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RUPTURE MODEL IN A RELAY-RAMP – CHIRPAN FAULT, SOUTHERN BULGARIA

A. Radulov, M. Yaneva

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Abstract

Relay structures are very important for segmentation of large active faults. Hard linkage of two fault segments in relay zones can define these two geometric fault segments as one behavioral fault segment.

Mesoscale geomorphic features and deformations in young deposits are used as paleoseismic indicators inside a relay ramp of two fault segments of the Chirpan fault, northeast of Chirpan. The young deposits and structures in a trench, which has been studied, record two surface rupturing events since the beginning of the Subatlantic climate phase. An oblique breach in the lower part of the relay ramp is traced on the basis of paleoseismic records. The breach connects the tips of the active parts of the fault segments. The hard linkage of the Orizovo – Chirpan fault segment and the Chirpan – Trakiya fault segment determines their capability to be an individual seismogenic segment.

Key words: Active fault, normal fault, relay ramp, fault segmentation, paleoseismology, Chirpan fault, Upper Thracian Depression.

Introduction. Faults grow by segment linkage. Geometric fault segments in map view often differ from seismic segments referred to seismic sources. More than one seismic source can be distributed along a fault. Well-constrained segmentation model provides a physical basis for the selection of rupture length used in the calculation of maximum earthquakes [1]. Relay structures play an important role in the development and linkage of fault segments [2]. Rupture model is important for identifying the stage of fault growth and whether the fault is capable to be an individual seismic source. Herein, we describe the geometry of fault linkage in a relay ramp, based on paleoseimological data. Relay-ramps are defined as zones connecting the footwalls and hanging walls of overlapping fault segments representing soft linkage of fault segments [2]; but soft and hard linkage are end members, and transition between them is expected in nature. The present study aims to define the stage and pattern of intraramp hard deformations connecting fault segments. The study area is a relay ramp of two large segments of the Chirpan fault of known historical rupturing in 1928.

Chirpan fault segmentation. Chirpan fault is about 110 km long normal fault striking E-W (Fig. 1). A part of this fault has been ruptured during M_S 6.8 earthquake on April 14, 1928 [3]. Different fault sections have been identified by geophysical methods [4], surface geological mapping, data from coring, geomorphologic evidence [5], and even by surface rupture [6, 7]. Typically for large seismogenic normal faults, the Chirpan fault is divided in separate segments of different scale, which are arranged en-échelon. Individual array length varies from tens of meters to several kilometers. At least three major segments in the part faulted in 1928 [6, 7] can be distinguished on the basis of different long-term slip rates recorded in the footwall and hanging wall geomorphology and geology. The three main segments are observed between Shishmantsy and Orizovo, between Orizovo and Chirpan, and between Chirpan and Trakiya (Fig.1). These three fault segments dip south, and border a graben filled in with young sediments in the middle of the Upper Thracian Depression. East of Trakiya, the fault changes the sense of dip, and, indeed, bifurcates [4]. The epicenter of April 25, 1928 M_S 5.7 earthquake near Gulubovo is situated close to the middle of the easternmost fault segment; and the event may relate to activation of the segment. Therefore, the easternmost fault segment appears to be an individual seismic source.

The segment between Shishmantsy and Orizovo runs mainly in Holocene low relief flood plain. Fault scarp bends, and the average height of the compound fault scarp varies between 8 m and 10 m. The surface rupture of 1928 event in the Shishmantsy – Orizovo section has been mapped only by one contemporary source [6]. The compound scarp of the Orizovo – Chirpan segment reaches maximal height of 40-50 m [3]. Dominantly erosive landforms in the footwall where Eocene outcrops, and thick Pleistocene and Holocene deposits in the hanging wall suggest continuous fault activity since Pliocene times. Long-term slip rate has been estimated to be 0.037 ± 0.017 mm/yr for Pliocene-Holocene time [3]. Most expressive surface rupture of 1928 event has been described along this segment [7]. Four or five surface rupturing events of average recurrence interval of 2350 ± 643 years have occurred since Atlantic climatic phase [3]. The compound fault scarp of Chirpan – Trakiya segment reaches 30-40 m. The scarp height is comparable with the Orizovo – Chirpan segment, but its slope angle is much lower. Mainly Neogene alluvial sand outcrops in both footwall and hanging wall, and only small Holocene alluvial fans and colluvium spread in hanging wall close to the fault. Absence of widespread thick Holocene deposits in the hanging wall and less erosive features in the footwall may mean a lower slip rate of the Chirpan – Trakiya segment than that of the Orizovo – Chirpan segment. Although the surface rupture of 1928 event has been mapped along Chirpan - Trakiya segment [7], details and the offset are unknown. Geology and geomorphology of Orizovo – Chirpan segment and Chirpan - Trakiya segment differ, and thus, suggest different long-term slip rates, but 1928 rupturing along both fault segments [7] assumes that they may form an individual behavioral fault segment. The detailed study of the relay zone of the two fault segments north of Chirpan would prove whether they form an individual seismic source or not.

