1661-8726/08/01S295-16
DOI 10.1007/s00015-008-1287-8
Birkhäuser Verlag, Basel, 2008

Swiss J. Geosci. 101 (2008) Supplement 1, S295–S310

The Rila-Pastra Normal Fault and multi-stage extensional unroofing in the Rila Mountains (SW Bulgaria)

CHRISTIAN TUECKMANTEL[1,2], SILKE SCHMIDT[1,3,*], MARKUS NEISEN[1], NEVEN GEORGIEV[4], THORSTEN J. NAGEL[1] & NIKOLAUS FROITZHEIM[1]

Key words: Extensional tectonics, Alpine orogeny, Rhodope Metamorphic Province, Rila-Pastra Normal Fault (RPNF), Southwest Bulgaria, Mylonite

ABSTRACT

The Rhodope Metamorphic Province represents the core of an Alpine orogen affected by strong syn- and postorogenic extension. We report evidence for multiple phases of extensional unroofing from the western border of the Rila Mountains in the lower Rila valley, SW Bulgaria. The most prominent structure is the Rila-Pastra Normal Fault (RPNF), a major extensional fault and shear zone of Eocene to Early Oligocene age. The fault zone includes, from base to top, mylonites, ultramylonites and cataclasites, indicating deformation under progressively decreasing temperature, from amphibolite-facies to low-temperature brittle deformation. It strikes E–W with a top-to-the-N-to NW-directed sense of shear. Basement rocks in the hanging wall and footwall both display amphibolite-facies conditions. The foliation of the hanging-wall gneisses, however, is discordantly cut by the fault, while the foliation of the footwall gneisses is seen to curve into parallelism with the fault when approaching it. Two ductile splays of the RPNF occur in the footwall, which are subparallel to the foliation of the surrounding gneisses and merge laterally into the mylonites of the main fault zone. The concordance between the foliation in the footwall and the RPNF suggests that deformation and cooling in the footwall occurred simultaneously with extensional shearing, while the hanging-wall gneisses had already been exhumed previously. The RPNF is associated with thick deposits of an Early Oligocene, syntectonic breccia on top of its hanging wall. Integrating our results with previous studies, we distinguish the following stages of extensional faulting: (1) Late Cretaceous NW–SE extension (Gabrov Dol Detachment), exhumation of the present-day hanging wall of the RPNF; (2) Eocene to Early Oligocene NW–SE to N–S extension (RPNF); (3) Miocene to Pliocene E–W extension (Western Border Fault), formation of the Djerman Graben; (4) Holocene to recent N–S to NW–SE extension (Stob Fault), reactivating the SW part of the Western Border Fault.

Introduction

In the past decades, the geology of the Rhodope Metamorphic Province in southern Bulgaria and northern Greece has undergone a major reinterpretation. Earlier, the province had been regarded as a rigid continental block sandwiched between Alpine chains, the Balkan Mountains to the north and the Hellenides to the south (Kossmat 1924; Kober 1928; Hsü et al. 1977; Burchfiel 1980; Dercourt et al. 1986; Boncev 1988). Numerous structural and geochronological studies have now established the Alpine shaping of the Rhodope Province (Meyer 1966, 1968; Kronberg & Raith 1977; Ivanov 1988; Burg et al. 1996; Ricou et al. 1998; Mposkos & Krohe 2000; Liati 2005). The recognition of Alpine eclogites (Kolcheva et al. 1986; Liati 1988) and ultrahigh-pressure metamorphic rocks (Mposkos & Kostopoulos 2001; Perraki et al. 2006) further increased the interest in the geology of the Rhodope Province. Structural studies established that crustal shortening and the related metamorphism were followed by extensional tectonics, leading to the formation of detachment faults and metamorphic core complexes (Bonev et al. 1995; Dinter 1998; Bonev et al. 2006). In spite of all this progress, key elements of the tectonic evolution of the area are still poorly understood. This applies to the pre-orogenic arrangement of continents and oceans, the timing and geometry of subduction and collision processes, and the respective roles of crustal shortening and extension in the formation of the major shear zones and tectonic boundaries.

The Rhodope Metamorphic Province comprises not only the Rhodope Mountains in a geographic sense but also the Rila and Pirin Mountains and, according to some authors (e.g. Ricou et al. 1998; Dinter 1998), also the southern part of the Serbomacedonian Massif. The province can be subdivided into two main tectonic units (Fig. 1). The lower unit, referred to as Pangaion-Pirin Complex (Ivanov et al. 2000), contains abun-

[1] Steinmann-Institut, Universität Bonn, Nußallee 8, 53115 Bonn, Germany.
[2] Present address: Rock Deformation Research, School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK.
[3] Present address: Geologisch-Paläontologisches Institut, Universität Münster, Corrensstraße 24, 48149 Münster, Germany
[4] Department of Geology and Paleontology Sofia University St. Kliment Ohridski, 15 Tzar Osvoboditel Blvd., 1000 Sofia, Bulgaria.
*Corresponding author: S. Schmidt. E-mail: schmidts@uni-bonn.de

dant marble and Tertiary granitoid intrusions and experienced an Alpine regional metamorphic overprint, which in most areas did not exceed greenschist-facies conditions. It comprises the Pangaion Unit (Kronberg et al. 1970) and its extension into the Pirin Mountains in Bulgaria. The overlying units include both continental and oceanic rocks (gneisses, schists, marbles and metaophiolites) and are intruded by Alpine granitoids as well. We summarize these units as the Upper Complex instead of using the more detailed subdivision schemes of other authors (e.g. Krohe & Mposkos 2002) because we do not know to which of the units defined by these authors the gneisses in our study area belong. The Upper Complex underwent Alpine regional amphibolite-facies metamorphism and contains several sites with eclogites and remnants of ultrahigh-pressure metamorphism (Mposkos & Kostopoulos 2001; Perraki et al. 2006). The timing of the high-pressure and ultrahigh-pressure metamorphic event(s) is controversial; geochronological data, interpreted to date high-pressure metamorphism, range from ca. 180 Ma to 42 Ma (Wawrzenitz & Mposkos 1997; Liati & Gebauer 1999; Mposkos & Krohe 2000; Liati et al. 2002; Liati 2005; Bauer et al. 2007).

The Rhodope Metamorphic Province is structurally overlain and framed by greenschist-facies, partly ophiolitic rocks, referred to as the Circum-Rhodope Belt in the older literature (Kaufmann et al. 1976; Kockel et al. 1977). However, these rocks do not represent a coherent tectonic unit. Greenschists to the southwest of the Rhodope Metamorphic Province belong to the Vardar Zone *sensu lato* (Fig. 1), a complex, Meso- to Cenozoic oceanic suture zone (Ricou et al. 1998). To the east, the Alexandropolis and Mandrica Greenschists represent an island arc and accretionary complex related to southward subduction during the Jurassic, emplaced from the south on top of the Upper Complex (Bonev & Stampfli 2003, 2008). Greenschists overlying the Rhodope Metamorphic Province to the northwest (Frolosh Greenschists), however, were formed from a Cadomian ophiolite complex (Haydoutov et al. 1992; Graf 2001) and do not represent an Alpine suture zone. The Frolosh Greenschists are intruded by the Struma Diorite Formation, which is latest Proterozoic in age (Graf 2001; Kounov 2002).

The formation of the Upper Complex is generally attributed to subduction and accretion since at least the Late Jurassic (Dinter 1998; Ricou et al. 1998; Bauer et al. 2007). The lower-grade units exposed in the Pangaion-Pirin Complex were overthrust by the Upper Complex after the exhumation of the latter from high-pressure conditions but possibly while high temperatures still prevailed (Mposkos & Krohe 2000; Krohe & Mposkos 2002). The present-day architecture of the Rhodope Metamorphic Province was significantly influenced by late and post-orogenic extension. According to Dinter (1998), the exposure of the Pangaion-Pirin Complex is related to a Miocene southwest-directed detachment fault, the Strymon Valley Detachment (Sokoutis et al. 1993; Fig. 1). Within and at the borders of the Upper Complex, prominent extensional structures of Alpine age have been identified as well, such as the detachment faults bounding the Kesebir-Kardamos Dome in the Eastern Rhodopes (Bonev et al. 2006) or the Gabrov Dol Detachment to the northwest (Bonev et al. 1995; Fig. 1). In the Eastern Rhodopes, the occurrence of Eocene amphibolite-facies metamorphism closely below unmetamorphic Eocene sediments and volcanics documents the existence of significant unroofing faults (Krohe & Mposkos 2002).

As compared to the eastern, central, and southern parts of the Rhodope Metamorphic Province, the northwestern part (Rila Mountains and surroundings) is much less known in terms of structure and tectonic evolution. In order to start filling this gap, the present study focuses on the lower Rila valley located in the northwestern part of the Upper Complex (Figs. 1, 2, 3). This area is largely made up of various amphibolite-facies gneisses intruded by granitic bodies. The gneisses occupy a structurally high position within the Upper Complex according to Burg et al. (1996) and Ricou et al. (1998). The Alpine age of the metamorphism and the igneous bodies is generally accepted and bordering extensional detachment faults have already been proposed to explain unroofing of this complex (Bonev et al. 1995; Shipkova & Ivanov 2000). The Gabrov Dol Detachment dips shallowly northwest and separates the Upper Complex in the footwall from the Frolosh Greenschists and Struma Diorite Formation in the hanging wall (Bonev et al. 1995). The shear sense is top-to-the-northwest. The Gabrov Dol Detachment is crosscut by the ca. 73 Ma old Plana Pluton (Fig. 1; Boyadjiev 1981) and must therefore be Late Cretaceous in age or older (Ricou et al. 1998). Shipkova & Ivanov (2000) described the northwest-dipping Djerman Detachment Fault, an important, mylonitic to cataclastic, moderate- to low-angle normal fault. It forms the northwestern border of the Rila Mountains ca. 15 km north of our study area (Fig. 2).

Here we present evidence for large-scale normal faulting within the Rila Mountains (Figs. 2, 3, 4). We describe the Rila-Pastra Normal Fault (RPNF), a major extensional fault and shear zone which is younger than the Gabrov Dol Detachment, probably Eocene to Early Oligocene, and interferes with the latter in a complex way. The RPNF and the underlying mylonites display progressively decreasing, amphibolite-facies to sub-greenschist conditions. It is associated with thick deposits of an Early Oligocene (Cernjavska 2000), syntectonic breccia on top of the hanging wall, close to the normal fault (Padala Formation, Zagorchev et al. 1999; Fig. 3). The fault strikes E–W and shows a top-to-the-north- to northwest-directed shear sense. Even though basement rocks in the hanging wall and footwall both display amphibolite facies conditions, we will show that cooling in the footwall occurred simultaneously with shearing along the RPNF whereas the hanging-wall gneisses had already been exhumed earlier. Previous to our study, Shipkova & Ivanov (2000) found that the Padala Formation is underlain by a major normal fault. They connected this fault with the Djerman Detachment exposed further to the north (Fig. 2), which is not confirmed by our mapping. Westaway (2006) also describes and interprets the tectonics of the lower Rila Valley. He did not notice the zone of mylonites and cataclasites that forms the RPNF.

