4.3.3. ON THE GEODYNAMICS OF BULGARIAN LANDS THROUGH SEISMOLOGICAL DATA

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4.3.3.1. Analysis of the seismicity

Bulgaria is well known by moderate to high seismicity: since I century BC at least 30 events with magnitude M ≥ 6 have been occured on its teritory and the adjacent lands (Grigorova et al., 1979; Christoskov et al., 1979). The strongest known event in the country is the earthquake of April 4, 1904 with a magnitude Ms 7.8 (Christoskov & Grigorova, 1968); it occurred in the present-day contact area between SW Bulgaria and Macedonia. The better knowledge on Bulgarian seismicity during the last three centuries provides data on the occurrence of aproximetaly 3 events with magnitude greater than 7 in each century, with a burst of activity in the period 1858-1928, when at least 6 events with magnitude greater than 7 (and about 20 with M>6.0) occurred. Since that time only moderate seismicity has been observed - the strongest event with magnitude M=5.7 hit the region of Strazhitza (central northern Bulgaria) in 1986 (Glavcheva et al., 2003).

The historical seismicity in Bulgaria has not been satisfactory covered by the existing information sources. The supporting dataset quality has been improving in the course of time, although the data points' number has not been significantly changed. For instance, more than 50 % of the earthquakes in Bulgaria occurred before establishing the national seismological service (1891) still correspond to a single locality report. Proceeding from the classical Bulgarian earthquake catalogue (Christoskov et al., 1979) supplemented by some later studies (for example Glavcheva, 1999; Christoskov, 2005), the strongest, i.e. the key-earthquakes, in Bulgaria and nearby territory are as follows: two earthquakes during the 1 sentury BC and 1444 with corresponding makroseismic magnitude M>7.0 destroyed the localities around the present towns of Kavarna and Varna (on the northern Black Sea coast); in 1641 one event with makroseismic magnitude approximately 7 affected the town of Kyustendil (western part of the country); in 1750 one event with magnitude M > 7.0 occurred in the region of Plovdiv (in the central part of the country); in 1858t the town of Sofia was destroyed by a local not very strong earthquake (M=6.5).

After establishing (in 1891) Bulgarian Service for regular observing and documenting earthquakes felt in this country, the seismicity over its territory as well as seismic impacts from seismic zones around are known quite better. Thus, a strong earthquake (maximum intensity of 8 degrees MSK, corresponding magnitude approximately 7) was felt on 14 October 1892 within the territories of Bulgaria (epicentral area in South Dobrudzha), Romania, Bessarabia, Ukraine, Turkey, Serbia and Transylvania (Glavcheva and Radu, 1994). A M7.2 earthquake occurred in 1901 near the northern Black Sea coastline of Bulgaria in an area known from Strabon's "Geographica" with a demolished earthquake in the antiquity. It provoked large landslides in the coastal area

and an aftershock sequence for about 10 years. The strongest event in this country (magnitude Ms = 7.8), that occurred in nowadays SW Bulgaria on 4 April 1904, was followed by a relatively short seismic sequence till the end of 1906. It was preceeded by two periods of high seismic activity – an early one in 1893-1894 and a later one in November 1903. An imminent catastrophic foreshock (M 7.1) occurred 23 minutes before the strongest shock. Going back to the initial documentation, a precursory anomaly in the energy release was recently established in the interval between the two largest earthquakes (Glavcheva, 2000). At present this seismogenic zone is of the highest activity in Bulgaria (see for example (Sledzinski /ed./, 2000)). Another strong earthquake (M7.0) occurred at the contact between the Fore-Balkan and Moesian platform in central North Bulgaria in 1913. It badly destroyed Gorna Oryakhovitza and Turnovo, two important towns of the region, as well as several small settlements in the vicinity. Fortunately, the aftershock sequence did not contain any other strong events and decreased till the mid-1916. The NE prolongation of the same seismogenic zone manifested new significant activity only after about 70 years (Christoskov et al., 1988) The epoch of catastrophic earthquakes in Bulgaria finished in 1928 with two large events (M6.8 and 7.0) in the Upper Thracia, central South Bulgaria. Many coseismic ruptures (cumulative length of ruptures on the Earth surface exceeds 120 km), hydrogeological and other primary and secondary effects were observed and have been studied even till now (see for example (Sledzinski /ed./, 2000). It is worth noting that high magnitude events failed to occur within the territory of Bulgaria after the 1928 large earthquakes - there were no events with M>6.0, and these ones with M>5.0 were less than 10. The latest moderate earthquakes (M5.1 and 5.7) occurred in 1986 in central North Bulgaria, the Gorna Oryakhovitza zone.

The nowdays monitoring of the weak earthquakes in Bulgaria is based on a modern National seismological network which was established in 1980. More than 15000 events recorded during the operation of this National network are located on the territory of Bulgaria and its close vicinity. Most of them are microeartquakes – more than 95% with a magnitude M<3.0. Preliminary information and analysis of the realized contemporary weak seismicity are periodically proposed by Botev et al., (1993 - 2005). Many other papers are devoted to the detailed analysis of different aspect and sources of this seismicity (for example see Glavcheva et al., 199..; Solakov et al., 1993; Glavcheva et al., 2000, Glavcheva & Botev, 2004, Botev et al., 2005 and many others).

In Fig. 4.3.3.1. the territorial distribution of earthquakes with M≥2.0 is presented; the database consists of the catalogue (Grigorova et al., 1979; Christoskov et al., 1979; Solakov & Simeonova (editors), 1993) and the parameters determination of the National seismological network (Botev et al., (1993 - 2005)). In this figure the size of symbols corresponds to the seismic source's size computed from magnitude by the Riznichenko (1985) relation. Different symbols indicate three time periods corresponding to different quality of location and magnitude estimation (i.e. before 1900, between 1900 and 1980, and after 1980).

As can be noticed (Fig. 4.3.3.1.), both, the seismicity prior to 1900 and that of the 20th century, show similar pattern: the Struma area in the southwestern sector as well as the lower Mesta valley form the most active space, the region of Plovdiv (central South Bulgaria) and the Black Sea coastline in the North of Bulgaria are also seismically active, the Gorna Oryakhovitza region seems to be at a lower level of activity.. More questionable is the seismicity of the Edirne area, along the Greek-Turkish border, where some strong past events are documented but the recent seismicity is very scarce.

The hypocenters of the earthquakes are concentrated in the surficial 10-30 km depth interval and rarely reach down to 50 km depth in the SW part of the country.

