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Alpine Metamorphism and Granitoid Magmatism in the Strandja Zone: New Data from the Sakar Unit, SE Bulgaria

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Abstract: The Strandja Zone is a pre-Cenomanian orogen consisting of three tectonic units: the Veleka, Strandja and Sakar units. The first two units display very low-grade Alpine metamorphism, whereas in the Sakar unit the Triassic sediments are metamorphosed to the amphibolite facies. For years this high-grade metamorphism was enigmatic and most of the metamorphic rocks were interpreted as a reworked Precambrian crust of the Rhodope. This contribution begins with a review of the recent data about the structure and evolution of the Sakar unit. Probably the most important recent finding was the demonstration of the lack of a structural break between the Triassic and older rocks in the Sakar unit. This paper present results of the structural analysis of a key area in the southeastern part of the Sakar unit. The oldest unit is a volcano-sedimentary association intruded by granitoids of probable Late Palaeozoic age. These rocks contain NE–SW-striking foliation and well-defined stretching lineation plunging to the SE or SSE, formed synchronously with the medium-grade metamorphism of pre-Cenomanian age. The synmetamorphic fabrics suggest top-to-the-NW shear. Younger, but also typically foliated granite bodies, termed the Varnik granites, cut the other units. No single large magmatic body could be defined because of the intimate interfingering with older rocks. The Varnik granites are clearly distinguished from the older granites by their higher temperature fabric, cross-cutting relations and the post-tectonic character of some of the associated veins and dykes. The solid-state fabric also records NW-vergent shear deformation. The emplacement of the Varnik granites is interpreted as syntectonic with respect to the pre-Cenomanian metamorphism. The regional-scale increase in metamorphic grade within the Sakar unit is most easily explained by a combined effect of several pluton-driven thermal pulses.

Key Words: Strandja zone, Sakar unit, Alpine tectonics, syntectonic granitoids, structural geology

Istranca Kuşağı'nda Alpine Metamorfizması ve Granitoyid Magmatizması: Sakar Birimi'nden Yeni Veriler, GD Bulgaristan

Özet: Senomaniyen öncesi bir orojen olan Istranca Kuşağı başlıca üç tektonik birlikten oluşur: Veleka, Istranca ve Sakar birimleri. Birimlerden, ilk ikisi düşük dereceli Alpin metamorfizması verileri sunarken Sakar birimi amfibolit fasiyesine çıkan koşullarda metamorfizmaya uğramıştır. Bu yüksek-dereceli metamorfizma uzun yıllar bir bilmece olmuş ve metamorfik kayaçlar çoğunlukla Rodop'a ait yeniden işlenmiş Prekambriyen temel olarak yorumlanmıştır. Bu makale Sakar biriminin yapısı ve evrimi hakkındaki yeni verilerin bir özeti ile başlar. Yeni buluşlar arasında en önemlisi Sakar birimini oluşturan Triyas ve yaşlı kayalar arasında yapısal bir boşluğun olmadığının ortaya konması sayılabilir. Makale, Sakar biriminin güneydoğu kesiminde anahtar bir alanda yapılan yapısal analiz sonuçlarını sunmaktadır. Bölgedeki en yaşlı birim olası Geç Paleozoyik yaşındaki granitoyidler tarafından kesilen volkano-tortul bir istiftir. Birimdeki en yaygın yapısal unsurlar Senomaniyen öncesi dönemde gelişen orta-dereceli metamorfizma sırasında oluşan KD–GB-uzanımlı foliyasyon ile GD veya GGD'ya dalımlı iyi gelişmiş mineral lineasyonudur. Metamorfizma sırasında oluşan doku/yapılar üst düzeylerin KB'ya doğru hareket ettiği bir deformasyona işaret eder. Genç fakat foliyasyonlu granitler (Varnik granitleri olarak adlandırılırlar) daha yaşlı birimleri keserler. Yaşlı birimlerle olan ilişkileri ve bu birimler içindeki konumları nedeniyle büyük ve tek bir magmatik kütle tanımlanamaz. Varnik granitleri kendilerinden yaşlı olan grantilerden yüksek sıcaklık koşullarında oluşmuş dokuları, kesme ilişkileri ve birlikte geliştikleri damar ve daykların tektonik sonrası özellikleri ile ayrılırlar. Granitlerdeki dokular da KB'ya doğru makaslamaya işaret eder. Varnik granitleri Senomaniyen öncesi gelişen metamorfizma sırasında yerleşen sinmetamorfik oluşumlar olarak yorumlanmıştır. Sakar birimi içerisinde metamorfizma derecesinin bölgesel ölçekte artması ise bir çok plütona bağlı gelişen termal olayların ortak sonucudur.

Anahtar Sözcükler: Istranca Kuşağı, Sakar birimi, Alpin tektonizması, sintektonik granitoyidler, yapısal jeoloji

Introduction

The pre-Cretaceous metamorphic basement in southeast Bulgaria and northwestern Turkey is exposed in several uplifts (Sakar and Strandja mountains, Dervent, Sveti Iliya and Manastir Heights, etc) (Figure 1). These rocks form part of a major early Alpine orogen known as the Strandja Zone. During the past 10 years, a large amount of data on the geology of the western part of the Strandja Zone has been collected (including new 1:25,000-scale mapping) and some data have been recently published in local journals (Gerdjikov & Ivanov 2000; Ivanov *et al.* 2001a). These data, as well as the results of recent study of the Turkish sector of the Strandja Zone (Okay *et al.* 2001) and new age determinations (Lakova *et al.* 1992; Boncheva & Chatalov 1998; Lilov & Maliakov 2001), have major implications for the evolution of this segment of the Alpine belt in southeastern Europe. The reinterpretation of the structure and evolution of the western part of the Strandja Zone is consistent with the reevaluation of the metamorphic complexes in the southern part of the Balkan Peninsula, which began with the Rhodope Zone (Burg *et al.* 1996; Ricou *et al.* 1998).

One of the aims of this paper is to present – brief overview of the Strandja Zone. The stratigraphic and structural record of each of the defined units will not be detailed, but a short presentation is necessary in order to highlight new data and to indicate where the main problems lay. A case study of a key area in the western part of the zone is presented in order to describe the synmetamorphic fabric and to constrain better the model for the important role of early Alpine granitoid magmatism. This new model has far-reaching consequences for the tectonic and metamorphic evolution of the Strandja Zone.

Structure of the Strandja Zone

Many local investigations and previous reviews have dealt with the stratigraphy and structure of the Strandja Zone. Some of these contributions demonstrate the existence of significant differences between parts of the Strandja Zone, for example, differences in the peak metamorphic conditions between the western and eastern parts of the zone (Dimitrov 1958) and the presence of several types of Triassic sequences (Chatalov 1990). These data, along with indications of an inverted metamorphic field gradient (Chatalov 1990), reported nappe systems (Go–ev 1991; Dabovski *et al.* 1993), and our own observations, are the basis for the tectonic subdivision of the Strandja Zone.

On the basis of structural, stratigraphic and metamorphic criteria, three units can be distinguished in the Strandja Zone. They are (from top to bottom): the Veleka, Strandja and Sakar units. The main reasons for this subdivision are: (i) the existence of faults or shear zones along the contacts of these units; (ii) the variable stratigraphic content of the units; and (iii) contrasting peak metamorphic conditions, reached during the pre-Cenomanian orogeny. The description of the units is limited to major features, with emphasis on recent findings and least internationally known data. For further details, the readers are referred to Chatalov (1990), Go–ev (1991), Ivanov *et al.* (2001), and Okay *et al.* (2001).

