4.3.8. CRUSTAL MOTION IN BULGARIA BASED ON GEOLOGICAL AND GPS DATA

Radoslav Nakov, Valentin. Kotzev, B. C. Burchfiel, R. W. King

4.3.8.1. Introduction

In this paper we integrate geological observations with GPS and seismic data from Bulgaria to compare the relationship between current strain field and long-term geological data.

As a part of the southern Balkans Bulgaria is located at the northern boundary of the Aegean extensional regime. The area encompassing Northern Greece, Southern Bulgaria and the FYROM has been recognized as the Southern Balkan extensional region (SBER) (Burchfiel et al., 2000) being the northernmost continuation of the late Cenozoic Aegean extensional province (Fig. 4.3.8.1.). Presently, to the south SBER is bounded by the prolongation of the North Anatolian fault system into the Aegean Sea. The northern limit of the Aegean extension, respectively of SBER is conferred to the Sub-Balkan graben system of central Bulgaria (Tzankov et al., 1996, Burchfiel et al., 2000) (Fig. 4.3.8.2.). Obtained GPS data confirm the geological observations and show this boundary as a diffuse zone of extensional strain across the Balkan Range (Stara Planina Mountains) (Kotzev et al., 2002, Kotzev et al., 2006). Inside the region the deformation is occurring at lower rates compared to the central Aegean (Burchfiel et al., 2000, McClusky et al., 2000, Kotzev et al., 2001, Kotzev et al., 2006), but the structures are well exposed on land, and thus offer good opportunity to reconstruct the evolution of the system.

4.3.8.2. Bulgaria and the Aegean extensional province

Major syn-collisional shortening and convergence in Bulgaria and the eastern Balkans occurred prior to Late Eocene time (Burchfiel, 1980, Boyanov et al., 1989, Dabovski, this volume). Since Late Eocene time the extension has been the major mode of deformation inside the region and respectively within Bulgaria (Zagorchev, 1992, Burchfiel et al., 2000, Dabovski, this volume).

Recent geological studies developed a neotectonic evolution in Bulgaria showing that complex changes in extensional deformation and related depocenters have taken place since Late Eocene time, suggesting a complex partitioning of extensional strain (Burchfiel et al., 2000, Nakov et al., 2001, Burchfiel et al., 2005, Kotzev et al., 2006).

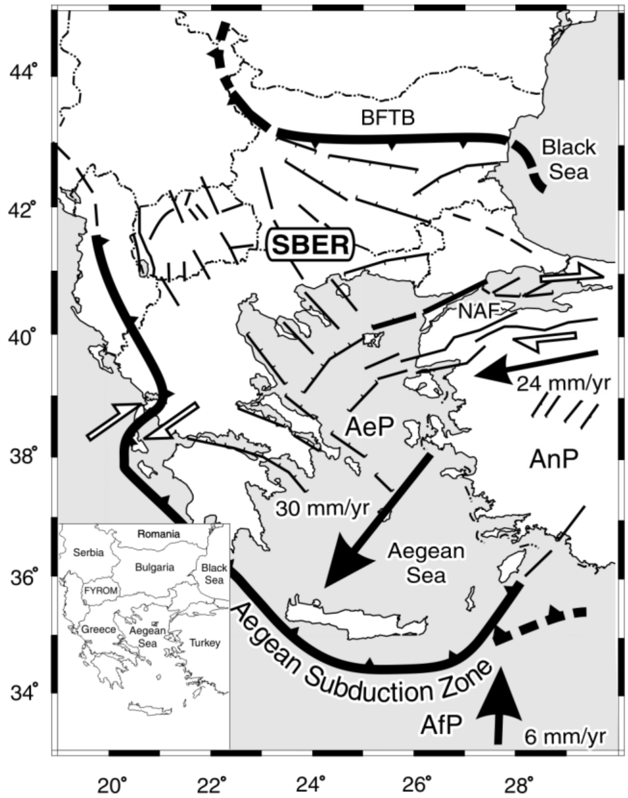

Fig. 4.3.8.1. Tectonic sketch of the Aegean extensional system. AeP, Aegean plate; AfP, African plate; AnP, Anatolian plate; BFTB, Balkan fault thrust belt; NAFZ, North Anatolian fault zone; SBER, Southern Balkan extensional region. GPS velocities given in black arrows are adopted from McClusky et al. (2000)

