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Cambrian magmatism, Variscan high-grade metamorphism and imposed greenschist facies shearing in the Central Sredna Gora basement units (Bulgaria)

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Abstract: Gneisses from the deep structural levels of the European Variscan Belt are well exposed in the Central Sredna Gora in Bulgaria. In general, migmatites predominate, but unmigmatized domains (or domains with incipient migmatization) are also documented in this area. This paper presents new structural, petrographic and U-Pb isotope geochronological data from such an unmigmatized part of the Variscan high-grade metamorphic basement (the Koprivshtitsa Unit). A predominant part of this unit represents an alternation of metagranitoids and metabasites. The protolith crystallization age of the metagranitoids is constrained at 491.5±7.6 Ma by U-Pb laser ablation method on zircons. This age coincides with the previously available Late Cambrian protolith ages of metabasic rocks that crop out within the adjacent migmatitic unit. The Korpivshtitsa Unit comprises also lesser orthogneisses with Late Neoproterozoic protoliths. Based on the available local and regional paleogeographic reconstruction schemes, we suggest that the Upper Cambrian magmatic rocks intruded Upper Neoproterozoic crust during the initial opening stages of the Rheic Ocean or a related basin. Subsequently, both were involved in the Variscan high-grade deformation. The contact of the Koprivshitsa Unit with the migmatitic part of the metamorphic complex coincides with a north-vergent greenschist facies thrust zone — the Chuminska Shear Zone. The exact time of the shearing is still not well constrained but it clearly postdates the Variscan high-temperature metamorphism of the gneisses.

Key words: Variscan high-grade basement, Central Sredna Gora Complex in Bulgaria, Late Cambrian magmatism, greenschist facies mylonitization.

Introduction

Variscan fragments are recognized all over the Alpine Belt of Europe (Dallmeyer et al. 1998; Neubauer & Handler 1999; Franke et al. 2000; Kroner et al. 2008; Froitzheim et al. 2008; Schulmann et al. 2014 and references therein). Although in the Balkans high-grade metamorphic rocks from the deep structural levels of the European Variscan Belt are well-exposed (Ivanov 1988; Kräutner & Kristic 2002; Iancu et al. 2005; Yanev et al. 2006; Kounov et al. 2012; Gerdjikov et al. 2013) (Fig. 1b), their Variscan and pre-Variscan history is still not well understood, thus hindering correlations with similar units in Central and Western Europe.

In Bulgaria, for a long time, the high-grade metamorphic complexes were considered as Precambrian (see the review of Zagorchev 2008). However, in the last twenty years numerous detailed studies from the Rhodope massif revealed their Alpine tectonic evolution (e.g. Burg et al. 1996, 2012; Kaiser-Rohrmeier et al. 2004; Liati 2005; Bosse et al. 2009; Turpaud & Reischmann 2010). Furthermore, Ivanov (1988) and Velichkova et al. (2004) suggested the Variscan age of high-grade metamorphic rocks north of the Alpine Rhodopes (Fig. 1b). Quite recently, three Variscan complexes have been distinguished in Bulgaria based on the common Middle Carboniferous age of the amphibolite facies metamorphic overprint — the Central Sredna Gora, the Ograzhden-Vertiskos and the Strandja Complexes (Gerdjikov et al. 2013).

The Central Sredna Gora Complex, which represents a basement unit within the Alpine Sredna Gora Zone of the Balkan Thrust Belt (e.g. Dabovski et al. 2002), is a well-exposed but poorly studied part of the Variscan Orogen in Bulgaria. At a regional scale, it has been correlated with the Getic-Supragetic basement units of the South Carpathians (Neubauer 2002; Velichkova et al. 2004; Iancu et al. 2005; Schmid et al. 2008). Only limited data about the protoliths of the metamorphic rocks from the Central Sredna Gora Complex, as well as about their ages and tectonic evolution are available (Velichkova et al. 2004; Peytcheva & von Quadt 2004; Carrigan et al. 2006; Gaggero et al. 2009). We carried out our research in the northern part of the complex (Fig. 2a) where high-grade basement rocks form a strip which extends along several tens of kilometers in an E-W direction. The metamorphic section comprises migmatitic gneisses and unmigmatized domains (Dabovski et al. 1966; Dabovski 1988; Zagorchev 2008; Antonov et al. 2010).