Veleka Unit

This unit is the most recently named unit in the Strandja Zone (Dabovski *et al.* 2002), and is the least known. The Veleka unit comprises two stratigraphically and lithologically distinct entities – the Strandja allochthon (the allochthon of the Zabernovo nappe – Chatalov 1990) and the phyllite-marble complex from the Dervent heights. The rocks of the Veleka unit form structurally complex synformal klippen that have been emplaced over the less-metamorphosed Strandja unit. Considerable controversy surrounds the age of the rocks from the Zabernovo nappe. According to Chatalov (1990), the Zabernovo nappe is built of Strandja-type Triassic metamorphic rocks, and this view was unquestioningly used in a number of tectonic models (e.g., Şengör *et al.* 1984). On the other hand, several lines of evidence (Sergeeva *et al.* 1979; Boncheva & Chatalov 1998; Lilov & Maliakov 2001) require reevaluation with regard to a Triassic age for the Zabernovo nappe. It now appears that at least subduction-accretion complex part of the Zabernovo nappe consists of Palaeozoic rocks.

The phyllite-marble complex builds a large part of the Dervent heights, comprising phyllites, calc-phyllites, metasandstones, slates and abundant marbles. The Palaeozoic age of these metasediments is well-documented (Latcheva *et al.* 1989; Lakova *et al.* 1992; Boncheva & Chatalov 1998).

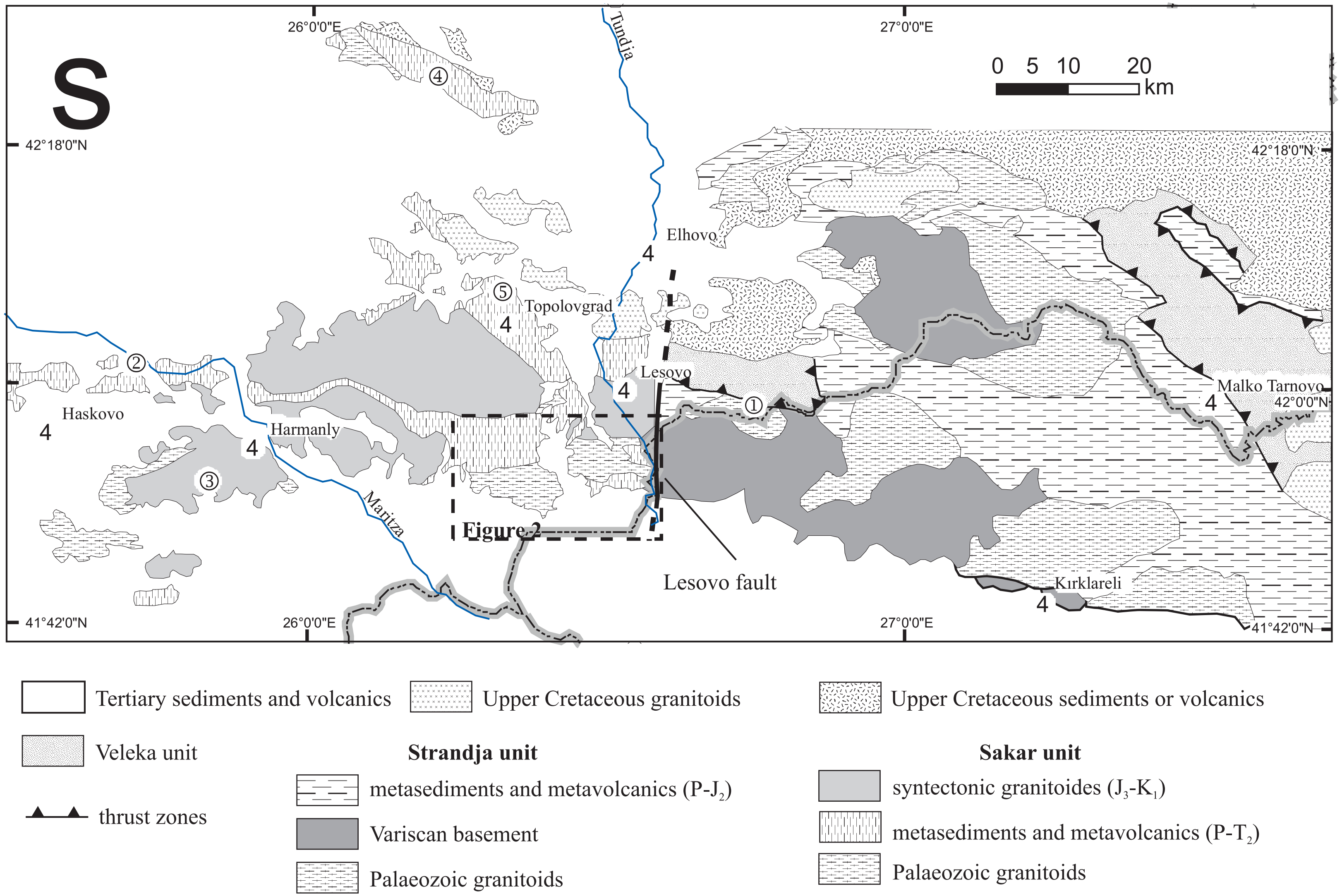

Figure 1. Simplified geological map of the western part of the Strandja Zone. Some map data taken from Chatalov (1990) and Okay *et al.* (2001). Locations of areas discussed in the text: 1 – Dervent heights; 2 – Maritsa area; 3 – Harmanly area; 4 - Sveti Iliya heights; 5 - Drenaka hill.

Very little is known about the internal structure of the Veleka unit and the kinematics of the shear zones at the base of the unit. The contacts between the Veleka and Strandja units have been traditionally interpreted as thrust surfaces, but the data of Dabovski & Savov (1988) as well as our own observations in the Dervent heights are more consistent with synmetamorphic emplacement of the Veleka unit. Our preliminary data from the Dervent heights also indicate NW-vergent penetrative shear deformation at the base of the unit concomitant with pre-Cenomanian low-grade metamorphism. The continuation of the Veleka unit into the territory of Turkey is enigmatic. If the preliminary data of Latcheva *et al.* (1989) about the presence of Palaeozoic metasediments north of Dereköy are confirmed, the reported areal extent of the Veleka unit must be revised.

Strandja Unit

This unit consists of Variscan crystalline basement and granitoids (Okay *et al.* 2001) overlain by Upper Permian–Middle Jurassic sediments and volcanic rocks (Figure 2). The Variscan high-grade metamorphic rocks and granitoids were unevenly reworked during pre-Cenomanian orogenesis. It is worth noting that the presence of high-pressure rocks (eclogites) in the Strandja Zone has only been indicated in the Variscan gneisses of the eastern part of the Dervent heights (Dabovski *et al.* 1993).

The post-Variscan cover is subdivided in two parts: lower (Upper Permian–Upper Triassic) and upper (Lower–Middle Jurassic). Due to widespread Late Cretaceous magmatism and also because of the complicated structure, the lower part of the cover is strongly disrupted in the Strandja Mountains and in the Dervent heights. The best preserved section could be observed in the Sveti Iliya heights where, from the palaeo-geodynamic point, of view three successions can be distinguished (from bottom to the top): (i) a volcano-sedimentary sequence, likely indicating an initial stage of rift formation. The basal part includes a mafic metavolcanic assemblage with MORB-like geochemical features (Sokol Formation – Chatalov 1990). Chatalov assumed an Early Palaeozoic age for the Sokol Formation, but this interpretation has been proved incorrect by data about the high-grade Variscan metamorphism from the Turkish part of the Strandja (Okay *et al.* 2001). Other important rock types are metarhyolites, acid metavolcanoclastic rocks, metabreccias and metaconglomerates. The volcano-sedimentary sequence is capped by metaconglomerates and metasandstones (Svetiiljska and Pitovo formations – Chatalov 1990); (ii) a terrigeneous-carbonate sequence, indicating a transition toward stable marine sedimentation; and (iii) a limestone-dominated sequence, indicating carbonate-platform development in the Middle–Late Triassic.