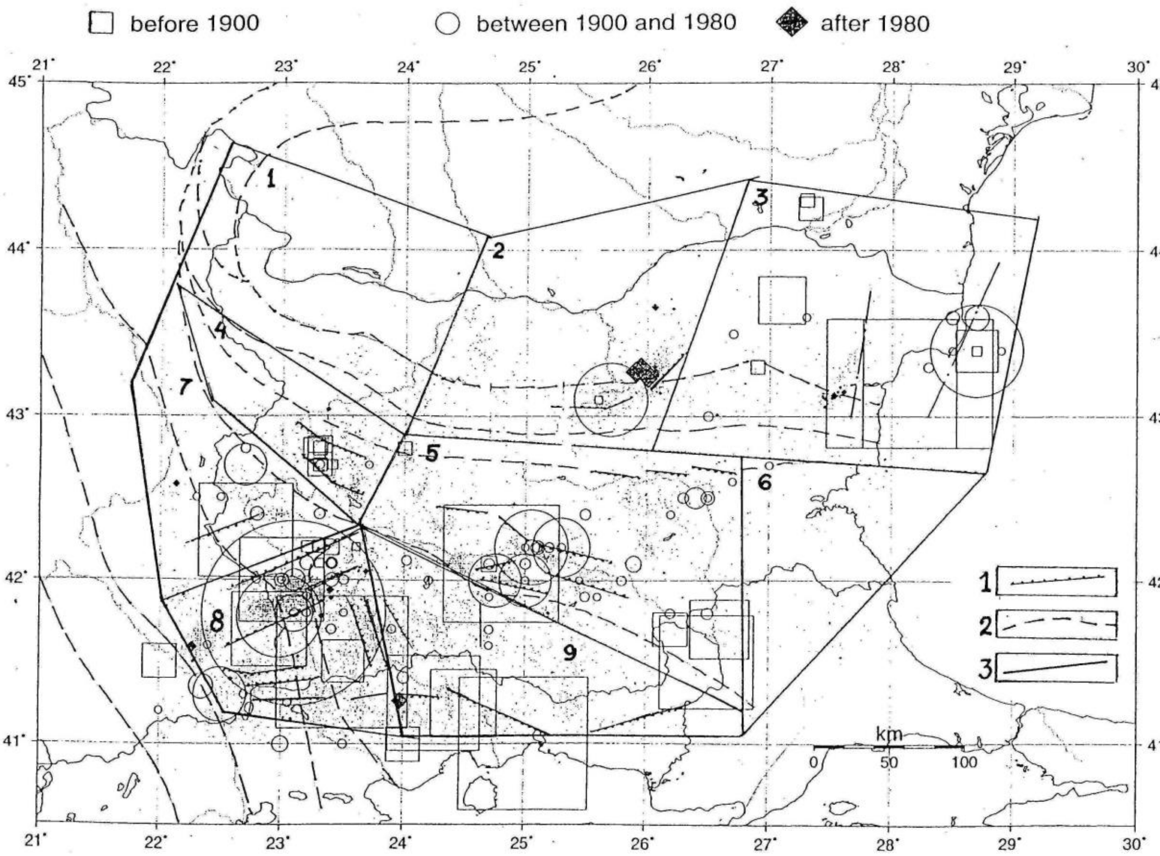

Fig. 4.3.3.1. Epicentral distribution for the events with magnitude M>2.0. The size of the symbols corresponds to the real source size of the earthquakes according to the relation of Riznichenko (1985). The used simbols and seismic zoning of the Bulgarian territory are explained in the text. In the Legend: 1- Quaternary active faults, 2- boundaries between the structural provinces, 3- boundaries between the seismic zones

The map of present-day weak seismicity (Fig. 4.3.3.1.) shows two spaces within the study territory with obvios differentiation - a large active polygon spread over the southwestern one-third of Bulgaria together with its neighboring areas in Macedonia and Greece, on the one hand, and another polygon in the eastern part of Bulgaria that might be specified by sparsely distributed seismic origins where two or three clouds of epicenters (due to aftershock sequences mainly) can be distinguished, on the other hand. These weak events originate predominantly at depths of 5-20 km. The deepest seismic foci can be oftenly met in the south and southwestern parts of the country.

For the purposes of the geodynamic analysis based on seismological data some seismic zoning is needed. A variant of such zoning is presented on Fig. 4.3.3.1, where the seismic zones are outlined by countor stright lines. The ordinar number of the zones is marked with big digits from 1 to 9, moving from the west to the east and from north to the south. This zoning is proposed in Botev, (2000- Italy) and Botev et al., (2002- rezume na Balk.Conf.), but it comes from the complex analysis of several previous seismic zoning (Grigorova et al., 1980; Bonchev at al.,1982; Christoskov, 1999-lekcionni zapiski; Christoskov 2000 - knizhkata), using several principal rules.

The identification of the main seismogenic sources by correlating the seismological and capable faulting data is the first principal rule (step) of the seismic zonation here performed. The information about the qwaternary active faults presented on Fig. 4.3.3.1. comes from Zagorchev (1992), Vrabljanski and Milev (1993), Vaptzarov et al. (1995), Alexiev (1999). The second step consists in the recognition, within the structural provinces, of the main seismogenic zones with similar geologic, geophysical and seismogenic features: this is based on the structural geometry of the main provinces (Moesian platform, Balkanides, Srednogorie, Kraistid and Rhodopian massif) and the well known regional zoning cited above (Grigorova et al., 1980 e.c.t...). The final step consists in the identification of some transverse dislocation lineaments (Bonchev at al.,1982; Dachev, 1988) which are important for the further subdivision of the main seismotectonic zones into the final zones. The geophysical characteristics of the deep structure of the crust (Dachev, 1988) are used as an additional information for defining the seismogenic zones and their borders.

On the basis of the above considerations, it had been possible to divide the investigated region into nine different specific seismogenic zones (Fig. 4.3.3.1.) within which the fault plane solutions (or the stress patterns) could be groupped and analysed.

4.3.3.2. Fault plane solutions

Fault plane solutions, based mainly on records of short period instruments, for more than 190 shallow moderate or weak earthquakes in Bulgaria have been computed by several authors during the last 20 years. The limits of these collections depend on two circumstances: the Bulgarian national network of standardised seismological stations was installed only in 1980, and no large earthquakes occurred in Bulgaria since 1928.

For the purposes of the present work, all the available focal mechanisms have been collected; they come from: Georgiev (1987, 1994, 1999), Oncescu et al. (1990), Stanishkova and Slejko (1991), Sokerova and Dineva (1992), Shanov et al. (1992), Shanov and Georgiev (1995), Catalogue of Bulgarian Academy of Sciences (Solakov and Simeonova-eds.,1993), Glavcheva et al. (1996), Aleksiev and Georgiev (1996, 1997, 1999), Dimitrov et al. (1999). For events before 1980, additional information was taken from Ritsema (1974), Glavcheva (1984), Jackson and McKenzie (1988) and Van Eck and Stoyanov (1996). When more than one solution was available for the same event, the most accurate solution was considered. Main criteria for the selection were: the quality factor (later defined), the total number of polarities, and the percentage of polarities in agreement with the solution. The number of focal parameters available for the solution and the method of their determination were used as additional selection criteria. When the above cited criteria were not enough for an unconditional choice, preference was given to the data of the Catalogue of Bulgarian Academy of Sciences (1993), which can be considered the most complete, convenient and checked data set.