Cenozoic extension in southern Bulgaria is split in two major episods, separated by a short period of compression in Early Miocene time (Zagorchev, 1992, Burchfiel et al., 2000). The younger stage began in Late Miocene time and was firstly recognized by Jaranoff (1963) as "Aegean tectonics" who clearly related it to the processes in the Aegean Sea "similar to those in the Pannonian Basin". From a modern plate tectonic point of view, this idea should be explained as related to the back-arc extension above the hanging wall of a subduction system (respectively the Aegean and the Carpathian). In southern Bulgaria the Late Cenozoic extension had not a uniform development through time, migrating in a general manner from southwest to east. Earliest extension in SW-NE direction is documented along the NW-SE trending grabens in southwestern Bulgaria, followed by extension in the Sofia graben, Sub-Balkan graben system and Northern Thracian graben. In Pliocene to early Quaternary time extensional deformation became generally N-S oriented throughout Bulgaria as well as in part of adjacent northern Greece and Macedonia. The pattern on faults and depocenters appears to have changed in Late Miocene to Pliocene time. This change in extensional deformation seems to be related to the propagation of the North Anatolian fault system into the northern Aegean Sea during early Pliocene time (Armijo et al., 1996, Burchfiel et al., 2000). Geological studies suggest that extension of early and middle Cenozoic age within Bulgaria and the south Balkan region was of larger magnitude than younger extension that followed the propagation of the North Anatolian fault.

A broad erosional surface was formed before the Quaternary. This surface is significantly displaced by young faults thus pointing to a major Quaternary tectonic activity and relief building. Following geological conclusions can be suggested that the

present day tectonic stage of the southern Balkans was imposed during Latest Pliocene-Quaternary time and present day topography of Bulgaria is mainly formed by extension. Numerous basins and ridges bounded by faults occur to the south of the Stara Planina Mountains. From field observation the main bounding faults may be divided in three categories according to the strength by the evidence for recent activity (see Fig. 4.3.8.2.). Most faults are normal, with strikes in E–W, WNW, NW and rarely NE direction, thus indicating general N–S extension within most of Bulgaria, except for the region north of the E–W-trending Stara Planina Mountain Range. To the north of this range active faults are reliably established only by seismical activity. Individual faults have variations in strike which suggest that there may be strike-slip components on the NW-to NE-striking faults. Most of the faults bound mountain fronts, further indicating that most of the present-day topography of Bulgaria is the result of extensional faulting.

4.3.8.3. GPS Network and data analysis

The Bulgaria-wide GPS network (Fig. 4.3.8.2.) was established in 1996 and fully measured during 3 surveys between 1996 and 2001. In 1997, these stations were augmented with a 22 station network for monitoring the strain accumulation in western Bulgaria. That denser network was measured in 1997, 2000, and partly in 2002, 2003 and 2004.

Bulgarian station velocities shown in Fig. 4.3.8.2. are part from a velocity solution for ~80 GPS stations in the southern Balkan region (Burchfiel et al., 2006, Kotzev et al., 2006) obtained by combining Balkan data with data from the global network of the International GPS Service (IGS).

The GPS data were analyzed using the GAMIT/GLOBK software (King et al., 2003; Herring, 2003) and applying the approach described in Kotzev et al. (2006).

The velocity uncertainties are based on a weighting of the position uncertainties such that the uncertainties of the randomly distributed velocities of 53 stations in the stable regions of northern Bulgaria, the central part of western Bulgaria, and central Macedonia match the consistency of the velocity scatter what we would expect for non-deforming areas.