The Jurassic part of the sedimentary cover starts with terrigeneous and carbonatic sediments (Lower Jurassic), whereas the Middle Jurassic sediments are deep-water shales. The Jurassic section finishes with supposedly neritic carbonatic sediments.

There is a marked change in the grade of Alpine metamorphism in the Bulgarian part of the Strandja unit. Using illite crystallinity and the evolution of clay-mineral parageneses, Chatalov (1990) demonstrated that all rocks from the Strandja unit underwent low-grade metamorphism, ranging from diagenetic to epizonal (up to 400° C) conditions. The Jurassic rocks are diagenetic, and metamorphic grade increases towards the lower part of the underlying Permo–Triassic succession.

The contact between the Strandja and Sakar units has a complicated character and, because of widespread Tertiary cover, is poorly studied. Along most of its length, the contact is represented by a late fault zone – the Lesovo fault zone of Chatalov (1965) that runs N–S and limits the easternmost exposures of the metamorphic rocks typical of the Sakar unit, especially the Sakar-type Triassic metasediments (see below). On the other hand, northwest of Topolovgrad (Drenaka hill – Go–ev *et al.* 1992) and northeast of the village of Lesovo, small klippen consisting of almost unmetamorphosed, mostly Jurassic sandstones and shales rest on the Sakar unit. The sharp metamorphic and structural break at the soles of these klippen indicates that their emplacement was post-metamorphic. These field data suggest that the Sakar unit is the lowermost unit in the Strandja Zone; that is, the actual relations are inconsistent with interpretation of Şengör *et al.* (1984).

Sakar Unit

The most striking feature of the Sakar unit is the higher grade of the pre-Cenomanian metamorphism that reach

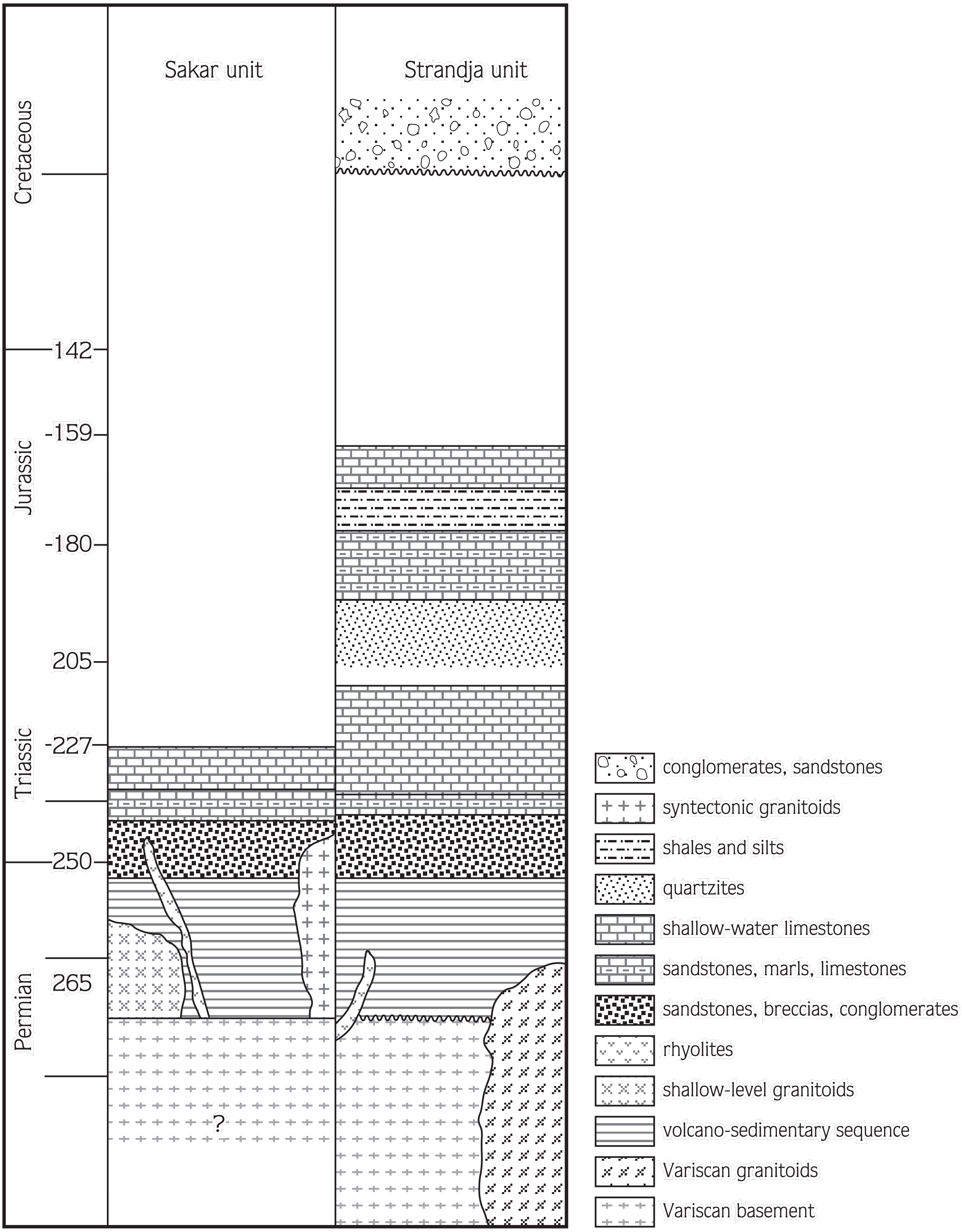

Figure 2. Generalized stratigraphic columns for the Strandja and Sakar units. Based on Chatalov (1990).

the amphibolite facies in some areas. In terms of metamorphism and synmetamorphic fabric, the Sakar unit is more similar to the neighbouring Rhodope Zone than to Strandja unit. Because of this, for a number of investigators the Sakar unit represents a reworked part of the supposedly Precambrian Rhodope Massif (Dimitrov 1958). Another key feature of the Sakar unit is the presence of well-studied and dated Triassic metasediments that provided important constraints on the synmetamorphic evolution of the pre-Cenomanian basement.

It was long assumed – and is still widely accepted – that the basement to the Sakar unit is mainly composed of Precambrian metamorphic rocks (Zagorchev 1993). The staurolite-facies metamorphism of the Triassic rocks used to be regarded as an unusual phenomenon and it was stressed that these rocks display no signs of intense synmetamorphic fabric. This model has only recently been challenged. On the basis of field relations and petrological data, Skenderov *et al.* (1986) were the first to propose that part of the presumably old basement is in fact an Upper Palaeozoic sedimentary succession, metamorphosed in Alpine time. Similar ideas were proposed for most of the eastern part of the Sakar unit (Chatalov *et al.* 1996). As a result of several years of intensive research a new model for the structure and Early Alpine evolution of the Sakar unit was proposed (Gerdjikov & Ivanov 2000; Ivanov *et al.* 2001a). The most important points about this model are: (i) the existence of the pre-Alpine basement in the Sakar unit was questioned; (ii) the lack of a structural break at the base of the Triassic section was demonstrated; (iii) two major stratigraphic units were distinguished – a volcano-terrigenous complex (Upper Palaeozoic) and the Topolovgrad Group (Triassic); (iv) the abundant granitoids were classified in two major groups according to their temporal relations with the pre-Cenomanian orogeny – pre-tectonic and syntectonic; (v) the emplacement of the syntectonic granitoids was regarded as a reason for the higher metamorphic grade in the Sakar unit (see also Skenderov *et al.* 1986); and (vi) the synmetamorphic fabric in the volcano-terrigenous complex and in the Topolovgrad Group was characterized as intense and penetrative, and was related to a complex transpressional setting.

In the following section, the stratigraphy and the structure of the pre-Cenomanian basement of the Sakar unit is briefly described.

