; Shanov and Dobrev, 1997).

The last detailed analysis by Dobrev and Košťák (2000) concerned the period up to May 1999 just before the strong Izmit (Kocaeli) Earthquake, Turkey, 17.08.1999, M=7.4. Despite the great distance from the epicenter (600 km) some major displacements were established. It was found that the movements had fluctuation character along the fault. These were so intense that the apparatus was seriously damaged. The average resulting displacements during seismic vibrations were calculated as follows:

**Fig. 4** A photograph of monitoring point B6. The left-lateral displacement of steel holders is obvious.

ΔX=–8.34 mm (shortening)

ΔY=–5.09 mm (right-lateral slip)

ΔZ=–0.96 mm (thrusting)

It may be noticed that the Krupnik fault, which is usually left-lateral, is doing a right-lateral slip after the earthquake (and short time after it, the right-lateral movement continues). Nearly a half an year later, the left-lateral movements restored again. Effects on the movements at this point due to subsequent Athens Earthquake (07.09.1999, M=6.0) have not been established.

Since August 1999, four stages of the movements have been established (Table 3). For the last 10 years, however, it has been noticed that the dynamics of the movements in the Y-axis is decreasing with increasing in the velocity along

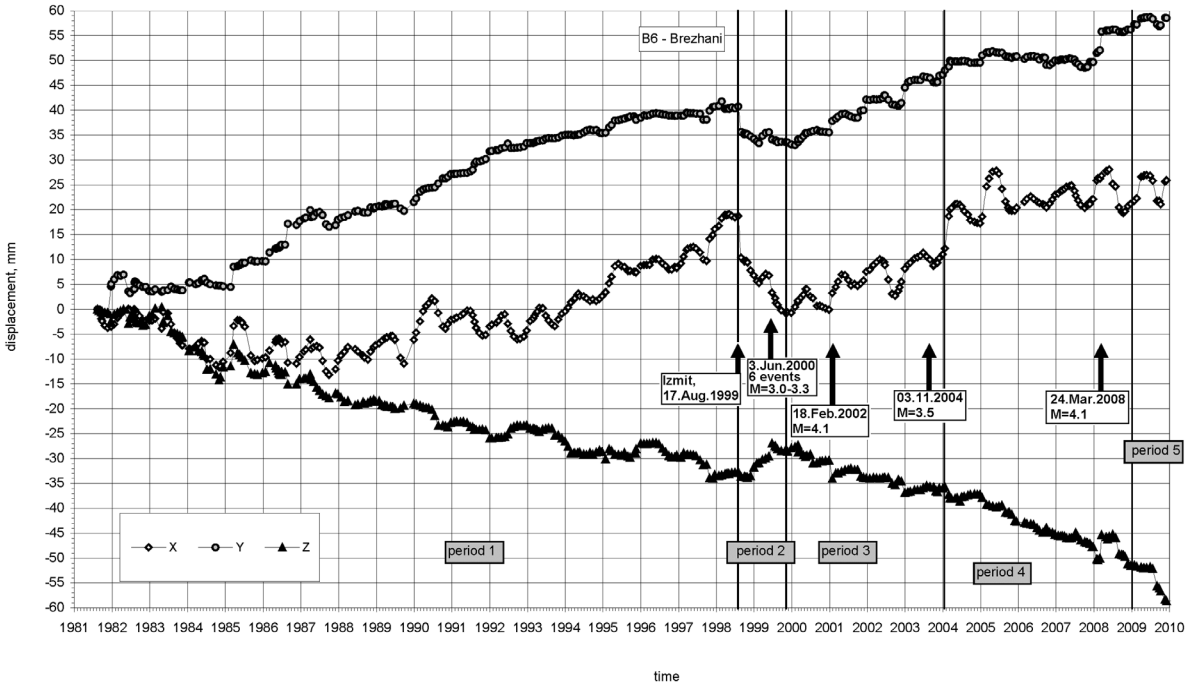


**Fig. 5** Diagram of displacements found at B6 with earthquake impacts and periods of movements (see Table 3).

**Table 3** General trends at point B6, in mm/a.

| Period | X | Y | Z |
|---|---|---|---|
| 1<br>1982 - Aug. 1999 | +1.02<br>extension | +2.61<br>left-lateral slip | -1.91<br>reverse slip |