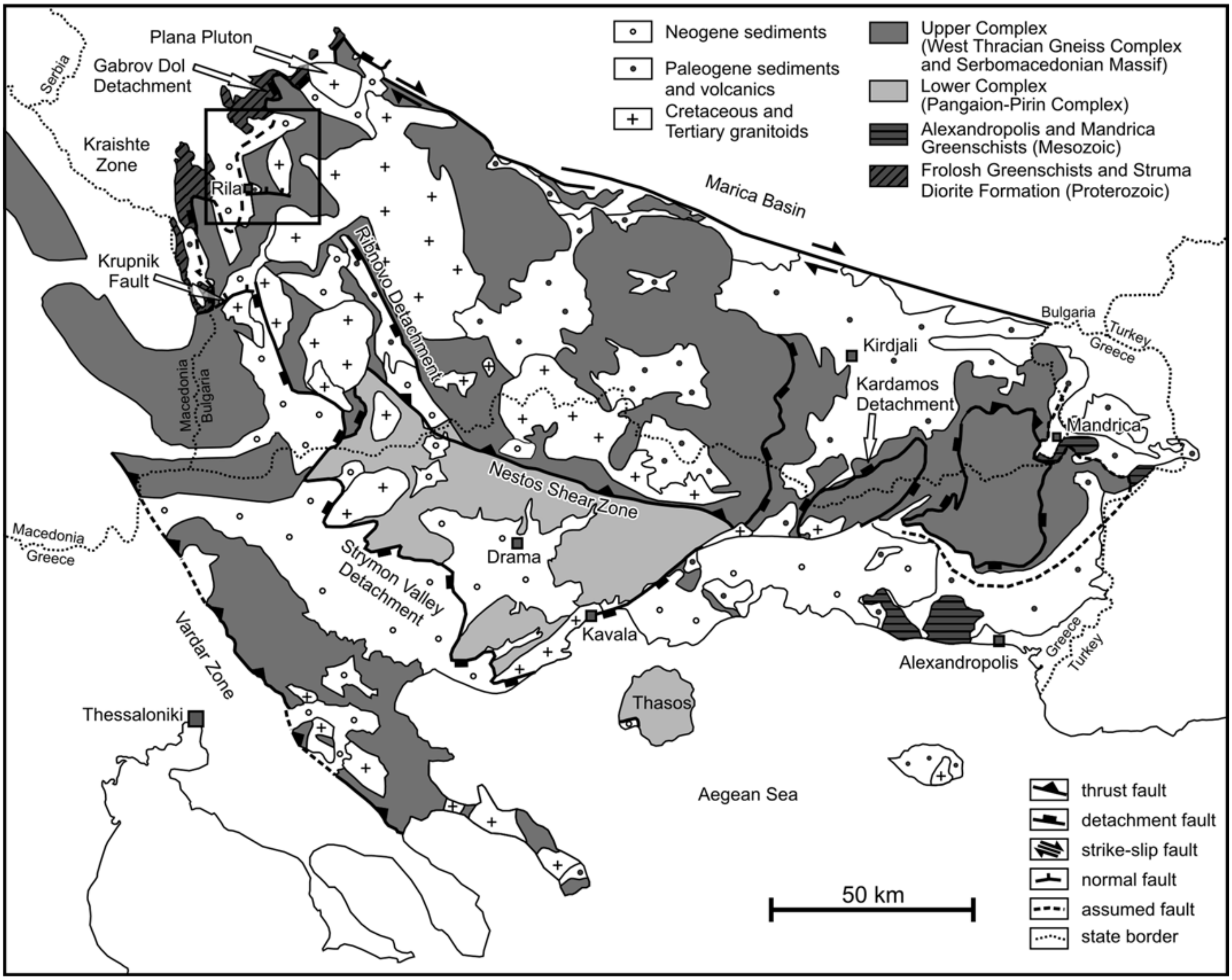


Fig. 1. Tectonic overview of the Rhodope Metamorphic Province, modified after Burg et al. 1996, Ricou et al. 1998 and Bonev et al. 2006. The box indicates the outline of Fig. 2.

In the following section, we describe the geological units in the study area in detail. After that, we present the structural record, especially features associated with the RPNF. Finally, we will reconstruct the extensional evolution of the northwestern-most Rhodope Metamorphic Province.

Geological edifice of the lower Rila valley

The lower Rila valley is dominated by amphibolite-facies gneisses (Gneiss Series in Fig. 3). They are bordered to the west by Neogene clastic sediments of the Djerman Graben. The associated west-dipping high-angle normal fault, termed Western Border Fault in the following, crops out only in few localities. In most places, Pleistocene alluvial-fan deposits cover the fault. The E–W-striking, mylonitic to cataclastic RPNF and two associated ductile splays in its footwall are located in the southern part of the study area. The main fault crosses the Rila valley 3 km east of Rila town. Immediately north of the fault, an unmetamorphic sedimentary breccia, the Padala Formation (Figs. 4, 5a, b), rests on the hanging-wall basement. Towards the north, the breccia is bounded by the brittle, steeply dipping Padala Fault. In the west, the hanging wall of the RPNF comprises a diorite body that is fault-bounded on all sides and represents an extensional klippe of the Struma Diorite Formation on top of the Upper Complex (see below). Two granite bodies intruded into the hanging-wall Gneiss Series, the Kalin Granite to the northeast and the Badino Granite to the northwest.

Struma Diorite Formation

A diorite body is exposed around the eastern part of Rila town (Fig. 3). It consists of plagioclase and amphibole and is greenish

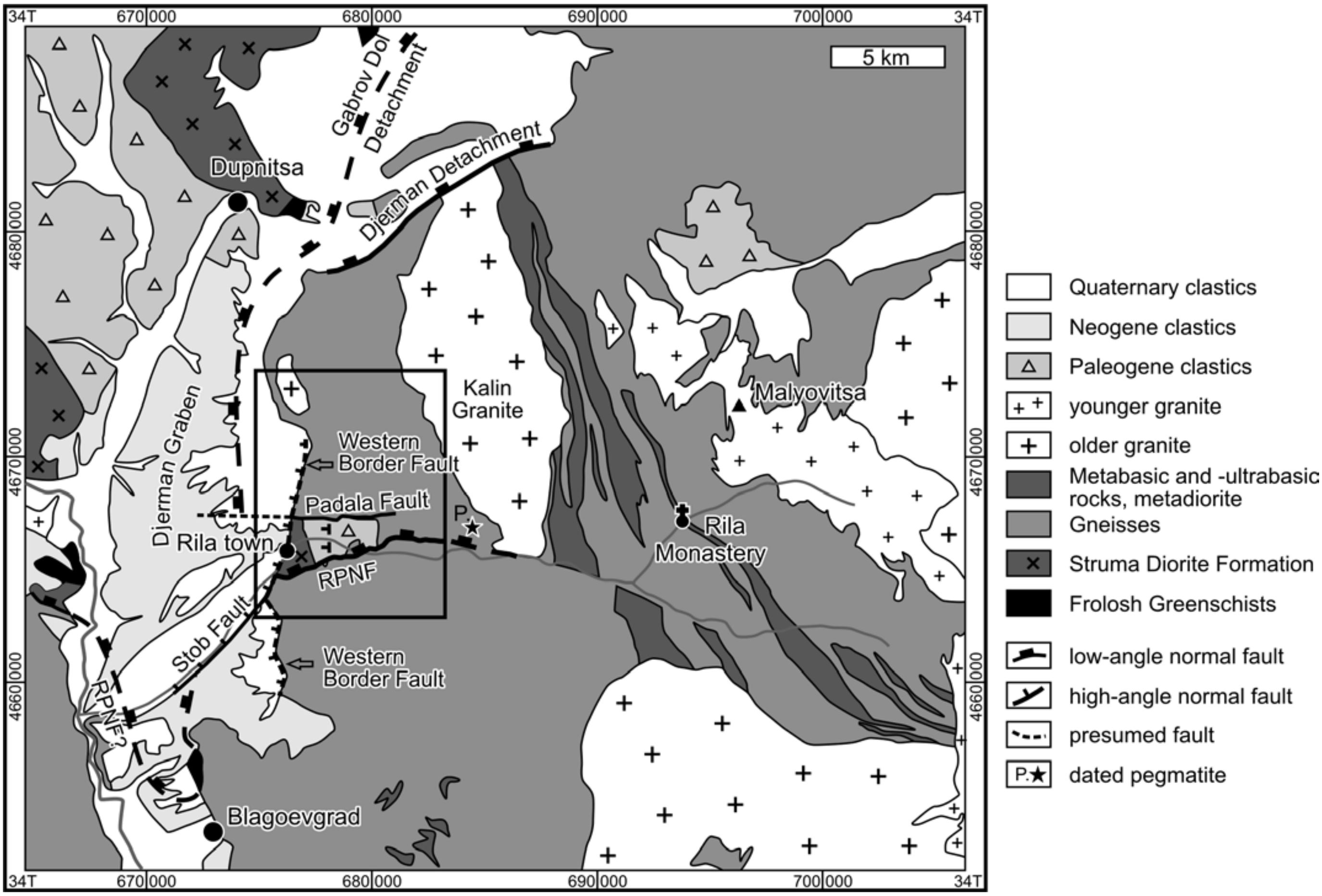


Fig. 2. Geological overview of the Rila Mountains, based on the geological map (1:100'000), sheet Blagoevgrad (Marinova & Zagorchev 1991). The box marks the outline of the study area (Fig. 3). UTM-Coordinates (WGS84) are given in units of meters.

in hand specimens. Additional mineral phases are biotite and clinopyroxene; the latter was partly replaced by amphibole. The diorite is crosscut by basalt dykes (Fig. 6 g) and thin epidote and quartz veins. The basalt has a glassy matrix and phenocrystals of plagioclase, clinopyroxene and some clinozoisite. Again, clinopyroxene was partly replaced by amphibole. Furthermore, a small fraction of the amphibole and clinopyroxene was replaced by prehnite, indicating metamorphism under prehnite-pumpellyite-facies conditions. This very low metamorphic overprint is in contrast to the amphibolite-facies metamorphism of the surrounding Gneiss Series. Towards the east, the diorite is separated from the sedimentary breccia by a subvertical layer of cataclasite and tectonic breccia (Fig. 3: Orlitsa Fault). These fault rocks are partly formed from the diorite, partly from a granite which is found only within these fault rocks. Granite fragments consist of quartz, microcline, plagioclase and chlorite. Biotite, muscovite and zircon occur in small quantities. Most of the biotite was replaced by chlorite.

The Struma Diorite Formation to which the diorite body at Rila belongs, was described by Stephanov & Dimitrov (1936) and Haydoutov et al. (1992). It comprises intrusive and volcanic rocks of dioritic and granitic composition, created in an island-arc setting (Haydoutov et al. 1992). The Struma Diorite intruded into the Frolosh Greenschists (Bonev et al. 1995; Zagorchev 2000). U-Pb zircon dating of the Struma Diorite Formation yielded ages of ca. 569 to ca. 544 Ma (Graf 2001; Kounov 2002).

Gneiss Series

The Gneiss Series is the main lithological unit of our working area. It comprises different ortho- and paragneisses with intercalated mica schists, amphibolites, foliated and unfoliated pegmatites, and unfoliated aplites. A distinction between ortho- and paragneisses in the field is difficult, but the occurrence of large feldspar porphyroclasts in most gneisses points to a preponderance of orthogneisses. In large parts of the working area locally developed leucosomes indicate beginning melting (Fig. 5f; see also Shipkova & Ivanov 2000). The gneisses consist of quartz, plagioclase, microcline, biotite, white mica and partly garnet in various proportions. Accessory minerals are apatite, zircon, clinozoisite, sphene and ilmenite. Abundant kyanite was found in three garnet-mica schist samples, two from the hanging wall (Fig. 6 h) and one from the footwall of the RPNF. In one sample from the hanging wall, kyanite is overgrown by staurolite, indicating conditions of the high amphibolite facies. East of the Kalin Granite, Kolcheva & Cherneva (1999) described kyanite- and staurolite-bearing metapelites. Amphibolites display an amphibole and plagioclase assemblage with accessory quartz, garnet, sphene, clinozoisite and epidote. In gneisses, mica schists and amphibolites outside the shear zones, garnet was partly transformed into biotite during the formation of the main foliation (Fig. 6 h). This indicates the breakdown of garnet and white mica during decompression from elevated pressures at amphibolite facies conditions.