In this paper, we present details for the unmigmatitic part known as the Koprivshtitsa Unit (Dabovski 1988; Zagorchev 2008; Antonov et al. 2010). Our research provides new data in several aspects: i) the lithological and structural characteristics of the unit; ii) its contact with the migmatitic unit; iii) U-Pb

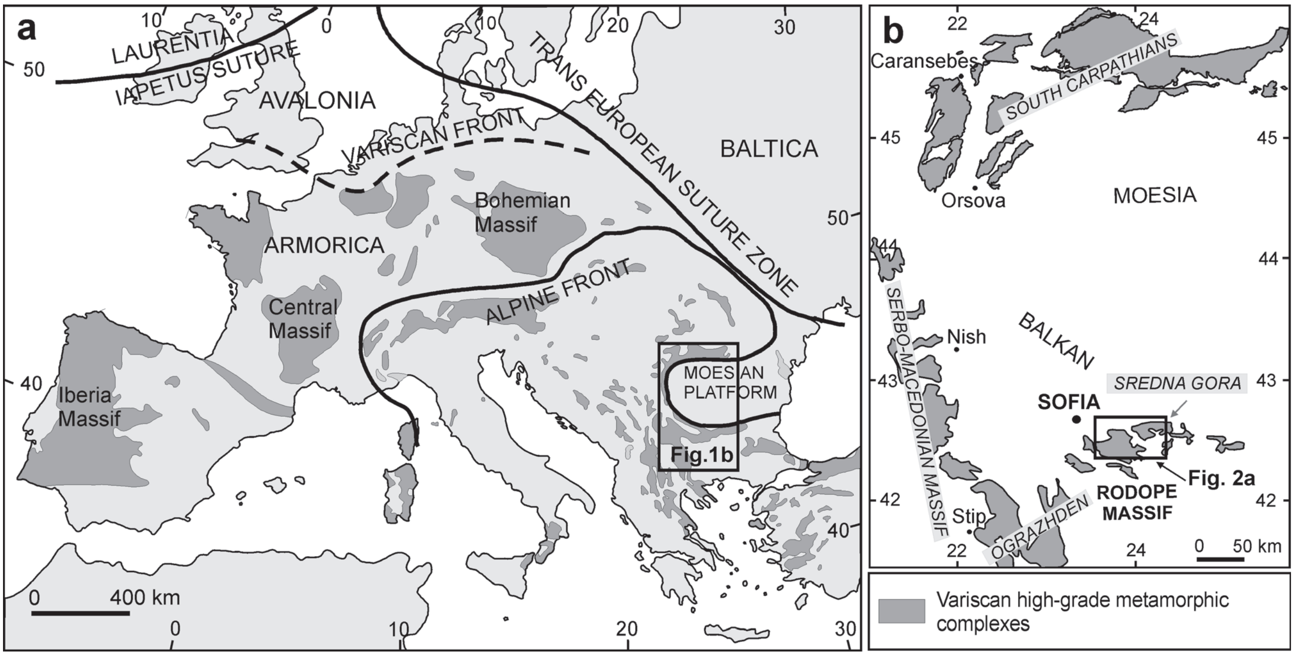


Fig. 1. Regional sketch map of the European Variscan terranes (**a**) with close-up view on high-grade basement in the western part of the Balkan Peninsula (**b**). Modified after Kounov et al. (2012) and Balintoni et al. (2014).