As final result fault plane solutions for 192 earthquakes have been collected. When some parameters were not explicitly presented in the data sources (as a rule in the recent papers), they have been calculated according to the procedure described by Christoskov (1999). The obtained focal mechanism parameters have been checked, tested and recalculated according to the Aki and Richards (1980) definitions. From this data set, after detailed additional analyses and preliminary tests, 34 not well-constrained focal mechanisms have been discarded, and the present catalogue consists of 158 fault plane solutions obtained from at least 8 reliable P-wave first motion polarities, with a few exceptions.

Table 4.3.3.1. shows the final catalogue of 158 earthquakes. The first column is the sequential number of the event. The next group of numbers represents the date: year, month, and day. The earthquake origin time (GMT) follows: hour, minutes, and seconds. Then geographic coordinates follow: latitude and longitude. After that, depth of the focus in kilometres is given followed by magnitude. The next six columns give information about the nodal planes of the focal mechanism according to Aki and Richards (1980): strike (0° - 360°), clockwise from north with the fault dipping to the right of the strike direction; dip (0° - 90°), from the horizontal plane; and rake (0° - 90°), measured within the fault plane, from the strike to the slip direction. The next six columns show strike and dip of the P (maximum compression), T (maximum tension), and B (null) axes. The next column gives the quality of solution, when it is known: size and configuration of the 85% marginal confidence area for both nodal planes as well as P- and T-axes are taken as factors for assessing the quality of the solution (Ritsema, 1974; Dineva, 1983; Dineva,1993). The next columns give the number of total polarities used for the solution and that of the polarities not in agreement with the solution itself. The following column gives the weight of the solution. Quality and weight of the solutions are described in details later. The sources of initial information are specified in the last column. It is seen that most of references (69%) come from the Catalogue of BAS (1993), while the minimum (only 1.5%) refers to Dimitrov et al. (1999).

Statistics on the hypocentral parameters are briefly summarised in the following. The mean errors of the hypocentral parameters are: 1.8 km in latitude, 1.9 km in longitude, 3.1 km in depth, and 0.32 s for RMS. The average magnitude is 3.9, the average depth is 11.8 km, with 90% of the events located between 8 and 20 km, and the average number of polarities is 28. All earthquakes have magnitude larger than 3.0, with only one exception, but most of them are weak: 111 have magnitude within 3.0 and 4.0, 20 within 4.0 and 5.0, 5 within 5.0 and 6.0, and only one exceeds magnitude 6.

Most of the fault plane solutions are qualified by a quality factor. It has been derived from the 85% confidence areas of the nodal planes and stress axes. Considering that the confidence areas represent a sort of deviation from the true solution, the quality factor is given by four classes of decreasing accuracy: A, B, C, and D. Consequently, a weight is assigned to the fault plane solutions according to the number of polarities and quality factor as summarised in Table 4.3.3.2.

Table 4.3.3.2. Statistics on the fault plane solutions.

N of polarities	8 - 10			11 - 20			21 - 40			41 – 80			81 – 160		
Quality	D	C	AB	D	C	AB	D	C	AB	D	C	AB	D	C	AB
Weight	1	2	3	2	3	4	3	4	5	4	5	6	5	6	7
N of events	3	19	11	6	70	19	11	9		2	3		2	3	
All events: 158	33			95			20			5			5		

The fault plane solutions for which it was not possible to assess objectively the quality factor (26%) were included in the quality class C (Georgiev, personal communication; Simeonova, personal communication). The fault plane solutions result classified as follows: 11 in class A, 34 in class B, 104 in class C, and 9 in class D. The low number of

events in the worst D class is due to the previous exclusion of 34 events badly constrained.

Analysing this set of focal mechanisms, we come to the result that almost all solutions are dip-slip with strike-slip component. The normal component of dip-slip motions is predominant (73%) in almost all parts of Bulgaria, with the exception of the Provadia area where reverse and normal mechanisms are in balance. For normal mechanisms, the predominant direction of the T-axis is NNW-SSE with 15-25° plunge, while for the reverse mechanisms the P-axis direction is less defined around ESE-WNW with 25-45° plunge.

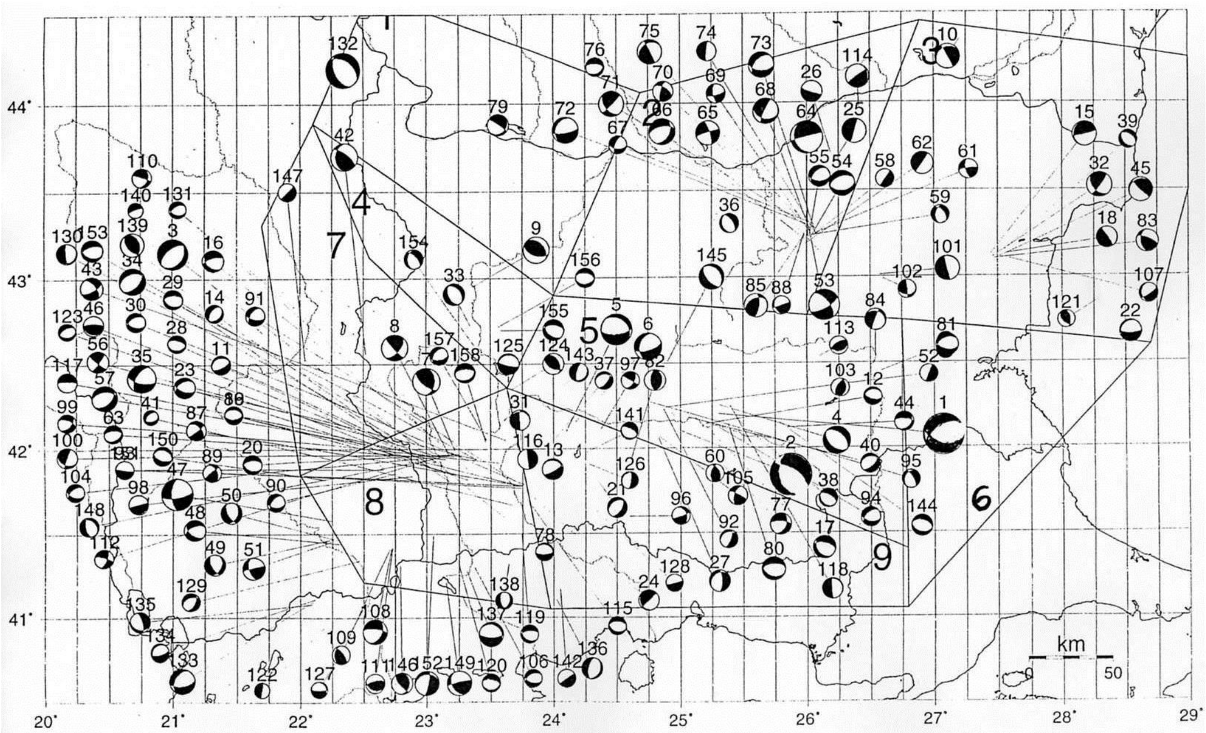

Fig. 4.3.3.2. Distribution of the focal mechanisms of the events with available fault plane solutions in the seismic zones. The size of the circles changes in correspondence with the magnitude of the events

