

Major active faults of SW Bulgaria: implications of their geometry, kinematics and the regional active stress regime

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Abstract: Southwest Bulgaria is an intracontinental region between the Dinaro-Hellenic and Balkan mountain ranges that has experienced infrequent, but strong and destructive earthquakes. The general geometric and kinematic characteristics of the major faults, mainly the active ones, are investigated, as the seismic activity is insufficient to describe thoroughly the active crustal deformation associated with the faulting. The results suggest a major rupture zone with a length of more than 50 km. The east–west-striking Kochani–Kroupnik–Bansko ‘rupture zone’ was potentially associated with the large 1904 Kroupnik earthquakes, and has been found to transect the region joining the Kochani, Kroupnik and Bansko faults. In addition, a long-term slip rate ranging from 0.14 to 0.7 mm a⁻¹ has been estimated for some large faults in the region using morphotectonic features. The most active faults are normal ones striking WNW–ESE to ENE–WSW, whereas the NNW–SSE- to NW–SE-striking faults tended to act as barriers to the growth of the former faults, as they do not exhibit much indication of recent reactivation. The stress regime determined is extensional with the least principal stress axis (σ_3) subhorizontal and oriented north–south. The fact that the active faults show geometric and kinematic characteristics, as well as estimated long-term slip rates, similar to those of the active faults of central and eastern Macedonia and Thrace (Northern Greece) suggests that both of these regions share a single contemporary stress field.

Intense seismic activity in SW Bulgaria is revealed by both historical information and instrumental records. The area has suffered severe damage caused by the 1904 Kroupnik earthquake ($M=7.8$), which was preceded by a strong foreshock just 23 minutes before (Shebalin *et al.* 1974). For the main shock, which is considered one of the largest events in the South Balkan Peninsula, a magnitude up to 7.8 has been estimated (Christoskov & Grigorova 1968). However, a recently re-estimated magnitude yields a much smaller value of 7.0–7.2 (Pacheco & Sykes 1992; Dineva *et al.* 2002). Although the seismic properties of the area have been investigated (Dineva *et al.* 1998; Rizhikova *et al.* 2000), the seismicity during the instrumental era is as yet insufficient to define the properties of the major rupture zones of the region. This is because the strongest events are infrequent and smaller magnitude seismicity is diffuse. The most reliable seismological information concerning the study

area includes the focal mechanisms of small earthquakes along the Strouma River (Van Eck & Stoyanov 1996), and isoseismals of the large events of the Kroupnik earthquake sequence (Grigorova & Palieva 1968; Shebalin *et al.* 1974; Papazachos *et al.* 1997). In general, the former determine a north–south extension, and the latter the existence of large rupture zones striking east–west. Studies based on global positioning system (GPS) measurements during the period 1996–1998 (Kotzev *et al.* 2001) indicate that SW Bulgaria, i.e. mainly the area along the Strouma River, is dominated by NNW–SSE extension. This supports the view that the North Aegean extensional regime extends to Bulgaria, as suggested by Burchfiel *et al.* (2000).

Geological information about the faulting in SW Bulgaria mainly refers to the fault network of the region (Zagorchev 1992*a,b*) and the NE–SW-striking Kroupnik fault, which is considered to be associated with the 1904 Kroupnik earthquake

(Zagorchev 1992*a*; Shanov 1997; Shanov & Dobrev 2000; Meyer *et al.* 2002). According to Zagorchev (1992*a,b*), the NNW–SSE-striking faults forming the Strouma fault system and smaller kilometres-long faults orthogonal or oblique to the Strouma River dominate the fault network of the region. However, more recent investigation of the faulting in the region indicates that the faults that trend orthogonally or obliquely to the Strouma River, i.e. those striking NE–SW, ENE–WSW, east–west and WNW–ESE, are more prevalent than NNW–SSE-striking ones (Tranos 2004). As a result, several differently oriented faults could be considered as rupture zones activated under the contemporary stress regime in the region, as well as for the Kroupnik earthquake. In addition, although the contemporary stress regime is extensional, arguments exist about the orientation of the least principal stress axis (σ_3) as derived from fault-slip data analysis (Shanov 1997; Shanov & Dobrev 2000; Shanov *et al.* 2001; Tranos 2004).

The purpose of this paper is to examine in detail the major faults of the region, mainly those that bound Quaternary basins in order to identify their geometry and kinematics, and obtain a better understanding of the fault activity as well as the active stress regime of the study area.

Geological and seismotectonic setting of the region

Southwest Bulgaria is a region where the NNW–SSE-trending Dinarides–Hellenides mountain belt and the east–west-striking Rhodope and Balkan orogen join (Fig. 1, inset map). In this region, several Alpine tectonic zones forming the inner part of the mountain chain are cut by the Strouma Lineament, as inferred by Bonchev (1958, 1971) and Jaranoff (1960), and described in detail by Zagorchev (1992*b*). An additional and more complete description of the geology of the area was given by Zagorchev (2001). The study area extends from Kresna and Bansko in the south to Kyustendil and Doupnitsa in the north (Fig. 1). The geology of the area comprises a pre-Alpine and Alpine basement consisting of: (1) Pre-Palaeozoic and Palaeozoic high-grade metamorphic rocks that belong to the Rhodopian Supergroup and the Ograzhdenian Supergroup, or to the Serbomacedonian massif; (2) a few relatively small outcrops of Mesozoic rocks; (3) Palaeogene sediments that include Middle Eocene to Lower Oligocene and Upper Oligocene continental clastic sequences.

The Neogene sediments are mainly exposed in basinal parts of the area and have been grouped into three depositional cycles (Nedjalkov *et al.* 1988): (1) the Late Badenian–Sarmatian cycle, which consists of red polymict conglomerates, siltstones and sandstones with clay interbeds; (2) the Meotian–earliest Pontian cycle, which consists of whitish or yellowish alluvial sand and clay, interbedded with pebble gravel lenses; (3) the Pontian–Pliocene cycle, characterized by well-sorted conglomerates and sandstones. Finally, Quaternary proluvial and alluvial sediments were formed along the NNW–SSE Strouma River and its tributaries, as well as along the ENE–WSW-striking fault bounded by the Doupnitsa and Kyustendil basins and the WNW–ESE Bansko–Razlog basin.

Since the Late Miocene the region appears to have experienced crustal extension, implying that it might represent the northernmost part of the Aegean extended domain (e.g. Jackson & McKenzie 1988; Burchfiel *et al.* 2000; Tranos 2004). The neotectonic movements succeeded and destroyed the planation surfaces of the initial peneplain formed in the Early–Mid-Miocene (Zagorchev 1992*b*). Recent focal mechanisms of small earthquakes (Van Eck & Stoyanov 1996), geodetic measurements (Kotzev *et al.* 2001) and fault-slip data (Tranos 2004) indicate that the mean extension axis in SW Bulgaria is oriented north–south, although a WNW–ESE extension of the area was previously suggested (Shanov 1997; Shanov & Dobrev 2000; Shanov *et al.* 2001).

The fault network of the area is complicated, comprising many inherited faults from the late orogenic stages (Zagorchev 1992*a,b*; Tranos 2004). Three main fault orientations can be distinguished: NNW–SSE-striking faults that follow the orogenic fabric of the Dinarides and Hellenides; NE–SW- to ENE–WSW-striking faults orthogonal to the previous fabric; WNW–ESE-striking faults that follow the Balkan and Rhodope structural fabric. These orientations include faults that could have experienced recent reactivation. In particular, Van Eck & Stoyanov (1996) mentioned that the faults along the Strouma River could have undergone recent reactivation as their lengths correspond to the strong earthquakes that have occurred in the area. Meyer *et al.* (2002) suggested that the 1904 Kroupnik earthquakes were related to reactivation of the Kroupnik fault, which strikes NE–SW.