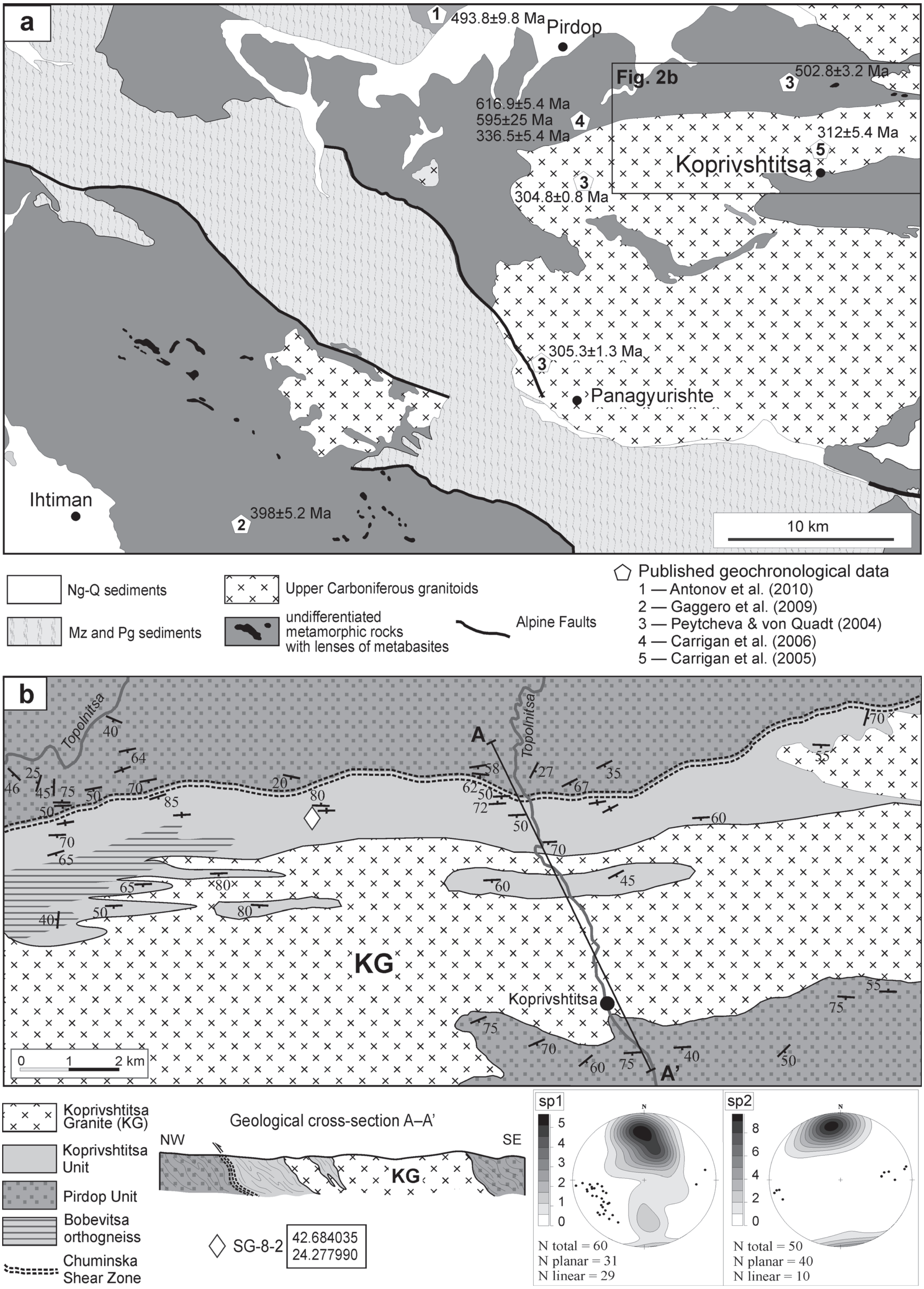
zircon geochronological data. On this ground, we suggest a possible scenario for the origin of the studied rocks in the context of the Paleozoic evolution of the area. This will help us to better understand the important features of the Variscan Belt in the Balkans and will contribute to further regional correlations with other fragments of the orogen in Europe.

Geological setting

The Variscan Central Sredna Gora Complex is exposed south and southeast of Sofia (Fig. 1b). Two high-grade metamorphic units have been distinguished in its northern part (Fig. 2a,b) — the migmatitic Pirdop Unit and the unmigmatized Koprivshtitsa Unit (Dabovski 1988; Zagorchev 2008; Antonov et al. 2010) where the rocks of the former dominate the metamorphic complex. Most widespread are migmatitic paragneisses (biotite and two-mica banded migmatites, and minor garnet-, kyanite- and sillimanite-bearing gneisses) and subordinate amphibole-biotite orthogneisses, amphibolites, metaserpentinites, and mafic eclogites (Dabovski et al. 1966; Dabovski 1988; Zagorchev 2008; Antonov et al. 2010). Mixed protoliths of continental and oceanic-crust affinities have been assumed for these rocks (Zagorchev 2008). A common feature of the unit is the intense post-migmatization greenschist to lower amphibolite facies retrogression related to Mid and/or Late Variscan shearing (Velichkova et al. 2004; Lazarova et al. 2010; Gerdjikov et al. 2010 and references therein) during which the migmatites obtained specific "augen"-gneiss texture. The Koprivshtitsa Unit occupies a limited area in the surroundings of Koprivshtitsa town (Fig. 2b). Up to now, it was regarded as derived from a Precambrian siliciclastic suit intruded by basic volcanic rocks (Zagorchev 2008). The described lithologies include mainly amphibolites and biotite gneisses, and minor biotite and two-mica schists, sillimanite-biotite and garnet-sillimanite-biotite schists, quartzites, marbles, garnet-pyroxene and garnet amphibolites, as well as orthogneiss bodies (Dabovski et al. 1966; Dabovski 1988; Zagorchev 2008; Antonov et al. 2010). One of the metagranitoids, the so called Bobevitsa Orthogneiss (Zagorchev et al. 1973), was dated to 616.9 ± 9.5 and 595 ± 23 Ma (Fig. 2a; HR-SIMS U-Th-Pb zircon age — Carrigan et al. 2006).