Petrographic differences between the high temperature rocks in the hanging wall and footwall of the RPNF are limited. Footwall gneisses contain only little white mica and much biotite, whereas gneisses of the hanging wall contain more white mica. Units in the hanging wall close to the RPNF were altered penetratively by brittle deformation and contain abundant pegmatitic dykes (Fig. 5e). Furthermore, the variety of rock types seems to be larger in the hanging wall, with abundant garnet-mica schists, pegmatites and amphibolites besides gneisses. On the other hand, the footwall basement is dominated by slightly migmatized, biotite-feldspar gneisses. Undeformed pegmatites in the hanging wall of the RPNF (Fig. 2) were dated at ca. 63 Ma using K-Ar on muscovite (Boyadjiev & Lilov 1976).

Although the footwall and hanging-wall gneisses are petrographically similar, they exhibit pronounced structural differences. In the footwall of the RPNF, the foliation mostly dips northwest rather uniformly at angles of 35 to 45° (Fig. 7b). In the hanging wall, in contrast, the Gneiss Series shows very heterogenic dip angles and dip directions (Fig. 7a) and is affected by large-scale folds (Fig. 4). Such folds were not observed in the footwall. Pegmatites in the hanging wall often crosscut the foliation, whereas syn-tectonic, foliation-parallel migmatitic leucosomes and pegmatites characterize the footwall. However, older, foliated pegmatites occur in the hanging wall as well. Outside the mapped shear zones, stretching lineations are predominantly oriented N–S (Fig. 3, 7).

Granite intrusions

The margin of the Kalin Granite body is exposed in the northeastern part of the study area (Fig. 2, 3). The mineral assemblage of this granite is quartz, K-feldspar, plagioclase, biotite and epidote. Zircon and ilmenite are less abundant. Growth zoning and growth twins can be observed in the plagioclase grains, most of which are idiomorphic and contain epidote inclusions. Biotite has a dark brownish colour due to a high Ti content and is often transformed into chlorite. Most of the grains are about 2 mm in diameter. The Kalin Granite shows no evidence of ductile deformation and its contact in the study area crosscuts the foliation of the gneisses. This indicates post-tectonic intrusion with respect to the deformation in the hanging-wall gneisses. The granite yielded K-Ar biotite ages between 54 and 42 Ma (Boyadjiev & Lilov 1976) and a U-Pb zircon age of ca. 46 Ma (Arnaudov et al. 1989).

The Badino Granite is a small intrusion in the northwestern part of the study area, exposed over an area of ca. 2.5 km^2. Most of its grains are about 0.5 mm in diameter, significantly smaller than in the Kalin Granite. The mineral assemblage is plagioclase, quartz, K-feldspar, biotite, and ilmenite. Biotite is dark greenish-brown and often contains ilmenite. Plagioclase grains are idiomorphic and have a clear growth zoning as well as growth (Albite and Karlsbader) and deformation twins. Most of the quartz grains show bulging and subgrain-rotation recrystallization. In contrast to the Kalin Granite, the Badino Granite shows a penetrative foliation often parallel to the contacts of the granite body and to the foliation in the adjacent Gneiss Series. Thus, it is not post-tectonic and may be older than the Kalin Granite. However, it is also possible that the ductile deformation lasted longer in this western part of the study area than in the east.

Padala Formation

The Padala Formation (Zagorchev et al. 1999) crops out to the east of Rila town, overlying the Gneiss Series. It is mostly a very poorly sorted and matrix-free breccia with angular to subrounded components ranging from sand size to blocks of several meters in diameter (Fig. 5b). In most places no bedding is visible. The breccia consists mainly of gneiss and mica schist components. Sporadically pegmatite, amphibolite, mylonitic gneiss and, near the boundary to the diorite, diorite fragments can be found. The mapping showed that the breccia was deposited on a non-planar, rugged surface with small valleys and ridges. The breccia is well lithified and forms rock towers and steep escarpments (Fig. 5a, b). In rare outcrops, up to 1 m thick greywacke layers can be found. In contrast to the unbedded breccia, these greywacke layers have bedding planes dipping gently to variable directions. Coal seams are also described from the Padala Formation (Zagorchev et al. 1999), which we did not find. The minimum thickness of the breccia is about 280 m.

The unsorted, matrix-free character of the breccia and the angular, up to several meters large clasts indicate deposition by rock avalanches and rockfalls. In contrast, the greywacke layers represent fluvial sediments. The dating of pollen and spores in the Padala Formation by Cernjavska (2000) established an Early Oligocene deposition age. Whereas the breccia rests on the hanging-wall gneisses with a depositional contact, it is separated from the footwall gneisses by the RPNF. An exception is an area south of the eastern end of the diorite, where the breccia rests on the footwall gneisses with a depositional contact (Fig. 3). This place is at a high level in the Padala Formation and, because of the overall shallowly-oriented layering, represents its youngest part. We therefore assume that the formation was mainly deposited during the activity of the RPNF (see below), its youngest layers postdating the activity.

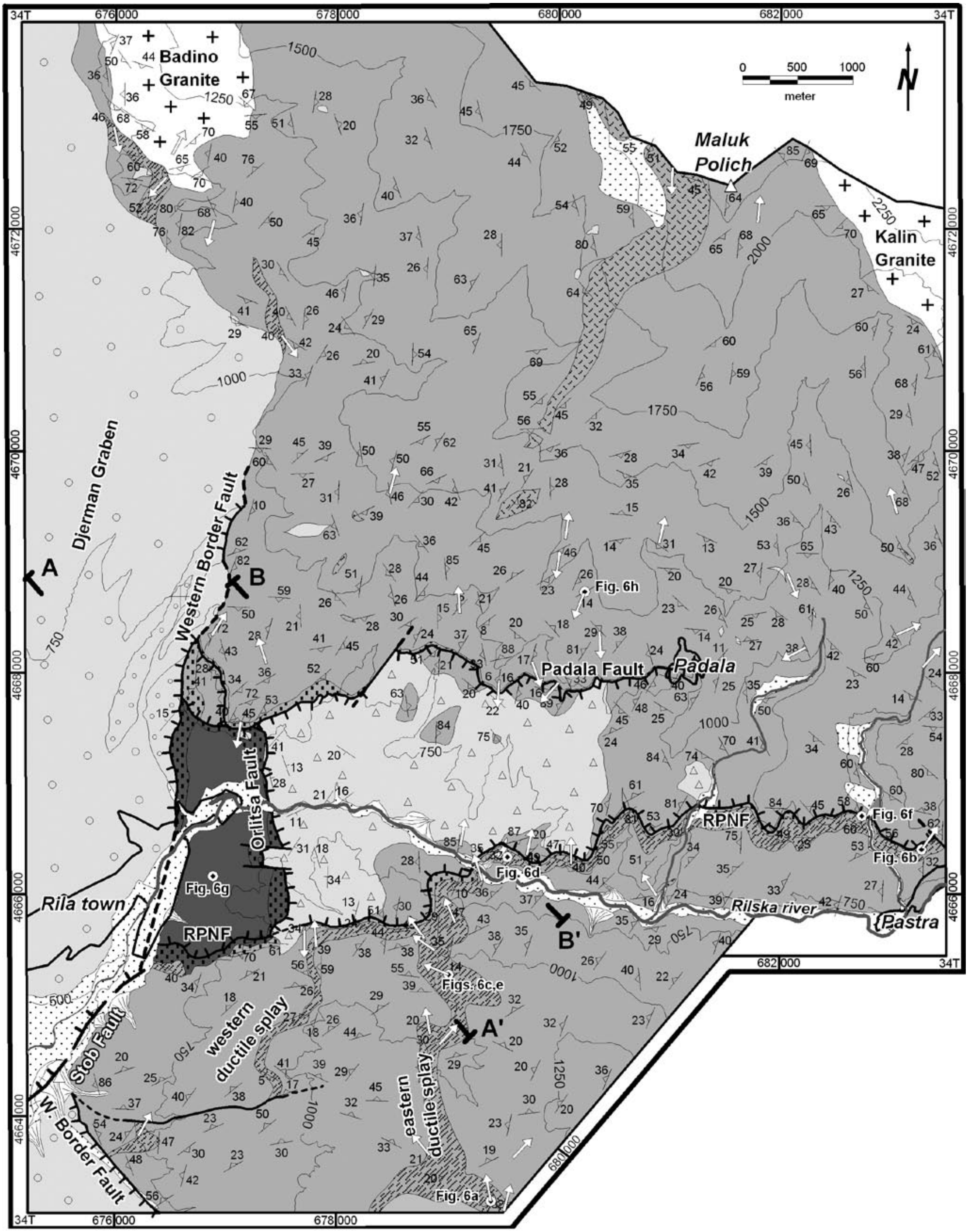


Fig. 3. Geological map of the study area. Senses of shear are indicated. UTM-coordinates (WGS84) are given in units of meters.

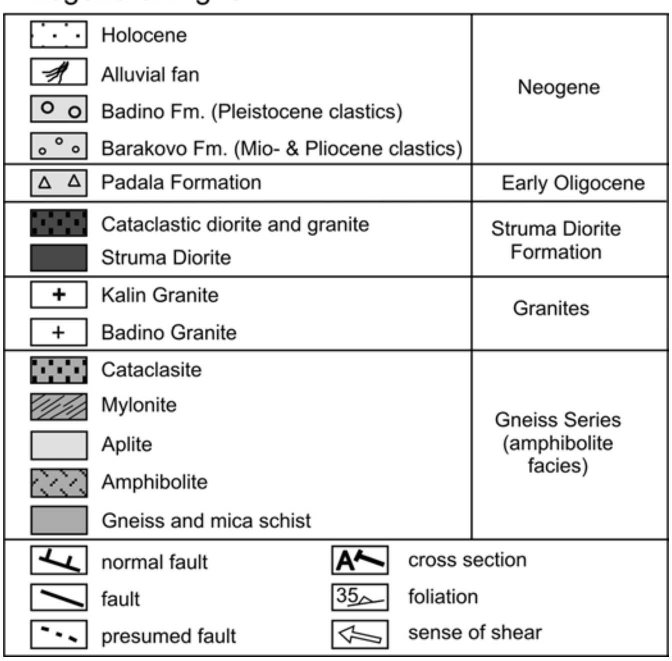
Neogene clastic sediments

The western part of the study area is covered by Neogene clastic sediments. Two units can be differentiated. The lower one is the Barakovo Formation of Miocene to Pliocene age (Zagorchev 1992). It is dominated by reddish sand with only few gravel components. The upper unit, the Badino Formation of Pleistocene age (Zagorchev 1992), is dominated by gravel and boulders of up to 2 m diameter. The components in both units are slightly to well rounded and comprise gneisses, mica schists, granites and diorites. Bedding is mostly subhorizontal. Near the western border of the exposed basement, bedding dips gently to the west. Both clastic units represent alluvial fan deposits filling the Djerman Graben.