4.3.3.3. Main seismological and stress pattern characteristics of the seismic zones

Some general features of the distribution of the stress pattern on the teritory of Bulgaria can be pointed out (Fig. 4.3.3.2.). The most evident is the large presence of normal mechanisms decreasing from SW to NE regarding each seismic zone. This phenomena could be recognized from the information presented below where the main seismological and stress pattern characteristics of the zones are presented. A few comments on the main faults, recognised as seismogenic sources, maximum observed earthquakes, main structural characteristics of each zone are given hereafter (see also Fig. 4.3.3.1.). In the geodynamic context, a special emphasis has been given to the stress pattern characteristics deduced from the focal mechanisms available for each zone (see also Figs. 4.3.3.2., 3).
As it was discused befor the investigated region has been divided into nine different zones with specific seismogenic and seismic stress pattern characteristics (Figs. 4.3.3.1.,

2, 3.). This zoning is closed to the zoning proposed by Christoskov (2005), that is why almost all names of the zones are taken from the cited work.

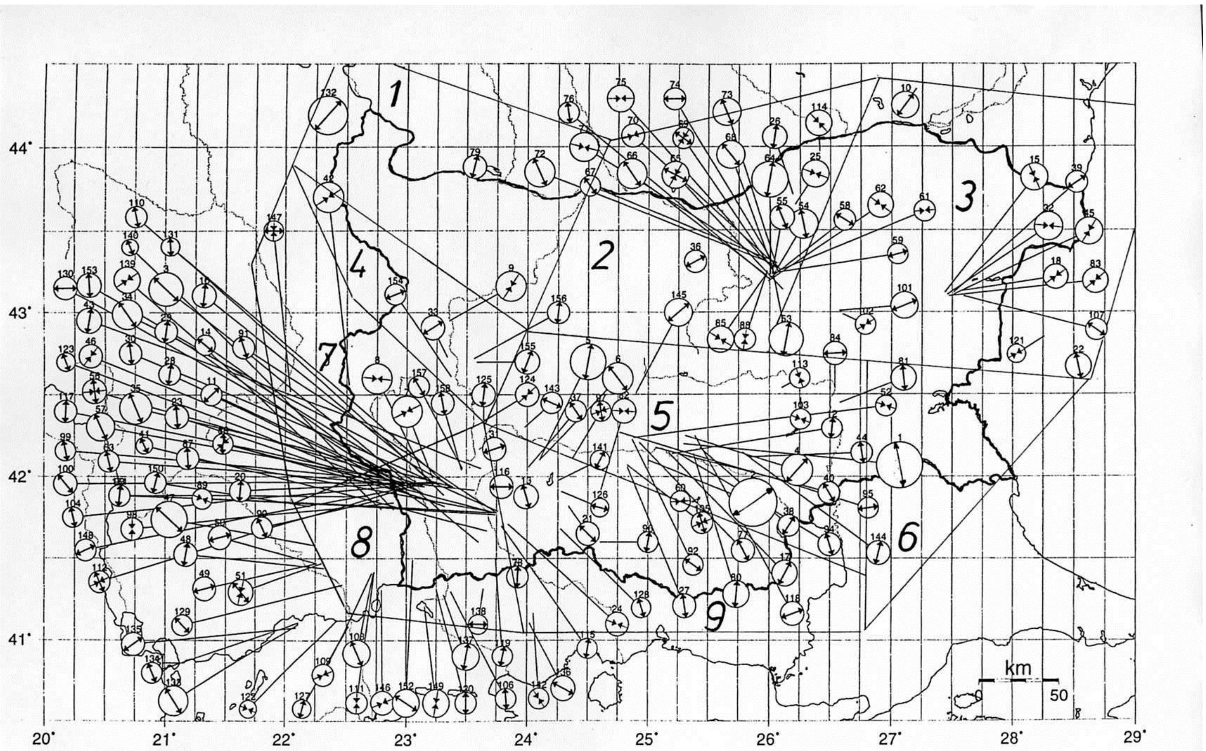

Fig. 4.3.3.3. Distribution of the P- and T- axes for the events with available fault plane solutions in the seismic zones – as an initial data base for the stress and strain invers modeling. The size of the circles changes in correspondence with the magnitude of the events

The Vidin zone (number 1 in Figs. 4.3.3.1, 2, 3) includes the western parts of the Moesian platform and the Fore-Balkan. The main morphostructure is the Lome depression (in the Moesian platform), where the thickness of the sediment cover reaches up to 10-12 km. The eastern border of the zone is associated with the position of the river Iskar valley. The lowest seismicity of Bulgaria occurs in this zone (Mmax = 4.2): it is connected to some local Fore-Balkan faults in the southeastern part of the zone (Vratza area). In fact this is the zone with the lowest level of seismicity for all over the country and only 2 seismic stress patterns are abailable.

The Gorna Orjahovitza zone (number 2 in Figs. 4.3.3.1, 2, 3) is situated in the central part of northern Bulgaria and includes the central parts of the Moesian platform, the central Fore-Balkans and the northern strip of the central Balkans. The strong seismic activity in this zone is mainly associated to the Resenski Trough, which is situated along the river Jantra, on the boundary between the Moesian platform and the Fore-Balkan. The main fault is the Hotnishki fault, which is 32 km long. The well documented maximum earthquake which occurred here is that of 1913 with magnitude 7.0, which destroyed the town of Gorna Orjahovitza. Information about another very strong event (M=7.0) during historical times is very poor. The active segment of the 25 km long Strazhica fault (N16), active in the Quaternary age, is associated with the local Strazhitza depression (northeastern extension of the Resenski Trough): it is located at the easternmost edge of the zone and is associated with the very long earthquake sequence of 1986 (maximum magnitude M=5.7).

The predominant type of the fault plane solutions (26 events – Fig. 4.3.3.2., Table 4.3.3.1.) is normal, but 10 are with reverse component of the slip vector. Three of the normal type solutions have a remarkable strike-slip component. The trend of the nodal planes in the Strazhishka area, where most of events have occurred, is not clear. The predominant trend of the T- axes is SSE - NNW. There are no subvertical axes and about 35% of T-axes are subhorizontal (within the interval 0° - 15°). The P-axes do not show remarkable peculiarities.