The high-grade metamorphic fabric of both the Pirdop and the Koprivshtitsa unit is sealed by the undeformed Late Variscan Koprivshtitsa Granite (Fig. 2) dated at 304.8 ± 0.8 Ma (U-Pb monazite age — von Quadt et al. 2004) and at 312.0 ± 5.4 Ma (HR-SIMS U-Th-Pb zircon age — Carrigan et al. 2005). On the other hand, the contact between the units north of Koprivshtitsa (Fig. 2b) was described as a steeply dipping, north-vergent reverse fault related to the Late Alpine thrust system (Stara Planina thrust system — Dabovski et al. 1966). During the last regional-scale mapping of the area

Fig. 2. a — simplified geological map of a part of the Central Sredna Gora area with published geochronological data (modified after Iliev & Katskov 1990a,b); **b** — geological map of Koprivshtitsa area (modified after Dabovski et al. 1966; Zagorchev et al. 1973; Iliev & Katskov 1990a,b; Cheshitev et al. 1994) with a cross-section A–A′ along the Topolnitsa River and stereographic projections (equal area; lower hemisphere) of foliations (density contours) and lineations (points) in the Pirdop (sp1) and Koprivshtitsa (sp2) Units. Location of sample SG-8-2 is indicated.


a
1 493.8±9.8 Ma
Pirdop
Fig. 2b
3 502.8±3.2 Ma
616.9±5.4 Ma
595±25 Ma
336.5±5.4 Ma
4
312±5.4 Ma
5
Koprivshtitsa
3
304.8±0.8 Ma
305.3±1.3 Ma
3
Panagyurishte
Ihtiman
2 398±5.2 Ma
10 km
Ng-Q sediments
Mz and Pg sediments
Upper Carboniferous granitoids
undifferentiated metamorphic rocks with lenses of metabasites
Alpine Faults
Published geochronological data
1 — Antonov et al. (2010)
2 — Gaggero et al. (2009)
3 — Peytcheva & von Quadt (2004)
4 — Carrigan et al. (2006)
5 — Carrigan et al. (2005)
b
Topolnitsa
Topolnitsa
A
A'
KG
Koprivshtitsa
0 1 2 km
Koprivshtitsa Granite (KG)
Koprivshtitsa Unit
Pirdop Unit
Bobevitsa orthogneiss
Chuminska Shear Zone
Geological cross-section A–A'
NW
SE
KG
SG-8-2
42.684035
24.277990
sp1
N total = 60
N planar = 31
N linear = 29
sp2
N total = 50
N planar = 40
N linear = 10

(Antonov et al. 2010), it was interpreted as a Variscan ductile shear zone, the Chuminska Shear Zone.

In the studied area, data for the protolith ages of the high-grade metamorphic rocks are still scanty. Besides the Cadomian age of the Bobevitsa orthogneiss, two late Cambrian U-Pb zircon protolith ages are available for the Pirdop Unit (Fig. 2b): 493.8 ± 9.8 Ma for a metagabbro sample (Antonov et al. 2010) and a poorly constrained age of 502.8 ± 3.2 Ma for a hornblende-biotite gneiss (Fig. 2a — Peytcheva & von Quadt 2004).