| 2<br>28.08.1999 – 17.02.2000 | -11.61<br>shortening | -4.60<br>right-lateral slip | 6.83<br>normal slip |
| 3<br>17.02.2000 – 29.12.2004 | +1.84<br>extension | +3.03<br>left-lateral slip | -1.91<br>reverse slip |
| 4<br>19.01.2005 – 27.02.2009 | +0.94<br>extension | ~0.00 | -3.04<br>reverse slip |
| 5<br>13.03.2009 – 02.12.2010 | -0.39<br>shortening | +1.71<br>left-lateral slip | -7.23<br>reverse slip |

Z-axis. Some latest relationships between local seismicity and the sharp displacements are shown in Figure 6a. It is clear that the seismic events that influenced the movements on faults, with epicenters located at north and NE parts the flanked frame of the Simitli graben.

### *MONITORING POINT K5 – KRESNA GORGE, STRUMA FAULT ZONE*

This point is characteristic with high amplitudes due to the direct atmospheric impact on the gauge (Table 2, Fig. 7).

For the whole period (1982-2010), a general direction of extension of the zone has been established. The general movements are as follows: extension 0.10 mm/a ($R^2$=0.58), left-lateral slip of 0.28 mm/a ($R^2$=0.78), and a subsidence of SW block (probably reverse) of 0.11 mm/a ($R^2$=0.62).

Since 1998, the rate of movement is left-lateral ranging from 0.4 to 0.8 mm per year. Minimum values of X, Y and Z are mainly during the summer period (June-July). In 2006, there was an anomaly – stable trends without the typical seasonal sinusoid-like fluctuations. This was the period of intense local seismic activity from February to June-July 2006 (Table 4). Similar anomalies we noticed in the following year when increased seismicity was also reported. During this period the seismic fault reacted