Relay-ramp description. An oblique lineament striking SW-NE that may coincide with a pre-existing fault (Krushevo-Chirpan fault [4]) controls the segmentation of the Chirpan fault [3] and the formation of a relay ramp between overlap fault sections at Rupkite Hill, north of Chirpan (Figs 1, 2a). The basement height is known as Chirpan threshold in previous studies and originated in Neogene time [4] contemporary with formation of the Neogene basins in the hanging wall of the Chirpan fault. Both fault segments are en échelon arranged in right step. The overlapping section is 1.5 km long, and the distance between the rear and front segment is about 2 km (Fig. 2a). Typically for normal faults, the basement height has been formed in the overlap zone. The basement height separates hanging wall Neogene and recent basins growing toward the middles of fault segments. The long-term slip rate is the lowest near the segment boundaries [1], which could be proved by geomorphology [8]. Interaction between long-term fault activity and surface processes results in morphologic features at mesoscale. Relatively major drainage basin developed on the western slope of the Rupkite Hill (Fig. 2a) shows tilt of the relay ramp toward the center of the Orizovo – Chirpan segment. The tilted hanging wall and the leveling of the footwall height to the hanging wall height of the Orizovo – Chirpan segment toward its eastern tip indicate decreasing of the total displacement along the eastern tip of the rear fault segment.

The total displacement of the western termination of the front fault segment also decreases, which is recorded in very low Holocene sedimentation rate in the hanging wall. Displacement deficit in the overlapping fault sections should cause soft or hard deformations inside the ramp in order to reach a physical linkage between fault segments through the time. Breaching in the overlap zone is a part of the process of fault growth by segment linkage [2]. Fault segment geometry, kinematics, and regional extension determine breach location [9]. Generally, Chirpan fault is considered to be a normal fault [4], but some oblique slip of dextral sense, evident from changes in river courses (Fig. 2a), also occurs. It is expected that combination of the regional N-S extension [10], right step and right slip would determine breaching in the lower part of the relay ramp.

Some geomorphic features show evidence for faulting geometry inside the relay zone. The most prominent tectonic form is a 6 m–high scarp, which displaces the main ridge of the basement height (Fig. 2a). The long-term fault displacement recorded in the scarp is 5-8 times less than the compound scarps of the active sections of the fault segments. This fact means that: 1) faulting inside overlapping section begun much later, and/or 2) coseismic slip was less than along fault segments. Taking into account the average event displacement of 0.51 ± 0.05 m for the last 4 events on the rear segment [3], the ridge should have undergone about 12 faulting events. Assuming contemporary faulting in the relay ramp with faulting of the rear segment, and knowing the average recurrence interval on the rear segment of 2350 ± 643 years [3], faulting events in the relay ramp have occurred at least since the Last Glacial Maximum.

Two small streams starting just close to the ridge scarp run in opposite directions toward the active fault segment tips. The fault scarp on the ridge and these two stream courses should reflect the general trend of the fault strike inside the relay ramp. The strike is 140º. The newly formed normal fault appears to be oblique to the regional extension.

Data for faulting in the Holocene deposits very close to the rear fault segment provides additional information for breaching process in the relay ramp. A fault scarp about 1 m high in the eastern periphery of the hanging wall Holocene basin (Fig. 2a) reflects recent surface faulting. Unfortunately artificial modification in landscape does not allow scarp analysis; the scarp could be recognized only on old aerial photographs.

We studied an 1 km long cross section through the eastern termination of the Orizovo – Chirpan fault segment and the fault scarp in the Holocene deposits (Fig. 2b). Two fault splays of the rear fault segment affect Upper Eocene deposits and control Quaternary deposition. Northern fault splay juxtaposes upper Eocene limestone in footwall against Upper Eocene sandy siltstone. The southern fault splay controls Quaternary deposition in its hanging wall. Topsoil seems not to be affected by these two fault splays, and therefore they have been inactive at least since modern soil formation. Recent surface faulting is recorded in the fault scarp and deformed Holocene deposits about 420 m to the south (Fig. 2b). The edge of the uneroded original upthrown block surface is 160 m upslope from the scarp crest in the studied cross-section (Fig. 2b).

