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Active faults in the Plovdiv Depression and their long-term slip rate

Alexander Radulov

Geological Institute, Bulgarian Academy of Sciences, 24 Acad G. Bonchev Str., 1113 Sofia; E-mail: radulov@geology.bas.bg

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Ал. Радулов — Активные разломы в Пловдивской депрессии и скорость долгосрочных движений по ним. На территории Пловдивской депрессии выявлены геометрические сегменты разломов. Предложены сценарии возможного сеисмогенного образования некоторых сегментов и вычислена скорость долгосрочного движения по ним. Выявление разломных сегментов, способных в будущем осуществить разрыв земной поверхности, основано на предположении, что в прошлом по этим сегментам уже происходили разрывы и что запись соответствующих событий сохранилась в морфологических формах и в четвертичных отложениях. Длина предполагаемых сеисмогенных разломных сегментов – между 5 и 76 km. Их ожидаемые магнитуды (между 5.8 и 7.3) вычислены по соотношениям между длиной поверхностного разрыва и магнитудой. Вычислены также скорость продолжительных движений по активным разломам в Пловдивской депресси за последние 820 лет (0.024–0.149 mm в год) и интервалы между повторяющимися крупными событиями (2000 лет – >10 000 лет).

Abstract. Geometric fault segments have been localized in the Plovdiv Depression, scenarios for probable seismogenic fault segments have been proposed, and long-term slip rates have been calculated. Defining of fault segments capable to produce surface rupturing in the future is based on the assumption that these faults were ruptured in the past and left records in the landforms and the Quaternary sediments. The length of the assumed seismogenic fault segments varies between 5 km and 76 km. Expected magnitudes of these seismogenic fault segments have been calculated by the relationships between surface rupture length and magnitude. Expected magnitudes vary between 5.8 and 7.3. The long-term slip rate of the active faults in the Plovdiv Depression is 0.024–0.149 mm/yr for the last 820 Ka. The recurrence intervals of the large events have been estimated to be between 2000 years and more than 10 000 years.

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Key words: active faults, fault segmentation, seismic hazard assessment, Plovdiv Depression, Upper Thracian Depression.

Introduction

The Plovdiv Depression is one of the most seismically active regions in Bulgaria. Two surface-rupturing events occurred in the region in 20th century. Although many seismotectonic studies were performed in the last decades, the localities of the faults capable to produce surface-rupturing events in the future, and fault characteristics necessary for probabilistic seismic hazard assessment, are very poorly known or unknown. The available data are extremely insufficient. The great advance in the understanding of earthquake phenomena in the world has improved the methods for active fault survey. Active faults are considered to be faults that can generate large earthquakes in the future. Such earthquakes are large enough to produce surface or near-surface rupturing. The magnitude of such events is M ≥ 5.5. Events on any individual fault recur. The records of the past events serve for identification of the active faults and their characteristics.

The Plovdiv Depression is a Neogene basin in the western part of the Upper Thracian Depression between the Rhodope Mountain and the Stredna Gora Mountain (Fig. 1). The mountains limit the Plovdiv Depression to the south, to the north and to the northwest, and the Chirpan threshold to the east (Fig. 1). The exact position of the limit between the Plovdiv Depression and the eastward situated Zagora Depression is controversial because the Pliocene-Holocene infillings of the Plovdiv Depression spread continuously in the Zagora Depression.

Faults striking 90–120° at distance from 3 to 13 km from each other affect the Pre-Paleogene basement in the western and central part of the Upper Thracian Depression (Крыстев et al., 1992). Another set of oblique NNE-SSW striking faults causes structural segmentation of the 90–120° striking faults of 2.5–53 km long segments. Generally N-S to NNE-SSW neotectonic (Zagorchev, 1992; Shanov, 2000) and present-day (Van Eck, Stoyanov, 1996; Kotzev et al., 2004) extension presumes that the 90–120° striking fault segments predominantly accommodate the present-day strain, and normal and oblique slip occurs on them.