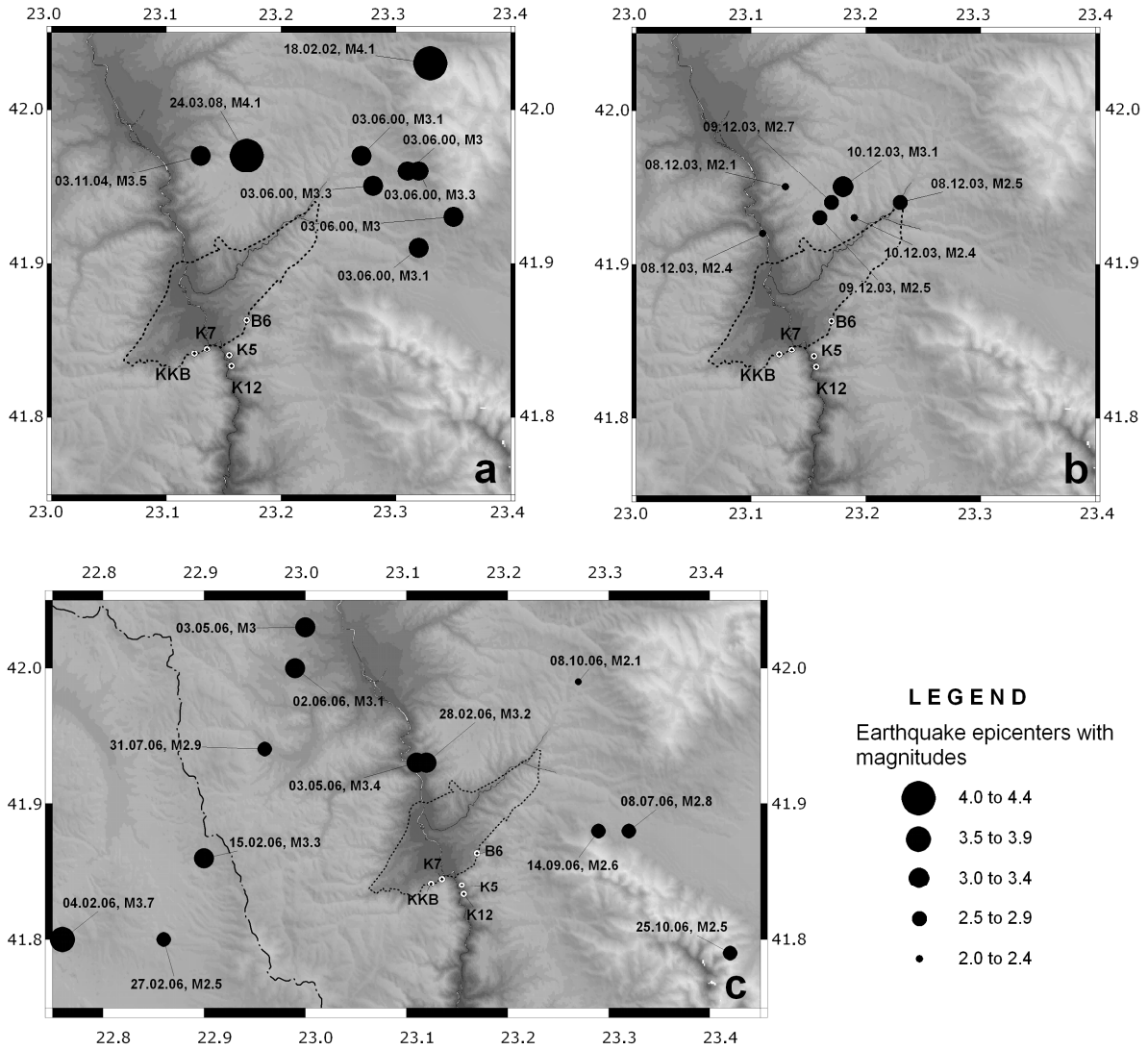


**Fig. 6** Selected possible co-seismic impacts found at monitoring sites in vicinity of the Simitli graben (dot line contour): a) earthquakes with possible impact at monitoring point B6; b) earthquake swarm 08-10 December, 2003 possibly connected with the sharp displacements at point K12; c) seismic events occurred during the fault creep found at point K12 within the period February-June 2006.

**Table 4** General trends at point K5, in mm/a.

| Period | X | Y | Z |
|---|---|---|---|
| 1<br>1983 – 1991 | ~0.00 | ~0.00 | 0.10<br>normal slip |
| 2<br>1991 – 1995 | 0.06<br>extension | 0.13<br>left-lateral slip | ~0.00 |
| 3<br>1996 – 1998 | 0.60<br>extension | -0.22<br>right-lateral slip | 1.17<br>normal slip |
| 4<br>1998 – 2004 | 0.12<br>extension | 0.78<br>left-lateral slip | -0.40<br>reverse slip |
| 5<br>2004 – 2007 | -0.26<br>shortening | 0.63<br>left-lateral slip | 0.51<br>normal slip |
| 6<br>2008 – 2010 | 0.37<br>extension | 0.41<br>left-lateral slip | 0.18<br>normal slip |