Paleoseismic records. In order to study paleoseismic records, we logged youngest sediments in an excavation 20 m long and 1.50 m deep along a new highway construction north of Chirpan (Fig. 2b). Trench wall exposes a soil profile and fault scarp related colluvial deposits, both affected by faulting (Fig. 3). Uppermost 0.30 m of the top deposits has been removed during excavation. Removed material represents recent humic horizon, and its structural details are unknown.

A single normal fault (F1 on Fig. 3) and a number of small fissures determine the fault zone about 2 m wide. Deposits and soil profile in the footwall of the main fault F1 differ from those in the hanging wall (Fig. 3). Units A, B and C in the footwall represent soil horizons in an old soil profile, which is progressively eroded towards the fault zone. The erosion evidences a paleoscarp. The age of the eroded soil profile could be estimated using the color indexes and indexes of melanization and rubification [[11, 12]], which reflect the stage of soil development. Soil structure and indexes of samples collected from these units (Sa, Sb, Sc on Fig. 3) are compared with indexes of soil horizons from a trench north of Cherna Gora with well known stratigraphy [[3, 13]]. Structure and indexes of unit A from this site show a similar stage of soil development as unit C1 from the trench north of Cherna Gora, and these of B from this site – as unit C2. Unit C1 is interpreted as a humic horizon of Subatlantic soil [[3]] and unit C2 is the illuvial horizon developed in deposits of Subboreal age [[13]]. This gives us a good reason to attribute Subatlantic age to scarp degradation.

The same soil profile in the hanging wall is eroded down to the carbonate horizon (unit C)(Fig. 3). The maximum erosion takes place in the fault zone and gradually decreases away from it. The first preserved fragments of unit B in the hanging wall appear five meters apart from the fault. This unusual erosion in the hanging wall could be explained by fault-associated upwelling water due to very shallow ground water table. Water emerged at 1.5 m below the surface during the highway construction works, and flooded the hanging wall. A nearby stream (Fig. 2a) could be an additional erosion agent especially shortly after event subsidence of the subsided block. Flooding in the hanging wall causes considerable erosion and influences on the depositional processes there.

Colluvial deposits bury the soil profile, eroded to different levels in both fault walls. In the footwall only unit L is detached, whereas in the hanging wall an additional unit H is deposited directly on the eroded surface. Units H and L (Fig. 3) consist of unsorted debris from units A and B and have clast-supported texture. Pieces are angular, and from 3 up to 40 cm large. Unit H is deposited at the fault free face. Unit H is compacted. Compaction could be explained by water flood immediately after deposition of the unit H. The upper part of H is composed of more sorted oriented colluvium with horizontally laminated structure as a result of fluvial deposition. Finer material from free face has been washed out and deposited as a miniature alluvial fan on the debris directly next to the fault free face. Such kind of deposition is typical for young fault scarps [14]. Texture, structure, shape and position regarding the fault free face determine the lower part of unit H as gravity dominated colluvium deposited immediately after a fault event.

Particle sizes in unit L gradually decrease upward over the paleoscarp and away from the fault zone in the hanging wall. This is combined with rough low angle cross stratification expressed at about 1.5 m apart from the fault zone (Fig. 3). Unit L is a colluvial wedge produced by scarp degradation.

The uppermost unit K imposed onto the unit L represents a sorted colluvium, composed of small particles (less than 20 mm) from units A and B among the matrix from the same material. These deposits are loose and with granular structure and matrix-supported texture. It is interpreted as wash dominated colluvium transformed subsequently in uppermost soil horizons of the modern soil profile.

The colluvial units H and L and the paleoscarp prove a fault event on fault F1 in the Subatlantic. However, F1 propagates up through the colluvial units H, L and modern soil K and thus proves a later event (Fig. 3). The looseness of unit K and the absence of uppermost humic horizon do not allow identification of any colluvial formations related to the later event. The later movement along fault F1 is recorded in the displaced units H, L and base of the unit K. Additional evidence for the later event are fault F2 affecting the paleoscarp surface (Fig. 3) and open fissures in unit L filled in with material from unit K.

Discussion. The described above paleoseismic records in morphology and young sediments inside the relay ramp allow us to build a model of the breaching process. The Orizovo – Chirpan fault segment and the Chirpan – Trakiya fault segment grew by increase in their length until they reached overlap of 1.5 km. The breaching process started then, and undertook the slip in the ramp. Overlapped fault section remained inactive or their slip significantly decreased. The fault scarp on the ridge, the stream courses, and the surface faulting recorded in the trench trace the breach. The breach connecting both active segment tips in the lower part of the relay ramp is oblique to the active fault segment strike. We found two surface rupturing events of Subatlanic age in the trench. Although the age is poorly constrained, those two events could be correlated with the two youngest events established in the trench north of Cherna Gora [3]. Most probably the event affecting unit K is 1928 event, and the older event may correspond to the penultimate event from Cherna Gora, which occurred between 2602 ± 126 cal. years BP and 1750 AD [3]. The fault scarp inside the ramp proves that rupturing started as least in the Last Glacial Maximum.