The North Bulgarian-fixed reference frame in which the velocity solution is presented (Fig. 4.3.8.2.) is defined in two steps using the method of generalized constraints (e.g. Dong et al., 1998). In the first step are estimated the translation and rotation rates which minimize the differences between our estimates for horizontal velocities for 27 globally distributed stations and their velocities in the International Terrestrial Reference Frame (ITRF2000) (Altamimi et al., 2002). In the second step is estimated the rotation vector for 7 stations in the non-deforming region of northern Bulgaria and southern Romania with respect to ITRF2000.

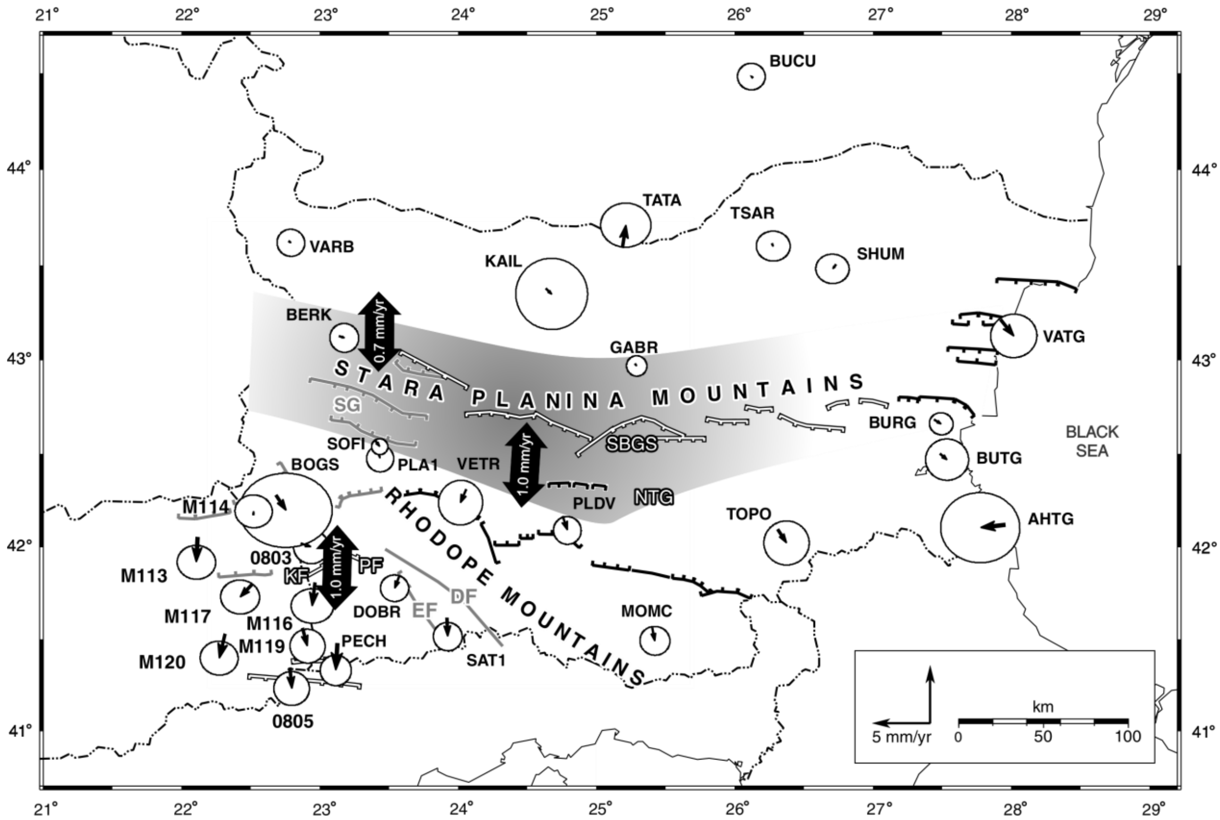

Fig. 4.3.8.2. Estimated velocities in the North Bulgarian-fixed reference frame (see text) adapted from Kotzev et al. (2006). Error ellipses represent regions of 95% confidence. Stations within the stable region of southern Romania and northern Bulgaria used to define the reference frame are BUCU, SHUM, TSAR, TATA, KAIL, GABR, and VARB (see text). The grey fountain filled area is the northern boundary of the Aegean extensional domain. Faults are white where geological evidence shows features of active fault movement. Faults in grey lines are associated with well-developed morphological evidence for recent activity. Faults in black lines are associated with only weak morphological evidence for recent activity. DF, Dospat fault; EF, East Pirun fault; KF, Krupnik fault; PF, Predela fault; NTG, Northern Thracian graben; SBGS, Sub-Balkan graben system; SG, Sofia graben

4.3.8.4. Velocity Field and Geological Data