Regional Geology

The metamorphic basement of the Sakar unit can be divided into two stratigraphic units: (1) the volcano-terrigenous complex (Upper Permian?), and (2) the Topolovgrad Group (Lower–Middle Triassic; Chatalov 1990). Both of these units were regarded by Ivanov *et al.* (2001) to represent a continuous section, related to sedimentation and volcanism during the formation of the Late Palaeozoic–Triassic passive continental margin.

The volcano-terrigenous complex (VTC) is a regionally extensive sequence dominated by metamorphosed acid volcanoclastic rocks, and metabasites and their tuffs, now transformed into feldspathic schists, gneisses and amphibolites. These are interlayered with a variety of less abundant lithologies including quartzite, biotite and biotite-muscovite paragneisses, metadiorites and schists. The thickness of this unit varies between 300 m and more than 1 km. The large variation in thickness is due at least in part to tectonism, but the primary variation in thickness itself is also important. The VTC is overlain by the Topolovgrad Group (Chatalov 1990), a unit with well-preserved stratigraphy despite of intense synmetamorphic reworking. It begins with the Paleocastro Formation – an undated clastic sedimentary sequence with metasandstones as its most widespread rock type. The base of the Paleocastro Formation is typically conglomeratic, with pebble- and cobble-rich layers dominated by clasts of vein quartz, metavolcanic rocks and equigranular biotite granites. These rocks grade upwards into the terrigeneus-carbonate Ustrem Formation with typical metapelites as the most common rocks. The uppermost formation of Topolovgrad Group is the Srem Formation, made up of dolomitic and calcitic marbles. Because of some of its lithological features and the higher metamorphic grade, this Triassic succession was described as Sakar-type Triassic (Chatalov 1990).

The VTC hosts several granitoids displaying unambiguous pre-tectonic character. Some of their main features are: (i) they are covered by the Paleocastro Formation, and abundant clasts from them are observed in the basal metabreccia-metaconglomerates; (ii) the solid-state foliation often truncates the contacts of the bodies and also is oblique to the magmatic fabric; and (iii) the solid-state fabric is low-temperature.

A number of these magmatites display features of deep-seated intrusions and could be of Variscan age, by analogy with the Turkish sector of the Strandja. Other granitoids are shallow-level intrusions with porphyroid fabric. They are spatially associated with granite porphyries and rhyolites. In the area north of the village of Lesovo, these shallow-level granitoids and volcanic rocks were designated the Melnitsa orthometamorphic complex (Chatalov 1992). Our field data indicate that Melnitsa-type migmatites are widespread and occur in all parts of the Sakar unit. It is important to note that there are indications for acid magmatism continuing into the Triassic (Kozhouharova & Kozhouharov 1978)

Typical of the Sakar unit is a well-expressed metamorphic field gradient. The greenschist-facies rocks of the Maritsa area increase in grade to amphibolite-facies rocks to the east and south. The amphibolite-facies rocks are characterized by porphyroblasts of garnet, staurolite and, in places, kyanite enclosed within a matrix dominated by muscovite, biotite, quartz, plagioclase and opaque phases. The greenschist-facies rocks reach garnet zone, but in some places the degree of alteration is as low as biotite zone. Thus, the Alpine metamorphism in the Sakar unit is of the medium P – medium T/low T type. Several authors have explained the metamorphic field gradient as a product of pluton-driven thermal pulses (Skenderov *et al.* 1986; Ivanov *et al.* 2001a).

Application of various structural criteria (e.g., Paterson *et al.* 1989; Druguet & Hutton 1998) and some field relations have allowed characterization of several granitoid bodies as syntectonic (i.e., as Upper Jurassic–Lower Cretaceous; Ivanov *et al.* 2001a). The batholitic-scale Sakar and Izvorovo plutons, as well as several small leucocratic and K-feldspar megacrystic granitoids, have been interpreted as syntectonic. Most of them were emplaced into the VTC, and just few leucocratic dykes are hosted by metasediments of the Topolovgrad Group. The occurrence of aplitic dykes with post-tectonic character (with respect to the regionally consistent foliation) is a clear indication that magmatic activity outlasted ductile deformation.

The proposed model for early Alpine magma emplacement explains some of seemingly enigmatic features of the pre-Cenomanian metamorphic basement: (i) a well-defined metamorphic field gradient in the Sakar unit; and (ii) occurrences of high-temperature gneissic fabric and migmatites, regarded as Precambrian metamorphic basement by Boyanov *et al.* (1965), Kozhouharova & Kozhouharov (1973), and Zagorchev (1993). Our field and microstructural studies have demonstrated that high-grade fabric is observed in the granitoids, reflecting transition from magmatic to high-temperature solid-state fabric. On the other hand, no *in situ* formed migmatites were found in the Sakar unit. However, in a number of places, especially near the contacts of some syntectonic granitoid bodies, the metamorphic rocks are penetrated by a dense network of aplitic and pegmatitic veins. All field data suggest that these migmatites are arterites (terminology of Wimmenauer & Bryhni 2002).

The metamorphic basement and associated granitoids contain evidence for two deformational events with regional significance (Gerdjikov 1999a). The penetrative synmetamorphic fabric formed during the first event (D_1), and it is important to note that the associated features are equally well presented in the VTC as well as in rocks of the Topolovgrad Group. One of the main arguments for the early Alpine age of deformation and metamorphism in the rocks – previously regarded as old basement (Dimitrov 1958; Boyanov *et al.* 1965; Kozhouharova & Kozhouharov 1973) – is the continuity of D_1 fabric and the same kinematics in both rock assemblages. Upright folding of the foliation associated with sporadic crenulation cleavage is characteristic of the second event (D_2). These folds are restricted to areas where first event foliation (S_1) runs E–W, and their axes are most often parallel to L_1. Microfabric observations suggest that penetrative S_1/L_1 fabric formed during the peak-metamorphic temperatures, whereas the D_2 phase was associated with retrograde evolution of the metamorphic basement.

The absolute age of deformation and metamorphism in the Sakar unit is not well constrained. Deformation probably began after the Middle Triassic – the youngest age of the deformed sediments in the region. The younger constraint on deformation is approximately 140–120 Ma – the cooling ages recorded by numerous K/Ar determinations (review in Ivanov *et al.* 2001a). The other upper age bracket is provided by Late Createaceus dykes that crosscut the metamorphic rocks in the northern part of the Sakar unit.

Geology of the Study Area

Levka Pluton

The study area is situated on the southeastern slope of the Sakar Mountains. Most of it is underlain by the Levka pluton – a large body of equigranular medium-grained biotite granodiorites and granites (Figure 3). In the south, the Levka pluton is covered by Tertiary sediments of the Thrace Basin, so its visible width in map view reaches 7 km.

Typical of the Levka pluton is the lack of obvious magmatic fabric; on the other hand, solid-state fabric is predominantly low-grade (terminology of Passchier & Trouw 1996) On the basis of the character of the solid-state fabric, two types of domains can be distinguished in the Levka pluton:

(1) A domain of heterogeneous low-grade fabric. This domain comprises the western part of the Levka pluton. Typical here are various degrees of solid-state reworking that in some cases reach the development of mylonites. Strongly deformed granitoids from the Levka pluton have foliation defined by elongate quartz and biotite aggregates, and aligned feldspars (± amphibole). Locally the shapes of mineral aggregates define an associated lineation plunging ESE. Except for sporadic top-to-the-WNW shear bands, the fabric does not display obvious evidence for non-coaxial flow. Feldspars show dominantly brittle deformation fabrics with limited and incipient marginal recrystallization.