Historical destructive earthquakes of $M \geq 6.0$ are known to be associated with the Kroupnik (1866, $M 6.7$) and Kyustendil (1641, $M 6.7$) faults (Papazachos & Papazachou 2003). In particular,

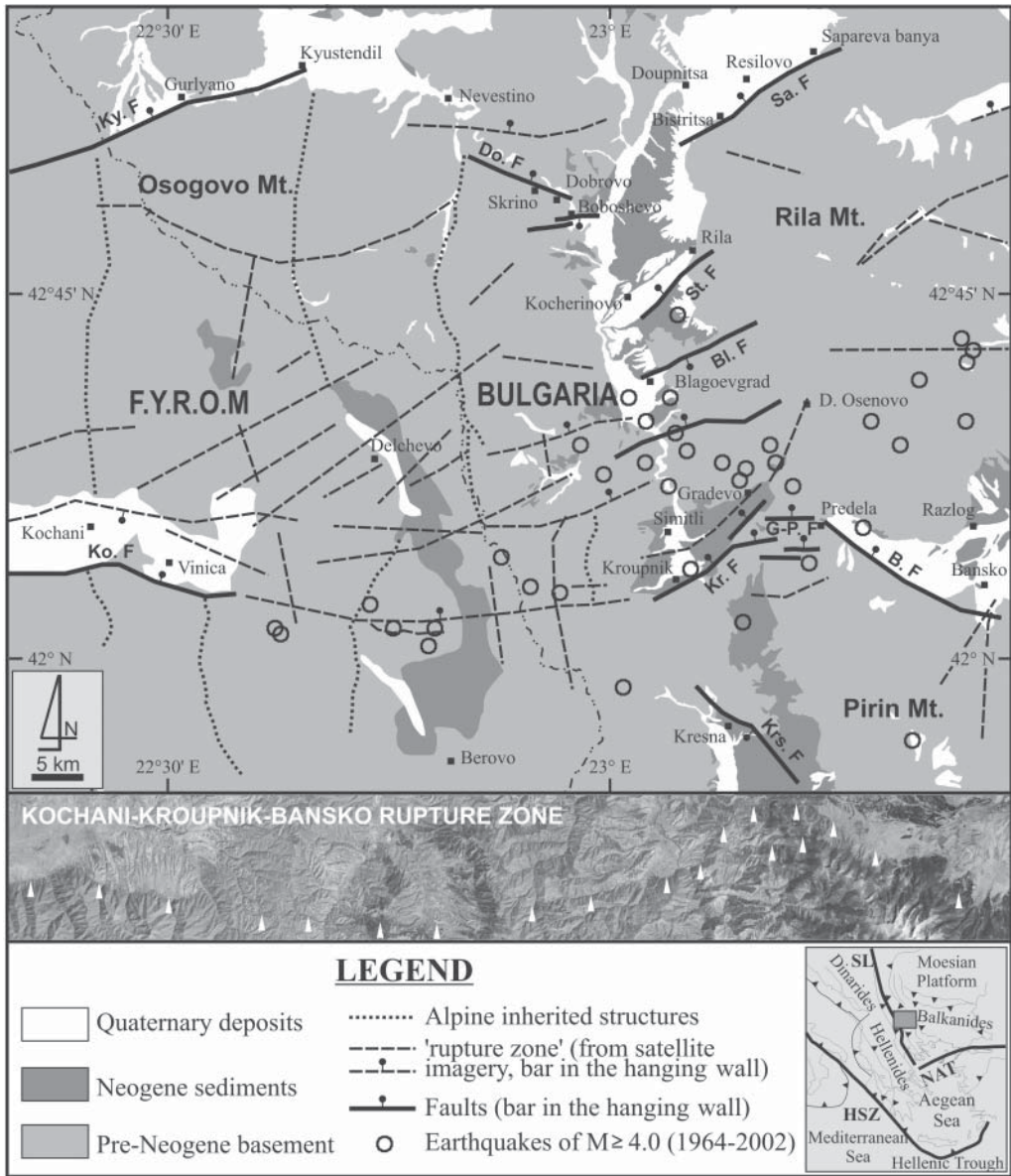


Fig. 1. Generalized tectonic map of SW Bulgaria and neighbouring Former Yugoslav Republic of Macedonia (F.Y.R.O.M.) indicating the large rupture zones and faults as compiled from Landsat satellite imagery, geological maps (Marinova & Zagorchev 1990a–d) and field observations. In the middle, the trace of the Kochani–Kroupnik–Bansko rupture zone is shown on the Landsat imagery with white arrowheads. The map at the lower right indicates the study area in the Balkan Peninsula with respect to the large alpine orogenic structures (HSZ, Hellenic subduction zone; NAT, North Anatolian Trough; SL, Struma Lineament). Ko. F, Kochani fault; Kr. F., Kroupnik fault; Krs. F., Kresna fault; G-P. F, Gradevo–Predela fault; B. F., Bansko fault; Bl. F., Blagoevgrad fault; St. F., Stob fault; Do. F., Dobrovo fault; Sa. F., Saparevo fault; Ky. F., Kyustendil fault.

the seismicity associated with the Kroupnik fault is characterized as the highest in Bulgaria (Rangelov *et al.* 2001). Recent seismicity of

$M \geq 4.0$ since 1964 (Fig. 1) is mainly concentrated along an ENE–WSW elongated zone, extending from the area west of the Bulgarian–FYROM

border toward the villages of Simitli and Kroupnik and the area east of Blagoevgrad (Karakostas *et al.* 2004).

Large faults of SW Bulgaria

Our investigation is based on the use and interpretation of Landsat imagery to define the dominant fault pattern of the area and consequently the large fault zones. This interpretation shows that the NE–SW- to ENE–WSW- and WNW–ESE- to east–west-striking faults are the most prominent fault lineaments in the region. The former are curved or rectilinear lineaments forming a large-scale anastomosing fault network of varied width, similar to that in a mountainous area NW of the Kroupnik–Simitli basin (Fig. 1). On the other hand, the WNW–ESE- to east–west-striking faults are commonly lineaments of larger length and spacing, i.e. Kochani and Bansko, that breach shorter and more diffuse ENE–WSW-striking faults, forming large rupture zones of arcuate shape with an east–west general strike. The well-defined east–west-striking Kochani–Kroupnik–Bansko ‘rupture zone’ has a total length of >100 km. This rupture zone joins faults that dip north, such as the Kochani, Kroupnik, Gradevo–Predela and Bansko faults. A concavity to the north and an abrupt bend between the NE–SW-striking Kroupnik fault and the WNW–ESE-striking Bansko fault also characterize this zone. This bend seems also to be common for the western part of the Rila Mt, as both WNW–ESE- to east–west- and NE–SW-striking faults could be traced there. The recent seismic activity shown in Figure 1 is distributed along the Kochani–Kroupnik–Bansko rupture zone and also delineates this bend. In addition, the isoseismals of the 1904 earthquake (Shebalin *et al.* 1974) fit better with the orientation and length of this zone than with the NE–SW Kroupnik fault alone.

Northwards, several discontinuous lineaments of NE–SW to ENE–WSW strike have been traced from the eastern part of the Kochani basin towards Bulgaria to form a horsetail-type structure or fan, opening eastwards. The discontinuity of these lineaments can be ascribed to persistent NNW–SSE, inherited Alpine structures (Fig. 1). In addition, Landsat imagery has allowed us to recognize that large Neogene and Quaternary basins, such as the Doupnitsa, Kyustendil, Kocherinovo–Rila–Stob (Rilska-reka), Kroupnik and Bansko–Razlog basins, have been oriented along both NE–SW- to ENE–WSW- and WNW–ESE-striking faults. For this reason, we attempted to define the geometric and kinematic

characteristics of these boundary faults and their kinematics. For the description of fault kinematics, we use the shortening (P) and extension (T) axes, as defined by Maret & Allmendinger (1990), as these axes are analogous to the P–T axes of the fault-plane solutions of the earthquakes. Thus, a direct comparison between the geological and seismological data could be achieved. Additionally, in the cases where we used the Holocene period for the estimation of the long-term slip rate of the faults, we used its nominal age, i.e. 10 ka.