Structures and tectonic evolution of the lower Rila valley

The study area records a long history of exhumation related to several generations of extensional shear zones and faults. The most prominent structure is the RPNF with its associated footwall mylonites. The older Gabrov Dol Detachment is not exposed in the study area, but most likely underlies the diorite. We suggest that the Padala Formation with a depositional contact covers its trace at the surface. Following the RPNF activity, the poorly exposed brittle Western Border Fault controlled the deposition of Neogene sediments to the west. Present day deformation takes place along the Stob Fault, reactivating a part of the Western Border Fault to the southwest of Rila town.

Legend of Fig. 3



Pre-Rila-Pastra-Normal-Fault structures; Gabrov Dol Detachment

The foliation and the predominantly N–S-striking stretching lineation of the Gneiss Series in the hanging wall of the RPNF are probably the oldest preserved tectonic structures in the lower Rila valley. Although the foliation is pervasive, some zones are distinguished by their particularly strong, mylonitic deformation (Fig. 3). Thin sections parallel to the stretching lineation show both top-to-the-north and top-to-the-south shear senses. It appears that quartz was predominantly recrystallized by grain boundary migration in rocks that display a top-to-the-south sense of shear, and that top-to-the-north shearing is mainly associated with subgrain-rotation recrystallization of quartz. Since grain boundary migration occurs under higher temperatures than subgrain rotation (Stipp et al. 2002; Passchier & Trouw 2005), and the overprinting of deformation structures in individual thin sections generally indicates decreasing temperatures, it is likely that top-to-the-south shearing took place before the top-to-the-north shearing. These relations require, however, a more detailed study before they can be interpreted in terms of tectonic evolution. The shearing of the Gneiss Series in the hanging wall took place before the intrusion of the post-tectonic Kalin Granite (ca. 46 Ma, Arnoudov et al. 1989) and also before the intrusion of the undeformed pegmatites dated at ca. 63 Ma (Boyadjiev & Lilov 1976), that is, before the earliest Tertiary. Therefore the exhumation of the hanging-wall Gneiss Series is related to unroofing events prior to the formation of the RPNF. Possible unroofing faults are the Gabrov Dol and Djerman detachment faults described by Bonev et al. (1995) and Shipkova & Ivanov (2000), respectively.

The contrast in metamorphic grade between the Struma Diorite body at Rila town, which was overprinted under prehnite-pumpellyite facies conditions only, and the surrounding and underlying high-amphibolite-facies gneisses, requires important relative displacements along faults separating these units. To the south, this could be the RPNF. To the north, a similar contrast exists between the diorite and the gneisses in the hanging wall of the RPNF. At the surface they are only separated by a steeply dipping, brittle fault zone with a north-side-up sense of movement (Padala Fault, Figs. 3, 4), which cannot explain the contrast in metamorphism. As outlined above, north of the study area the Gabrov Dol Detachment separates the Struma Diorite Formation and Frolosh Greenschists in its hanging wall from the Upper Complex in its footwall (Bonev et al. 1995; Fig. 1). It is a major detachment fault with a northwestward to westward sense of shear that unroofed the Rhodope Metamorphic Province (Bonev et al. 1995). The Gabrov Dol Detachment was formed under greenschist facies conditions and active under progressively decreasing temperatures. The 73 Ma old Plana Pluton (Boyadjiev 1981) cuts the Gabrov Dol Detachment (Ricou et al. 1998; Fig. 1). Consequently, this detachment fault must also be older than the Early Oligocene Padala Formation in our study area.

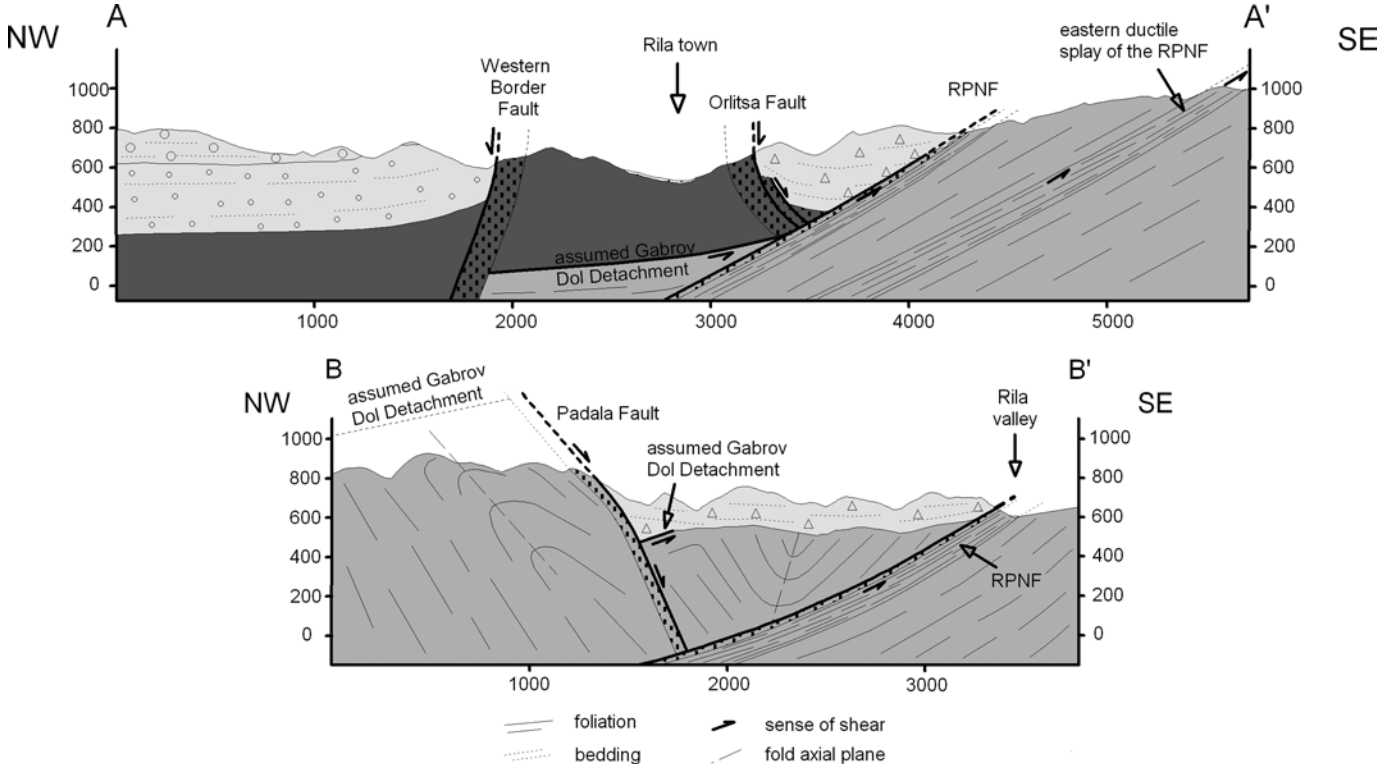


Fig. 4. NW–SE running cross sections AA' and BB' (for location see Fig. 3). Lithological signatures are the same as in Fig. 3.

By combining our observations with the results of Bonev et al. (1995) we suggest that the Gabrov Dol Detachment lies in a gently dipping orientation at the base of the diorite. East of the diorite, it reached the paleo-surface in the area now covered by the Padala Formation (Fig. 4). South of the diorite and the breccia, the Gabrov Dol Detachment was excised by the RPNF. North of the diorite it was cut by the Padala Fault.

Rila-Pastra Normal Fault (RPNF)

The RPNF crops out in the southern part of the study area. It is an E–W-striking brittle fault, underlain by cataclasites and mylonites (Fig. 4), and two associated ductile fault splays within its footwall. Both splays trend N–S to NE–SW and merge into the main fault zone to the north (Fig. 3).

The RPNF forms the boundary between the Struma Diorite Formation and the Gneiss Series in the western part of the study area. To the east, it represents the boundary between the Padala Formation and the Gneiss Series and still further east it lies within the Gneiss Series. The fault is made up of 10 to 30 m thick cataclasites throughout the study area, derived from diorite and gneiss in the west and derived from gneiss and mica schist in the east. In general, the cataclastic rocks show no foliation or lineation.

A mylonitic gneiss and mica schist layer of 30 to 140 m thickness underlies the cataclasites. The footwall splays are made up exclusively of mylonitic gneiss and mica schist. The mylonitic rocks exhibit a pronounced foliation and lineation (Figs. 5c, 5d, 6a-d, 7). The foliation of the mylonites directly below the RPNF strikes E–W and shallowly to moderately dips north, whereas the foliation of the ductile splays strikes more NE–SW and dips northwest. The mylonite lineation strikes NW–SE to NNE-SSW and mostly plunges gently to the NW to NNE (Fig. 7f). Shear-sense criteria at various scales show that shearing was consistently top-to-the-north to -northwest (Figs. 3, 5, 6) with only few exceptions, which can be explained by conjugate shear domains.

The mylonites show signs of deformation under high greenschist- to amphibolite-facies conditions and a variable degree of retrograde overprinting. Several samples show dynamic recrystallization of quartz by grain boundary migration, typical for high greenschist- to amphibolite-facies conditions (above 500 °C, Stipp et al. 2002), and only minor retrograde overprinting (Fig. 6a). In these samples, feldspar is often dynamically recrystallized, leading to core-and-mantle structure of porphyroclasts (Fig. 6b). In other samples, subgrain rotation is the dominant recrystallization mechanism in quartz (between 400 and 500 °C, Stipp et al. 2002). Bulging recrystallization, typical for the temperature range 280 to 400 °C (Stipp et al. 2002) is observed as well (Fig. 6e). Lower-greenschist-facies overprinting (chloritisation) is almost ubiquitous within mylonites of the RPNF itself, close to the cataclasites. The structurally uppermost mylonites are in some places ultramylonites with an extremely small grain size (Fig. 6d). The cataclastic fault rocks