(2) A domain of medium-grade homogeneous fabric comprises most of the eastern part of the Levka pluton. Here the equigranular granitoids of the Levka pluton are densely intruded by leucocratic and K-feldspar megacrystic granites and associated swarms of aplitic and pegmatitic veins. In this domain, the fabric of the granitoids is usually protomylonitic, and a number of microscopic features suggest higher temperatures during shearing. Dimitrov (1999) also noticed more intense strain in this area. Microfabrics show plastic deformation of feldspars, namely formation of subgrains and recrystallization.

Because there are no isotopic data, nor relations with dated stratigraphic units, the only indications about the age of the Levka pluton are provided by structural data. Study of the northern contact with the host rocks provides unequivocal support for the pre-tectonic origin of the Levka pluton. This contact is traced between the villages of Levka and Studena and is well exposed along the Levchanska River valley. Here, a well-expressed discordance between the strike of the contact and the strike of the regionally-dominant foliation (S_1) is observed. In map view, the orientation of the foliation is accentuated by the strike of numerous bands of amphibolites interbedded with acid volcanoclastic rocks and metasediments (Figure 3). The strike of the foliation is N55–N60°, whereas the general strike of the northwestern contact of the Levka pluton is N78°. The observed discordance is typical of the pre-tectonic plutons in the Sakar unit, whereas all granitoids termed syntectonic are perfectly concordant. It is important to note the lack of concentration of granitoid dykes along the contact, in opposition to the margins of the syntectonic granitoids.

Wall Rocks of the Levka Pluton

Metamorphic rocks of the southeastern part of the Sakar unit display a rather simple deformational style. At a regional scale, only one penetrative synmetamorphic fabric – that includes foliation (S_1) and often pronounced lineation – was observed in the study area.

In the most southeastern part of the Sakar unit (in the vicinities of the villages of Varnik and Radovets), quartzites, medium-grained amphibolites, fine-grained biotite gneisses and scarce gabbroic lenses are typical of the VTC and are found as comparatively thin packages enclosed in the Levka granitoids or, more often, in porphyritic and leucocratic granitoids. These host rocks display a single penetrative foliation (S_1) dipping steeply to the SSE, often with clear stretching lineation plunging moderately to the SE (Figure 4). The mylonitic foliation is defined by biotite, recrystallized quartz and feldspars that form lenses or ribbons. In places, these rocks display a layered appearance accentuated by quartz or aplitic veins that parallel the foliation. Shear-sense indicators include asymmetric boudins and shear bands indicating consistent SE-side-up simple shear. Folding is restricted to domains including rheologically distinct lithologies and are represented by tight to isoclinal folds with axes approximately E–W and axial planes that dip steeply to the south. Because axial planar foliation typical of the D_2 event was not observed, the origin of these folds was likely related to local strain heterogeneity.

North of the Levka pluton, the VTC is represented by acid volcaniclastic rocks, minor metasediments and amphibolites. What is spectacular for this area is the very

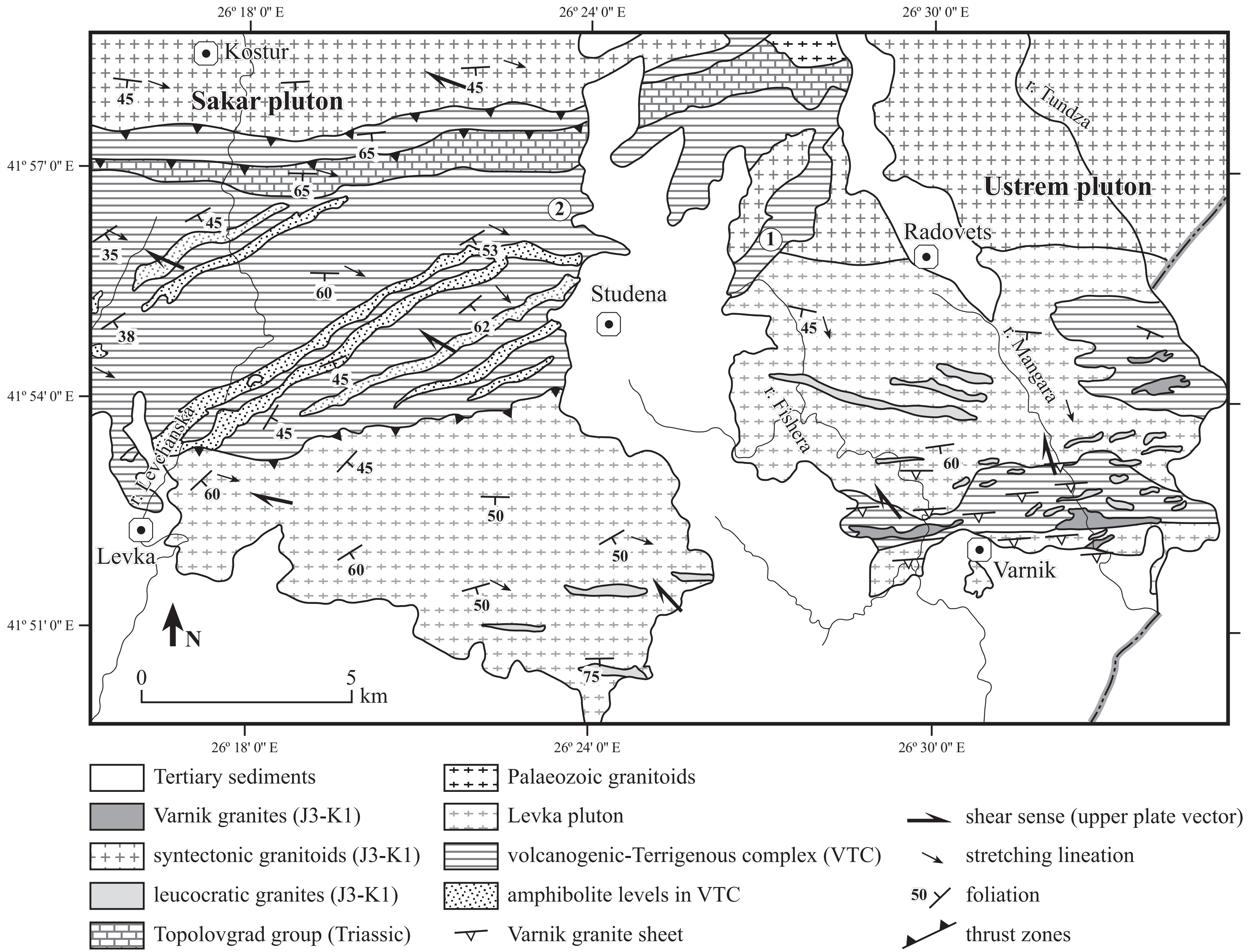

Figure 3. Geological map of the southeastern part of the Sakar unit, based on own observations, as well as data from Kozhouharov *et al.* (1995) and Dabovski *et al.* (1993). The locations of the domains, displaying complicated deformational style, are indicated by numbers.