The Variscan metamorphic evolution is constrained by U-Pb and $^{40}Ar/^{39}Ar$ data (Fig. 2a): i) an $^{40}Ar/^{39}Ar$ amphibole age of 398 ± 5.2 Ma obtained from a garnet-biotite-ilmenite-bearing amphibolite east of Ihtiman was interpreted as the time of an early amphibolite facies re-equilibration shortly after an eclogite facies metamorphic peak (Cortesogno et al. 2005; Gaggero et al. 2009); ii) the age of the high-temperature metamorphism and migmatization is estimated at 336.5 ± 5.4 Ma (HR-SIMS U-Pb zircon data on leucosome in migmatitic gneisses — Carrigan et al. 2006); iii) the intense greenschist to lower amphibolite facies regional-scale retrogression of migmatites of the Pirdop Unit and contemporaneous emplacement of muscovite-bearing granites is dated to 333.9 ± 0.2 Ma ($^{40}Ar/^{39}Ar$ of muscovite — Gerdjikov et al. 2010); iv) the post-metamorphic cooling ages of the gneisses west and south of the studied area range between 317 and 305 Ma ($^{40}Ar/^{39}Ar$ of muscovite and biotite — Velichkova et al. 2004). These data coincide with the time of a voluminous magmatism since the crystallization ages of the Late Variscan granitoids in this part of the Sredna Gora Complex are between 312 and 290 Ma (Carrigan et al. 2003, 2005; von Quadt et al. 2004; Velichkova et al. 2004).

The age constraints of several greenschist facies shear zones indicate that the high-grade rocks from the southern part of the Central Sredna Gora Complex were affected by Alpine tectono-thermal events ca. 140 Ma and ca. 106–100 Ma ($^{40}Ar/^{39}Ar$ of muscovite and biotite — Velichkova et al. 2004).

Analytical methods

U-Th-Pb isotope zircon analyses were carried out by a laser ablation (LA) technique using a New Wave Research (NWR) 193 nm excimer laser UP-193FX attached to a Perkin-Elmer ELAN DRC-e quadrupole inductively coupled plasma mass spectrometer (ICP-MS) at the Geological Institute of the Bulgarian Academy of Science in Sofia, Bulgaria. In-laboratory designed ablation cell with lowered position effects, energy density on sample ca. 8.8 J/cm^{-2} and repetition rate of 8 Hz are used. The ablation craters are ca. 35 μm in diameter. The analyses were carried out in blocks of 22, using the GJ1 zircon standard (Jackson et al. 2004) for fractionation corrections (2 analyses at the beginning, 2 in the middle and 2 at the end of the block) and Plešovice (Sláma et al. 2008) as "unknown" standard (to control the correct data reduction). The results were calculated off-line using GLITTER 4.0 (Macquarie University). All concordant zircons were used to calculate a mean $^{238}U/^{206}Pb$ age, or a concordia age. Concordia plots, ages and averaging were processed using ISOPLOT 3.0 (Ludwig 2003).