The Shabla zone (number 3 in Figs. 4.3.3.1, 2, 3) includes the eastern parts of the Moesian platform and the Fore-Balkan, as well as small parts of the Eastern Balkans. The main morphostructure here is the North-East Bulgarian Swell. The boundary with the Gorna Orjahovitza zone has been traced approximately along the north prolongation of the Tvardica line (Bonchev et al., 1982), which is well defined in the Balkan mountain. The eastern border of the zone is associated with the Black sea coast and the location of the Kaliakra fault, which is well defined by numerous seismic profiles performed in the Black Sea. The earthquakes are strong and rare and reach 40 km depth. The seismicity is associated mainly with the Kaliakra fault system (Shabla source) - with maximum magnitude M=7.5, and with the minor Provadia and Dobritch faults - with maximum magnitude below 5. There is some evidence for induced seismicity in the Provadia area, where a very big salt deposit mine is located.

The percentages of the reverse focal mechanisms is increased and only 6 out of 12 fault plane solutions (Fig. 4.3.3.2., Table 4.3.3.1.) are with normal slip component. There is no significant horizontal slip component in all the solutions, as well as a predominant nodal plane direction. There is no clear trend of stress axes. For the reverse mechanisms, the average plunge angles of 30° for P-axes and 50° for T-axes are observed. A tentative explanation of these reverse mechanisms is given by the activity of the Provadia and Kaliakra faults, both parallel to the sea coast, which accumulate the westward pressure of the sea plate, which is caused by the opening of the crust in the central part of the Black Sea.

The Sofia zone (number 4 in Figs. 4.3.3.1, 2, 3) is situated in the western part of the Srednogorie structural province and it comprises also the southern strip of the western Stara Planina. The main morphostructure is the Sofia depression with NE oriented prolongation. The main Quaternary active fault is the Vitosha fault, which is located on the southern margin of the Sofia graben. The seismic activity is mainly associated with the Sofia graben with 2 historical earthquakes with magnitude larger than 6.0 and diffuse moderate recent seismicity. The maximum earthquake which occurred in the past is the aproximately magnitude 6.5 of 1858. During the present century the principal events are those in 1904 (M=5.0) and 1917 (M=5.2).

There are only five fault plane solutions for the earthquakes in the Sofia zone (Fig. 4.3.3.2, Table 4.3.3.1.). Four of them are located in the Sofia depression: they are of normal type and the nodal planes are subparallel to the margins of the valley. The T-axes have sub-horizontal NNE orientation , and the P-axes are subvertical. This result is in a good agreement with the geological concepts of Late Alpine evolution of the depression with the general trend of continuous subsidence of the graben itself.

The Srednogorie zone (number 5 in Figs. 4.3.3.1, 2, 3) is located to the west of the Sofia zone, and it refers to the central parts of the Srednogorie structural province. It also includes the southern parts of the central Stara Planina and the northern slopes of the Rilo-Rhodopean massif. The main morphostructure is the Upper Thracian depression, the biggest negative structure in the Bulgarian territory. The eastern border of the zone

is associated with the submeridional oriented Tundzha river valley. The seismic activity is mainly associated with the Maritza and Tundzha fault systems. The last strong earthquakes in the Bulgarian territory (in 1928), with magnitudes 6.8 and 7.0, can be associated with the first fault system: these events caused a total length of more than 120 km ruptures on the surface, with the longest segment of 75 km. The largest observed event is the magnitude aproximetly 7.4 of 1750. The Quaternary activity has developed along the fault system of the Tundzha river (Jambol source) in the eastern part of the Srednogorie zone and shows E-W oriented moderate seismicity. The strongest event is the magnitude 5.9 of 1909. Another seismic source in this zone is the Edirne area, which is located near the border region in the Turkish territory. The main quakes are those of 1509 with magnitude 6.8 and that of 1766 with magnitude 7.2, both poorly documented. This region displays presently very weak seismicity, with less than 20 small events during the 20th century, with concentration of the epicentres east of the town of Edirne in Turkey.

The Srednogorie zone includes 24 fault plane solutions (Fig. 4.3.3.2, Table 4.3.3.1), most of which with normal slip component (around 75%). The orientation of the nodal planes does not manifest a clear trend, although a slight tendency in the E-W direction can be suggested. The dip of the nodal planes is randomly distributed in the whole range from 30° to 90°. These fault plane peculiarities are consistent with the tectonic structure of this zone, which can be regarded as a system of many superimposed basin depressions with a predominant E-W orientation. In fact, most of earthquakes are grouped along the active margins of the asymmetrical Maritza and Jambol depressions. The majority (65%) of the plunge angles of T-axes are within the interval 0° - 23°, while the P-axes are subvertical. Only 5 events have subhorizontal P-axis, without a clear direction of grouping.

The Burgas zone (number 6 in Figs. 4.3.3.1, 2, 3) is located in the eastern part of the Srednogorie structural province and includes the southern part of the Stara Planina mountain and the Strandzha mountain to the south. The main morphostructure is the Burgas depression, which is marked by an evident positive gravity anomaly. The seismicity is very poor without information for historical or recent earthquakes with magnitude larger than 5.0.

The Kjustendil zone (number 7 in Figs. 4.3.3.1, 2, 3.) is located in the central part of western Bulgaria and comprises the northern part of the Struma(Kraiste) structural province. To the NW the zone extends in the Serbian territory, and to the NE it is limited by the Sofia zone. The main morphostructure is the Kraiste dome formation. This is the smallest zone in the Bulgarian territory. The strongest known quake occurred in 1641 with magnitude aproximately 7 and is associated with the Kjustendil fault, which bounds the Kraiste positive morphostructure to the south. The present seismicity is scarce with the central and northern parts more active. The strongest events here occurred at the beginning of the 20th century: in 1904 with M=6.5 (Trun seismic source), in 1907 with M=4.7, and in 1911 with M=5.0. Only two focal mechanisms are available.

The Struma zone (number 8 in Figs. 4.3.3.1, 2, 3) comprises the southern part of the Struma structural province, as well as the western part of the Rhodope structural province (Rila and Pirin horsts) and the eastern part of the Serbo-Macedonian massif (Belasitza and Ograzhden horsts). The seismic activity is mainly associated with the Kroupnik source, where more than 30% of the present day Bulgarian earthquakes are localised. One of the strongest crustal quake for all Europe occurred here: it is the

magnitude 7.8 event of 1904. The diffuse epicentres to the NNE of the Kroupnik source belong to the Rila source: they are mainly historical events macroseismically located on the basis of scarce data. Another seismic area is the Belasitza source which is situated in the southwestern corner of the zone (Mmax=6.7, in the Macedonian territory). Both the Kroupnik and Belasitza fault systems intersect normally the Struma lineament, which is not recognised as an Holocene fault. The eastern border of the zone, which was drawn on the western slopes of the Rhodopean mountain, comprises the Mesta fault, which shows relevant seismicity and hystoricaly experienced the maximum magnitude up to 7 (on Greece territory).