The estimated velocities (Fig. 4.3.8.2.) show south oriented motion at a rate of ~1 mm/yr away from the fixed region in northern Bulgaria and southern Romania. That motion develops a diffuse extensional boundary across Bulgaria, which encompasses the E-W trending Sub-Balkan graben system of central Bulgaria and its westward continuation into the Sofia graben. GPS data show ~1.5 mm/yr extension across the central part of the Sub-Balkan graben system which is in a good agreement with the lower bound on the N-S extension rate of 1-2 mm/yr, estimated from geological data (Tzankov et al., 1996). The velocity field suggests that extension at a rate 0.7 mm/yr is transferred to the north of the Sofia graben across the westernmost part of the Stara Planina Mountains. The statistical significance of that extension is weaker than for the deformation across the Sub-Balkan graben system in central Bulgaria. There is no fully consistent velocity pattern that would justify extending the strain belt to the Black Sea coast. Geological

observations, however, indicate present day activity at a low rate of the faults in the onshore area.

Stations in SW Bulgaria and adjacent Macedonia move to the south at a rate of ~1 mm/yr relative to stations to the north and east. This motion is consistent with the geologically established N-S extension across the Krupnik (SW-NE strike) and Predela faults (NW-SE strike). The velocity pattern in southwestern Bulgaria suggests that extension in N-S is combined with a strike-slip motion along the NW-SE trending faults in that region (Fig. 4.3.8.2) but there is no evidence for extension in W-E direction. Local zones of extension or compression are expressed due to velocity differences between tectonic blocks with approximately one and the same direction of motion.

