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"EVALUATION AND COMPARATIVE ANALYSIS OF STRESS AND DEFORMATIONS IN SEISMIC HAZARD ZONES ON BULGARIA AND ADJACENT LANDS"

ABSTRACT

In current paper an attempt to elucidate the geodynamic situation in Bulgaria and adjacent lands from a seismological paint of view is proposed. The fault plate solutions of 418 earthquakes and corresponding stresses and deformations are also analyzed. For the purposes of the quantitative stress and strain modeling, a seismic zonation is carried out and the Bulgarian territory and surroundings is divided on nine seismic hazard zones. The main seismological and focal mechanisms characteristics for each zone are presented. The stress tensors for the zones/fault systems are calculated by inversion of the focal mechanisms data using the technique of Gephart (1990). The released strain is computed from the moment tensors of the focal mechanisms according to the relation of Kostrov (1974). In general, the obtain mean strain tensors of deformation show some agreement with the calculated mean stresses. Several local misfits and the whole geodynamic situation are analyzed under the lights of some present tectonic hypothesis. On the base of the analysis of the nowadays seismicity, stress and deformation in the territory of north Balkans are presented.

1. INTRODUCTION

The earthquake sources and the environment in which seismic waves propagate are characterized by their hidden and inaccessible nature. The determination of the physical properties of the source determines the processes of excitation of the waves and how seismic energy is emitted. The types of the tectonic faults can be defined by determining the source mechanisms. Information about the geodynamic environment can be obtained from detailed study of the physical properties of the various earthquakes and the environment in which the seismic waves propagate.

Bulgaria is located in the northern part of the Balkan Peninsula. The contemporary tectonic environment in the area is characterized by a complex geological structure and geodynamics, caused by the collision of the Arabic, Anatolian and African plaques with the Eurasian (McKenzie 1970; Jackson and McKenzie 1984, 1988; Jackson 1992, 1994, McClusky et al., 2000). They suggest the existence of an Aegean plate that moves at a different speed from that of the Anatolian plateau and a north-south extension zone in Western Turkey.

The territory of Bulgaria is characterized by a high seismic hazard, the assessment is based on the large number of earthquakes, as stronger had significant catastrophic consequences in the past. At present, the higher magnitude earthquakes expose an even greater risk of destructive consequences due to the higher degree of urbanization of our lands (Tsenov and Botev, 2007). The earthquake activity on northern Balkan peninsula is a prove for recent geodynamic movements in the region. The study of seismicity, source mechanisms, Earth crust stress, deformations and geodynamics, seismic zoning on the territory of Bulgaria and adjacent lands has scientific and economic significance. Such studies are necessary and important as they can serve as a basis for predicting seismic hazard and refining seismic building standards in each area.

2. SEISMIC ZONING AND FOCAL DATA

In Figure 1 are presented 418 solutions for focal mechanisms of stronger earthquakes, for the period April 1928 – March 2018 and their distribution into nine seismic zones. The zoning presented in Figure 1 is similar to that proposed by Botev (2000), suitable with specific seismogenic and seismic stress pattern characteristics. Northern part of the observed area consists of four seismic zones – Vrancea zone (Z1) - located on Romanian territory, but causing serious macro-seismological impact on Bulgarian territory.