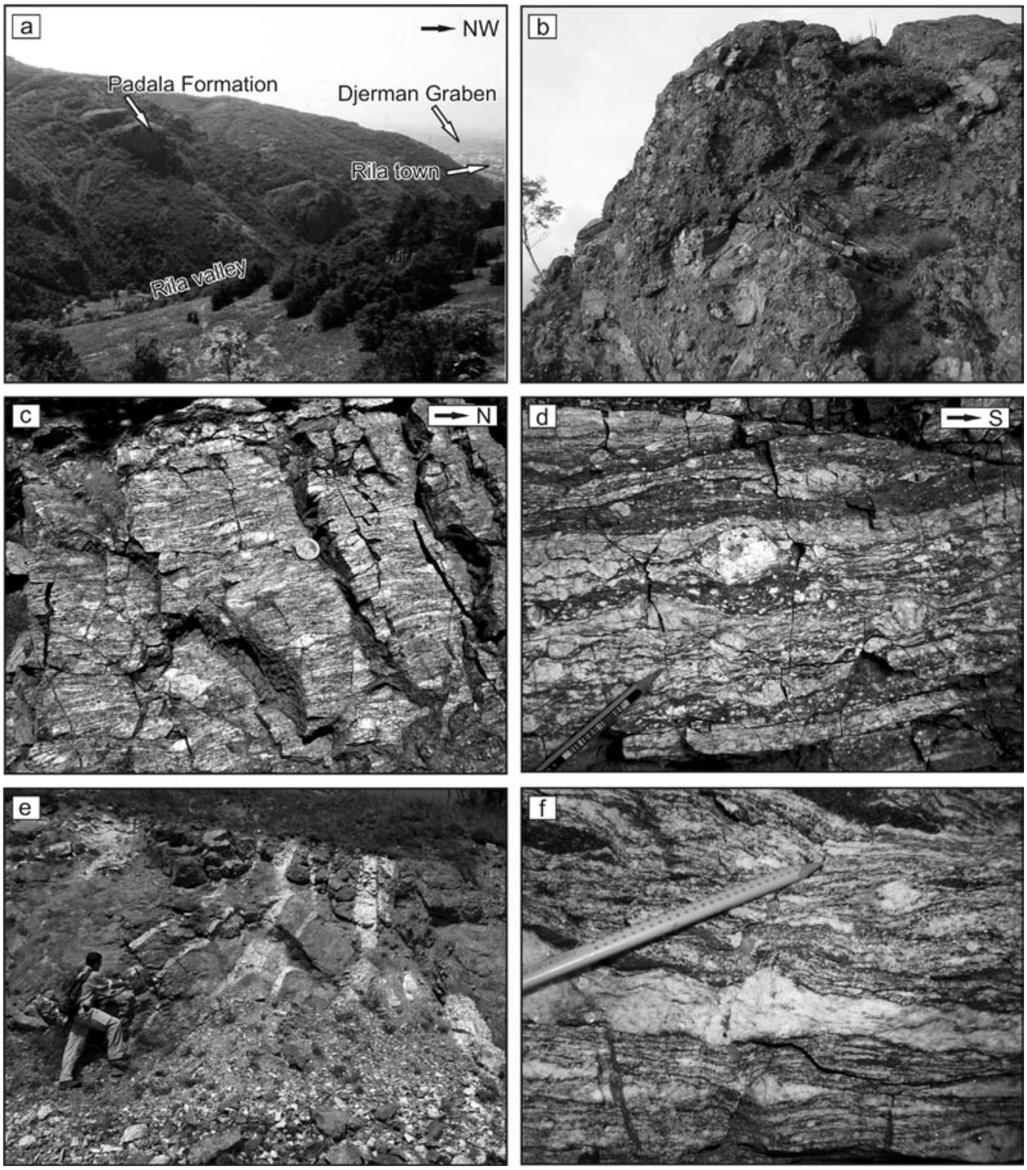


Fig. 5. Field pictures. a) Looking southwest across the lower Rila valley. These escarpments are built by the Padala Formation. Roughly southward-dipping bedding is visible. b) Escarpment of the Padala Formation. The components consist mainly of gneiss and mica schist fragments (34 T, r 677931, h 4666343). c) Top-to-the-north, greenschist-facies mylonite of the RPNF. The coin is 3 cm in diameter (34 T, r 679380, h 4666385). d) Top-to-the-north, greenschist-facies mylonite of the RPNF. Quartz flows around large feldspar porphyroclasts. Shear bands and sigma clasts show sinistral shear-sense (34 T, r 680121, h 4666272). e) Cataclastic gneiss with numerous pegmatite dykes in the hanging wall of the RPNF (34 T, r 680451, h 4667417). f) Migmatitic, biotite-rich orthogneiss in the footwall of the RPNF, 2 km west of Pastra village (34 T, r 680894, h 4665984).

are derived partly from mylonites, partly from hanging-wall rocks (diorite) and have a variable, generally small grain size (Fig. 6f). Thus, the RPNF shows a successive development from amphibolite-facies ductile flow to near-surface brittle deformation. The fault rocks reflect progressively lower temperatures towards the hanging wall, as is typical for extensional faults and shear zones. Hanging wall rocks are partly unmetamorphic to very-low-grade metamorphic (Struma Diorite Formation, Fig. 6 g), partly experienced similar conditions as the footwall rocks but at an earlier time (Gneiss Series, Fig. 6 h).

On a whole, the RPNF is oblique to the pervasive, amphibolite-facies foliation of the footwall (Fig. 3). However, when approaching the RPNF, the foliation of the footwall smoothly curves into parallelism with it. Moreover, the two ductile splays in the footwall are approximately parallel to the footwall foliation and merge upward into the mylonites underlying the RPNF. Therefore, the RPNF nowhere truncates structures of the footwall. We suggest that the pervasive foliation of the Gneiss Series in the footwall is related to the same extensional deformation that produced the RPNF. It de-

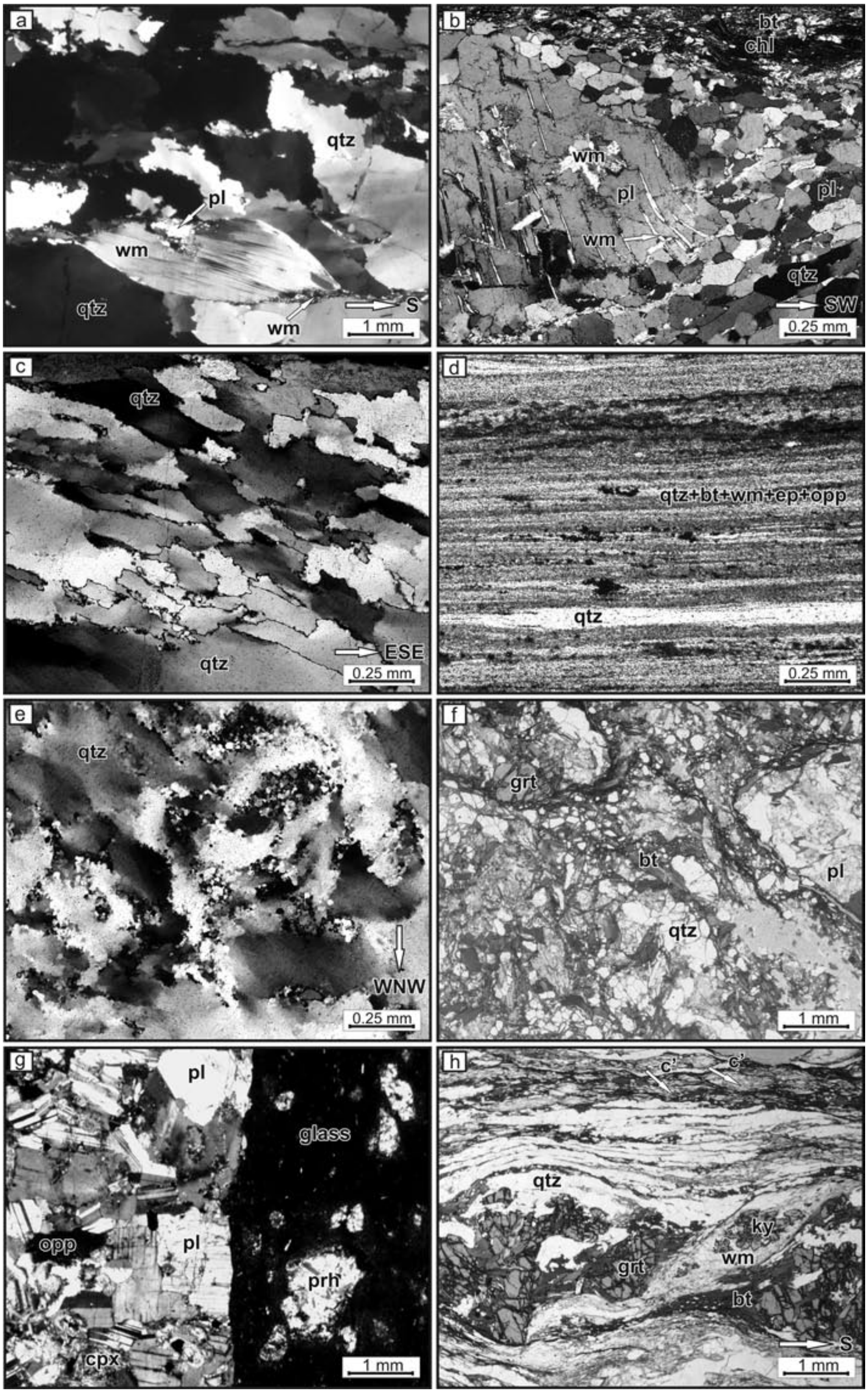


Fig. 6. Thin section micrographs of RPNF fault rocks and two samples from its hanging wall (g, h). From a) to f) the pictures show deformation under progressively colder conditions. For sample localities see Fig. 3. a,b,c,e: crossed polars; d,f,g,h: plane polarised light. Mineral abbreviations after Kretz (1983), wm = white mica, opp = opaque phase. If not mentioned otherwise the thin section shows the X-Z plane of strain parallel to the stretching lineation and normal to the foliation. a) Quartz recrystallized by grain boundary migration. The large mica fish shows a top-to-the-north sense of shear. b) Strongly mylonitized orthogneiss. Large plagioclase crystal surrounded by recrystallized plagioclase grains (core-mantle structure) showing triple junctions. c) Quartz recrystallized by subgrain rotation. Oblique foliation showing a top-to-the-WNW sense of shear. d) Ultramylonitic gneiss, containing few bright quartz-rich layers. e) Bulging recrystallization of quartz in an X-Y thin section. f) Cataclastic gneiss of the RPNF. g) Diorite of the Struma Diorite Formation (left) with basalt dyke (right) in the hanging wall of the RPNF. The magmatic texture is well preserved in both. Note the occurrence of prehnite in the basalt. h) Garnet-mica schist from the hanging wall of the RPNF, showing garnet partly transformed into biotite and a mica fish containing kyanite. Shear bands (parallel to the arrows) and sigma clasts indicate top-to-the-south sense of shear.

veloped before the extensional deformation was localized in relatively narrow shear zones. The different strike directions of the RPNF (E–W) and the footwall shear zones (NE–SW) suggest that during the development of the extensional fault system, the extension direction rotated from NW–SE to N–S. This may also explain the large scatter of stretching lineations (Fig. 7f).

The Padala Formation was deposited on top of the RPNF hanging wall and consists of rock fragments derived from the exhumed footwall, except for minor diorite clasts near the