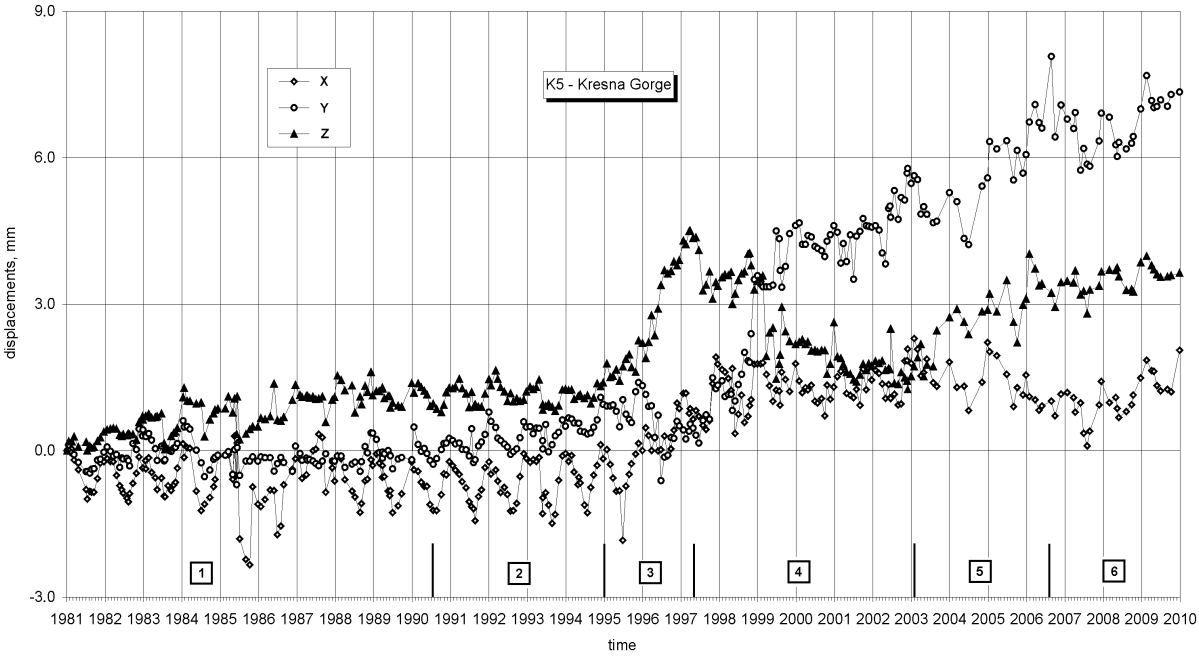


**Fig. 7** Diagram of displacements found at Point K5 with periods of movements (see Table 4).

with "shrinkage" and varying slips: left-lateral and right-lateral at Y-axis, and reverse slip at Z-axis.

***MONITORING POINT K12 – KRESNA GORGE, STRUMA FAULT ZONE***

Here the amplitudes are with low values because the instrument is located in the dank space (a narrow creek) where there is a poor climatic impact (Table 2, Fig. 8).

Seven periods of movement are distinguished (Table 5). In the first period some sharp displacements at Y- and Z-axes are established. Movements of a sharp left displacement ($\Delta Y$=–3.34 mm) and a thrusting ($\Delta Z$=–3.79 mm) have been recorded, which coincide with the earthquake swarm between 8 and 10 December 2003. Then several earthquakes of magnitude M= 2.1–3.5 were recorded in the research area (Fig. 6b). From January to October 2006 there was an interesting period of vertical movement on the fault. This is a typical creep, initially starting with a slow movement (0.91 mm/a) from January to late May, and after that begins an acceleration of the motion with constant velocity ~7 mm/a. Interesting is the stable velocity of this creep. During this period there is a hard seismic activity, starting from early February to early June 2006 in the west and northwest of the Struma fault zone. These are earthquakes in the territories of Bulgaria and FYR of Macedonia (Fig. 6c). The strongest of them occurred in FYR of Macedonia with M=3.7. As it is seen in this figure, a SW-NE orientation of the epicenters of the local earthquakes is obvious following direction ~20-30°. Other events have been registered at this period north of Simitli and in Pirin Mts.

The second period of acceleration is established from October 2008 to January 2009. About a year before this creep, there was a high seismicity N and NW of the research area. The strongest event had magnitude M=4.1.

In Sept. 2009 a small jump is recorded, which cannot be explained. There was a shallow earthquake M=2.9 (11 Oct. 2009) with the approximate coordinates NE of Kresna Gorge (close to point B6). At the other 2 axes (X and Y) the movements are fairly constant, with characteristic low amplitude of seasonal temperature fluctuations.

The whole monitoring period 2003-2010 is characteristic by extension of zone of 0.08 mm/a ($R^2$=0.30), left-lateral slip of -0.09 mm/a ($R^2$=0.26), and a reverse slip of 0.72 mm/a ($R^2$=0.68).