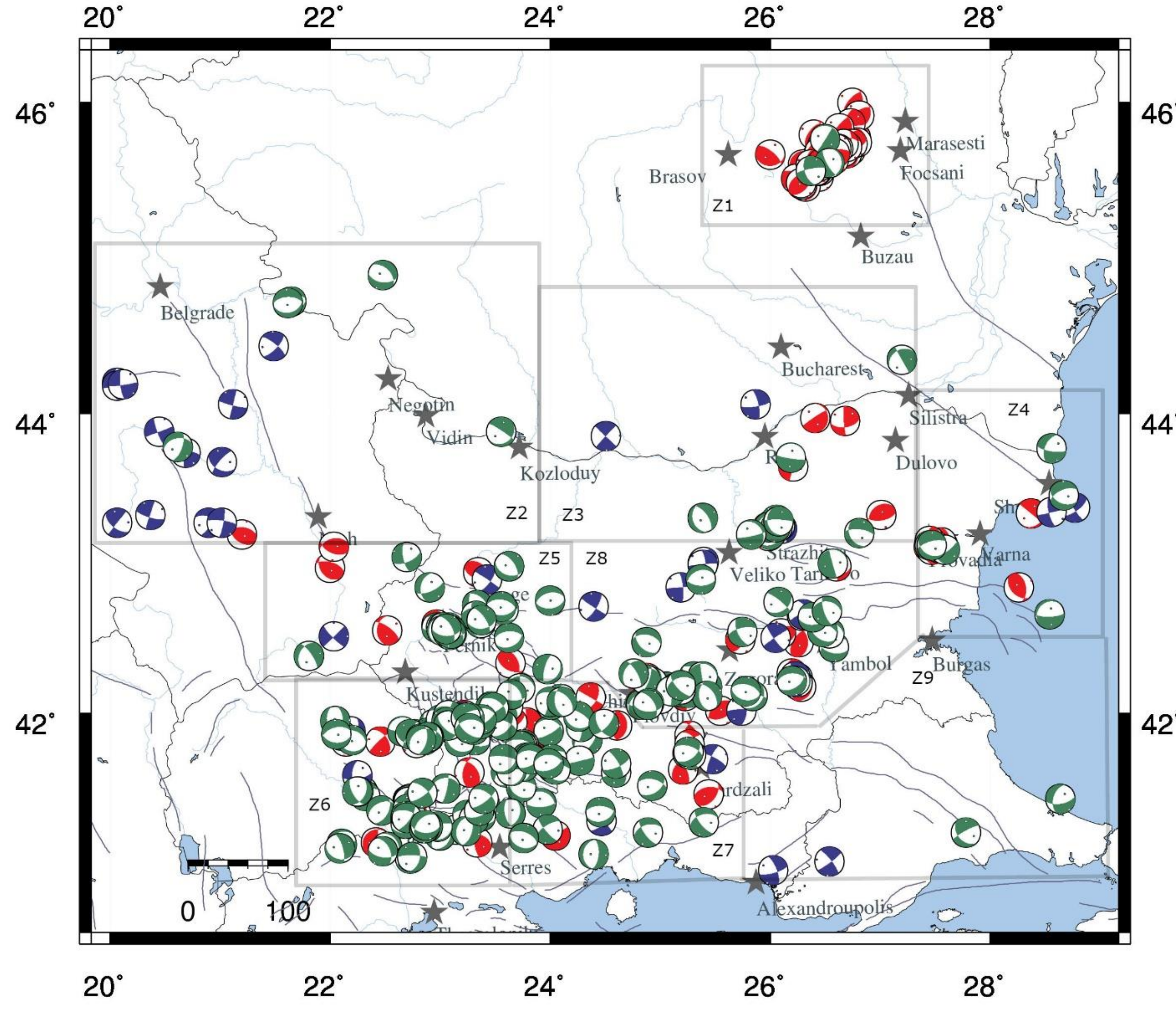

FIGURE 1. The distribution of 418 focal mechanisms in Bulgarian territory and adjacent lands. Z1 - Z9 - seismic zones: Z1 – Vrancea (Romania); Z2 - Negotin (Serbia/North-Western Bulgaria); Z3 - Gorna Oryahovitsa zone; Z4 - North-Eastern Bulgaria; Z5 – Sofia seismic zone; Z6 – Struma river (South-Western Bulgaria); Z7 – Rodopie sesmic zone; Z8 – Maritsa seismic zone, Z9 – Burgas seismic zone. Green color – normal faulting; Red color – Thrust faulting; Blue color – Strike-slip faulting. The tectonic map: Barrier et al. (2004), Georgiev et al. (2007).