Activity of a fault in the Plovdiv Depression could be: 1) inferred from the geological information about the Neogene Ahmatovo Formation (Коюмджиева, Драгоманов, 1979) and the covering Quaternary sediments; 2) proved from evidence for surface rupturing in Late Pleistocene and Holocene deposits and landforms; and 3) proved by a directly observed surface rupture. The approach choice depends on the state of art of the study on the active faults in the region and the aim of the investigation. Data about observed surface ruptures in the Plovdiv Depression are very limited. The only observed surface ruptures relate to the April 14, 1928 M_S 6.8 Chirpan earthquake and the April 18, 1928 M_S 7.1 Popovitsa (Plovdiv) earthquake. Even the main contemporary sources (Бончев, Бакалов, 1928; Direction for Support and Reconstruction of the Area Damaged by the 1928 Earthquakes (DIPOZE), 1931) show contradictions and do not localize the exact propagation of the 1928 co-seismic ruptures.

The lack of historical data for surface ruptures in the Plovdiv Depression limits the active fault survey to be performed by geological and paleoseismological methods. In the present study, defining of fault segments capable to produce surface rupturing in the future is based on the assumption that these faults were ruptured in the past and left records in the landforms and the Quaternary sediments.

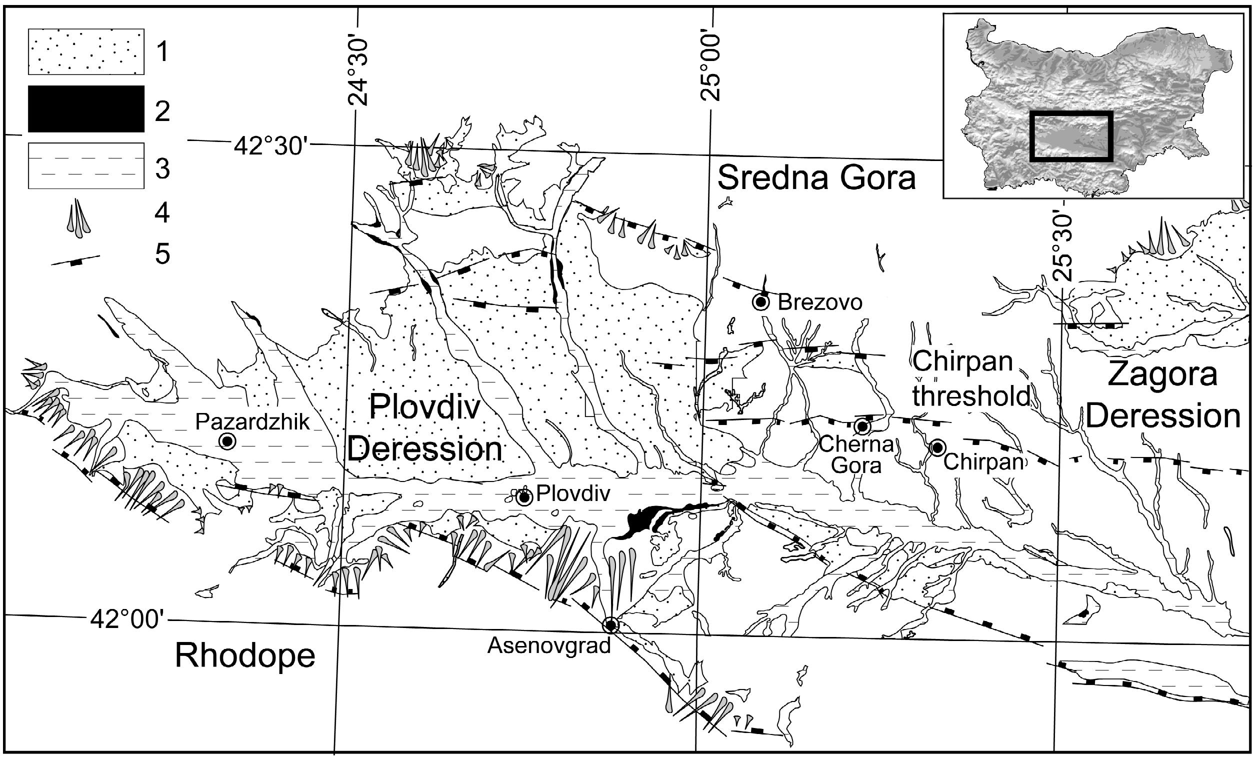

Fig. 1. Quaternary sediments (from Geological map of Bulgaria 1:100 000 scale) and fault scarps in the Plovdiv Depression. 1 – Quaternary mainly alluvial sediment; 2 – Late Pleistocene river terrace in fault footwalls; 3 – Holocene floodplain; 4 – alluvial fan; 5 – fault scarp. Projection is UTM Zone 35, Northern Hemisphere