The geometric and kinematic characteristics of the faults investigated are described as follows.

Kroupnik fault

This ENE–WSW- to NE–SW-striking fault has brought into contact basement rocks and the Neogene and Quaternary sediments that filled the Simitli–Kroupnik basin (Figs 1, 2a and 3a), and has been studied by several workers, e.g. Zagorchev (1970, 1975), Vrablianski (1974) and Vrablianski & Milev (1993), and more recently by Shanov & Dobrev (2000) and Meyer *et al.* (2002). Zagorchev (1970) described it as a normal fault that strikes N025° to N040° and dips at 40–70° to the WNW. However, this description reflects the geometry of the easternmost part of the Kroupnik fault, more than that of the entire fault system that bounds the basin.

Our observations, taking into account the strike, suggest that the fault is subdivided into two segments (Fig. 2a): an eastern one with NE–SW (*c.* N045°) strike, which is exposed east of the Strouma River, throwing the Neogene sediments against basement rocks; and a western one that strikes ENE–WSW (N065–070°) and is mainly exposed west of the Strouma River, juxtaposing basement rocks and rocks as young as Holocene proluvial deposits. The latter fault, as traced by the juxtaposition of the sediments against the basement rocks, appears to be shifted *c.* 200 m towards the south, possibly as a result of NNW–SSE-striking faults that form the Strouma River (Fig. 2a, point A). The same shift is also evident on the map presented by Dobrev & Kostak (2000). East of the Strouma River, the ENE–WSW-striking fault continues for about 1 km, where it truncates a NE–SW-striking fault (Fig. 2a, point B). Although the trace of both fault segments is easily recognizable in the landscape, the strike deflections and the cross-cutting NNW–SSE-striking faults might act as barriers where high stress levels could be concentrated.

The 1904 Kroupnik earthquake was associated with many rock fall and landslide phenomena (Dobrev & Tacheva 2000) and the formation

of a fault scarp (Meyer *et al.* 2002). Meyer *et al.* also suggested that the Kroupnik fault is an active normal fault exhibiting uniform reactivation of the order of *c.* 0.1 mm a⁻¹ slip rate during the last 6 Ma. Shanov (1997), Shanov & Dobrev (2000) and Shanov *et al.* (2001), from their fault-slip data analysis carried out along the Kroupnik fault, suggested that the stress regime is extensional with the least principal stress axis (σ_3) subhorizontal and oriented WNW–ESE (*c.* 280–290°). However, their conclusions are mainly based on the dip-slip slickenlines collected along the NNE–SSW to NE–SW fault slickensides that affect the basement rocks and belong to the eastern NE–SW-striking fault segment that separates the basement from the Neogene sediments (Shanov & Dobrev 2000, pp. 120–121, points 2, 3 and 4). The fact that the NNE–SSW to NE–SW-striking faults are inherited structures that were previously reactivated as normal faults by WNW–ESE extension during the Mid–Late Miocene (Tranos 2004), raises questions about whether the fault-slip data reflect the contemporary stress regime. In any case, the WNW–ESE extension determined by Shanov & Dobrev (2000) does not match the north–south extension determined by focal mechanisms (Van Eck & Stoyanov 1996) and GPS measurements (Kotzev *et al.* 2001). Therefore, we argue that the dip-slip slickenlines that indicate a normal reactivation of the ENE–WSW- to east–west-striking fault slickensides are more reliable indicators of the contemporary regional stress field, as their reactivation, owing to older deformation events, is that of oblique or strike-slip faults (Tranos 2004). Furthermore, their kinematics, which defines a subhorizontal extensional kinematic axis (T) and slip vectors along the NNW–SSE to north–south orientation (Fig. 4a), suggests an extension orientation similar to that defined from the GPS measurements and focal mechanisms.

Stob fault

A 10 km long, NE–SW-striking narrow depression into which the Rilska River flows is the dominant topographic feature of the area, in which the towns of Kocherinovo, Stob and Rila are located (Figs 1 and 2b). This depression, named Rilska-reka, intersects a well-defined plateau of mainly Neogene sediments onto which Early Pleistocene talus–proluvial deposits of the Badino Formation (Zagorchev 1992b) and Pleistocene alluvial sediments have been deposited, forming well-extended pediments. The depression is filled with Pleistocene and Holocene

alluvial sediments of the Rilska River, and is characterized by a relative asymmetry, as the youngest deposits are parallel and close to the SW edge of the depression. At its NW edge, it forms a rectilinear terrace > 40 m high, whereas at its SW edge it is bounded by the NE–SW-striking Stob fault, which affects pre-Alpine crystalline rocks and Neogene sediments. This fault has been considered as active by Zagorchev (1975), because it is very well defined in relief. Although the strike of the fault and the plateau front indicate the prevalence of a NE–SW strike, several physiographic features also indicate recent activity along faults that strike ENE–WSW. In particular, *c.* 2 km SW of Rila village, along the Stob fault, we have observed a rectilinear shutter ridge that forms an apparent right-lateral shifting of the proluvial fan (Fig. 3c). In addition, rectilinear trench-rills and landslides have formed along the ENE–WSW orientation in the area upslope of Stob village, where erosion of Neogene sediments forms the ‘Stobski Piramidi’ geomorphological features. At the same location (Fig. 2b, site A), an ENE–WSW-striking fault dipping at high angles towards the NNW has been found to displace not only the Neogene sediments but also the overlying Pleistocene gravelly silty–sandy deposits of the Badino Formation by about 1 m, forming a colluvial wedge that is potentially Holocene in age (Fig. 3d). Assuming that this colluvial wedge resulted from a palaeo-earthquake event, then a vertical slip of about 1 m can be estimated for the Holocene period. Taking an average fault dip of 45° for the Stob fault, a value that typifies active normal faults in the seismogenic crust (e.g. Jackson & White 1989) and the nominal age of the Holocene, i.e. 10 ka, a long-term slip rate of *c.* 0.14 mm a⁻¹ since the Holocene can be suggested.

Saparevo fault

This ENE–WSW-striking fault, here named the Saparevo fault, bounds the graben east of Doupnitsa city (previously Stanke Dimitrov) until Sapareva Banya village and then aligns itself with the northern mountain front of the Rila mountain range (Figs 1 and 2c). The fault was first described as an active one by Jaranoff (1960), who mentioned that it strikes N065° and is associated with thermo-mineral springs. Vrablianski (1977) named it the Klisoura fault, whereas Zagorchev (1969) referred to it as the Saparevo fault. This fault affects the large, anastomosing fault zones that dip at medium angles