**DISCUSSION AND CONCLUSION**

The 3D monitoring shows the present activity on the observed faults at the three observation points. The movements are not permanent, “calm” periods are observed, with linear slips, accelerations and sudden displacements. Strong geodynamics of the region does not allow to distinguish clearly the effects of many earthquakes. The instrument is sensitive and reacts to most of the earthquakes. Mainly, the sharp displacements are co-seismic. There are also effects from more distant seismic events - eg Izmit Earthquake, Turkey, 17.08.1999.

The most intense movements are along the Krupnik Fault. They were clearly expressed in directions Y and Z, where velocities calculated for the entire observation period (1982-2010) are 1.88 mm/a left lateral slip and –1.59 mm/a thrusting. The sharp

**Table 5** General trends at point K12, in mm/a.

| Period | X | Y | Z |
|---|---|---|---|
| 1<br>29.12.2003 – 14.01.2006 | 0.08<br>extension | -0.09<br>left-lateral slip | -0.19<br>normal slip |
| 2a<br>14.01.2006 – 31.05.2006 | | | 0.91<br>reverse slip |
| 2b<br>31.05.2006 – 04.10.2006 | | | 6.99<br>reverse slip |
| 3<br>04.10.2006 – 20.10.2008 | | | 0.13<br>reverse slip |
| 4<br>20.10.2008 – 26.01.2009 | | | 2.64<br>reverse slip |
| 5<br>26.01.2009 – 25.09.2009 | | | -0.26<br>normal slip |
| 6<br>25.09.2009 – 29.01.2011 | | | 0.08<br>reverse slip |

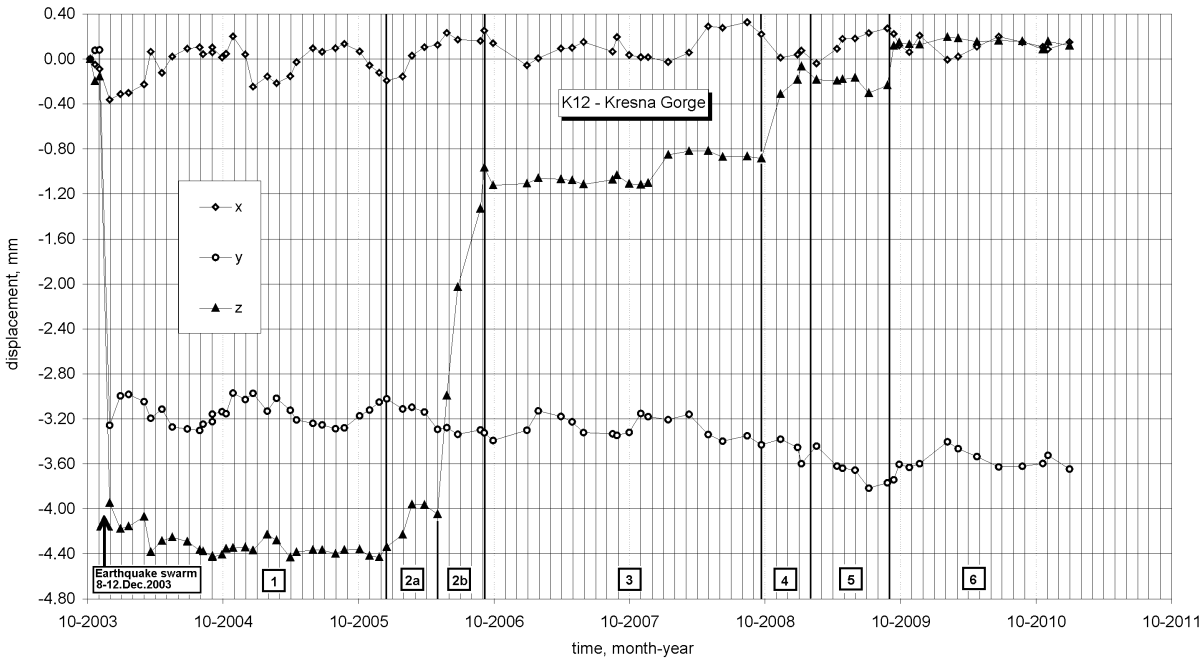


**Fig. 8** Diagram of the displacements found at K12 with periods of movements (see Table 5).

displacements occur frequently and are closely related to local seismicity. They are established on the basis of coincidences between seismic events and sharp movements. A second type of relationship (already established by Dobrev et al., 2003) is of weak earthquakes located NE from B6 (around the contact zone of Predela Fault and Krupnik Fault). The acceleration of movements is during the relatively quiet periods in seismic terms. However, as it is shown in Figure 6a, some earthquakes occurred in the NE from the graben have caused sudden slips at B6.