Conclusion. Internal deformations in the relay ramp indicate that displacement has been transferred mainly from both segment terminations in the past to the oblique rupture inside the ramp in recent time. The hard linkage of the Orizovo – Chirpan fault segment and the Chirpan – Trakiya fault segment determines their capability to be an individual seismogenic segment.

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Geological Institute
Bulgarian Academy of Sciences
1113 Sofia, Bulgaria
e-mail: radulov@geology.bas.bg
marlena@geology.bas.bg

FIGURES

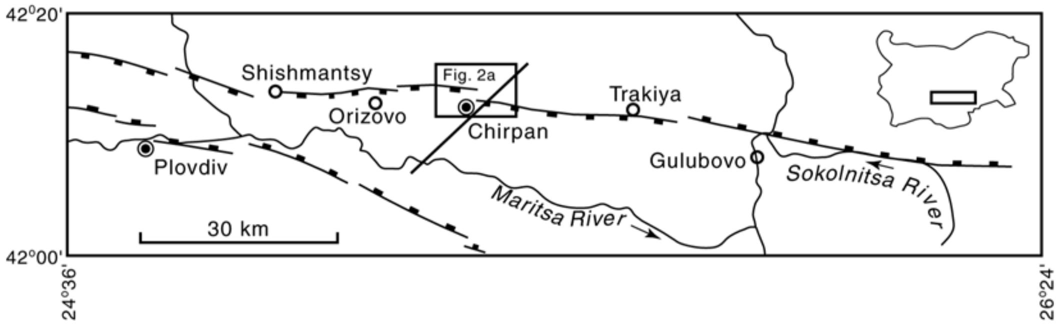


Fig. 1. The Chirpan normal fault is a northern border of a young graben in the middle of the Upper Thracian Depression. Separate segments of the Chirpan fault are en échelon arranged. Solid line shows the Krushevo – Chirpan fault that controls Chirpan fault segmentation northeast of Chirpan.