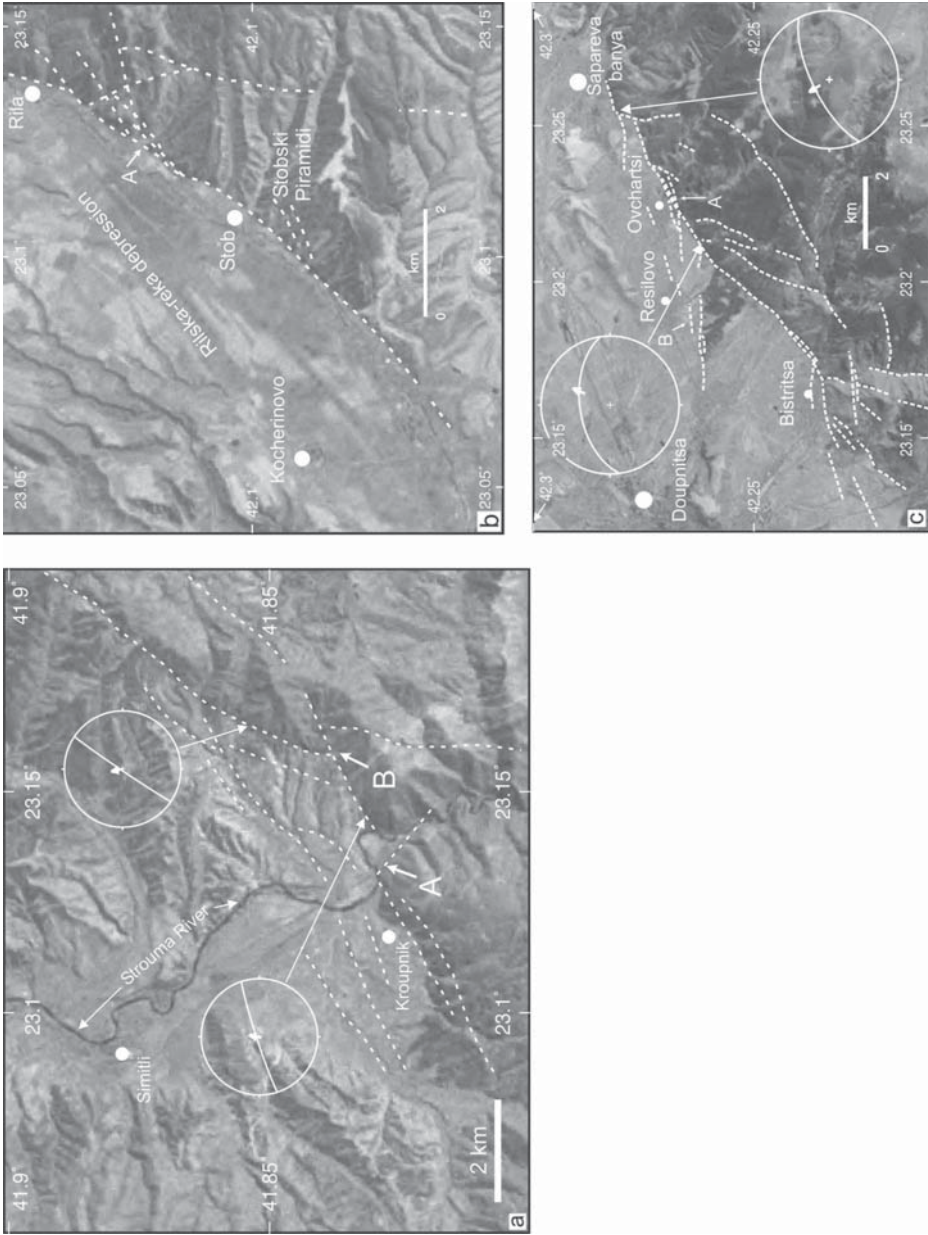
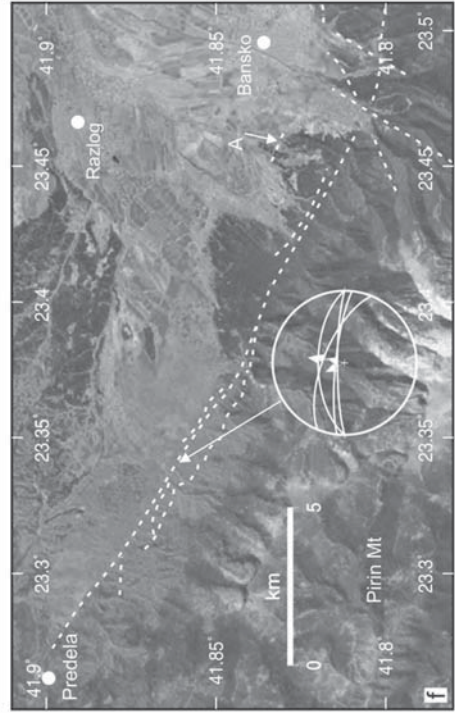
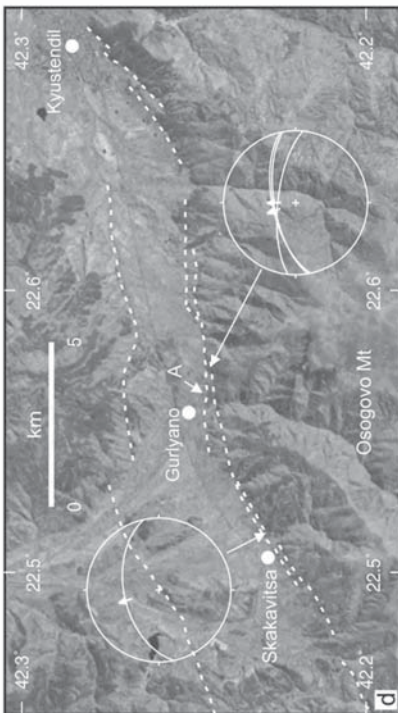
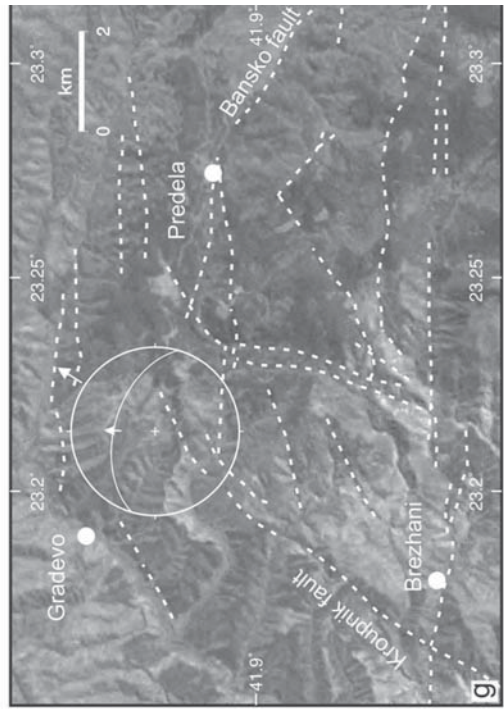
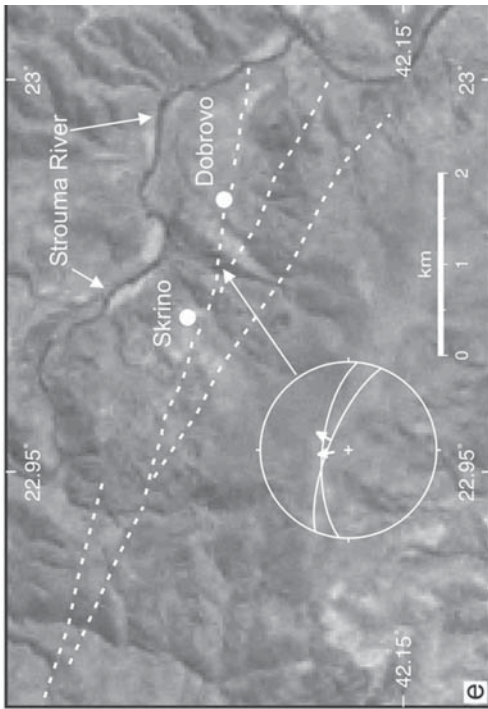


Fig. 2. Mapping of the large faults of SW Bulgaria utilizing Landsat satellite imagery: (a) Kroupnik fault; (b) Stob fault; (c) Saparevo fault; (d) Kuystendil fault; (e) Dobrovo fault; (f) Bansko fault; (g) Gradevo–Predele fault. Dashed white lines indicate the traces of faults. Capital letters (A, B, etc.) are sites described in the text, and stereographic projections (equal area, lower hemisphere) indicate the fault-slip data measured on the outcrops indicated by white arrows.