Fifty-seven fault plane solutions are available for this zone (Fig. 4.3.3.2, Table 4.3.3.1.): more than 80% are with normal dip-slip component and the predominant orientation of the nodal planes is 70° to 90°. This prevailing plane direction coincidences with the orientation of the Kroupnik and Belasitza. The sector 30° to 60° collects the majority (60%) of the plunge values, and less than 10% are sub-horizontal (plunge between 0° and 30°). The most relevant evidence for this zone is the almost horizontal orientation of the T-axes in the NNW - SSE direction. There is no clear predominant trend of the P-axes, but mainly for the cases of subhorizontal axes, the ENE - WSW direction dominates. In many of these cases a strike-slip mechanism of faulting (with relevant normal dip component) could be recognized. The plunge angle of the P-axes is larger in comparison with that of T - axes.

The Rhodopean zone (number 9 in Figs. 4.3.3.1, 2, 3) is situated between Struma and Maritza zones and comprises almost all the area of the Rhodope mountain and a little part of the Rila mountain. The seismic activity is mainly associated with the Chepino, Dospat, Devin and Ardino depression fault systems. Further small seismic faults represent the boundaries between uplifted local dome structures within the Rhodope mountain. The maximum observed earthquake in the 20th century is the event of 1905 with magnitude 5.4. There is no information for larger events before 1900 in the Bulgarian territory of this zone but the strong historical earthquakes of 1829 (magnitudes 7.2 and 6.9) in the Greek territory can be assign to this zone. These quakes occurred at the southern margin of the Rhodope mountain and are associated with the activity of the Middle Mesta fault.

The epicentres of the 20 earthquakes with fault plane solution (Fig. 4.3.3.7, Table 4.3.3.1.) are diffused in the western and central Rhodopes without any clusterization. The predominant slip component is normal, without a predominant orientation and dip of the nodal planes. The T-axes have a main (50%) N-S direction and a subhorizontal plunge, while a tendency of the P-axes around the vertical orientation is observed (50% of the plunge angles are bigger than 50°). However more than 30% of the events manifest strike-slip mechanism (with relevant normal dip component).

4.3.3.4. Stress and strain modeling from the focal mechanism data

- **Stress tensor inversion**

The directions of the principal tectonic stresses 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 $\sigma_1, \sigma_2, \sigma_3$ **(maximum, intermediate, minimum stress, respectively) and the parameter** $R = \frac{\sigma_2 - \sigma_1}{\sigma_3 - \sigma_1}$**, as measure of relative stress magnitudes. The main assumption of the method is that the stress tensor is the same for**

a given population of focal mechanisms; *i.e.* even if different types of focal mechanisms are observed in a given space, the tectonic stress tensor is uniform. This condition is fully satisfied if the slip direction on a plane of any focal mechanism is aligned with the direction of the resolved shear stress tensor.

The method consists in determining the stress tensor which minimizes the differences betweeen the slip direction, computed from the stress tensor, and the observed slip on each plane of the focal mechanisms. The difference between computed slip and observed slip is evaluated through an angular rotation (misfit) about an arbitrary axis. So the misfit is the minimum rotation which brings the slip of one of the two nodal planes to match the resolved shear stress tensor. It is calculated through a grid search, varying sistematically the orientation of the principal stresses and the parameter R. The stress tensor corresponding to the minimum average rotation angle is assumed to be the best stress tensor for that population of focal mechanisms.

Assuming that all the misfits follow a Gaussian distribution around the minimum misfit (best stress model), Gephart and Forsyth (1984) found that the L1 norm is an appropriate measure of the misfit because it limits the effect of poorly fitting data (residuals with high misfits will be eliminated). The quality of the inversion is tested through the evaluation of the 95% confidence limits of best-fitting model according to the expression (Gephart and Forsyth, 1984):

(1) $$\alpha = \left(\frac{1.96(\pi/2-1)^{1/2} n^{1/2} + n}{n-k}\right)\alpha_{\min},$$

where $\alpha_{\min}$ is the minimum average rotation angle, n is the number of focal mechanisms, and k is the number of variables of the model, in this case k=4.

The test consists in determining the stress models with average rotation angle α statistically acceptable with respect to the minimum misfit. The stress tensor is well resolved when the areas defined on a stereonet by the 95% confidence limits of σ_1 and σ_3 orientations do not overlap. According to Gephart and Forsyth (1984) the actual failure plane of each focal mechanism has a smaller misfit than the auxiliary plane. They considered a good fitting of data when the real nodal plane has an angular rotation (α_1) of less than 20°, and the differences in angular rotation between the auxiliary plane (α_2) and the actual fault plane are greater than 10°.

The final results of stress tensor inversion (after some testing and redusing of the initial data) are summarized in Table 4.3.3.3. (see below).

- **Strain tensor inversion**

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

(2) $$\varepsilon_{ij} = \frac{1}{2\mu V}\sum_k M_{ij}^k$$

where μ : rigidity modulus ($3 \cdot 10^{10}$ Pa), V :crustal volume (the thickness of the crust by the area affected by the earthquakes), M_{ij}^{k} : moment tensor of the kth earthquake. The moment tensor is related to the scalar seismic moment by:

(3) $$M_{ij}^{k} = M_{0}^{k}(u_{i}^{k} n_{j}^{k} + u_{j}^{k} n_{i}^{k})$$

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 M with the relation (Riznichenko, 1985):

(4) $$\text{Log } M_0 = 1.6M + 8.4 \pm 0.5$$

The computed orientations of the principal axes of the strain tensor are shown in Table 4.3.3.4.

Table 4.3.3.3. Orientations of maximum (σ_1), intermediate (σ_2) and minimum (σ_3) stress axes of the best inverted stress tensors for each zone. The corresponding average misfit and the R values are also shown. All values, except R which is dimensionless, are expressed in degrees. N is the number of focal mechanisms used in the inversion.

Zone	N.	Misfit	σ_1		σ_2		σ_3		R
			Azimuth	Plunge	Azimuth	Plunge	Azimuth	Plunge	
Z2	22	5.2	84	67	244	22	337	7	0.3
Z3	12	7.8	103	79	257	10	348	5	0.8
Z5	20	5.0	45	75	213	15	304	3	0.8
Z8	49	7.1	79	37	270	52	173	5	0.5
Z9	18	7.3	264	6	12	72	172	17	0.7

Table 4.3.3.4. Orientations of principal strain axes. All values, are expressed in degrees. N. is the number of focal mechanisms.

ZONE	N.	ε_1		ε_2		ε_3	
		Azimuth	Plunge	Azimuth	Plunge	Azimuth	Plunge
Z2	22	133	43	260	33	12	30
Z3	12	113	34	220	23	337	47
Z5	20	54	16	314	31	167	55
Z8	49	134	80	235	2	325	10
Z9	18	324	65	92	16	188	19

- ## Results and discussion

The final results of stress and strain tensor inversion (presented in Tabls. 4.3.3.3, 4.) are briefly described below for each zone. In the tables the seismic zones are presented by their numbers (Z1 - Z9). There are no enough focal mechanisms data for stress tensor inversion in the zones Z1, Z4, Z6 and Z7 and they are not included in the tables.The most evident common characteristic of the stress tensors regarding all seismic zones (Table 4.3.3.3.) is the domination of a normal stress regime.