Some movements of shortening of fault zone and thrusting have been established, coinciding with the GPS measurements on monitoring located on the horst above B6. These movements have confirmed the movement of the horst to W-NW direction (Dobrev et

al., 2005). All this shows that at present the graben is under pressure from E direction (ie from Pirin Mts).

The observations on the Struma fault zone undeniably indicate recent activity, although at a lower magnitude than those measured along the Krupnik Fault. This fault zone is less influenced by local seismicity. The seismic activity in 2006 and 2007 had an influence on both observation points. While the reaction at K5 is expressed by mutual slip (in Y-axis), the movements in K12 are mainly along the Z-axis. The fault creep in 2006 at point K12 seems to be connected with activation of fault structures NW of the graben (Fig. 6c). The SW-NE orientation of the epicenters of the local earthquakes is obvious. In all probability, point K12 is sensitive mainly to earthquakes located in NW direction, but impact from earthquakes with epicenters located in Pirin Mts. should not be excluded.

The frequent seismicity N of Simitli graben and the shallow depth range of a part of the local earthquakes, shows probable active fault structures parallel to the Krupnik-Gradevo fault system. To be more complete this study, it is necessary a further search for opportunities to expand the monitoring system in the direction north of the graben.

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**REFERENCES**

Ambraseys, N.N.: 2001, The Kresna earthquake of 1904 in Bulgaria. Annali di Geofisica, 44 (1), 95–117.

Avramova-Tacheva, E., Vrablyanski, B. and Košták, B.: 1984, An attempt to detect recent movements along seismogenic faults. Review of the Bulgarian Geological Society, XLV, part 3, 276–288, (in Bulgarian).

Avramova-Tacheva, E.B. and Košťák, B.: 1995, Local three-dimensional extensiometric measurements for the determination of displacements in the Krupnik fault zone, Bulgaria. Acta Montana IRSM ASCR, Ser. A, No.8 (97), 87–98.

Botev, E. and Glavcheva, R.: 2003, On seismic circumstances in Bulgaria during 1997-2002. Rep. National Conf. On Preventive Works at Earthquakes and Landslides, Sofia, 10 Dec. 2003, 56-64, (in Bulgarian).

Christoskov, L. and Grigorova, E.: 1968,. Energetic and space-time characteristics of the destructive earthquakes in Bulgaria after 1900. Bull. Geophys. Inst., BAS, 12, 79–105, (in Bulgarian).

Dabovski, C., Boyanov, I., Zagorchev, I., Nikolov, T., Sapounov, I., Khrischev, K. and Yanev, Y.: 2002, Structure and Alpine evolution of Bulgaria. Geologica Balcanica, 32, 2–4, 9–15.

Dobrev, N.: 1999, Geological hazard processes in the Simitli graben. PhD Thesis, Geological Institute, BAS, Sofia. 181 pp., (in Bulgarian).

Dobrev, N.: 2005, Registered movements along active faults in SW Bulgaria. Rev. Bulg. Geol. Soc., 66, 1-3, 115–124, (in Bulgarian, English abstract).

Dobrev, N. and Avramova-Tacheva, E.: 2007, 3D Monitoring of active faults and slope movements in Bulgaria included in COST 625 Project. Acta Geodyn. Geomater., 4, No. 1 (145), 39–51.

Dobrev, N. and Petrov P.: 2007, Terrain effects caused by 1904 Krupnik Earthquake. - In: Proc. of International Project "Seismo-Hydrogeological Vulnerability of the Environment and Society in the Balkan Region", Second Meeting, 22-26 November 2006, Sofia.