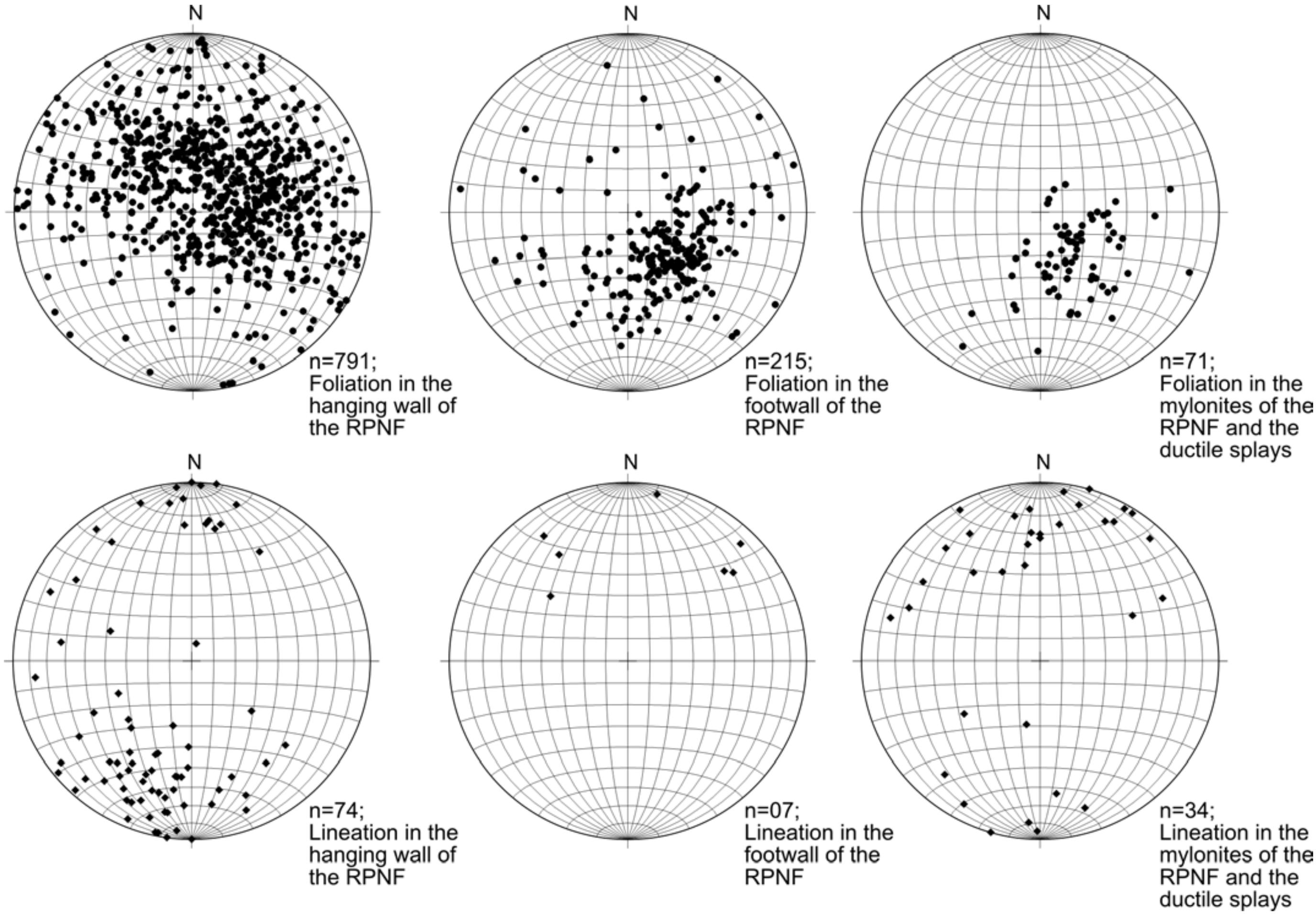


Fig. 7. Stereographic projections of measured foliations and lineations, lower hemisphere.

contact to the diorite. The onlap of the youngest parts of the breccia on the footwall southeast of Rila town indicates that the breccia deposition locally outlasted the activity of the fault. In the remaining area, the breccia is separated from the footwall by the fault. Therefore we assume that the breccia deposition was syn- to post-tectonic with respect to the RPNF. As the breccia was deposited in the Early Oligocene (Cernjavska 2000), we interpret the RPNF as an Eocene to Early Oligocene structure.

The brittle Padala Fault north of Rila town trends E–W and is marked by a zone of 10 to 30 m thick cataclastically deformed gneisses, mica schists and pegmatites. This fault defines the northern limit of the Padala Formation and the Struma Diorite Formation. The outcrop pattern indicates that the orientation of the fault changes significantly along its length. The dip direction varies from north- to southward and the dip angle from ~30 to 90°. This may be partly explained by recent slope instability. However, the map pattern indicates that the Padala Fault developed from several independent fault segments subsequently linked together to form the observed, variably oriented fault. We assume that these faults developed as steeply dipping normal faults, conjugate to the RPNF (Fig. 8). The Orlitsa Fault, i.e. the eastern, steeply dipping, N–S-striking border fault of the diorite against the Padala Formation (Fig. 3, 4), probably formed as an antithetic, hanging-wall-block-bounding fault of the Gabbrov Dol Detachment. It may have been reactivated during the activity of the RPNF and deposition of the Padala Formation.

Western Border Fault

Extension along the brittle Western Border Fault postdates the activity of the RPNF. This structure crops out in few locations along the border between the Neogene sediments and the Gneiss Series, but is mostly covered by sediments. The outcrop pattern indicates that the Western Border Fault strikes roughly N–S and dips steeply west. Where it is exposed (north of Rila town), the fault truncates the foliation in the gneisses, and is characterized by cohesionless fault breccia and gouge. We did not find any mylonites related to this fault. Sand and gravel of Pleistocene age (Badino Formation, Zagorchev 1992) cover parts of the fault, showing that the activity of the Western Border Fault mostly ended before the Pleistocene. It controlled the sedimentation of the Neogene clastics in the Djerman Graben.

Due to its completely brittle character and steep orientation, the Western Border Fault cannot be the continuation of the Djerman Detachment (Shipkova & Ivanov 2000), a moderately northwest-dipping, greenschist-facies mylonite zone overlain by cataclasites. We assume that the Western Border Fault truncates the Djerman Detachment north of our study area. Since the Djerman Detachment has a similar orientation as the RPNF, these two faults may be of the same age.

Stob Fault and active tectonics

The present-day deformation in southwestern Bulgaria as determined by GPS data and earthquake fault plane solutions (Kotzev et al. 2006) is still extensional, but with a N–S direction of extension, and forms the northernmost part of the Aegean extensional domain. Presently active normal faults mostly trend WNW–ESE and ENE–WSW (Tranos et al. 2006). The earthquake-generating Krupnik Fault (Fig. 1; Zagorchev 1970; Tranos et al. 2006) is located ca. 20 km south of our study area. Within the study area the active Stob Fault (Tranos et al. 2006) is the NE–SW striking part of the Western Border Fault to the southwest of Rila town, reactivated in the Holocene. It forms the northwestern border of the southernmost basement outcrops (Fig. 2, 3). Further southwest, the fault represents the boundary between relatively uplifted Neogene sediments to the southeast and Pleistocene to Holocene alluvial sediments of the Rilska River to the northwest. Tranos et al. (2006) estimated a Holocene vertical offset of ca. 1 m along the Stob Fault.

Discussion

Comparison with earlier tectonic studies of the Rila area

Shipkova & Ivanov (2000) described the northwest-dipping Djerman Detachment Fault that forms the northwestern border of the Rila Mountains ca. 15 km north of our study area. We have visited this area and agree with Shipkova & Ivanov (2000) that the Djerman structure is an important, mylonitic to cataclastic, moderate- to low-angle normal fault. They assumed that this detachment continues south along the western slope of the Rila Mountains, that is, where we mapped the Western Border Fault, turns east at Rila town, follows the northern border of the Struma Diorite body and the Padala Formation (our Padala Fault), curves around the eastern end of the outcrop area of this formation, and continues along the fault which we have described as the RPNF. Thus, they already described the mylonites and cataclasites of the RPNF in the Rila valley as belonging to an extensional detachment fault. This is confirmed by our work. However, we cannot confirm their assumption that the Djerman Detachment Fault continues into the RPNF. We found no mylonites related to the Western Border Fault but just a steep zone of brittle deformation, neither did we find a mylonite zone along the Padala Fault. Instead, our mapping indicates that the RPNF extends east along the Rila valley to Pastra and probably further on.

Westaway (2006) also reports some observations from the profile in the Rila Valley. He “could see no evidence of mylonitization of the underlying basement” (below the Padala Formation) and therefore assumes that the basement / Padala Formation contact is an unconformity surface. This is true for the Rila valley road itself (Fig. 3), because there the Padala Formation rests on a thin layer of hanging-wall gneiss, but only some hundred meters away, on the small side road to Padala, mylonites and cataclasites directly underlying the Padala Formation are well exposed (e.g., Fig. 6d).

Prolongation of the Rila-Pastra Normal Fault towards the east and west

We followed the RPNF up to Pastra village, at the eastern border of the map area (Fig. 3). Its continuation further east is still speculative. The map pattern (Fig. 2) shows that the southern end of the Kalin Granite lies along the eastward extrapolation of the RPNF trace. If the fault in fact continues like this, the Kalin Granite should be older than at least the late activity stages of the RPNF, which is in line with the ages determined for the Kalin Granite (ca. 46 Ma; Arnaudov et al. 1989) and for the syn-RPNF Padala Formation (Early Oligocene, Cernjavska 2000). The large granite mass exposed in the southeast corner of the map area (Fig. 2) might then even represent a lower part of the Kalin Granite pluton, exhumed by top-to-the-northwest displacement along the RPNF. Southeast of the Kalin granite, the map pattern suggests a sinistral offset of metabasite layers by ca. 5 km. This offset appears quite small for the RPNF, if it continues in this direction. However, in view of the top-to-the-north to -northwest kinematics of the RPNF, this sinistral offset may just be the horizontal component of a much larger displacement. On the other hand, it is possible that the RPNF follows a different trace towards the east, and that the sinistral offset is caused by some other fault. Additional field and laboratory work is necessary to answer these questions. Towards the southwest, a low-angle normal fault contact between Frolosh Greenschists and gneisses near Blagoevgrad (Fig. 2) may represent the continuation of the RPNF.

Age of metamorphism in the hanging-wall gneisses

Since the Gabrov Dol Detachment is, according to Ricou et al. (1998), cut by the ca. 73 Ma Plana Pluton, it is probably Late Cretaceous in age or older. A Late Cretaceous age appears most likely because the detachment is nowhere sealed by strata older than Tertiary (Ricou et al. 1998). Having explained the contrast in metamorphism between the diorite and the Gneiss Series by the unroofing Gabrov Dol Detachment, we then have to assume that the metamorphism of the Gneiss Series north of the Rila Detachment is also Cretaceous in age (or, less likely, older). This is supported by the ca. 63 Ma age of the undeformed, post-metamorphic pegmatite (Boyadjiev & Lilov 1976), although this K-Ar muscovite age may not be very reliable. In contrast, the metamorphism in the footwall of the RPNF is probably Eocene in age, but not younger than Early Oligocene because the footwall rocks were at the surface in the Early Oligocene when they were locally covered by the Padala Formation.

Tectonic evolution of the western Rila Mountains

South of the Rila valley, the Strymon Valley Detachment was active in the Miocene (16 to 3.5 Ma) as a top-southwest, low-angle detachment fault (Dinter 1998). Thus, it is younger than the RPNF and localized at a deeper level, forming the top of the Pangaion-Pirin Complex. From the existing maps and our own observations, we assume that the Strymon Valley Detachment does not continue to the north as far as our study area, but that it looses displacement and dies, which may be explained by a vertical-axis relative rotation of the two fault blocks (Brun & Sokoutis 2007). The northward loss of displacement of the Strymon Valley Detachment is paralleled by the narrowing and final disappearance of the Pangaion-Pirin Complex, which was exhumed by the detachment (Fig. 2). The west-dipping Ribnovo Detachment Fault along the east side of the Mesta Graben (Burchfiel et al. 2003) is Late Eocene to Oligocene in age, similar to the RPNF. Taken together, three generations of important normal faults can be observed in the western part of the Rhodope Metamorphic Province: A Late Cretaceous one at the top of the Upper Complex (Gabrov Dol Detachment), an Eocene-Oligocene one within the Upper Complex (RPNF, Ribnovo Detachment), and a Miocene one at the base of the Upper Complex (Strymon Valley Detachment).

This situation is similar to the Alps where Late Cretaceous extensional detachment faults are found in the uppermost units, the Austroalpine nappes (e.g. Schlinig Fault, Froitzheim et al. 1997), Eocene to Oligocene detachments at an intermediate structural level (e.g. Turba Normal Fault, Nievergelt et al. 1996), and Miocene detachments at the deepest levels (e.g. Simplon Fault, Mancktelow 1985). It should be noted that the extensional faults in the uppermost units (Austroalpine) were active before these units were emplaced by thrusting on the lower structural levels. A similar situation may apply to the Western Rhodopes, where the emplacement of the Upper Complex on the Pangaion-Pirin Complex along the Nestos Thrust (Fig. 1) probably occurred in the Early Tertiary (Dinter 1998), postdating the activity of the Gabrov Dol Detachment. This suggests repeated changes between crustal shortening and extension during the evolution of the Rhodopes, as also observed in the Alps (Froitzheim et al. 1994; Beltrando et al. 2007).