Negotin (North-Western Bulgaria, Z2), with very low seismicity on Bulgarian territory and significantly higher activity on Serbian territory; Gorna Oryahovitsa zone (Z3) and North-Eastern Bulgaria (Z4), with records for strong earthquakes in the past. Southern part of the observed area consists of four high seismic zones – Sofia (Z5) and Maritsa (Z8) in central Bulgaria, Struma river (South-Western Bulgaria, Z6), Rhodope (Z7) in the southwestern Bulgaria, and aseismic Burgas zone (Z9) in the South-Eastern part.

An updated database of earthquake focal mechanisms has been received by collecting all available solutions till 31st of March 2018 (Georgiev, 1987, Solakov and Simeonova, 1993, Botev, 2000, Botev et al., 2006, Oncescu et al., 1990, ISC web catalog, EMSC/CSEM web catalog, Dimitrov, 2009, Botev et al., 2014, Protopopova, 2015), and by adding some new solutions, determined by P-wave first motion polarities method. 188 of all fault plain solutions are determined by the authors. Each focal mechanism is evaluated qualitatively, with different weighting ratios based on magnitude, number of first P-wave polarities, and confidence band of the nodal planes. The weighted coefficients were used in the subsequent stress tensor inversion calculations.

Vrancea seismic zone is a unique place on the Earth with continental intermediate focus earthquakes activity (80-160 km depth). It is specific that almost all earthquakes with available focal mechanisms in Vrancea are reversed. In Negotin seismic zone the predominant movement is strike-slip. In Strajitsa fault system (Gorna Oryahovitsa zone) and Provadia fault system (North-eastern Bulgaria) the number of normal and trust faulting focal mechanisms is almost equal. The distributed other seismic zones focal mechanisms show predominant normal faulting, some of them with insignificantly strike-slip movements. The Monastery uplifts fault system (Maritsa seismic zone) is the only place in Bulgaria, where the trust faulting is predominant.

3. STRESS TENSOR INVERSION

The directions of the principal tectonic stress for all seismic zones are determined from the inversion of focal mechanism data, using the technique of Gephart and Forsyth (1984) and Gephart (1990), which gives the orientation of σ1, σ2, σ3 (maximum, intermediate and minimum stress, respectively) and the parameter R, as a measure of relative stress magnitudes. The best fit stress tensor is the one characterized by the minimum sum of misfit rotation (Θ), which is the sum of angle of rotation between each observed slip vector and calculated (model) slip vector.

$$R = \frac{\sigma_2 - \sigma_1}{\sigma_3 - \sigma_1} \quad , 0 \leq R \leq 1 \qquad [1]$$

According to Wyss et al (1992), the condition of homogeneous stress distribution is fulfilled if the average misfit Θ is smaller than 6° and that it is not fulfilled if Θ is greater than 9°. In the 6°≤ Θ ≤9° range, the solution is considered as acceptable, although it may reflect some heterogeneity. For reduction of the misfit in every seismic zone, where it is possible, the volume of focal mechanisms is separated in sub-volumes (faults, faulting systems, sub-regions). Some of the earthquake focal mechanisms are excluded from the sub-volume data processing (not good quality of the beach balls, too less or marginal events, focal mechanisms related with other faults/fault systems), because they are leading to unreliable misfits. The results are presented in Table 1.

The Vrancea region (Z1) in Romania is characterized by compressional stress regime. The maximum compressive stress is orientated horizontally, with north-northwest – south-southeast (NNW-SSE) direction. The extensional component is sub-vertical. Similar results are obtained by Polonic et al. (2005). Oncescu (1987) is defining Vrancea as complex tectonic zone, which is characterized by clustered intermediate depth seismic activity, with subduction-type features.

In Negotin seismic zone (Z2 – known also as Kraishte zone) the maximum and minimum stress are perpendicular, close to the horizon plunges projections. The compressional axis has northeast-east – southwest-west (NEE-SWW) direction and the extensional axis has NNW-SSE direction. These results can be explained with the predominant strike-slip focal mechanisms.