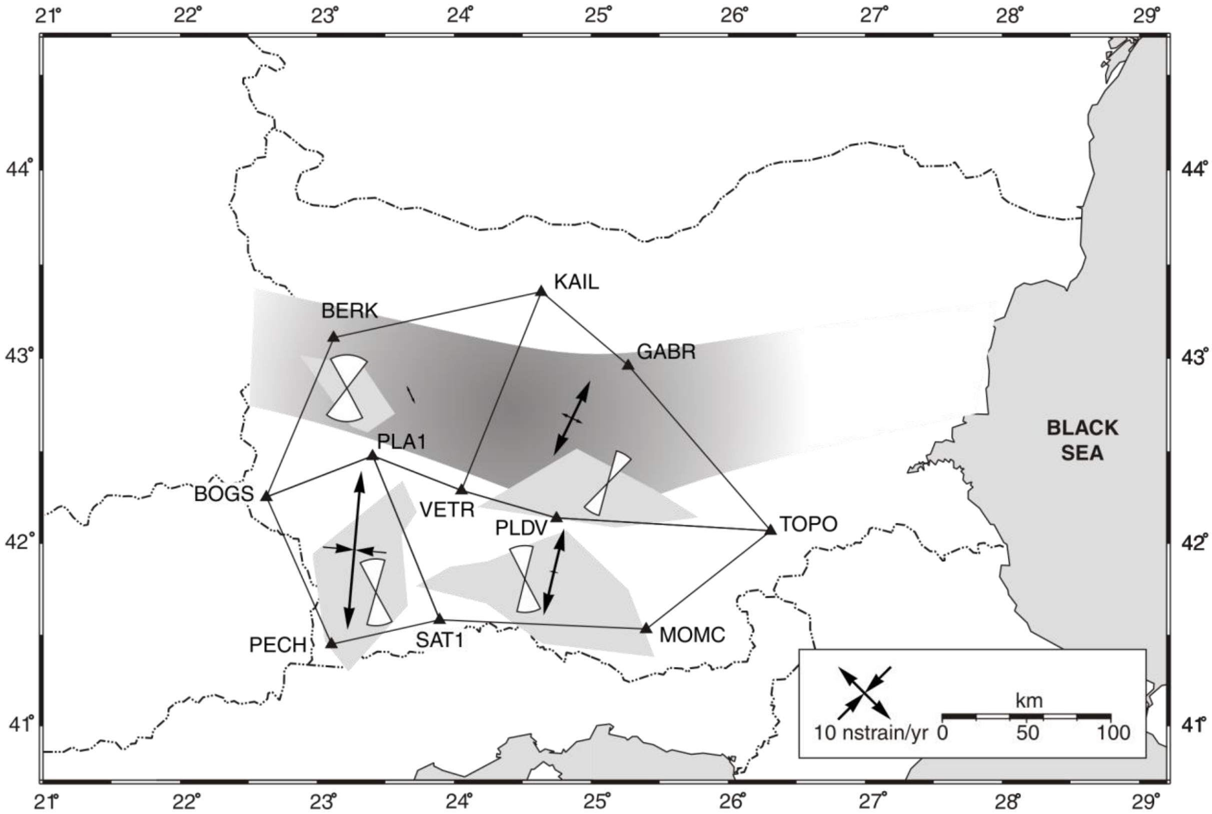

Fig. 4.3.8.3. Principal strain axes for polygonal regions adapted from Kotzev et al. (2006). Strain crosses are determined from geodetic data. Data for the extensional direction from seismic data are shown by a rose diagram that includes the greatest concentration of T data points. The rose diagrams show the uncertainty in the data set. Shaded areas show seismic domains. The grey fountain filled area is the northern boundary of the Aegean extensional domain

4.3.8.5. Strain and stress fields

To compare geodetically derived strain with the stress inferred from seismic data in western Bulgaria we computed surface strain from the GPS velocity solution (Kotzev et al., 2006) using the technique described by Dong (1993). Strain computations involved an estimation of the velocity gradient tensor within a set of polygonal regions with GPS stations at the vertices assuming a uniform strain field at each location. The examined seismic data consist of fault plane solutions for 54 earthquakes with a range in magnitude of 3.0 to 5.7 spanning the period l956 to 1998. In Fig. 4.3.8.3. are plotted together the principal strain axes for that domain and the best fitting sector for the

horizontal projections of the minimum compression axes for 4 seismic zones mainly based on spatial clustering of earthquakes. For three of the four domains, the direction and style of the geodetically determined strains is consistent with the stress inferred from the seismic data.

4.3.8.6. Conclusions

The geological and GPS data are broadly consistent in identifying regions of significant extension within Bulgaria, but are not yet sufficiently quantitative to test dynamic models. The geological data suggest deformation rates of 1–2 mm/yr or less which are consistent with the slow present day rates implied by the geodetic data. The obtained results provide reliable data for quantifying crustal deformation in Bulgaria. However, due to the low rates of deformation further studies are necessary for a more detailed understanding of the local deformation pattern. With several more years of high-precision GPS measurements, velocities in the current network could be estimated with uncertainties near or below 0.5 mm.

4.3.8.7. References

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