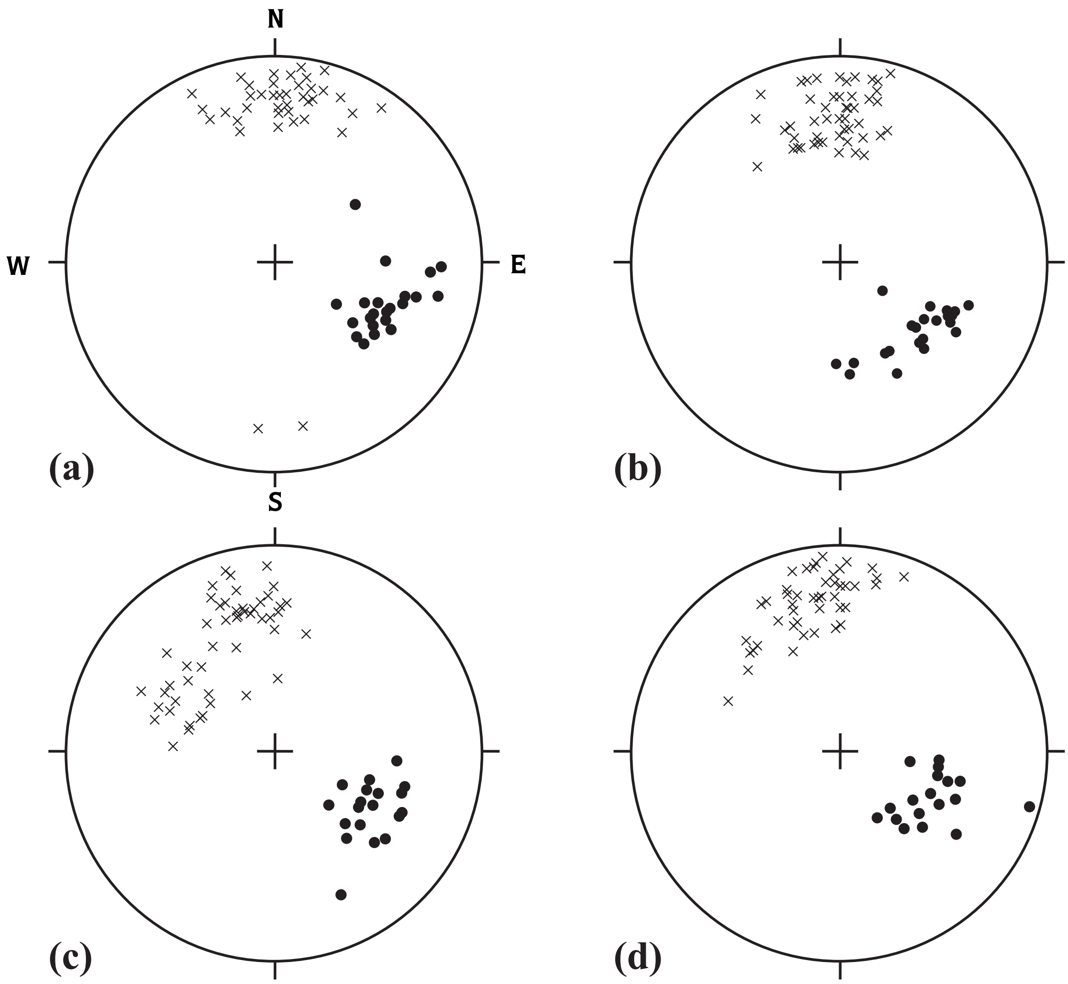

Figure 4. Lower hemisphere stereographic plots of structural data collected from: (a) Varnik granites – west from Varnik village; (b) wall rock of the Varnik granites – west from Varnik village; (c) Varnik granites and associated wall rocks east of the village of Varnik; (d) Varnik granites and associated wall rocks in the area NE of the village of Varnik. Filled circles – plunge of lineation, x – poles to solid-state foliation.

weak synmetamorphic deformation of these rocks. This is one of the few places where folds deforming primary bedding (with foliation S_1 parallel to the axial planes) could be observed in the metasediments and metavolcanoclastic rocks of VTC. These observations sharp contrastly with the high-grade fabric and arterite-type migmatites observed just several kilometers north along the margins of the Sakar pluton.

Moving just 10 km to the north, a narrow strip of Triassic metasediments (Topolovgrad Group) is squeezed between the rocks of the VTC Previous authors regarded this strip as a fault or shear-zone-bounded fragment of metasedimentary cover (Boyanov *et al.* 1965; Zagorchev 1993). Our re-examination of the boundaries of this metasedimentary belt reveals that there is no break in metamorphic grade, nor is there a structural discordance. The Triassic rocks bear the same deformation fabrics which, according to microfabric studies, formed at lower-amphibolite facies conditions. These data, as well as numerous K/Ar cooling ages (review in Ivanov *et al.* 2001a), suggest an early Alpine age of metamorphism and associated deformation in the study area.

Only in two domains (labeled on Figure 3) is there evidence for a complicated deformational style. Outcrops in these domains preserve consistent evidence for at least two generations of penetrative structures. The latest foliation is parallel to the regionally dominant foliation, but the intensity of this fabric is low and older structures are well-preserved. Based on structural criteria only, it is impossible to deduce whether the various generations of structures represent a single progressive heterogeneous event. They could just as well represent incompletely reworked Variscan basement.

The Varnik Granites and Associated Magmatic Rocks

The K-feldspar megacrystic granites that crop out in the southeasternmost part of the Sakar unit were informally named the Varnik granites and were interpreted to form a compact magmatic body (Gerdjikov 1999a). The Varnik granites are composed of feldspars (microcline and plagioclase), quartz, biotite, ± muscovite and, as accessories, zircon, apatite and opaque phases. The main diagnostic feature of the Varnik granites is the abundance of white or pinkish K-feldspar megacrysts reaching up to 7 x 2 cm in size. Previous workers have held different views as to the nature of these rocks; Dimitrov (1958) regard them as old gneissic granites, whereas Kozhouharova & Kozhouharov (1973) and Dabovski *et al.* (1993) interpreted them as Precambrian porphyroblastic migmatites.

New field mapping in the southeasternmost part of the Sakar unit has revealed more complicated relations between the different rock units. The Varnik granites turn out to represent a swarm of sill-like bodies in many cases separated by thin wall-rocks screens. The K-feldspar megacrystic granites comprise sheets with thicknesses of 0.5–400 m emplaced concordantly into the dominantly mylonitic rocks of the VTC and Levka granitoids. Because of the often intense mylonitization, it is difficult to distinguish different rock units – even the contacts of the Varnik granites. Extreme grain-size reduction in some mylonitic levels leads to transformation of the Varnik granites into banded gneisses with small (up to 1 cm diameter) K-feldspar porphyroclasts. But not all the contacts of the Varnik granites are intensely deformed. In the less deformed cases, the contacts are rather sharp and no chilled margins are present.

No obvious contact aureole has been observed, but some observations suggest that the Varnik granites had significant thermal influence: (1) On a regional scale, there is a tendency toward higher-grade fabrics toward the area occupied by the Varnik granites. For example, schistose structure is replaced by more gneissic fabric near the Varnik granites; (2) the wall rock typically displays recovery features and, in many places, indications of static recrystallization, namely lack of undulose extinction, straight grain boundaries, and an abundance of foam structure and polygonized micas. On an outcrop scale, static recrystallization is suggested by the difficult splitting of rocks along foliation planes, despite clear indications of mylonitization.

A large number of leucogranitic bodies are related to the Varnik granites. The abundance of leucogranites in this area is documented on the 1:100,000 geological map, and they are interpreted to represent Precambrian magmatic rocks (Dabovski *et al.* 1993). Analogous to the Varnik granites, they also form concordant sill-like bodies with thicknesses up to 200 m. These leucocratic rocks most often display equigranular structure and are medium- to fine-grained. In most cases these rocks contain muscovite, however biotite is scarce.

Swarms of aplitic and pegmatitic veins are spatially associated with the Varnik and leucocratic granites. In some places these rocks densely penetrate the host rocks, and there is local formation of arterite-type migmatite. It is important to note that features which suggest *in-situ* melting have not been observed in the study area (melanosome along the rims of leucosomes, melt-filled boudin necks or shear zones – e.g., Sawyer 1999). In contrast to the concordant Varnik and leucocratic granites, these veins display various contact geometries. This, as well as the variable deformational patterns, provides the best evidence for time overlap in the processes of granitoid magmatism and deformation. The earliest veins are transposed to the foliation, boudinaged, and sometimes mylonitized. Another piece of evidence for the early emplacement of some of these veins is provided by the cross-cutting relations: in the Mangara River valley, a mylonitic aplitic vein is cross-cut by weakly deformed K-feldspar megacrystic granite (Figure 5). Another group of veins is discordant to the foliation, but is also deformed by it. Some veins are emplaced along the axial planes of the metre-scale folds, with axes trending E–W. At least some of the melts are post-tectonic; these veins are not foliated or boudinaged, and may be concordant or discordant (Figure 6) to the foliation.