The Strajitsa fault system, part of Gorna Oryakhovitza zone (Z2) is characterized by a compressive stress regime, maximum compressive stress is oriented east – west (E-W) and minimum compression is oriented northeast – southwest (NE-SW). The misfit angle is a gather then 9º, which shows some heterogeneity of the focal mechanisms volume.

A compressional stress regime affects also the Provadia fault system in North-eastern Bulgaria zone (Z3). The stress axis orientations are similar with Strajitsa. Similar is the stress regime on Black sea crust, but the maximum extension has almost sub-horizontal north – south (N-S) orientation.

Zone	Region	№	Misfit Θ [º]	R	σ_{1pl} [º]	σ_{1az} [º]	σ_{2pl} [º]	σ_{2az} [º]	σ_{3pl} [º]	σ_{3az} [º]
Z1	Vrancea - Romania	52	6.289	0.3	7	338	1	68	83	166
Z2	Negotin - Serbia/North-Western Bulgaria	14	3.301	0.3	35	238	54	43	7	143
Z3	Gorna Oryahovitsa - Strajitsa	29	9.838	0.1	23	97	34	351	47	215
Z4	North-Eastern Bulgaria - Provadia	13	8.745	0.2	11	278	8	187	76	63
Z4	North-Eastern Bulgaria - Bleck Sea	7	1.986	0.3	19	266	70	103	5	358
Z5	Sofia seismic zone	36	8.098	0.4	70	250	20	70	0	160
Z5	Sofia seismic zone - Pernik	20	4.391	0.8	50	260	40	71	4	165
Z6	Struma zone - Krupnik	40	10.319	0.5	66	196	10	82	22	348
Z6	Struma zone - Bulgaria-Macedonian border	14	6.743	0.5	60	210	29	46	7	312
Z6	Struma zone - Belasitsa	29	7.456	0.4	56	255	33	87	5	354
Z6	Struma zone - Macedonia	21	8.146	0.4	70	271	16	54	11	147
Z7	Rodopie zone - Mesta river valley	27	6.321	0.6	51	234	34	88	17	346
Z7	Rodopie zone - Central Rodopie	24	6.59	0.3	53	267	37	89	1	358
Z7	Rodopie zone - South Rodopie	7	1.452	0.5	85	314	4	102	3	193
Z7	Rodopie zone – Arda river valley	9	2.481	0.5	34	303	45	77	25	195
Z8	Maritsa zone - Maritsa river	30	8.709	0.7	56	215	11	107	31	10
Z9	Maritsa zone - Maritsa river	26	7.914	0.6	62	209	9	99	26	4
Z8	Maritsa zone - Tundzha river	14	9.575	0.6	35	122	40	248	31	8
Z8	Maritsa zone - Monastery uplifts	10	6.019	0.1	0	270	36	180	54	0
Z9	Burgas seismic zone	4	0.582	0.8	41	248	42	106	20	356

TABLE1. Stress tensor inversion results. Z – seismic zones (same as in Figure 1), Region – area (faults, faulting systems, sub-regions) including sub-volume of focal mechanisms, N - number of used focal mechanisms in each region, Θ misfit rotation angel, R- stress magnitude, σ1, σ2, σ3 - maximum, intermediate and minimum stress, pl - plunge angles, az – azimuths.

In Sofia seismic zone (Z5) the stress regime is normal with north-northeast – south-southwest (NNE-SSW) sub-horizontal orientation. The misfit is around 8º, calculated by using all focal mechanism distributed on Bulgarian part of the zone, which shows some heterogeneity in the volume of focal mechanisms. For the Pernik fault system, the misfit shows homogeneous stress, with same axes orientations like in Sofia seismic zone.