Recognizing active faults

Stratigraphic interval

A separate fault segment among all known basement faults should affect young strata and young landforms to be defined as active or potentially active fault. One can understand “young strata” to be the entire Neogene, or the Pleistocene, or the Holocene. The stratigraphic interval of the Ahmatovo Formation infilling the Plovdiv Depression is very large. It varies from the uppermost Miocene to the Lower Pleistocene (Коюмджиева, Драгоманов, 1979; Ненов, 1987). Faults affecting the Ahmatovo Formation will present faulting for a too wide time span since the last 7 Ma. Many of these faults cannot be active in recent time. On the other hand, poorly known stratigraphy of the Ahmatovo Formation at different places does not provide the necessary information about the age of the faults and their slip rate. So called “Quaternary” in the Plovdiv Depression is easily recognizable, and the limit between the Ahmatovo Formation and the “Quaternary” has been accurately fixed and mapped (Fig. 1). However, there is no special study on the lower limit of the “Quaternary” in the Upper Thracian Depression. The lower limit could be inferred from the available data about the stratigraphy of the Ahmatovo Formation and by comparison with the Quaternary in the Northern Bulgaria. The upper third of the Ahmatovo Formation belongs to the Lower Pleistocene (Ненов, 1987). By analogy with the well studied Lower Pleistocene in Northern Bulgaria (Евлогиев, 2000), the upper third of the Ahmatovo Formation should correspond to the alluvial sediments from Northern Bulgaria deposited before the marine isotopic stage 20 (MIS 20), and the “Quaternary” from the Upper Thracian Depression should correspond to the Pleistocene-Holocene loess-paleosol sequence in the Northern Bulgaria. It is very possible that the general climatic change during MIS 20 caused remarkable change in the continental sedimentation in the Plovdiv Depression.

The age of the faults that affect the “Quaternary” or control the geometry of its basins is hundred thousands years; and these faults are considered to be active at the initial state of the active fault survey in the Plovdiv Depression.

Faults inferred from geomorphology and Quaternary deposits

Only a fault scarp and related colluvium mark the fault trace on the surface. The resolution of the used digital elevation model SRTM3 of 80–90 m allows compound fault scarps formed in a number of seismic cycles to be traced (Fig. 1). Some other geomorphic evidence, e.g. linear features in footwall and stream inflection, can help mapping the fault trace. Other strong evidence for surface faulting came from alluvial rivers crossing a fault (Schumm et al., 2002). Change in alluvial sedimentation, floodplain’s width and slope, meandering indexes in fault walls steady prove Holocene and Late Pleistocene faulting.

The scarps in the depression are between 5–8 m and 50–60 m high. Small alluvial fans cover the slopes. Transverse alluvial rivers crossing the fault scarps show typical features for fault activity. Their meandering indexes increase significantly few hundred meters from the faults in the footwalls. Floodplains widen in the hanging walls. Late Pleistocene alluvial terraces are uplifted in the footwalls (Fig. 1). Most of the Quaternary depocenters in the depression are very close to the traced fault scarps (Fig. 2). The Quaternary deposits reach their maximum thickness in the hanging walls just close to the fault planes. The thickness varies from more than 120 m to few tens of meters. The positions of the depocenters indicate the places of maximum slip of the related faults since the MIS 20.

The surface expression of the faults along the northern border of the Rhodope Mountain and southern border of the Sterdna Gora Mountain differs from the fault inside the Plovdiv Depression. Faults run along the mountain fronts. Fault segments cut mainly large Quaternary alluvial fans and mountain debris. Hanging wall basins are smaller.

Fault segmentation

Fault segmentation in the Plovdiv Depression is mainly based on the size of the step-overs between overlapping tips of two neighboring fault segments. The shortest continuous fault scarps separated by rivers, streams, or small structural step-overs of few hundred meters can obviously be combined in larger geometric fault segments. Step-overs up to 2–3 km separate two geometric fault segments that are able to react as an individual seismogenic fault. The relationship between fault segments separated by larger step-overs requires careful study for each case.