The northwestern Rhodope Province shares several characteristics with the Eastern Rhodopes. The Alpine evolution of both areas was determined by extensional detachment fault systems that cut through the Upper Complex. Exhumation and subsequent cooling of detachment fault footwall units in the Eastern Rhodopes (Kardamos and Kechros domes) occurred between 55 and 35 Ma (Lips et al. 2000; Krohe & Mposkos 2002; Marchev et al. 2003). North of the Kardamos dome a coarse, syn-detachment breccia, comparable to the Padala Formation, crops out. Phytofossils in marl and clayey limestone beds within this breccia point to a Maastrichtian to Paleocene age (Bonev et al. 2006). This region was also affected by intrusions of granitoids, between 70 and 53 Ma in age (Ovtcharova et al. 2003; Marchev et al. 2004). An important difference is that the marine transgression in the Eocene, which took place in the Eastern Rhodopes during the Eocene, did probably not reach the Rila area. A further distinction is the lack of evidence for a high-pressure or ultrahigh-pressure metamorphic history in the northwest. However, this may be due to the fact that this region has been less well examined so far. It is possible that the Gneiss Series we described has been exhumed from deep structural levels, comparable to the metamorphic units in the Eastern Rhodopes.

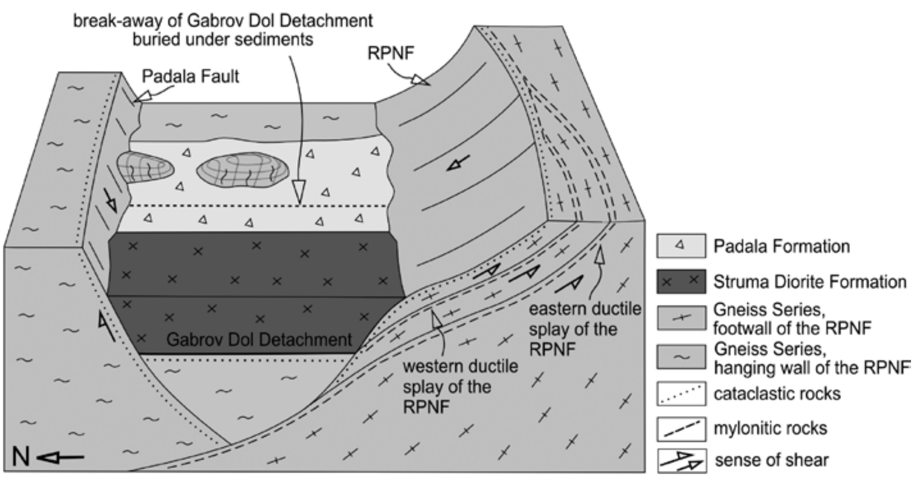


Fig. 8. Block diagram schematically showing the main tectonic features of the study area: The RPNF and its two ductile splays, the buried Gabrov Dol Detachment and the brittle Padala Fault.

Conclusions

We have shown that the lower Rila valley was subject to multistage extensional unroofing from probably the Late Cretaceous up to the present day. Based on the work presented above and that of other authors we distinguish four stages:

(1) Late Cretaceous NW–SE extension

The Gabrov Dol Detachment (Bonev et al. 1995), probably of Late Cretaceous age, contributed to the exhumation of the Gneiss Series in the present-day hanging wall of the RPNF. This major detachment dips shallowly to the northwest with a top-to-the-northwest sense of shear. It was formed under greenschist-facies conditions and active under progressively decreasing temperatures. We suggest its location at the base of the diorite in the lower Rila valley. This would explain the considerable difference in metamorphic grade between the Gneiss Series (footwall of the detachment) and the low-grade overprint of the diorite (hanging wall of the detachment).

(2) Eocene to Early Oligocene NW–SE to N–S extension

The RPNF was active from Eocene to Early Oligocene time. Its fault zone includes, from base to top, mylonites, ultramylonites and cataclasites, indicating deformation under progressively decreasing temperature, from amphibolite-facies to low-temperature brittle deformation. With a top-to-the-north to -northwest sense of shear, it exhumed the southern part of the Gneiss Series and probably truncated the Gabrov Dol Detachment. Thereby two different blocks of the Gneiss Series were established, both displaying amphibolite-facies conditions. However, the foliation of the hanging-wall gneisses is discordantly cut by the fault, while the foliation of the footwall gneisses is seen to curve into parallelism with the fault when approaching it. The concordance between the foliation in the footwall and the RPNF suggests that deformation and cooling in the footwall occurred simultaneously with extensional shearing, while the hanging-wall gneisses had already been exhumed previously. The Early Oligocene Padala Formation was deposited syn-kinematically on top of the RPNF hanging wall. Fig. 8 schematically shows the relationship between faults of the first two extensional stages and the deposition of the Padala Formation, covering the Gabrov Dol Detachment.

(3) Miocene to Pliocene E–W extension

The steeply westward dipping brittle Western Border Fault represents the border between the Neogene sediments and the Gneiss Series. Where it is exposed (north of Rila town), the fault truncates the foliation in the gneisses, and is characterized by cohesionless fault breccia and gouge. No mylonites related to the Western Border Fault were found. Pleistocene clastic sediments cover large parts of the fault trace. The Western Border Fault is responsible for the formation of the Djerman graben and the deposition of the Neogene clastic sediments.

(4) Holocene to recent N–S to NW–SE extension

The Stob fault (Tranos et al. 2006) is the NE–SW striking part of the Western Border Fault to the southwest of Rila town that was reactivated in the Holocene. It dips to the northwest and forms the northwestern border of the basement outcrops in the southern part of the study area. Further southwest, the Stob fault represents the boundary between relatively uplifted Neogene sediments to the southeast and Pleistocene to Holocene alluvial sediments of the Rilska river to the northwest.

We presented structural and microstructural data to help unravel the extensional tectonic history of the northwestern Rhodope Metamorphic Province. Further work is essential to test our conclusions and to better tie the inferred relative timing of events into an absolute time frame.

Acknowledgments

We thank reviewers Alexandre Kounov and Clark Burchfiel as well as guest editor Stefan Schmid for their careful reviews, which helped us significantly to improve the article. We also thank Zhivko Ivanov for introducing us to the geology of Bulgaria and in particular the Rila area. Supported by DFG project FR700/10–1 and by DAAD program "PPP Bulgaria".

REFERENCES

Arnaudov, V., Amov, B., Bratnitskij, E. & Pavlova, M. 1989: Isotope geochronology of magmatic and metamorphic rocks in Balkanides and Rhodopean massif (in Russian). In: XIV KGBA Conference, Ext. abstr., 1154–1157.

Bauer, C., Rubatto, D., Krenn, K., Proyer, A. & Hoinkes, G. 2007: A zircon study from the Rhodope metamorphic complex, N-Greece: Time record of a multistage evolution. Lithos 99(3–4), 207–228.

Beltrando, M., Hermann, J., Lister, G. & Compagnoni, R. 2007: On the evolution of orogens: Pressure cycles and deformation mode switches. Earth and Planetary Science Letters 256(3–4), 372–388.

Boncev, E. 1988: Notes sur la tectonique alpine des Balkanides. Bulletin de la Société géologique de France 2, 241–249.

Bonev, K., Ivanov, Z. & Ricou, L.-E. 1995: Dénudation tectonique au toit du noyau métamorphique rhodopien-macédonien: La faille normale ductile de Gabrov Dol (Bulgarie). Bulletin de la Société géologique de France 166(1), 49–58.

Bonev, N. & Stampfli, G. 2008: Petrology, geochemistry and geodynamic implications of Jurassic island arc magmatism as revealed by mafic volcanic rocks in the Mesozoic low-grade sequence, eastern Rhodope, Bulgaria. Lithos 100(1–4), 210–233.

Bonev, N., Burg, J.P. & Ivanov, Z. 2006: Mesozoic-Tertiary structural evolution of an extensional gneiss dome – the Kesebir-Kardamos dome, eastern Rhodope (Bulgaria-Greece). International Journal of Earth Sciences 95(2), 318–340.

Bonev, N.G. & Stampfli, G.M. 2003: New structural and petrologic data on Mesozoic schists in the Rhodope (Bulgaria): geodynamic implications. Comptes Rendus Geoscience 335(8), 691–699.

Boyadjiev, S. 1981: Potassium-Argon Studies of the Middle Alpine intrusions in the Central Srednogorie. Bulletin de l'Institut de Géochimie,