The Struma seismic zone (Z6) is characterized by the highest number of focal mechanisms – more than 100 and very complicated tectonic settings. The high number of the all available focal mechanisms were separated on four smaller groups, related with the most active fault systems in observed area. Although, the misfit angles in all four fault system are pretty high and show some heterogeneity in calculated stresses, the orientations of the extensional stress axes have similar NNW-SSE directions and almost horizontal plunges.

Normal stress regime is characterizing all fault systems in Rodopie mountain massif (Z7). The seismic activity is mainly associated with the Mesta river valley, Chepino, Dospat, Devin and Ardino depression fault systems. The available focal mechanisms are separated on four groups Mesta river fault system, Central Rodopie including Chepino, Dospat and Devin fault systems, Arda river fault system and fault systems on southern slope of Rodopie massif and northern Greece. The stress regime in all zone is normal, with good heterogeneity of the calculated stress, but it is interesting that the extensional axes are changing a bit their directions from NNW-SSE for western part of the zone to NNE-SSW for the eastern part.

The main morpho-structure in Struma seismic zone (Z8) is the Upper Thracian depression, the biggest negative structure within the territory of Bulgaria. The seismic activity is mainly associated with the Maritza and Tundzha fault systems, but during the last nine years moderate magnitude seismic activity has increased in the Monastery uplifts fault system. Due to the high misfit in the rotation angle of the calculated stress, it was necessary to reduce the initial number of available focal mechanisms in mentioned sub-zones. The mechanisms located in the lower riverside of the Maritsa River were excluded from the stress calculations, but still the stress shows some heterogeneity. In both calculation cases the stress regime is normal with almost NNE-SSW orientation. Same stress regime is calculated for the Tundzha river fault system, with misfit higher than 9º and pretty small amount of focal mechanisms, distributed on large area. The dominant stress regime in Monastery uplifts faults system is compressional with horizontal maximum stress in E-W direction, but the extensional axis is oriented in N-S direction with plunge 54º.

In Burgas seismic zone (Z9) the stress regime is normal with N-S orientation. The calculated stress is not very plausible, due to the only four available focal mechanisms, which is the minimum amount for tress tensor inversion calculation.

On Figure 2 are presented the horizontal projections of calculated extensional stress axes (σ_3) of all fault systems. The results show increasing of the extension from north to south and changing the stress trend from NNW-SSE for western part of the observed area to NNE-SSW trend for eastern part.

4. STRAIN TENSOR INVERSION – DEFORMATION

The strain field is analyzed with the estimation of the orientation of the principal strain axes. The released deformation is computed from the moment tensors of the focal mechanisms according to the relation developed by Kostrov (1974):

$$\varepsilon_{ij} = \frac{1}{2\mu V}\sum_k M_{ij}^k \qquad [2]$$

Where μ is rigidity modulus (3x10^{10} Pa); V is crustal volume (the thickness of the crust by the area affected by the earthquakes); M_{ij}^k is the moment tensor of the k-th earthquake. The moment tensor is related to the scalar seismic moment by:

$$M_{ij}^k = M_0^k (u_i^k n_j^k + u_j^k n_i^k) \qquad [3]$$

where u_i^k is a unit vector normal to the fault plane and u_j^k is a unit vector parallel to the slip direction. The scalar seismic moment is computed from the magnitude with the relation by Riznichenko (1985):