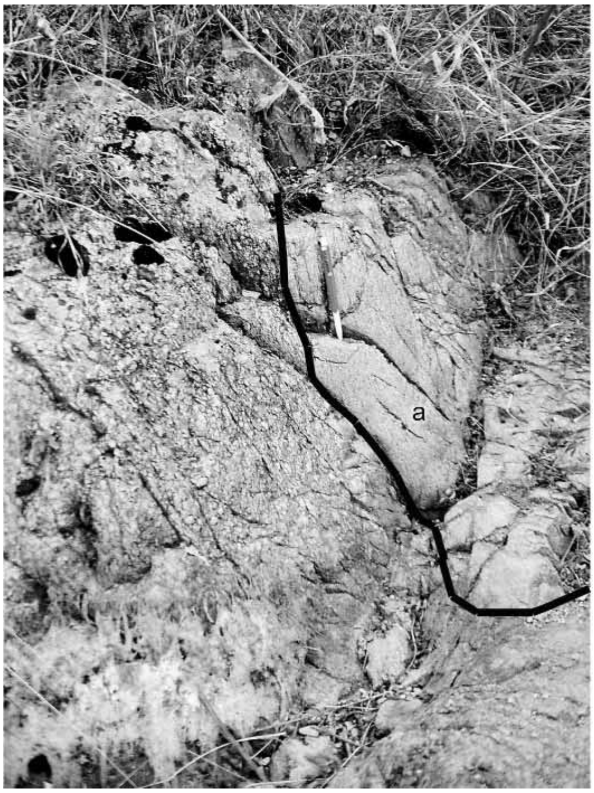

Figure 5. The mylonitic foliation in the aplitic vein (a) is truncated by K-feldspar megacrystic granite. In this case, the megacrystic granite shows less intense solid-state overprint. Pencil is 13 cm long.

Figure 6. Strongly sheared and folded amphibolites from the VTK intruded by an undeformed aplitic vein. This relationship indicates that deformation (including folding) took place before crystallization of all magma associated with the Varnik granites and leucogranites. Location: Mangara River valley.

Fabric Within the Varnik Granites

The Varnik granites contain both magmatic and solid-state fabrics. Scarce magmatic foliation is defined by alignment and sometimes tilling of K-feldspar megacrysts, and also by alignment of mafic xenoliths. The foliation parallels the contacts of the individual bodies, and most frequently dips steeply to the south.

Most often the fabrics of the Varnik granites record intense mylonitization. Solid-state fabrics include protomylonites, mylonites and scarce ulramylonites. Often the mylonitic zones are located near the margins of the magmatic bodies or near large wall-rock xenoliths. Most of the mylonites are well-developed S/L tectonites displaying evidence of recrystallization of all rock-forming minerals. The solid-state fabric is parallel to the S/L fabric in the wall rocks and also to the contact of the bodies. In the mylonites, K-feldspar crystals are transformed to elongated and strongly flattened recrystallized aggregates. Pronounced lineation is defined by stretched feldspar and quartz aggregates, parallel alignment of micas, and also by oriented growth of dynamically recrystallized quartz and feldspars in the strain shadows around K-feldspar porphyroclasts (Figure 7). Folds-deforming, solid-state fabric in the Varnik granites is quite scarce; this is restricted to some thin bodies (thickness less than several metres) or is localized in the vicinity of wall-rock inclusions. Fold axes strike almost E–W and axial planes are almost vertical. L-tectonites are observed at the cores of these folds. Numerous shear-sense indicators are associated with solid-state fabric in the Varnik granites and indicate SE-side-up shear sense. Most of the kinematic indicators are observed at the outcrop scale and include σ-type feldspar porphyroclasts (Figure 8), S/C fabric, and discrete ductile shears. Whereas feldspar porphyroclasts (cf. Passchier & Simpson 1986; Hooper & Hatcher 1988) are found

Figure 7. Stretched feldspar and quartz aggregates and elongated strain shadows around K-feldspar porphyroclast define lineation in the Varnik granites. Pencil is 13 cm long.

Figure 8. Sigma-type feldspar porphyroclasts with tails consisting of recrystallized microcline grains indicating top-to-the-NW displacement during solid-state deformation of the Varnik granites. NW is to the right. Location: Mangara River valley. Pencil is 13 cm long.

almost everywhere in the mylonites. S/C fabric (cf. Berthe *et al.* 1979; Lister & Snoke 1984) is not penetrative and is restricted to some levels. The lack of penetrative S/C fabric can be explained by the high-grade nature of the fabrics, with its extensively recrystallized K-feldspar megacrysts and rather homogeneous foliation. These rocks were probably capable of ductile flow with no tendency for shear localization at specimen scale. Such an interpretation is in agreement with the symmetrical θ-type porphyroclasts, widespread in these mylonites, which are considered to be typical of high-grade, shear-zone rocks (cf. Passchier & Trouw 1996).

The study of microfabrics in the mylonitic Varnik granites provides additional data for moderate- to high-temperature solid-state deformation. The igneous plagioclase is extensively recrystallized to small- and medium-sized grains (0.15–0.3-mm long). In the strain shadows of larger K-feldspar porphyroclasts, optically strain-free plagioclase grains form polygonal mosaics. In some cases plagioclase comprises polycrystalline, highly elongated ribbons one grain wide, composed of elongated grains. Other larger plagioclase grains display highly sutured grain boundaries, suggesting grain-boundary migration recrystallization. In many places, the K-feldspar porphyroclasts show coarsely recrystallized tails (recrystallized grains up to 0.3 mm diameter; Figure 9). In most of cases, porphyroclasts as well as recrystallized grains display microcline twinning. Myrmekites are typical at the foliation-parallel margins of the larger K-feldspar porphyroclasts. Elongated K-feldspar relics are locally surrounded by plagioclase-quartz aggregates suggesting extensive replacement of K-feldspars (Figure 10). Smaller K-feldspar porphyroclasts are fully recrystallized, forming rectangular new grains with straight boundaries. The nearly polygonal texture of the matrix grains may imply either dynamic recrystallization at high temperatures or static annealing (cf. Hirth & Tullis 1992; Snoke *et al.* 1998). Quartz grains form long ribbons (interpreted as the type 4 of Boullier & Bouchez 1978), often with deeply sutured grain boundaries.

Discussion

Significance of Synmetamorphic Fabric in the Southeastern Part of the Sakar Unit

In the area where the Varnik granites occur, microstructures suggest higher temperatures (>500 °C)

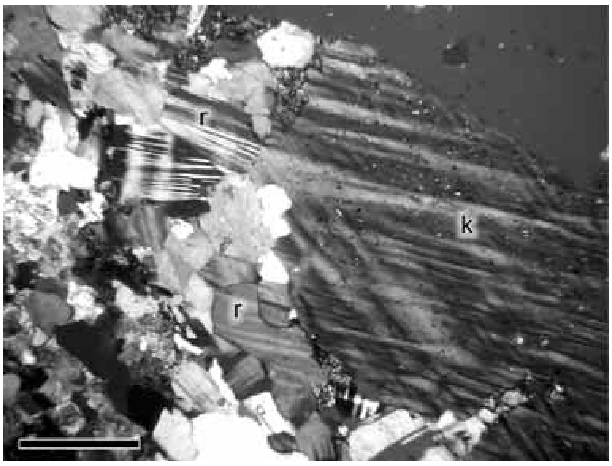

Figure 9. Coarsely recrystallized K-feldspar (r) in the strain shadow of feldspar porphyroclasts (k). Crossed polarizers; scale bar – 0.3 mm.