Minéralogie, Pétrologie de l'Académie Bulgare des Sciences 14, 28–45.
Boyadjiev, S. & Lilov, P. 1976: Data obtained by the K/Ar method on the south-Bulgarian granitoids in the Western Rhodope Block and the Kraishtides (in Bulgarian). Review of the Bulgarian Geological Society 37(2), 161–169.
Brun, J.P. & Sokoutis, D. 2007: Kinematics of the Southern Rhodope Core Complex (North Greece). International Journal of Earth Sciences 96(6), 1079–1099.
Burchfiel, B.C. 1980: Eastern-European Alpine System and the Carpathian Orocline as an example of collision tectonics. Tectonophysics 63(1–4), 31–61.
Burchfiel, B.C., Nakov, R. & Tzankov, T. 2003: Evidence from the Mesta half-graben, SW Bulgaria, for the Late Eocene beginning of Aegean extension in the Central Balkan Peninsula. Tectonophysics 375(1–4), 61–76.
Burg, J.-P., Ricou, L.-E., Ivanov, Z., Godfriaux, I., Dimov, D. & Klain, L. 1996: Syn-metamorphic nappe complex in the Rhodope Massif. Structure and kinematics. Terra Nova 8, 6–15.
Cernjavska, S. 2000: Palynological analysis of samples from the Padala Formation. Geologica Balcanica 20, 1–2.
Dercourt, C., Zoneneshain, L.P., Ricou, L.-E., Kazmin, V.G., Le Pichon, X., Knipper, A.L., Grandjacquet, C., Sbortshikov, I.M., Geyssant, J., Lepvrier, C., Perchesky, D.H., Boulin, J., Sibuet, J.-C., Savostin, L.A., Sorokhtin, O., Westphal, M., Bazhenov, M.L., Lauer, J.P. & Biju-Duval, B. 1986: Geological evolution of the Tethys belt from the Atlantic to the Pamirs since the Lias. Tectonophysics 123, 241–315.
Dinter, D.A. 1998: Late Cenozoic extension of the Alpine collisional orogen, northeastern Greece: Origin of the north Aegean basin. Geological Society of America Bulletin 110(9), 1208–1226.
Froitzheim, N., Schmid, S.M. & Conti, P. 1994: Repeated Change from Crustal Shortening to Orogen-Parallel Extension in the Austroalpine Units of Graubünden. Eclogae Geologicae Helvetiae 87(2), 559–612.
Froitzheim, N., Conti, P. & van Daalen, M. 1997: Late Cretaceous, synorogenic, low-angle normal faulting along the Schlinig fault (Switzerland, Italy, Austria) and its significance for the tectonics of the Eastern Alps. Tectonophysics 280(3–4), 267–293.
Graf, J. 2001: Alpine tectonics in western Bulgaria: Cretaceous compression of the Kraište region and Cenozoic exhumation of the crystalline Osogovo-Lisec Complex. PhD thesis. ETH Zürich, 182 pp.
Haydoutov, I., Kolcheva, K. & Daieva, L. 1992: On the genesis of the Struma Diorite Formation. Comptes rendus de l'Académie Bulgare des Sciences 45(6), 67–69.
Hsü, K.J., Nachev, I. & Vuchev, V. 1977: Geologic evolution of Bulgaria in the light of plate tectonics. Tectonophysics 40, 245–256.
Ivanov, Z. 1988: Aperçu général sur l'évolution géologique et structurale du massif des Rhodopes dans le cadre des Balkanides. Bulletin de la Société géologique de France 8(IV-2), 227–240.
Ivanov, Z., Dimov, D. & Sarov, S. 2000: Tectonic position, structure and tectonic evolution of the Rhodopes massif. In: Z. Ivanov (Ed.): Structure, Alpine Evolution and Mineralizations of the Central Rhodope area (South Bulgaria). ABCD-GEODE 2000 Workshop, Borovets, Sofia University, Bulgaria, 1–20.
Kaufmann, G., Kockel, F. & Mollat, H. 1976: Note on the stratigraphic and palaeogeographic position of the Svoula formation in the Innermost Zone of the Hellenides (Northern Greece). Bulletin de la Société géologique de France 18(2), 225–230.
Kober, L. 1928: Der Bau der Erde. Borntraeger, Berlin. 499 pp.
Kockel, F., Mollat, H. & Walther, H.W. 1977: Erläuterungen zur geologischen Karte der Chalkidiki und angrenzender Gebiete 1:100'000 (Nordgriechenland). Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover, 119 pp.
Kolcheva, K. & Cherneva, Z. 1999: Metamorphic evolution of metapelites from the northwestern Rila Mountain. Geochemistry, Mineralogy and Petrology 36, 45–66.
Kolcheva, K., Zeljazkova-Panajotova, M., Dobrecov, N.L. & Stojanova, V. 1986: Eclogites in the Rhodope Metamorphic group and their retrograde metamorphism (in Russian). Geochemistry, Mineralogy and Petrology 20–21, 130–144.
Kossmat, F. 1924: Geologie der zentralen Balkanhalbinsel. In: Wilser, J. (Ed.): Die Kriegsschauplätze 1914–1918 geologisch dargestellt. Gebrüder Borntraeger, Berlin, 1–198.
Kotzev, V., Nakov, R., Georgiev, T., Burchfiel, B.C. & King, R.W. 2006: Crustal motion and strain accumulation in western Bulgaria. Tectonophysics 413, 127–145.
Kounov, A. 2002: Thermotectonic evolution of Kraishte, Western Bulgaria. PhD thesis, ETH Zürich, 219 pp.
Kretz, R. 1983: Symbols for Rock-forming Minerals. American Mineralogist 68(1–2), 277–279.
Krohe, A. & Mposkos, E. 2002: Multiple generations of extensional detachments in the Rhodope Mountains (northern Greece): evidence of episodic exhumation of high-pressure rocks. In: Blundell, D.J. et al. (Eds.): The Timing and Location of Major Ore Deposits in an Evolving Orogen, Geological Society, London, Special Publications 204, 151–178.
Kronberg, P. & Raith, M. 1977: Tectonics and metamorphism of the Rhodope crystalline complex in the Eastern Greek Macedonia and parts of Western Thrace. Neues Jahrbuch für Geologie und Paläontologie, Monatshefte 45, 697–704.
Kronberg, P., Meyer, W. & Pilger, A. 1970: Geologie der Rila-Rhodope-Masse zwischen Strimon und Nestos (Nordgriechenland). Beihefte zum Geologischen Jahrbuch 88, 133–180.
Liati, A. 1988: Amphibolitized Eclogites in the Rhodope Crystalline Complex, near Xanthi (Northern Greece). Neues Jahrbuch für Mineralogie-Monatshefte 1988(1), 1–8.
Liati, A. 2005: Identification of repeated Alpine (ultra) high-pressure metamorphic events by U-Pb SHRIMP geochronology and REE geochemistry of zircon: The Rhodope zone of Northern Greece. Contributions to Mineralogy and Petrology 150(6), 608–630.
Liati, A. & Gebauer, D. 1999: Constraining the prograde and retrograde P-T-t path of Eocene HP rocks by SHRIMP dating of different zircon domains: inferred rates of heating, burial, cooling and exhumation for central Rhodope, northern Greece. Contributions to Mineralogy and Petrology 135(4), 340–354.
Liati, A., Gebauer, D. & Wysoczanski, R. 2002: U-Pb SHRIMP-dating of zircon domains from UHP garnet-rich mafic rocks and late pegmatoids in the Rhodope zone (N Greece); evidence for Early Cretaceous crystallization and Late Cretaceous metamorphism. Chemical Geology 184(3–4), 281–299.
Lips, A.L.W., White, S.H. & Wijbrans, J.R. 2000: Middle-Late Alpine thermotectonic evolution of the southern Rhodope Massif, Greece. Geodinamica Acta 13(5), 281–292.
Mancktelow, N. 1985: The Simplon Line – a Major Displacement Zone in the Western Lepontine Alps. Eclogae Geologicae Helvetiae 78(1), 73–96.
Marchev, P., Singer, B., Andrew, C., Hasson, S., Moritz, R. & Bonev, N. 2003: Characteristics and preliminary 40Ar/39Ar and 87Sr/ 86Sr data of the upper eocene sedimentary-hosted low-sulfidation gold deposits Ada Tepe and Rosino, SE Bulgaria: possible relation with core complex formation. In: Eliopoulos, D.G. et al. (Eds.): Mineral exploration and sustainable development. Millpress, Rotterdam, 1193–1196.
Marchev, P., Raicheva, R., Downes, H., Vaselli, O., Chiaradia, M. & Moritz, R. 2004: Compositional diversity of eocene-oligocene basaltic magmatism in the eastern Rhodopes, SE Bulgaria: implications for genesis and tectonic setting. Tectonophysics 393, 301–328.
Marinova, R. & Zagorchev, I. 1991: Map sheet Blagoevgrad, 1:100'000. Commission of Geology, Sofia.
Meyer, W. 1966: Alterseinstufung von Tektonik und Metamorphose des Rhodopen-Kristallins im Boz Dag (Griechisch-Ostmazedonien). Neues Jahrbuch für Geologie und Paläontologie, Monatshefte 7, 399–409.
Meyer, W. 1968: Zur Altersstellung des Plutonismus im Südteil der Rila-Rhodope-Masse (Nordgriechenland). Geologica et Paleontologica 2, 173–192.
Mposkos, E. & Krohe, A. 2000: Petrological and structural evolution of continental high pressure (HP) metamorphic rocks in the Alpine Rhodope Domain (N Greece). In: Panayides, I. et al. (Eds.): Proceedings of the 3rd International Conference on the Geology of the Eastern Mediterranean, 221–232.

Mposkos, E.D. & Kostopoulos, D.K. 2001: Diamond, former coesite and supersilicic garnet in metasedimentary rocks from the Greek Rhodope: a new ultrahigh-pressure metamorphic province established. Earth and Planetary Science Letters 192(4), 497–506.

Nievergelt, P., Liniger, M., Froitzheim, N. & Ferreiro Mählmann, R. 1996: Early to mid Tertiary crustal extension in the Central Alps: The Turba Mylonite Zone (Eastern Switzerland). Tectonics 15(2), 329–340.

Ovtcharova, M., Quadt, A.V., Heinrich, C.A., Frank, M., Kaiser-Rohmeier, M., Peycheva, I. & Cherneva, Z. 2003: Triggering of hydrothermal ore mineralization in the central Rhodopean core complex (Bulgaria) – insight from isotope and geochronological studies on tertiary magmatism and migmatisation. In: Eliopoulos, D.G. et al. (Eds.): Mineral exploration and sustainable development. Rotterdam, 367–370.

Passchier, C.W. & Trouw, R.A.J. (2005) Microtectonics. Springer-Verlag, Berlin, Heidelberg, 366 pp.

Perraki, M., Proyer, A., Mposkos, E., Kaindl, R. & Hoinkes, G. 2006: Raman micro-spectroscopy on diamond, graphite and other carbon polymorphs from the ultrahigh-pressure metamorphic Kimi Complex of the Rhodope Metamorphic Province, NE Greece. Earth and Planetary Science Letters 241(3–4), 672–685.

Ricou, L.-E., Burg, J.P., Godfriaux, I. & Ivanov, Z. 1998: Rhodope and Vardar: the metamorphic and the olistostromic paired belts related to the Cretaceous subduction under Europe. Geodinamica Acta 11(6), 285–309.

Shipkova, K. & Ivanov, Z. 2000: The Djerman Detachment fault – An effect of the late Tertiary extension in the north-west part of the Rhodope Massif. Comptes rendus de l'Académie Bulgare des Sciences 53(2), 81–84.

Sokoutis, D., Brun, J.-P., Van den Driessche, J. & Pavlides, S. 1993: A major Oligo-Miocene detachment in southern Rhodope controlling north Aegean extension. Journal of the Geological Society (London) 150, 243–246.

Stephanov, A. & Dimitrov, Z. 1936: Recherches géologiques dans la région de Kjustendil (in Bulgarian). Review of the Bulgarian Geological Society 8(3), 1–28.

Stipp, M., Stunitz, H., Heilbronner, R. & Schmid, S.M. 2002: The eastern Tonale fault zone: a 'natural laboratory' for crystal plastic deformation of quartz over a temperature range from 250 to 700 °C. Journal of Structural Geology 24(12), 1861–1884.

Tranos, M.D., Karakostas, V.G., Papadimitriou, E.E., Kachev, V.N., Ranguelov, B.K. & Gospodinov, D.K. 2006: Major active faults of SW Bulgaria: implications of their geometry, kinematics and the regional active stress regime. In: Robertson, A. H. F. & Mountrakis, D. (Eds.): Tectonic development of the Eastern Mediterranean region. Geological Society, London, Special Publication 260, 671–687.

Wawrzenitz, N. & Mposkos, E. 1997: First evidence for Lower Cretaceous HP/HT-Metamorphism in the Eastern Rhodope, North Aegean Region, North-East Greece. European Journal of Mineralogy 9(3), 659–664.

Westaway, R. 2006: Late Cenozoic extension in SW Bulgaria: a synthesis. In: Robertson, A. H. F. & Mountrakis, D. (Eds.): Tectonic development of the Eastern Mediterranean region. Geological Society, London, Special Publication 260, 557–590.

Zagorchev, I.S. 1970: On the neotectonic movements in a part of South-West Bulgaria (in Bulgarian with French summary). Bulletin of the Geological Institute, Bulgarian Academy of Science 19, 141–152.

Zagorchev, I.S. 1992: Neotectonic development of the Strouma (Kraištid) Lineament, southwest Bulgaria and northern Greece. Geological Magazine 129(2), 197–222.

Zagorchev, I.S. 2000: Rhodope and Vardar: the metamorphic and the olistostromic paired belts related to the Cretaceous subduction under Europe. Comment: Rhodope facts and Tethys self-delusions. Geodinamica Acta 1, 55–59.

Zagorchev, I.S., Goranov, A., Vulkov, V. & Boyanov, I. 1999: Palaeogene sediments in the Padala graben, northwestern Rila Mountain, Bulgaria. Geologica Balcanica 29(3–4), 57–67.

Manuscript received 29 January, 2008
Revision accepted 9 May, 2008
Published Online first November 1, 2008
Editorial Handling: Stefan Schmid & Stefan Bucher