Relay ramp structures connect the geometric fault segments *a1*, *a2*, *a3* and *a4* (Fig. 2). The distance between the overlapping fault tips vary between 700 m and 2500 m, which is quite small distance allowing the geometric fault segments to be connected in a single fault. Detailed study on the relay ramp between segments *a2* and *a3*, being the place of the largest distance between faults tips (2500 m), shows that both segments ruptured together in the last seismic events (Radulov, Yaneva, 2006). The total length of the seismogenic fault *a1-a2-a3-a4* is 67 km. According to the relationship between the surface rupture length and the moment magnitude for normal faults (Wells, Coppersmith, 1994), the fault *a1-a2-a3-a4* can produce an earthquake of M_W 7.3 (Table 1). However, the fault partially ruptured in the 1928 M_S 6.8 Chirpan earthquake. Contemporary descriptions of the fault rupture (Бончев, Бакалов, 1928; DIPOZE, 1931) report surface rupturing along the fault segments *a2* and *a3* with certainty. Most probably, the fault segments *a1* and *a4* have partially rup-

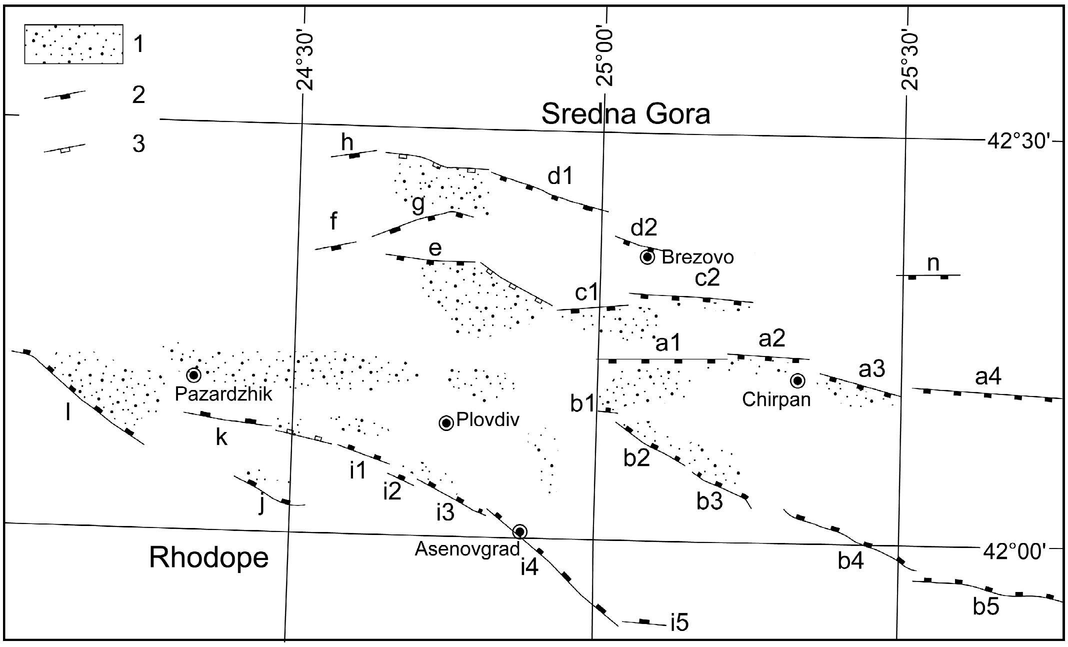

Fig. 2. Geometric fault segments in the Plovdiv Depression. Geometric fault segments labeled by letters or letters and numbers. 1 – Quaternary depocentre; 2 – geometric fault segment based on fault scarps; 3 – fault segment assumed from Quaternary hanging wall basin. Projection is UTM Zone 35, Northern Hemisphere

tured. Paleoseismologic data from a trench near the village of Cherna Gora on the fault segment *a2* show that the fault has undergone two larger than the 1928 earthquake events before the penultimate event (Vanneste et al., 2006). The surface offsets of these two events are 0.55–0.70 m and even more, which is consistent with surface rupture along the entire fault *a1-a2-a3-a4*. Obviously, the fault has experienced surface ruptures of different size (length and offset).

The geometric fault segments *b2* and *b1* coincide with the surface rupture of the 1928 M_S 7.1 Popovitsa earthquake. The 1928 surface rupture has propagated to the west (DIPOZE, 1931) or northwest (Бончев, Бакалов, 1928) in the floodplain, and the fault scarp has entirely been eroded. The ESE tip of the 1928 rupture (Бончев, Бакалов, 1928) coincides with the ESE tip of the geometric fault *b2*. The fault segment *b3* has its own well-developed hanging wall basin (Fig. 2), and could represent an individual active fault segment. The geometric segments *b4* and *b5* could also be individual seismogenic segments or could compose larger seismogenic segments: *b3-b4*, *b4-b5*, or *b3-b4-b5* because very short distances separate the overlapping tips of the geometric segments. Although the geometric segment *b3* was not ruptured in 1928, its cohesion to the geometric segment *b2* in a future event seems possible.