Dobrev, N., Georgiev, I. and Košťák, B.: 2005, Extensometric and GPS monitoring of recent tectonic movements in the Simitli graben, SW Bulgaria, Geodesy, BAS, 17, 98–107.

Dobrev, N., Glavcheva, R., Frangov, G. and Shanov, S.: 2003, Observation of fault movements in SW Bulgaria and the impact of the local seismicity. Rep. National Conf. On Preventive Works Earthquakes And Landslides, Sofia, 10 Dec. 2003, 75–87, (in Bulgarian).

Dobrev, N.D. and Košťák, B.: 2000, Monitoring tectonic movements in the Simitli Graben, SW Bulgaria. Engineering Geology, Elsevier, 57 (3-4), 179–192.

Ganas A., Shanov S., Drakatos G., Dobrev N., Sboras S., Tsimi C., Frangov G. and Pavlides S.: 2005, Active fault segmentation in southwest Bulgaria and Coulomb stress triggering of the 1904 earthquake sequence. Journal of Geodynamics, 40, 2-3, 316–333.

Georgiev, I., Dimitrov, D., Belijashki, T., Pashova, L., Shanov, S. and Nikolov, G.: 2007, Geodetic constraints on kinematics of southwestern Butgaria from GPS and levelling data. DOI: 10.1144/SP291.7 Geological Society, London, Special Publications 2007, 291, 143–157.

Glavcheva, R.: 2004, State-of-the-art of the historical earthquake investigation in Bulgaria. Annals of Geophysics, 47, 2/3, 705–721.

Glavcheva, R.: 1999, Arguments for removing from the catalogues the strong 1866 earthquake in the Struma valley. Proc. Symp. "Geodynamical investigations, connected with the 1904 earthquakes in the Krupnik-Kresna area", Blagoevgrad, 77–84, (in Bulgarian).

Gutenberg, B. and Richter, C.: 1954, Seismicity of the Earth and Associated Phenomena. Princeton University Press, 310 pp.

Karnik, V.: 1968, Seismicity of the European area. Publ. Academia Praha, Part 1, 116–122.

Košťák, B. and Avramova-Taceva, E.: 1988, A method for contemporary displacement measurement on a tectonic fault. Journal of Geodynamics 10, 115–125.

Košt'ák, B., Cacoń, S., Dobrev, N.D., Avramova-Tačeva, E., Fecker, E., Kopecký, J., Petro, L., Schweitzer, R. and Nikonov, A.A.: 2007, Observations of tectonic microdisplacements in Europe in relation to the Iran 1997 and Turkey 1999 earthquakes. Izvestiya Physics

of the Solid Earth, Springer, Moscow, 43, no. 6, 503–516.

Košťák, B.: 1991, Combined indicator using moiré technique. Proc. 3rd Int. Symp. Field Measurements in Geomechanics, Oslo, 53–60.

Kotzev, V., Nakov, R., Burchfiel, B. C., King, R. and Reilinger, R.: 2001, GPS study of active tectonics in Bulgaria: results from 1996 to 1998. Journal of Geodynamics 31, 189–200.

Kotzev, V., Nakov, R., Georgiev, Tz., Burchfiel, B.C. and King, R.W.: 2006, Crustal motion and strain accumulation in western Bulgaria. Tectonophysics 413, 127–145.

Marinova, R. and Zagorchev, I.: 1990, Geological map of Bulgaria, scale 1: 100000. Sheet Razlog. MTS, Troyan.

McClusky, S., Balassanian, S., Barka, A., Demir, C., Erginav, S., Georgiev, I., Gurkan, O., Hamburger, M., Hurst, K., Kahle, H., Kastens, K., Kekelidze, G., King, R., Kotzev, V., Lenk, O., Mahmoud, S., Mishin, A., Nadarya, M., Ouzounis, A., Paradissis, D., Peter, Y., Prilepin, M., Reilinger, R., Sanli, I., Seeger, H., Tealeb, A., Toksoz, M.N. and Veis, G.: 2000, Global Positioning System constraints on plate kinematics and dynamics in the eastern Mediterranean and Caucasus. J. Geophys. Res. 105, 5695–5719.