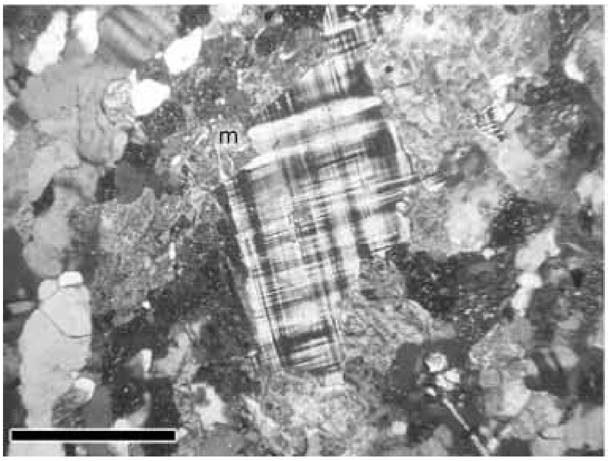

Figure 10. K-feldspar porphyroclast with microcline twining, the margins of which are extensively replaced by myrmekite (m). Crossed polarizers; scale bar – 0.5 mm.

than those typical of the host rocks (<~500 °C). Accordingly, the synmetamorphic fabric is intense near the Varnik granites, whereas north of the Levka pluton preserved primary features are present. Ductile shear fabric shows no low-temperature or brittle overprinting, implying relatively high temperatures during and after deformation. A great number of kinematic indicators observed in the rocks of the VTC, the Topolovgrad Group, and Levka pluton and Varnik granites indicate top-to-the-NW shear sense. The E–W- to NE–SW-striking reverse-sense fabric has a dextral component that increases toward the north. Classically, north-vergent fabric in the Balkanides has been interpreted as compressional. On the other hand, the regional-scale kinematic of ductile deformation is rather complicated, with a typically large strike-slip component – for example, along the southern margin of the Sakar pluton and in the Konstantinovo shear zone (Gerdjikov 1999b). It is well known that oblique convergence along continental margins is commonly partitioned into strike-slip and contractional structures (cf. Harland 1971; Beck 1983; McCaffrey 1991). The style and pattern of the ductile shear zones in the basement of the Sakar unit suggest that oblique plate convergence was translated into large-scale strike-slip and convergent movements, with localized extension in a few areas adjacent to syntectonic granitoids (Gerdjikov 1999a).

It is important to emphasize again that the described fabric is penetrative and is not related to discrete thrust surfaces as proposed by Go–ev (1991). In the entire study area, there not a single piece of evidence for the existence of important post-metamorphic fault zones.

Palaeozoic and Early Alpine Magmatism in the Sakar Unit

The presence of variably deformed granitoids in the basement of the Sakar unit has been known since the first detailed work in the area (Dimitrov 1958; Boyanov *et al.* 1965), but there has been no detailed description of the fabric of these magmatic rocks. The existence of pre-Triassic magmatic rocks (rhyolites, granitoids, diorites) is well known; most are related to the voluminous acid magmatism of probable Permian–Early Triassic age (Melnitsa complex). Others bodies, such as the Levka pluton, could be of late-Variscan age.

The data presented above allow interpretation of the Varnik granites as syntectonic. Main arguments for this are: (1) continuity of fabrics within and outside the Varnik granites; (2) concordance of the magmatic bodies with regional structures; (3) parallelism between magmatic and solid-state foliations; (4) local increase in metamorphic grade towards the area occupied by Varnik granites; (5) localization of intense ductile deformation in the area where the Varnik granites occur; (6) structures reflecting interaction between magmatism and deformation, displayed by associated aplitic and pegmatitic veins.

Emplacement of variably sized plutons into active reverse-sense shear zones is well documented (Ingram & Hutton 1994; Brown & Solar 1998; Paterson & Miller 1998), and it has been demonstrated that this is a mechanically possible process. In the case of the Varnik granites, the space problem is not so acute, because they are not a single compact body but, instead, make up separate intrusive sheets. One possible model is that the Varnik granites and associated magmatites were emplaced as a series of sheets that interfingered into its wall rocks whilst they were undergoing oblique compression.

It is worth noting that, at present, at least for precise U-Pb ages, the Bulgarian part of the Strandja Zone is *terra incognita*. To test the proposed model, a serious campaign for isotopic dating has to be undertaken.

Some Regional Implications

A great number of features observed in the study area are typical of the Sakar unit. For example, close interfingering between syntectonic and pre-metamorphic granitoids is widespread in the western part of the Sakar unit (Gerdjikov 2004). Other ubiquitous features of the metamorphic basement to the Sakar unit are the occurrence of arterite-type migmatites along the margins of the syntectonic granitoids, often pronounced S/L fabric, the absence of late brittle shear zones, etc. These data, as well as the evidence for an early Alpine age for the metamorphism in the study area, are in disagreement not only with ideas widespread in Bulgaria about the Precambrian age of the high-grade metamorphism in the Strandja Zone (Dimitrov 1958; Boyanov *et al.* 1965; Dabovski *et al.* 1993; Zagorchev 1993), but also with the recent data of Okay *et al.* (2001). The last authors provided the first unambiguous isotopic data regarding the existence of pre-Alpine metamorphic basement in the Strandja Zone, and also stressed the lack of pronounced lineation and shear-sense indicators in these rocks in the Turkish part of the Strandja. Furthermore, taking into account the data presented by Chatalov (1990) and Okay *et al.* (2001) concerning the lower grade of the Alpine metamorphism in the area east of the Tundza River, it is obvious that significant differences exist between the metamorphic basement of the Sakar and Strandja units.

All available structural data suggest that, during the pre-Cenomanian orogeny, synmetamorphic deformation was concentrated in the thermally softened western part of the Strandja Zone. Despite the lack of needed isotopic data, at this stage of the research, it appears that the significant thermal perturbation of the metamorphic field gradient in the Sakar unit is related to the emplacement of several syntectonic granitoids. The syntectonic early Alpine magmatism in the Sakar unit is probably related to crustal-scale shear zones, in a way similar to the western Srednogorie (Ivanov *et al.* 2001b). This model for early Alpine syntectonic magmatism in the western part of the Strandja Zone is compatible with observed differences between the Sakar and Strandja units and also provides explanation for the similarities in metamorphic grade and fabric between the Sakar and Rhodopes.

A remaining key question is the existence of pre-Triassic metamorphic basement in the Sakar unit. The favoured interpretation here is that there is such basement in the Sakar unit, but it is typically completely reworked and can only be recognized in a few places (e.g., the domains displaying complicated deformational styles; Figure 3). In any case, occurrences of suspected basement are rather limited compared to the Strandja unit or central Srednogorie.

Conclusions

1. Metamorphic rocks and granitoids in the SE part of the Sakar unit display strong S/L fabric that contains evidence for top-to-the-NW shearing. Since the same S/L fabric is observed in the Triassic metasediments (Topolovgrad Group), an early Alpine age (J3-K1) is inferred for metamorphism and penetrative deformation in the Sakar unit.
2. There is a complicated interfingering between the pre- and syn-tectonic granitoids as shown by the relations between the Varnik granites and their wall rocks. The pre-tectonic granitoids include shallow-level granitoids from the Melnitsa complex, as well as some deep-seated intrusions of possible Variscan age. The sheeted nature of the syntectonic plutons in the Sakar unit is more widespread that previously recognized.
3. The Varnik granites provide a nice example of how the concept of “emplacement-related increase in metamorphic grade” could be applied at various scales. Most probably the seemingly regional-scale increase in metamorphic grade in the Sakar unit is a result of a combined effect of a several pluton-driven thermal pulses.

4. The presence of pre-Alpine metamorphic basement in the Sakar unit is questioned, but the problem must remain open until enough isotopic data accumulate.

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