Geometric fault segments *c1* and *c2* could form a seismogenic fault segment *c1-c2*. A possibility for continuation of the fault segment *c1-c2* through the floodplain to the west exists. The Quaternary depocenter between the eastern tip of the geometric fault segment *e* and the western tip of the fault segment *c1* (Fig. 2) should correspond to a hanging wall basin. The maximum thickness of the Quaternary in the Plovdiv Depression was found in this basin – 122 m (Драгоманов et al., 1989). In this case, a fault compound by segments *e*, *c1*, and *c2* could be another seismogenic fault segment. Relationship between geometric segments *g*, *f* and *e* allows two interpretations in term of connecting them in seismogenic fault segments. First, geometric segment *f* connects with geometric segment *e*; and second, geometric segments *f* and *g* form an individual seismogenic fault.

The distance between the tips of the geometric segments *d1* and *d2* in the overlapping area is about 3000 m (Fig. 2). They can be individual seismogenic faults or to compose one seismogenic fault. The fault segment *d2* continues eastward through the Sredna Gora Mountain. The Quaternary basin between the geometric segments *h* and *d1* may be evidence for a connection between them.

Geometric fault segments *i1*, *i2*, *i3*, *i4* and *i5* could form an individual active fault. This fault could connect to the geometric segment *k* through a small Quaternary basin in between them (Fig. 2). The geometric segments *l* could also extend to the NW.

Long-term slip rate

The quantitative estimation of the fault activity is the long-term slip rate. The estimation of the long-term slip rate requires data about the total fault slip of known age. The summarized data about the thickness of the Quaternary in the Plovdiv Depression (Драгоманов et al., 1989) and the assumption that the Quaternary deposition started after MIS 21 or 820 Ka BP (Bassinot et al., 1994) are used for calculation of the long-term slip rate. The long-term slip rates vary between 0.149 mm/yr and 0.024 mm/yr (Table 1). The most active fault is the seismogenic segment *c1-c2-e* (with or without the geometric fault segment *f*).

Calculated in this way long-term slip rate (Table 1) is underestimated because: 1) the maximum thickness in the "Quaternary" hanging wall basins reflects only the downthrows of the hanging walls, and it is not the total fault slip; and 2) the base of the "Quaternary" in some basins could be younger than 820 Ka. Proposed long-term slip rates are tentative, and further absolute dating of the youngest sediments and landforms is obligatory for better seismic hazard assessment.

Discussion and conclusion

Subparallel set of active normal faults dip toward an axis in a graben formed in the middle of the Plovdiv depression. Fault kinematics is consistent to the recent N-S to NNE-SSW extension. All fault segments are active during the Pleistocene. Most of the faults seem to be also active during Late Pleistocene and Holocene time.

Determined relationships between surface rupture length and magnitude on the base of a number of world-wide events allow calculation of the magnitude of an event that a fault of known length can produce. Magnitudes of the assumed seismogenic fault segments in the Plovdiv Depression are calculated fallowing the equations of Wells and Coppersmith (1994) and Ambraseys and Jackson (1998) in Table 1. The main active fault segments can generate events of magnitude between 5.8 and 7.3. The active faults have slow slip rate. The recurrence interval of the events is equal to the slip per event divided by the slip rate. The slip per event for each of the possible seismogenic fault segment can be calculated from the seismic moment equation. Taking into account the large uncertainties in the input data about fault segment length, fault depth and slip rate, the recurrence intervals should vary from 2000 to more than 10 000 years. Recent paleoseimological studies on the Chirpan fault and the Popovitsa fault also indicate recurrence intervals of few thousands of years.

The long recurrence intervals and the lack of historical data require paleoseismological study of the individual seismogenic fault segments in order to evaluate the potential for future large events. More precise slip rate, slip per event, recurrence interval, time elapsed since the last event are characteristics that must be obtained by detailed survey.