$$LogM_0 = 1.6M + 8.4 \pm 0.5 \qquad [4]$$

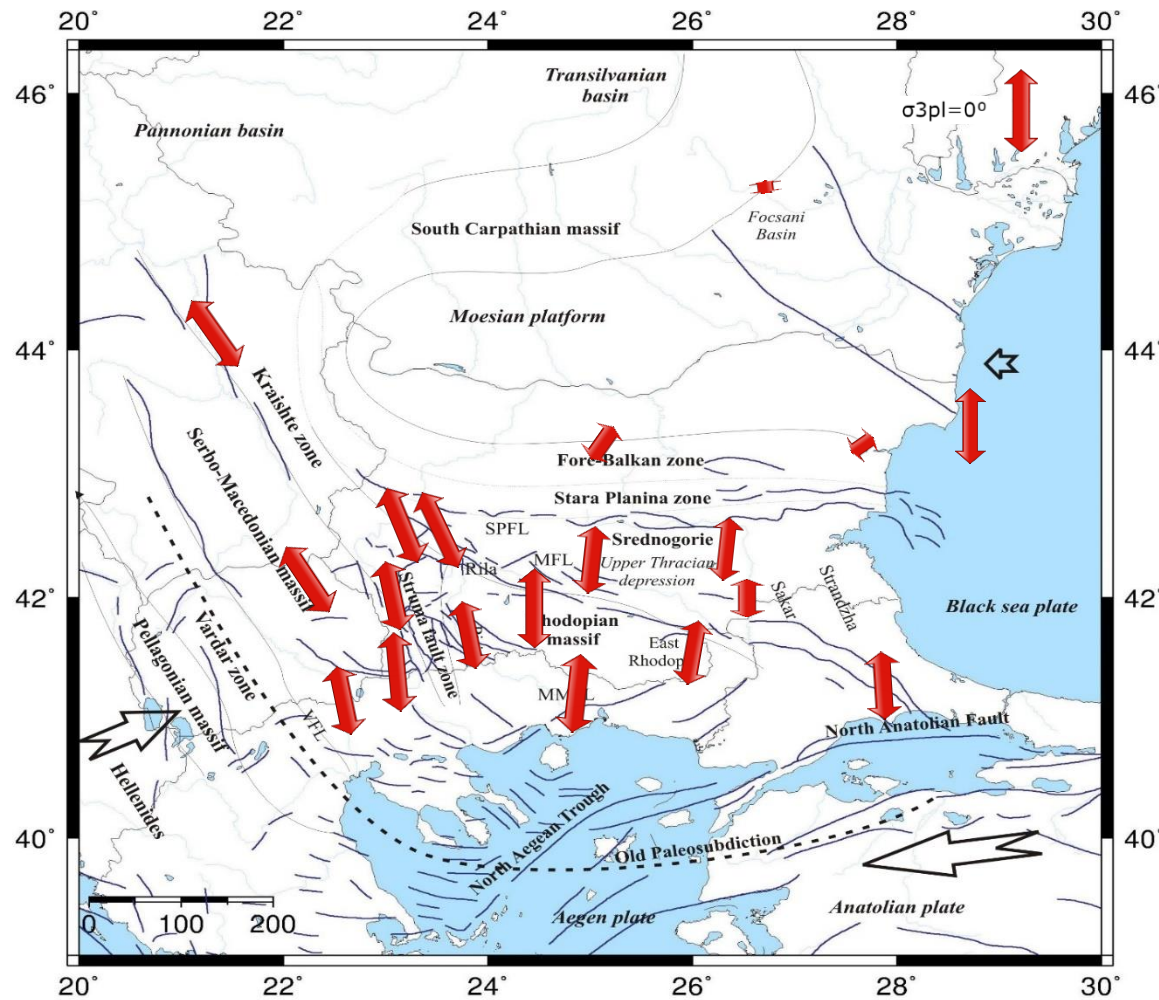

FIGURE 2. The horizontal projections of the stress rate (red arrows - extension - σ_3. from Table 1) obtained by seismological data, white arrows present the movement of the tectonic blocks.