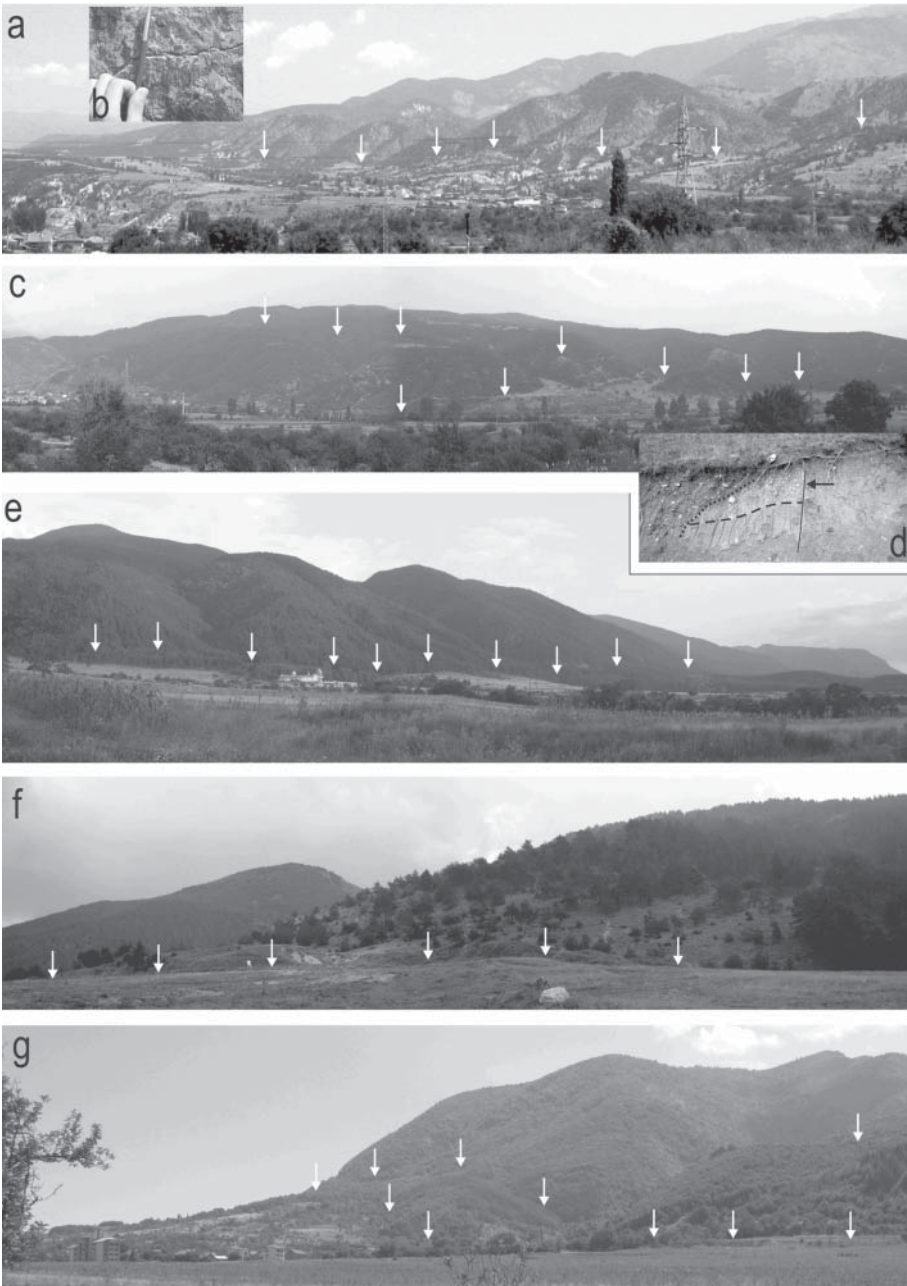


Fig. 3. Field photographs of the large fault zones exposed in SW Bulgaria. (a) Kroupnik fault: a general view (towards the SE) of the fault east of Kroupnik village and the Strouma River. (b) Detail of the surface of the fault (site A, Fig. 2) showing the dip-slip striations that indicate the normal reactivation of the fault. (c) Stob fault: a general view (towards the south) of the fault, SW of Rila village, where the right-lateral offset of the Holocene alluvial fan deposits is clearly observed. (d) Detailed view of the (?)palaeo-earthquake fault exposed in the right abutment of the fan shown in (c), arrow indicates the trace of the fault. (e) Saparevo fault: a general view (towards the south) of the fault, west of Resilovo village. (f) Saparevo fault: abrupt vertical surface offsets within the Holocene proluvial sediments along the Saparevo fault close to Ovchartsitsi village. (g) Kyustendil fault: view of the two branches of the Gurlyano-Skakavitsa fault south of Gurlyano village (view towards the ESE). The lower branch affects the Holocene proluvial deposits.

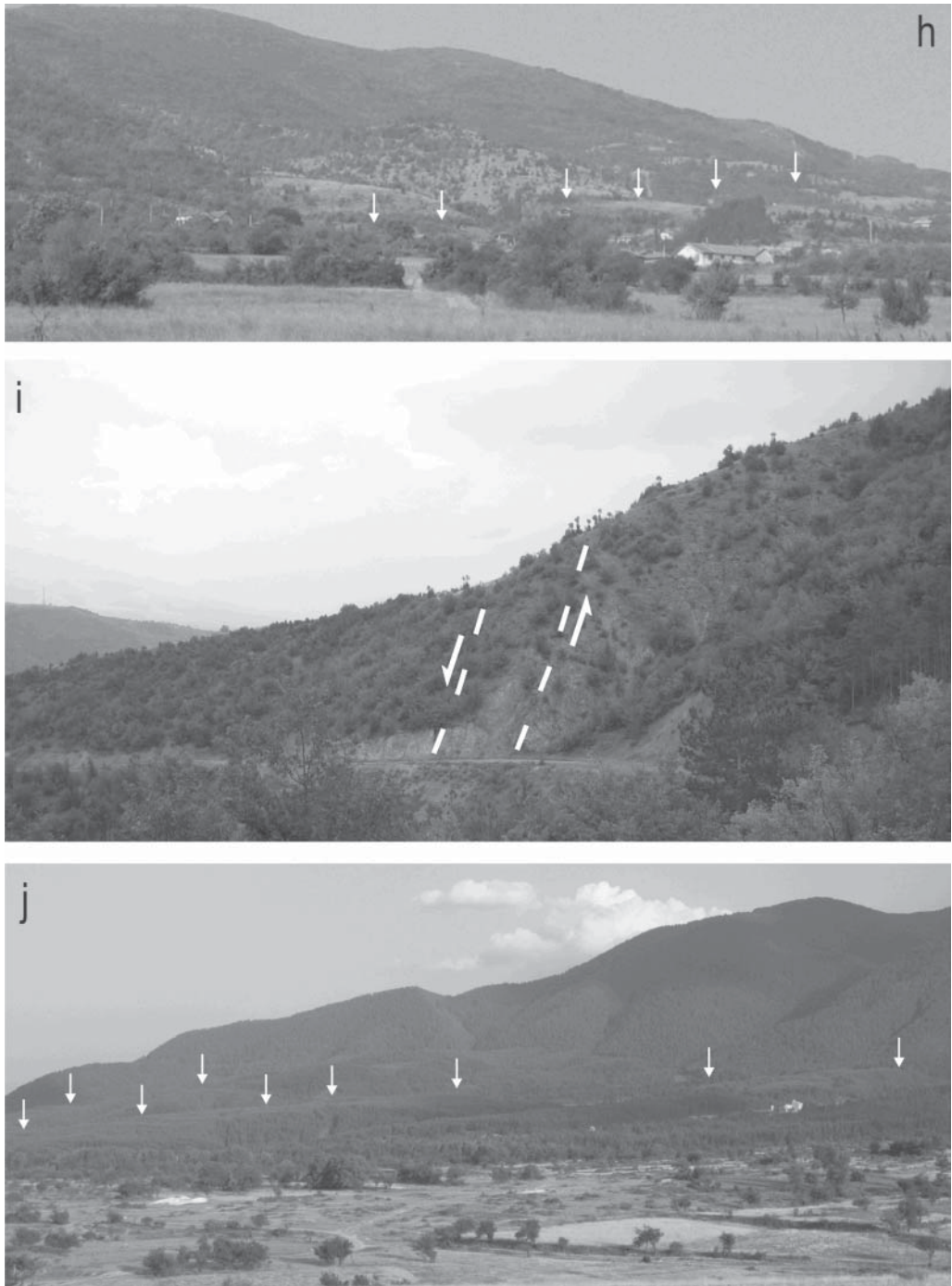


Fig. 3. (h) Dobrovo fault: a very well-formed fault scarp in the western edge of Dobrovo village (view towards the west). (i) Close-up view (towards the ESE) of the Dobrovo fault cutting the Frolosh Formation (Dobrovo–Skrino road). Dashed white lines indicate the fault zone and white arrows the normal sense of shear. (j) Predela–Bansko fault: view of the fault (towards the SSE) in the slopes south of Bansko town. White arrows indicate successive points on the fault trace.