Table 1

Possible seismogenic fault segments in the Plovdiv Depression, magnitude of events they can generate and long-term slip rate for the last 820 000 years calculated on the base of maximum thickness of the Quaternary sediments in associated hanging wall basins. The seismogenic fault segments are indicated by the symbols of the geometric fault segments that they consist of

Possible seismogenic fault segment	Length, km	Moment magnitute, M_W. Equation for normal faults from Wells & Coppersmith (1994)	Surface-wave magnitude, M_S. Equation from Ambraseys & Jackson (1998)	Maximum thickness of the Quaternary in the hanging wall basins from Драгоманов и др. (1989), m	Slip rate since MIS 20 (820 Ka), mm/yr
a1-a2-a3-a4	67	7.3	7.2		0,037±0,017****
b1-b2	>14*			>40	>0,049
b3	11	6.2	6.3	>40	>0,049
b4	19	6.5	6.6		
b5	30	6.8	6.8		
b3-b4	34	6.9	6.9	>40	>0,049
b4-b5	48	7.1	7		
b3-b4-b5	62	7.2	7.2	>40	>0,049
b1-b2-b3-b4-b5	>76*	>7,3	>7,3		
c1-c2	27	6.8	6.8	>60	>0,073
c1-c2-e	50	7.1	7.1	122	>0.149
c1-c2-e-f	60	7.2	7.2	122	>0.149
f-e	21	6.6	6.6		
f-g	21	6.6	6.6		
d2	6**	5.9	6		
d1-d2	25**	6.7	6.7		
d1-h	38	6.9	6.9	>20	>0,024
d2-d1-h	46**	7	7	>20	>0,024
h	5	5.8	5.9		
d1	17	6.5	6.5		
i1-i2-i3-i4-i5	51	7.1	7		
k-i1-i2-i3-i4-i5	72	7.3	7.2		
j	10	6.2	6.3		
l	22	6.6	6.7	70	>0,085
*l-m****	46	7	7	70	>0,085

* The real rupture of the April 18, 1928 MS 7.1 Popovitsa earthquake is larger than the segment b1-b2; ** Possible eastward continuation; *** Geometric fault segment m is not shown on Fig. 2; **** from Vanneste et al. (2006) for the Plio-Pleistocene period.

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Резюме. Ал. Радулов – Активни разломи в Пловдивската депресия и скорост на дългосрочните движения по тях. Пловдивското понижение е един от най-активните в сеизмично отношение райони в България. Местоположението на разломите, способни да предизвикат повърхностни разломявания в бъдеще, и разломните характеристики, необходими за вероятностна оценка на сеизмичната опасност не са били обект на обстойни проучвания. В настоящата работа е определено местоположението на геометричните разломни сегменти, предложени са сценарии за вероятни сеизмогенни разломни сегменти и е изчислена дългосрочната скорост на разломите за района на Пловдивското понижение. Дефинирането на разломни сегменти, способни на бъдещо повърхностно разломяване, се основава на схващането, че тава са разломите, които са се активирали в миналото като са оставили следи в релефа и кватернерните седименти.

Чрез геоморфоложки анализ се отделят разломните откоси – резултат от многократни повърхностни разломявания. Допълнителни геоморфоложки белези, основните от които са свързани с горноплейстоценски и холоценски речни тераси, подпомагат доказването на разломна активност и трасирането на разломите. Кватернерните басейни във висящите крила служат за определяне на разломите в заливните тераси на по-големите реки, където ерозията и бързата скорост на седиментация са заличили разломните откоси.

Разломни откоси, разделени помежду си от няколкостотин метрови застъпвания, отстъпи или малки дерета, формират геометричен разломен сегмент. Приема се, че два геометрични разломни сегмента могат да се свържат в един сеизмогенен разломен сегмент при разстояние до 2–3 km между тях в зоната на застъпване. Дължината на предполагаемите сеизмогенни разломни сегменти варира от 5 km до повече от 76 km. Въз основа на зависимостите между дължината на повърхностното разломяване и силата на земетресението са изчислени очакваните магнитуди. В Пловдивското понижение могат да се очакват магнитуди между 5,8 и 7,3.

Активните разломи в Пловдивското понижение се характеризират с ниски скорости за последните 820 000 години. Изчислените дългосрочни скорости са от порядъка на 0,024–0,149 mm/година. Скоростите са подценени, вероятно някои от тях с пъти, защото използваните дебелини на кватернерните отложения отразяват само потъването на висящите крила и защото основата на кватернера в много от басейните вероятно е по-млада. Интервалите на възвръщаемост на силните събития са между 2000 и повече от 10 000 години.