It is very hard to estimate the exact volume that is affected by every earthquake or group of earthquakes. This is why the tensor of deformation is calculated only as principal strain axes directions, not as absolute measure. The crustal thickness on the territory of Bulgaria varies between 30 and 50 km (Georgieva and Nikolova, 2013). The depth of the Moho boundary is about 30 km beneath northern Bulgaria (Negotin, Gorna Oryahovitsa and North-eastern Bulgaria) and Upper-Thracian valley (Maritsa and Burgas seismic zones). The crust is thickening beneath the Rhodopie massif and Pirin Mountain, where it reaches about 50 km. The Moho structure in South western Bulgaria is very complex, reaches around 30 km (Sofia and Struma seismic zones). The crustal thickness under Vrancea is around 42 km (Ivan, 2011), but the observed seismicity is between 80-160 km depth, which mean it is realized in Earth mantle, and for that reason the deformation in Vrancea seismic zone is not calculated. The area affected by earthquakes is evaluated approximately (square or rectangular boundaries for easer calculations), as in zones where there is more than one calculated stress tensor, the area is divided by the number of calculations (fault systems).

The computed orientations of the principal axes of the strain tensor are shown in Table 2. The principal strain axes of the seismic zones which are showing normal stress regime are plotted on Figure 3. Excluded are Z2, Z3, Z4 – Provadia and Z8 - Monastery uplifts, because of their compressional stress regime. The deformation is clearly marking two directions – horizontal in NNW-SSE direction and vertical, but the confidence bands are overlapping in some areas, which is marking heterogeneity of the Earth crust strain.

Zone	Region	№	ε_{1pl} [º]	ε_{1az} [º]	ε_{2pl} [º]	ε_{2az} [º]	ε_{3pl} [º]	ε_{3az} [º]
Z2	Negotin - Serbia/North-Western Bulgaria	14	27	230	79	18	17	140
Z3	Gorna Oryahovitsa - Strajitsa	29	43	133	33	260	30	12
Z4	North-Eastern Bulgaria - Provadia	13	16	264	57	168	60	51
Z4	North-Eastern Bulgaria - Bleck Sea	7	34	113	33	220	47	337
Z5	Sofia seismic zone	36	60	266	31	57	14	155
Z5	Sofia seismic zone - Pernik	20	55	240	37	70	6	165
Z6	Struma zone - Krupnik	40	80	134	3	235	10	325
Z6	Struma zone - Bulgaria-Macedonian border	14	70	120	14	248	7	340
Z6	Struma zone - Belasitsa	29	66	144	4	48	16	317
Z6	Struma zone - Macedonia	21	81	138	0	230	10	320
Z7	Rodopie zone - Mesta river valley	27	44	22	50	230	11	330
Z7	Rodopie zone - Central Rodopie	50	240	32	103	19	2	50
Z7	Rodopie zone - South Rodopie	88	300	2	94	13	185	88
Z7	Rodopie zone – Arda river valley	83	337	4	96	17	188	83
Z8	Maritsa zone - Maritsa river	16	54	40	324	55	167	16
Z9	Maritsa zone - Maritsa river	25	58	42	318	44	177	25
Z8	Maritsa zone - Tundzha river	27	66	39	320	60	167	27
Z8	Maritsa zone - Monastery uplifts	7	282	58	182	30	24	7
Z9	Burgas seismic zone	45	237	31	114	16	15	45

TABLE 2. Strain tensor inversion results. Z – seismic zones (same as in Figure 1), Region – area (faults, faulting systems, sub-regions) including sub-volume of focal mechanisms, N - number of used focal mechanisms in each region, ε1, ε2, ε3 – principal strain axes, pl - plunge angles, az – azimuths.

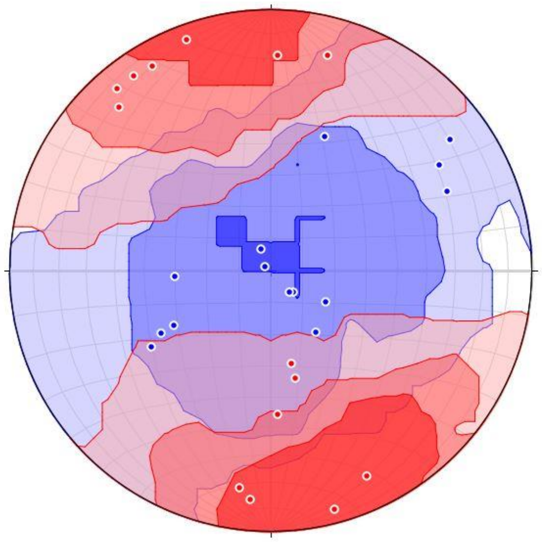

FIGURE 3. The principal strain axes of 14 zones, with normal predominant stress.