Mercier, J.L.: 1981, Extensional-compressional tectonics associated with the Aegean Arc: Comparison with the Andean Cordillera of south Peru-north Bolivia, Philos. Trans. R. Soc. London, Ser. A, 300, 337–355.

Meyer, B., Armijo, R. and Dimitrov, D.: 2002, Active faulting in SW Bulgaria: possible surface rupture of the 1904 Struma earthquakes. Geophysical J. International, 148 (2), 246–255.

Milev, G., Vrablyanski, B. and Simeonova, R.: 1984, Recent movements along Kresna Gorge and Krupnik Fault. In: Zagorchev, I., Mankov, S. and Bozhkov, I. (eds), Problems of the geology in SW Bulgaria, Sofia, Technica, 72–79, (in Bulgarian).

Moskovski, S. and Georgiev, A.: 1970, On the Structure of the structure of the Kresna Gorge Region. An. Sofia Univ., Geology, 95–112, (in Bulgarian).

Papadimitriou, E, Karakostas, V., Tranos, M., Ranguelov, B. and Gospodinov, D.: 2006, Static stress changes associated with normal faulting earthquakes in South Balkan area. International Journal of Earth Sciences (Geol. Rundsch.), DOI: 10.1007/s00531-006-0139-x.

Ranguelov B., van Eck T., Papadopoulos G., Pavlides S., Shanov S. and Schenk V.: 2000, Initial data for the magnitude reevaluation of the strong earthquakes during 1904 in Kresna-Kroupnik Zone (SW Bulgaria), Geodynamic Investigations on the Territory of Bulgaria. Investigations of the Krupnik-Kresna Region Related to the 1904 Earthquake. Reports of Geodesy. Warsaw University of Technology, No 4 (49), 51–55.

Ranguelov, B., Rizhikova, S. and Toteva, T.: 2001, The earthquake (M 7.8) source zone (south-west Bulgaria). Prof.Marin Drinov Publ. House, Bulgarian Academy of Sciences, Sofia, 279 pp.

Shanov, S.: 1993, Medium-time earthquake prediction based on tectonic fault zone displacement data. Acta Montana, Praha, Series A, No.4 (90), 52–62.

Shanov, S.B. and Dobrev, N.D.: 1997, Impact of the seismic processes on the movements along the Kroupnik fault zone (SW Bulgaria). Comptes rendus de l'Academie bulgare des Sciences, 6, 95–98.

Shebalin, N., Karnik, V. and Hadzievski, D. (eds): 1974, Catalogue of earthquakes. UNDP/UNESCO survey seismicity of the Balkan region, Printing Office of the University Cyril and Methodius, Skopje.

Solakov D. and Simeonova S., eds.: 1993, Bulgaria Catalogue of earthquakes. 1981-1990. Geoph. Inst. Bulg. Acad. Sci., 39 pp.

Tranos, M.D., Kachev, V.N. and Mountrakis, D.M.: 2008, Transtensional origin of the NE-SW Simitli basin along the Strouma (Strymon) Lineament, SW Bulgaria. Journal of Geological Society London, 165, 2, 499–510, DOI: 0.1144/0016-76492007-089.

Tranos, M.D., Karakostas, V.G., Papadimitriou, E.E., Kachev, V.N., Ranguelov, B.K., Gospodinov, D.K.: 2006, Major active faults of SW Bulgaria: implications of their geometry, kinematics and the regional active stress regime. Journal of Geological Society, London, Special Publications 260, 671–687.

Watzof, S.: 1902, Tremblements de terre en Bulgarie observés pendant le XIX-ème siècle. Institut météorologique central, Sofia, Imprimerie de l'Etat. 96, (in Bulgarian, Summary in French).

Zagorcev, I.: 1970, On the tectonic movements in a part of South-west Bulgaria. Bull. of the Geophysical Institute, Bulg. Acad. of Sci., Series Geotectonics 19, 141–152, (in Bulgarian).

Zagorchev, I.: 1992, Neotectonic development of the Struma (Kraištid) Lineament, southwest Bulgaria and northern Greece. Geological Magazine, 129, 2, 197–222.