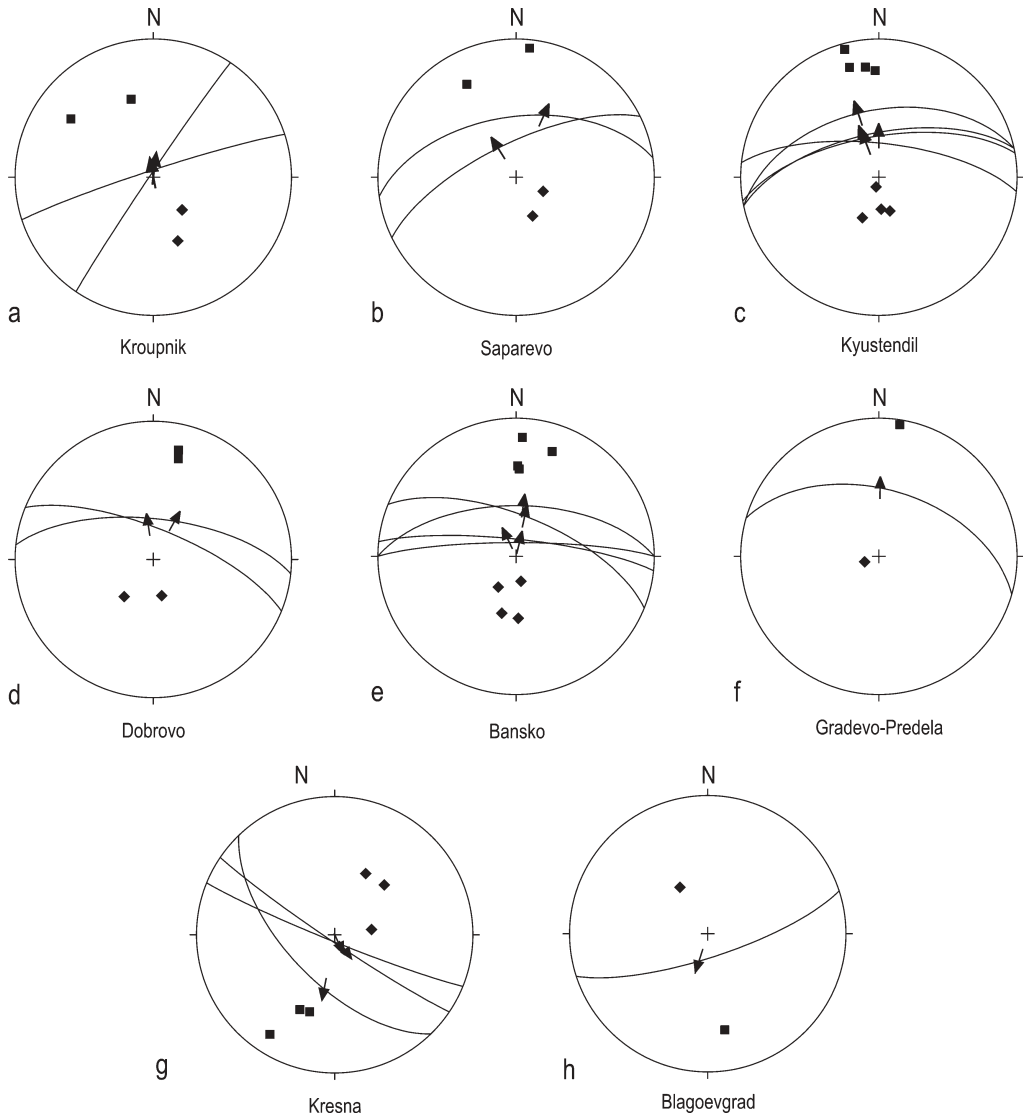


Fig. 4. Stereographic projections (equal area, lower hemisphere) indicating the latest kinematics of the large faults exposed in SW Bulgaria: (a) Kroupnik fault; (b) Saparevo fault; (c) Kyustendil fault; (d) Dobrovo fault; (e) Bansko fault; (f) Gradevo–Predela fault; (g) Kresna fault; (h) Blagoevgrad fault. Filled squares and diamonds indicate the extension (T) and shortening (P) axes, respectively, from the fault-slip data. Slip vectors are shown by arrows.

towards the NW to west and that, according to Shipkova & Ivanov (2001), form part of the Djerman detachment fault. These fault zones are the dominant structures that affect the basement rocks of the Rila Mt in its WNW part (i.e. between Sapareva Banya and Rila towns) and are related to a WNW–ESE extensional stress regime during the Mid–Late Miocene (Tranos 2004).

The Early Pleistocene talus and proluvial sediments of the Badino Formation that have been deposited along the escarpments of this part of the mountain (SSW of Bistritsa village) were entirely cut by ENE–WSW-striking fault surfaces that dip at steeper angles towards the NNW and belong to the Saparevo boundary fault. As a result of this retreat, younger Pleistocene and

Holocene proluvial and alluvial sediments were deposited along the mountain front (Fig. 3e). However, the most recent reactivation of the mountain front occurs along faults that strike ENE–WSW to east–west, resulting in further retreat of the NE–SW-striking mountain front. This is well observed west of Bistritsa village (Fig. 2c), where successive fault scarps striking N70–80° within the Pleistocene and Holocene proluvial and alluvial sediments retreat to the preceding NE–SW boundary fault. A retreat of the mountain front as a result of an active stress regime has been also observed in an escarpment south of Ovchartsi village (Fig. 2c, site A). There, proluvial sediments, dated as young as Holocene (Marinova & Zagorchev 1990a), have been deposited against the low-dipping NNW boundary fault surface and form a very gentle, north-dipping slope. In the hanging-wall part and close to the boundary fault, steeply inclined to almost vertical ENE–WSW- to east–west-striking faults cut these proluvial sediments, forming steeply inclined rectilinear fault scarps (Fig. 3f). The length of these fault scarps is a few tens of metres, whereas they cause a vertical offset of about 3.8–4 m to the very gentle, north-dipping slope formed by the Holocene sediments. Taking into account the fault dip and the Holocene age, as for the Stob fault, we estimated a long-term slip rate of $c. 0.6 \text{ mm a}^{-1}$ for the Saparevo fault since the Holocene.

Moreover, the westward extension of these ENE–WSW- to east–west-striking faults is recognized as far as Resilovo village, where an abrupt fault scarp of east–west-strike is also well observed, and separates the Holocene proluvial deposits from the older Neogene and Palaeogene sediments (Fig. 2c, site B). Thus, the overall observations along the Saparevo boundary fault suggest that the most recently reactivated faults are ENE–WSW- to east–west-striking faults that lead to a retreat of the mountain front along the Saparevo boundary fault.

The kinematics of the Saparevo fault was defined from fault surfaces exposed in basement rocks in several places. Observed slickenlines suggest normal to oblique right-lateral normal movements driven by a north–south extension axis and a subvertical shortening axis (P) (Fig. 4b).

Kyustendil fault

The Kyustendil fault is located west of Kyustendil city along the northern front of Mt Osogovo, and forms a 50 km long, ENE–WSW to east–west narrow basin filled with Pleistocene and Holocene proluvial and alluvial sediments

(Figs 1 and 2d). Jaranoff (1960) mentioned that in this area faults striking ENE–WSW to east–west, segments of the Kyustendil fault, continue to be active, and some of them are associated with the hottest thermo-mineral springs of Bulgaria. Jaranoff also stated that these faults are shorter than the longitudinal NW–SE-striking faults, i.e. the faults parallel to the orogenic fabric, and in several cases, the latter bound the former.