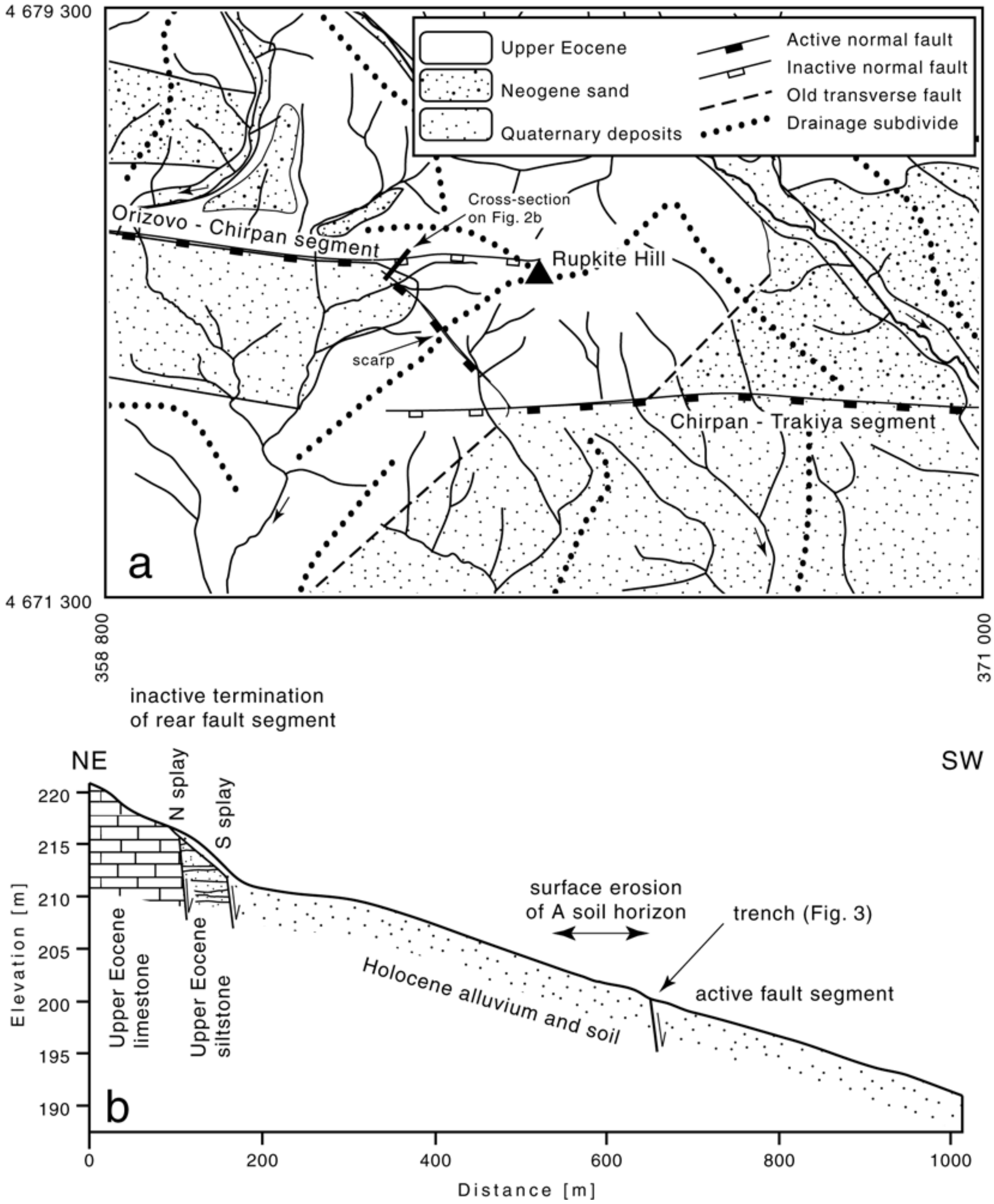
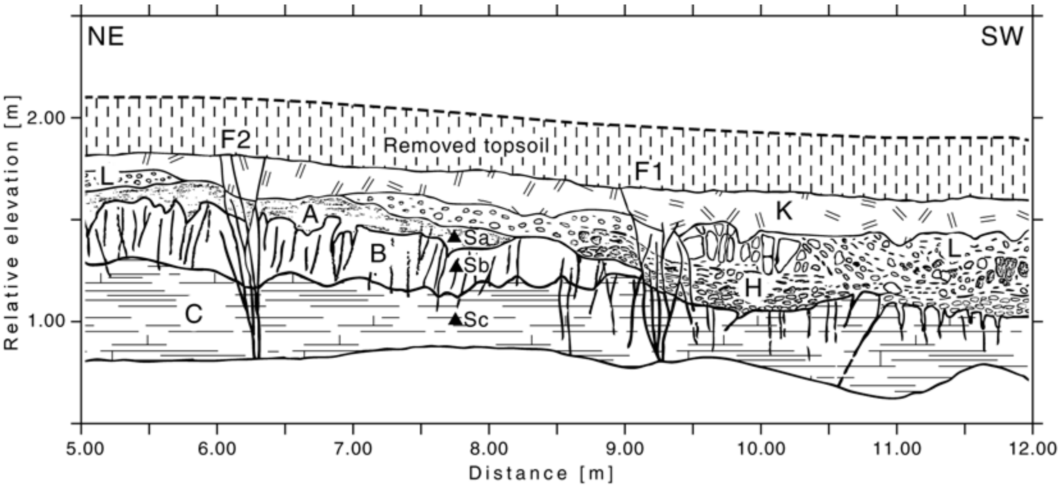


Fig. 2. Active and inactive fault segments: a – Map view of the relay ramp between the Orizovo – Chirpan fault segment (rear segment) and the Chirpan – Trakiya fault segment (front segment). Note the drainage basin at the eastern termination of the rear fault segment that evidences decrease in the slip rate on the segment termination. A scarp at the ridge and creek courses inside the relay ramp mark oblique breach connecting the active fault segment tips. Projection is UTM zone 35, Northern Hemisphere (WGS-84 datum); b – Cross-section along the inactive termination of the rear fault segment and the newly formed breach in the Holocene hanging wall basin. Position shown on Fig. 2a.



					Indexes	
Unit	Soil horizon	Description	Structure	Colour	Rubification	Melanisation
A	A	clayey loam	granular	7.5YR3/1	0	80
B	B upper	silty loam	prismatic	7.5YR5/2	10	40
	B lower	silty loam, carbonaceous	prismatic	10YR5.5/2	10	25
C	C	limy clay	massive	10YR8/1	10	20
H		unsorted colluvium	clast supported			
L		unsorted colluvium	clast supported			
K		sorted colluvium, modern soil	matrix supported			

Fig. 3. Trench log. Location shown on Fig. 2b. Units labeled by letters are described in the table. F1 and F2 – faults. Sa, Sb, and Sc – sample location.