The Gorna Orjahovitza zone (Z2) is characterized by a normal stress regime, with maximum compressive stress oriented E-W. A normal stress regime affects also the Shabla zone (Z3) and the Maritza zone (Z5); the maximum compressive stress is oriented ESE-WNW in the Shabla zone while it is oriented NE-SW in the Maritza zone. The maximum compressive stress for the previous three zones is subvertical, while the minimum stress is almost horizontal and oriented NNW-SSE for Z2 and Z3 and NW-SE for Z5. A strike-slip stress regime, with relevant normal component, affects the Struma zone (Z8). The maximum compressive stress is oriented ENE-WSW, with 37° plunge angle, while the minimum stress is almost horizontal and N-S oriented. The Rhodopean zone (Z9) is characterized by a strike-slip regime of stress, with maximum compressive stress oriented E-W.

The values of the R parameter indicate that the magnitudes of the principal stresses are variable. The resulted stress tensor of the Shabla zone could be considered as an approximated evaluation of the acting stress tensor, considering the low number (12) of available events. The stress tensors are characterized by some degree of heterogeneity (the low misfit in Z2 and Z5 is not supported by an adequate number of events), the most heterogeneous stress field is acting in the Z8 and Z9 zones. The inverted stress tensors for each zone are in agreement with the tectonic model. The stress tensors of Z2 and Z3 are similar. A similarity is found also for the stress tensor of Z8 and Z9.

It should be pointed out that the stress tensor obtained from the inversion of the focal mechanisms is computed by minimizing the differences between observed and resolved slip direction, while the strain tensors for each zone (Table 4.3.3.4.) are eveluated 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 tectonic field. The comparison between the obtained stress and strain tensors evidences that the direction of the principal axes of stress and the principal axes of strain are not the same, for almost all considered zones. These differences suggest that the stress field is heterogeneous because the crust is not uniform in strength (Wyss et al., 1992). In a material relatively uniform in strength, the principal axes of stress and strain are the same, or nearly the same. But if there are planes of low shear strength or zone of weakness, like preexisting faults, the orientations of the principal axes of stress and strain may differ substantially. Small shear stress resolved on the weakness plane, even if it is not favourably oriented for fracturing with respect to the stress tensor, may induce slip on that plane. This phenomenon could be relevant in rock volumes affected by listric faulting, with inherited faults from previous tectonic phases.

4.3.3.5.Tectonic interpretation of the focal mechanisms and stress modeling

- **Gedynamic evolution and state of the investigated region**

The main result from the focal mechanism and the stress tensors analysis is the prevailing of a normal or extensional stress regime in all seismic zones. It is well known that the present subduction along the Hellenic trench causes in the Aegean region prevailing extensional movements, but the study Central Balkan's area is relatively far away from the typical back-arc domain at present.

n the same time there are many evidences about the paleosubductions beneath the Central Balkans (Boccaletti et al., (1974), Papazachos (1976), Botev (1985), Babushka et al. (1986), Spakman (1986), Botev et al. (1987), Shanov et al. (1987), Shanov (1987), Dabovski et al. (1989), Riazkov and Shanov (1990), Shanov et al. (1992), Kondopoulou et al. (1996), Papazachos and Nolet (1997), Shanov(1998)).All these pieces evidence support at least two paleosubduction hypotheses: an older one which is oriented from S and SW to N and NE in the Vardar-Izmir ophiolitic arc like zone, and an yonger paleosubduction oriented from WSW to ENE in the Ionian and Adriatic basins. The paleosubductions caused the formation of big crustal and litospheric "roots" in the Macedono-Rhodopian massif area. The crustal thickening and low density (melted) mass in the crust and uppermost mantle (caused by the subductions) induced isostatically compensated uplifting (Zagorchev, 1992) with mantle diapirs effects and the consequent superficial extensional collapse of the Late Alpine Macedono-Rhodopian area and its surroundings (Fig. 4.3.3.4.). The existence of the recent tectonic activity in and around the Macedono-Rhodopian area is related to the recent uplift of the region, characterised by the thickest crust in the Central Balkan region. The model of Dewey (1988) for the post-collisional extensional collapse of orogens could be applied to explain the existence of the contemporary sub-horizontal extensional stresses. This extensional collapse of the most thickened area (orogens) had leaded to differentiation into first order domes (the bigger domes of Pelagonian, Serbo-Macedonian, Rhodopian, Sredna Gora). Afterwards, the permanent isostatic uplift causes differential neotectonic movement along the domes forming fault zones like the Vardar, Struma, Maritza, Middle-Mesta fault zones (Fig. 4.3.3.4.) and building up the second order domes (Zagorchev, 1992; 1996). The results of these tectonic movements is the formation of a complex mosaic pattern of horst and graben structures bounded by many transversal faults. An additional reason for the existence of subhorizontal extensional tectonic patterns in the area is suggested by Shanov (1998), who hypnotised thermal dome formation on the basis of several thermal water sources and high temperature patterns, observed in and around Rhodopes.

According to Papadopoulos et al. (1986) and Kondopoulou et al. (1996) there is evidence of the increasing influence of the Anatolian plate over the Balkans after Late Miocene. The influence of the westward movement of the Anatolian plate consists in the opening of the marginal eastern parts of the Srednogorie zone (with consequent clock-wise rotation of the Strandzha and Sakar blocks inside the same area) and of the Rhodopes (Fig. 4.3.3.4.). According to Tzankov et al. (1998), the Late Miocene clock-wise rotation of the western part of the Rhodopian massif, connected with mantle diapir movements in proximity of the Rhodope-Srednogorie border originating from the Late Oligocene paleosubduction, caused extension and "opening" of the crust along the boundary between Rhodopian and Sredna Gora swells. A further consequence was the formation of the Upper Tracian depression. These movements have been continuing up to present time.