The Kyustendil fault can be subdivided into two segments (Fig. 2d): the Gurlyano–Skakavitsa fault segment in the west and the Gurlyano–Kyustendil fault segment in the east. The former dips at very high angles towards the NNW, forming a very steep rectilinear mountain front. Along this mountain front, Holocene proluvial and alluvial sediments (dating according to Marinova & Zagorchev 1990c) were deposited against the gneissic granite that constructs the mountain (Fig. 3g). The eastern fault is traceable from Gurlyano village to the city of Kyustendil and exhibits a complicated geometry, as it consists of several fault branches that strike either ENE–WSW or east–west. In particular, east of Gurlyano village the mountain front is aligned east–west, as a result of the presence of east–west-striking inherited vertical discontinuities that behave as short fault bridges. Further east, to the city of Kyustendil, two distinct ENE–WSW-striking right-stepping fault branches, partly overlapped, have been observed; these diminish gradually towards the northern slopes of the mountain. The kinematics of the Kyustendil fault zone is well defined along the very steep slopes east of Gurlyano village, where the ENE–WSW-striking slickensides of the fault are well exposed; dip-slip slickenlines indicate an extensional strain field with the extension axis (T) almost horizontal along the NNW–SSE orientation (Fig. 4c). In addition, in the abutment east of Gurlyano village (Fig. 2d, site A) two rectilinear successive and almost vertical faults displace Holocene proluvial sediments and form a steeply dipping fault scarp with a total vertical offset of about 4.7–5 m. As for the previous faults, we estimated the long-term slip rate of the Kyustendil fault as $c. 0.7 \text{ mm a}^{-1}$ since the Holocene.

Dobrovo fault

This is a $c. 10 \text{ km}$ long WNW–ESE-striking fault that cuts the mountainous terrain of Mt Vlahina along the course of the Strouma River and southwards (Figs 1 and 2e). The fault is better observed from the villages of Skrino and Dobrovo towards the Strouma River, where for about 6 km it is

quite rectilinear, dipping NNE at high angles (Fig. 3h and i). In particular, at the western edge of Dobrovo village, the fault throws Pleistocene reddish proluvium pebble to cobble sandy gravel against basement rocks (Fig. 3h). In addition, between Dobrovo and Skrino villages the fault cuts the Quaternary erosion mantle material at high angles, as well as NNW–SSE- and NNE–SSW-striking faults that dominate the broader area and control the flow of the Strouma River. The exposed slickensides of the fault there exhibit dip-slip slickenlines that define a subhorizontal NNE–SSW extension axis (T) and subvertical shortening axis (P) (Fig. 4d).

Bansko fault

This is a 30 km long WNW–ESE-striking fault that dips at high angles to the NNE, diminishes towards the northern slopes of the Mt Pirin and forms the wedge-shaped Bansko–Razlog graben (Fig. 1). The fault consists of two segments that form a left-stepping geometry around Bansko town, possibly because of the existence of NNE–SSW-striking faults that act as barriers. The western fault segment is rectilinear and forms very abrupt steep slopes and a mountain front (Fig. 2f). Beyond Bansko town the mountain front shifts *c.* 2 km to the NNE, where the eastern fault segment is defined by a similar WNW–ESE strike for *c.* 14 km.

At the base of the mountain front of the western fault segment (Fig. 3i), a dense vegetation cover in conjunction with soft-weathering Holocene proluvial and drift fan deposits (sands and unsorted pebble to boulder gravels) inhibit the recognition of fresh fault surfaces. However, in the upslope direction we have found parallel fault slickensides within marbles of the Rhodopian Supergroup that exhibit dip-slip slickenlines. The latter define a NNE–SSW extensional kinematic axis (T) and a steeply inclined shortening kinematic axis (P) (Fig. 4e). Some doubtful observations to the SW of Bansko town (Fig. 2f, site A) concern a few small rectilinear north-facing scarps that set down the hills made of granite and superficial Holocene sandy proluvium. This feature may indicate recent fault activation. Along these scarps, small landslide phenomena affect the sandy proluvium and the soil developed on it.

Gradevo–Predela fault

The hilly to low-mountainous terrain that separates the Simitli–Kroupnik and Bansko–Razlog basinal areas, i.e. the area of Gradevo

and Predela villages, is an area where the Kochani–Kroupnik–Bansko rupture zone bends (Fig. 1). Here, the east–west-striking faults are the most prevalent in the fault network and have lengths from about 2 km to 10 km (Fig. 2g). In particular, three distinct fault strands tend to bridge the NE–SW-striking Kroupnik fault and the WNW–ESE-striking Bansko fault. The fault surfaces that dip towards the north and belong to the northern strand, namely the Gradevo–Predela fault, exhibit slickenlines and microstructures that suggest normal kinematics. This is similar to the kinematics of the Bansko fault and defines a NNE–SSW subhorizontal extensional kinematic axis (T) (Fig. 4f).

Kresna fault

In the area of Kresna, the regional topography is dominated by the faults striking NNW–SSE to NW–SE. Several of these faults, and particularly those exposed SW of Kresna, have been described by Zagorchev (1970, 1971) as the ‘Gradeshka fault zone’, whereas some other faults, such as those east of Kresna village, were described by Moskovski & Georgiev (1970) as the Kresna fault. These faults have been recorded on the geological map (Razlog sheet) of Bulgaria (Marinova & Zagorchev 1990*d*) and their lengths vary between 6 and 12 km. They dip at high angles, towards either the NE or SW, and form rectilinear or anastomosing zones that control the course of the Strouma River and its tributaries. The most well-traced one dips towards the SW and bounds the Pontian–Pliocene upper sandstone–conglomerate member of the Kalimanci Formation (Marinova & Zagorchev 1990*d*) in the area ENE of Kresna village. Along several fault slickensides striking NNW–SSE to NW–SE, we observed two generations of slickenlines, the chronological order of which has been well established using overprinting criteria. The older slickenlines correspond to a prevalent strike-slip movement, whereas the later ones correspond to a normal movement that is compatible with a NE–SW-trending extension axis (T) (Fig. 4g). The extension axis (T) deviates significantly from the north–south extension defined by the GPS measurements and the focal mechanisms, and fits well with the NE–SW extension that governed the area during the Late Miocene–Pliocene (Tranos 2004). This last feature suggests that these faults are not optimally oriented parallel to the contemporary stress regime and therefore their reactivation was not enhanced.

Blagoevgrad fault

The approximately 12 km long ENE–WSW-striking Blagoevgrad fault (first reported by Vrablianski 1977) is a linear structure that affects the Ograzhdenian gneissic basement and dips at high angles towards the SSE. It forms a narrow valley that reaches the northern suburb of the city of Blagoevgrad, where it seems to control the deposition of Quaternary sediments relative to Neogene sediments (Fig. 1). Dense vegetation cover along the valley prevents the exposure of fresh fault surfaces; however, the few exposed ones indicate that the Blagoevgrad fault dips at about 60–70° towards the SSE and its kinematics is characterized by an oblique right-lateral normal movement that defines a NNW–SSE extension axis (T) (Fig. 4h). Some smaller antithetic fault surfaces have been also found and indicate normal slickenlines.

Active stress regime

Burchfiel *et al.* (2000) considered the region of Bulgaria as the northern end of the Aegean extensional province. They suggested that during latest Pliocene and Quaternary time Bulgaria and Northern Greece were affected by somewhat different extensional regimes, involving north–south extension in Bulgaria and both north–south and NE–SW extension in Northern Greece; a complex of strike-slip and extensional faults in SW Bulgaria could represent a diffuse boundary between the two regimes.