It should be pointed out that the stress tensors obtained from inversion of the focal mechanisms is computed by minimizing differences between observed and resolved slip direction, while the strain tensors for each zone (Table 2) are evaluated directly from observed data. The stress tensor is related to the regional stress field while the strain is related only to seismic deformation and not to the overall regional tectonic field.

The comparison between the obtained stress and strain tensors evidences that the direction of the principal stress axes and the principal strain axes are not the same throughout the considered zones. This discrepancy suggests that the stress field is much more heterogeneous because the crust is not uniform in strength (Wyss et al., 1992).

5. CONCLUSION

In general, for the territory of the Bulgaria has predominant horizontal extension in north-south (according to the defined principle axes of the regional stress tensors - Figure 2) corresponds well with the formation of depression structures with east-west direction, (Z5), the Sofia valley in the Seismic Zone of Sofia (Z5), the Simitli and Struma valleys in the Struma Seismic Zone (Z6), the Upper Thracian valley in the Maritsa seismic zone (Z8), and others. The extension does not coincide with the basic morpho-structures, but lies across them, suggesting a relatively young stage of deformation (Botev, 2000, Botev et al., 2006). The extension processes are more significant in Western Bulgaria and especially in Southwestern Bulgaria, where the decompression axes of the defined stress tensors are almost horizontal and have a slight orientation to the north-northwest - south-southeast. Stress tensors from the central to the eastern part of the observed area alter the directions of the decompression axes towards the north-north-east - south-south-west direction, and a partition in the orientation of extensive stresses in the central part of the country. At same time it has zones with a local areas of relative compression, probably due to differences in the relative movement of individual faults. For example, in the northeastern Bulgaria the horizontal extension is very small, but the compression is dominant. In the Vrancea seismic zone, a significant compression is realized in the near-horizontal direction, which marks the palaeosubduction characteristics of the seismic zone.

The GPS measurements in recent years (McClusky et al., 2000; Georgiev et al., 2007; Georgiev et al., 2013; Mouslopoulou, 2014) show that the largest horizontal movements (about 35 mm/yr) are recorded in the central and the southern part of the Aegean area. Measurements in northern Greece show significantly lower velocities in the southern direction (9-11 mm/yr.), while in southwest Bulgaria velocities are about 3-4 mm/yr. According to the same authors, several measuring points in Northeastern Bulgaria demonstrate lower speeds (1-2 mm / yr) of movement in a similar direction. The significant difference in the speed of movement indicates the existence of an extension province in the region of North Aegean Greece. According Burchfiel et al., (2006), southern Bulgaria and Northern Greece define the South Balkan Extensional Region. The northern boundary of the Aegean extensional region passes through the Central Bulgaria (Stara planina Mountain) and the analysis of the active faulting has indicated that huge part of the Balkan Peninsula has been characterized by extensional tectonism.

The main result from the focal mechanism, stress and deformation tensors analysis is the prevailing of a normal - extensional stress regime in almost all seismic zones, with incensement from north to south. These results confirm the hypothesis that the neotectonic movements in Balkan Peninsula region are consequence of the long lasting extensional movements in the inner parts of the Aegean and

Central Balkan regions (Burchfiel et al., 2006), and are in agreement with the newly obtained model for present day kinematics of central and eastern Mediterranean (Pérouse et al., 2012). The misfit between the principal axes of the obtained stress and strain tensors, could be explained with the considerations in Wyss et al. (1992), that the crust is not uniform in strength, and if there are planes of low shear strength or zones of weakness, like preexisting faults, the orientations of the principal axes of stress and strain may differ substantially.

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