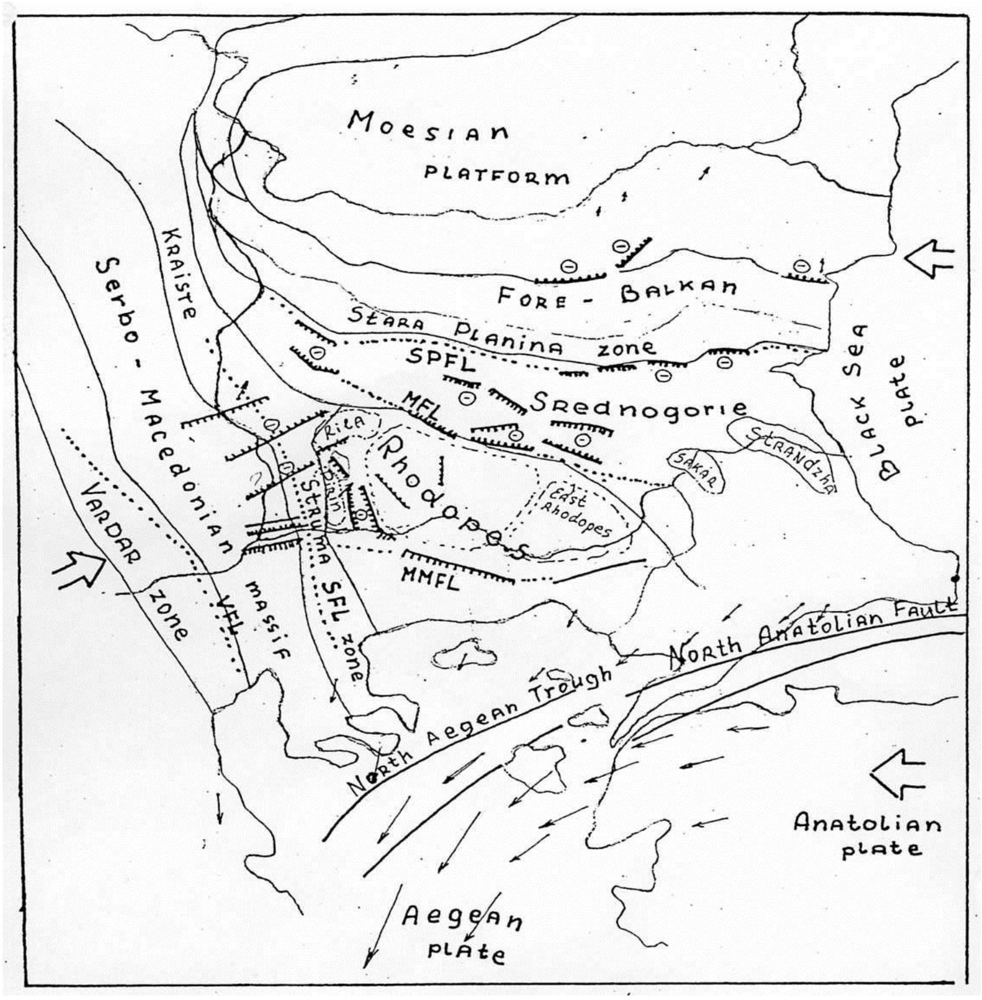

Fig. 4.3.3.4. Regional geodynamic model of the Bulgarian territory and the adjacent lands as derived from the present state of the geodinamics of the region. The symbols used are explained in the text

The results from the interpretation of GPS-measurements of the present state of the crustal deformation in the Eastern Mediterranean (Kotzev et al., 1998, Papazachos et al., 1998) indicate that the biggest movements (around 30-40 mm/y) are observed towards SSW in the central and southern parts of the Aegean plate (Fig. 4.3.3.4.). At the same time, a few measurements in northern Greece reveal much more smaller movements in the south direction (around 5-6 mm/y). This big difference determines the existence of an extensional province in Northern Greece. According to Kotzev et al. (1998), the SW zone of Bulgaria is characterised by NE movements with velocity around 3-4 mm/y. According to the same outhers some places in Northern Bulgaria are characterised by N-NE oriented movements with almost the same velocity. The different orientations of the present crustal movements in northern Greece, western and northern Bulgaria (marked by arrows in Fig. 4.3.3.4.) can explain the existence of predominant extensional subhorizontal stresses in central Balkans. In this picture, the Middle Mesta Fault Lineament (MMFL) is the margin between the north Aegean and the central Balkan region. The extensional regime in the north Aegean area and the influence of the Anatolian plate have caused one additional opening of the southeastern part of the Srednogorie structural province. The NNE-ward recent crustal movements (scarcely documented) in north Bulgaria (small arrows in Fig. 4.3.3.4.) can be associated

to the general NE-ward pushing of the Adriatic plate (marked by a large arrow in the Vardar area, Fig. 4.3.3.4.) and the westward movements of the Anatolian plate and north Black sea area (large arrows in Fig. 4.3.3.4.).

- ## Interpratation of the focal mechanisms and stress modeling results

In Bulgaria, the focal mechanisms and stress tensor inversion show that the present acting state of stress is strictly connected to the complex geodynamics of the Central Balkan area. The obtained prevailing normal extensional stresses from the seismological data could be explain by the above discussed two main regional processes which are responsible for the present extensional environment in the Central Balkan tectonic space. The first is the post-collisional extensional collapse of orogens under the influence of the paleosubduction in the Ionian sea from WSW towards ENE. The second process is the complex influence of the existing SW horizontal movements along the North Anatolia fault in the Aegean Sea , which causes the extension of the eastern parts of the Srednogorie zone and formation of an extensional province towards N from the North Aegean Trough (Fig. 4.3.3.4.). The predominant strike-slip stress field (Table. 4.3.3.3.) affecting Z8(Struma zone) and Z9(Rhodopean zone) could be accepted as a consequence of the motions induced by the strong subhorizontal movements along the North Aegean Trough, which are transmitted to the MMFL (see the previous chapter and Fig. 4.3.3.4.).

The significant number of vertical movements from the focal mechanisms data is supported by geological and geodetic data in Z2 (Gorna Orjahovitza zone) and Z3 (Shabla zone), where the stress inversion shows a normal stress regime (Table 4.3.3.3.). The maximum compressive stress oriented aproximetely E-W for the Z3 could be associated with the remnent effects of the pushing of the west Black Sea basin (Fig. 4.3.3.4), result of the longtime lasting riftogenesis in the central part of the north Black Sea.

The normal stress regime acting in Z5 (Srednogorie zone) results also from geological and tectonic evidence of rifting processes and agrees with the interpretation of the present day extensional tectonics. This result is in a good agreement with the geological concepts of Late Alpine evolution of the depressions with the general trend of continuous subsidence of the grabens itself (Vaptzarov et al., 1995, Alexiev, 1999). The main morphostructures in the Srednogorie structural province are bounded by active neotectonic and Quaternary faults (Fig. 4.3.3.4.). The differential vertical movements give rise to the formation of differently subsided superimposed depressions filled with Neogene-Quaternary sediments with a thickness varying between 500 and 1500 meters (Milev, Vrabljanski, 1988; Vaptcarov, Aleksiev, 1995). According to Vaptzarov et al.(1995) and Alexiev (1999), all used geomorphological criteria for recognising the Quaternary active faults in these areas evidence a predominant listric faulting. This listric faulting, together with the basins formation, allows us to accept the presence of a subhorizontal extension of the upper part of the crust. According to Alexiev (1999), Tzankov and Nikolov (1998), Tzankov et al. (1998), the presence of the listric faulting is the most esential feature of almost all neotectonic and quaternery depresions not only for the Srednogorie zone. The misfiting between the principal axes of the obtained stress and strain tensors for almost all zones could be explain with the dominated quaternary listric faulting in the zones with many inhereted faults from previous tectonic activities.

4.3.3.6. References

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