The contemporary stress regime of SW Bulgaria, and consequently the present tectonic framework, is not as much investigated as that of Northern Greece. Controlling factors could include the Hellenic subduction zone, the southwestward motion of the Aegean microplate (McKenzie 1972; Jackson 1994; Papazachos 1999), the right-lateral strike-slip of the North Anatolian Fault and the large NNW–SSE-striking Strouma (Kraïštid) Lineament formed in Tertiary times (Zagorchev 1992b). The Hellenic subduction zone has been well established to dominate the Greek region (Mercier *et al.* 1989), whereas the influence of the North Anatolian Fault, including in southern Bulgaria, was discussed by Pavlides *et al.* (1990), and more recently by Burchfiel *et al.* (2000) and Koukouvelas & Aydin (2002). Burchfiel *et al.* (2000) suggested that the north–south extension in central Bulgaria increased in intensity as a result of the propagation of the North Anatolian Fault system into the southern Balkan region during the last 4 Ma, and that the Pliocene–Quaternary faults, which parallel the North

Anatolian Fault (i.e. the faults striking ENE–WSW), may have both normal and dextral components. Burchfiel *et al.* also considered that the NW–SE-striking faults and the NE–SW-striking faults bound mountains and adjacent valleys, implying recent reactivation. Koukouvelas & Aydin (2002) also considered the North Anatolian Fault as the first-order structure that produced a basin-and-range type morphology in the area north of the North Aegean Trough.

The Strouma Lineament is an inherited structure with repeated reactivation and a length of >800 km (Zagorchev 1992b). Its length is rather overestimated, and it is questionable whether it could act as a boundary element to the regional stress regime. Accordingly, Van Eck & Stoyanov (1996) suggested that the large magnitude earthquakes of the region could relate to the many fault segments of the Strouma Lineament, with lengths ranging between 15 and 50 km.

A detailed knowledge of the kinematics of plate motions and interpolate deformations is necessary to help constrain forces responsible for deformation. In particular, in SW Bulgaria, where the available GPS measurements (Kotzev *et al.* 2001) and the seismological data (Van Eck & Stoyanov 1996) are insufficient to establish the active deformation pattern, a geological approach that provides geometric and kinematic information on crustal deformation is very helpful.

In addition to the geometry and kinematics of the main faults exposed in SW Bulgaria, one of the most important issues of active deformation is the definition of the contemporary stress regime. For this purpose, we utilized the stress ellipsoid by applying the algorithm of Carey & Brunier (1974) to the youngest-formed slickenlines along the large active faults described above. This algorithm has been widely used in many neotectonic studies to determine the stress regime in the neighbouring Greek mainland (e.g. Mercier *et al.* 1989; Mercier & Carey-Gailhardis 1989) and also worldwide (e.g. Carey-Gailhardis & Mercier 1992; Bellier & Zoback 1995). From this analysis it is concluded that the normal movement on the main faults of the area, that is the youngest ones, has been controlled by an extensional stress field, which has a vertical greatest principal stress axis (σ_1) and a horizontal least principal stress axis (σ_3) trending north–south (Fig. 5). This stress field is in accordance with the extension defined by focal mechanisms of small earthquakes in the region (Van Eck & Stoyanov 1996). It also fits well with the north–south-striking extensional stress field recognized further south in central northern Greece

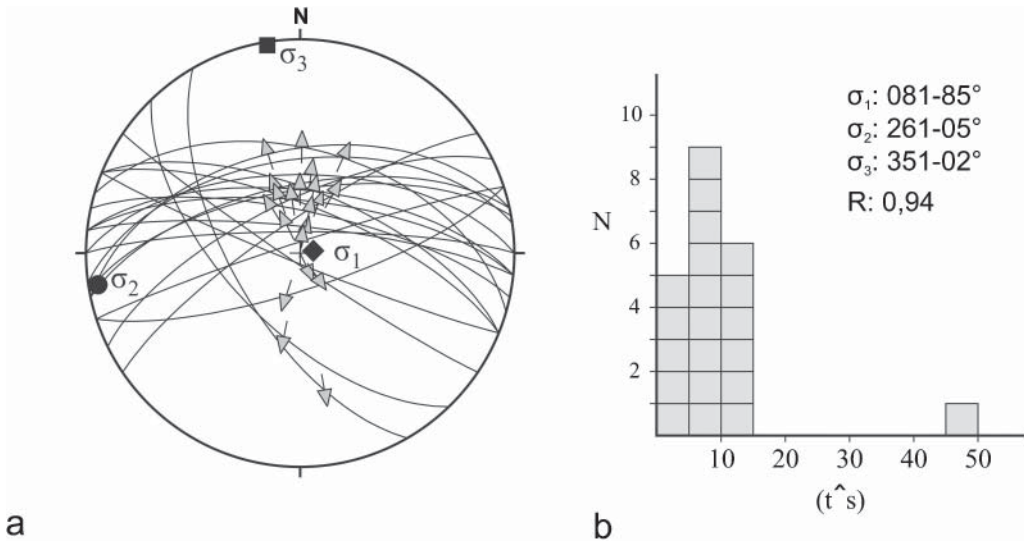


Fig. 5. (a) Stereographic projection (equal area, lower hemisphere) indicating the latest kinematics of the faults and the principal stress axes σ_1 , σ_2 , σ_3 of the strain ellipsoid defined by the algorithm of Carey & Brunier (1974). (b) Bar diagram showing the angle between theoretical and measured slip vector (\hat{t}) of the faults shown in (a) as calculated using the algorithm of Carey & Brunier (1974). N, number of fault-slip data; R, stress ratio.

from fault-slip data stress-inversion methods (Mercier *et al.* 1989; Tranos 1998), neotectonic joints (Tranos & Mountrakis 1998) and focal mechanisms (Mercier & Carey-Gailhardis 1989; Papazachos *et al.* 1998, 2001). It is also in good agreement with a north-south-trending stress regime, as defined by the similarly ENE-WSW- to east-west-striking active rupture zones of central Macedonia and Thrace, i.e. the Thessaloniki-Gerakarou fault zone (Tranos *et al.* 2003), the Serres fault zone (Tranos & Mountrakis 2004), and the Kavala-Xanthi-Komotini fault zone (Mountrakis & Tranos 2004).

Conclusions

Our investigations in SW Bulgaria suggest the presence of major normal faults striking ENE-WSW (70–80°) and WNW-ESE (100°), both related to seismic activity of a broader area. The ENE-WSW-striking faults are more common along the Strouma River, in contrast to the WNW-ESE-striking faults, which are more prevalent in central and eastern Bulgaria. The former are kilometres-long normal faults that bound narrow basins such as the Doupnitsa, Kyustendil and Kroupnik basins; these are characterized by long-term slip rates that vary from 0.1 to 0.7 mm a⁻¹. However, both WNW-ESE

and ENE-WSW-striking faults merge to form major kilometres-long arcuate rupture zones. Such a main rupture zone joining the Kochani, Kroupnik, Gradevo-Predela and Bansko faults is well defined, as confirmed by recent seismic activity distributed along it. This zone can be considered as the seismogenic fault for the strong Kroupnik earthquakes that struck the region in 1904. By contrast, the inherited NNW-SSE and NW-SE Alpine structures and faults (Fig. 1) do not exhibit any significant reactivation in the contemporary stress regime, and were apparently barriers to rupture propagation. The ENE-WSW-striking faults are normal faults without a significant strike-slip component and demonstrate similar geometric features (e.g. strike and length) and similar kinematics to the active faults of central-eastern Macedonia and Thrace (Northern Greece). Therefore, they could be considered as active or possibly active faults.

The driving stress regime as proposed here is a north-south extensional stress field, which corresponds to the well-recognized north-south extension of Northern Greece since the Quaternary. Therefore, we suggest that SW Bulgaria and central-eastern Macedonia and Thrace (Northern Greece) share seismotectonic properties at least during the Quaternary to the present, whereas the influence of the North Anatolian

Fault in Northern Greece and SW Bulgaria has been overestimated in previously published models.

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