Results

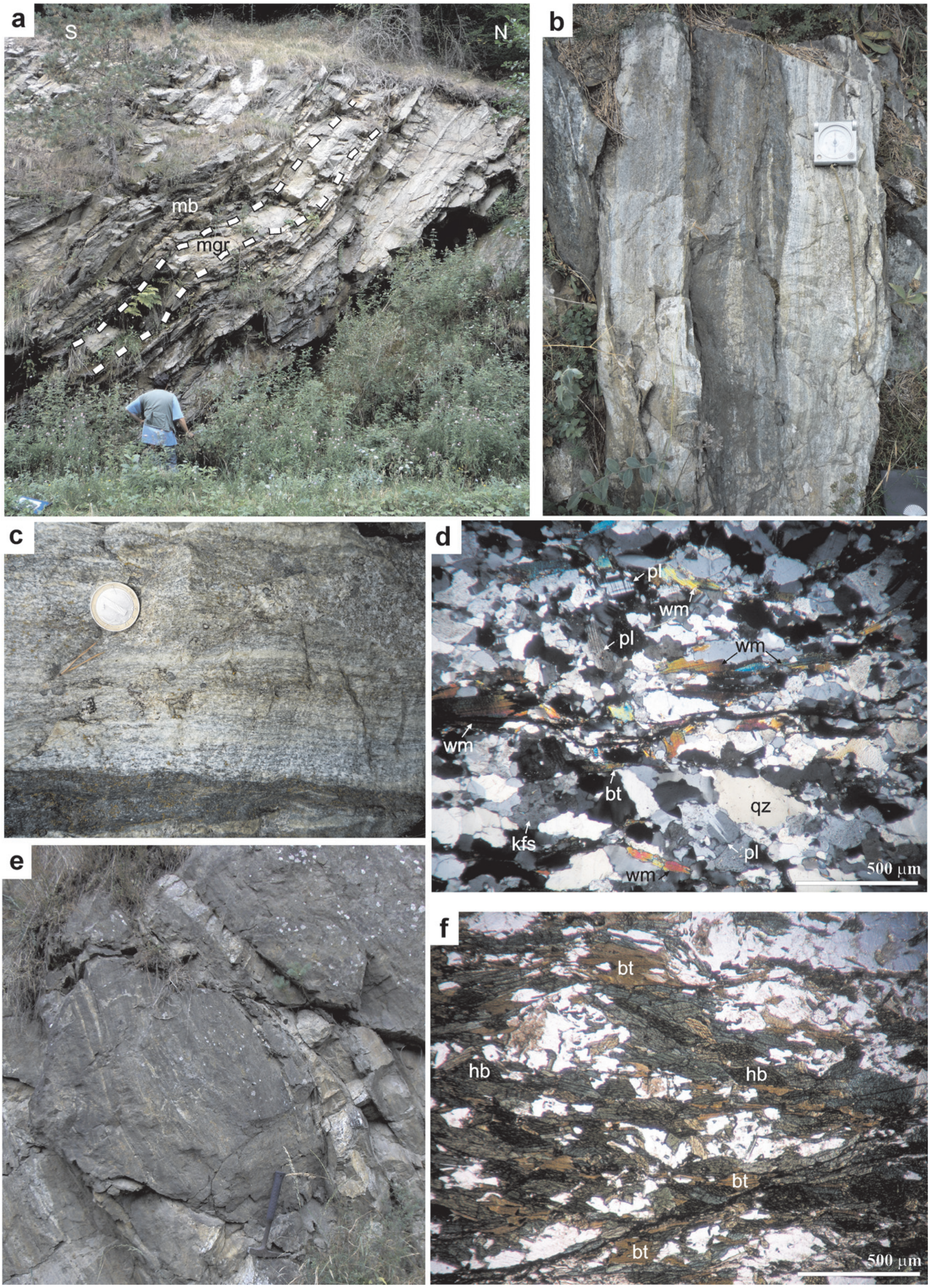
Structural characteristics of the Koprivshtitsa Unit

The unmigmatized Koprivshtitsa Unit is exposed as a narrow E-W trending and ca. 30 km long strip between the Pirdop Unit to the north and the Late Variscan Koprivshtitsa Granite to the south and southeast (Fig. 2b). Our field observations were carried out along several N-S profiles across the unit generally normal to the orientation of the regional foliation. The unit represents an alternation of metamorphic rocks with felsic and mafic protoliths (Fig. 3a,b), both in approximately equal proportions. The sillimanite-biotite schists, garnet-sillimanite-biotite schists, quartzites and marbles, reported before (Dabovski et al. 1966; Dabovski 1988; Zagorchev 2008), were not observed in the studied area.

The *felsic part* of the Koprivshtitsa unit consists of two-mica metagranites, which form up to several meters wide, sheet-like bodies with sharp contacts with the metabasic rocks (Fig. 3a,b). Generally, the contacts are parallel to the foliation fabric, but locally, slightly oblique contacts have been preserved as well. The thinner metagranite sheets are penetratively foliated (Fig. 3c), while in the thicker ones, the foliation is well developed only near the contacts. The foliation and mineral lineation are defined by the preferred orientation of micas, quartz and feldspars. The main rock-forming minerals are quartz, K-feldspar, and plagioclase with subordinate white mica and biotite and accessory titanite, zircon, and apatite. Under the microscope, the metamorphic foliation of the metagranites is defined by the preferred orientation of small (up to 1–2 mm along the long axis), elongated quartz and feldspar grains as well as unevenly distributed white mica flakes or two-mica aggregates (Fig. 3d).

The *mafic part* of the metamorphic section (Fig. 3a,b,e) is dominated by biotite-amphibole and amphibole-biotite gneisses and less abundant amphibolites. These rocks are derived

Fig. 3. Field and microscale characteristics of the Koprivshtitsa Unit. **a** — alternation between centimeter-thick sheet-like bodies of metagranitoids (mgr) and metabasic (mb) rocks (Topolnitsa River Valley north of Koprivshtitsa); **b** — a detailed view of the same relationships; **c** — well-foliated metagranitoid body with a foliation-parallel contact (Topolnitsa River Valley north of Koprivshtitsa); **d** — photomicrograph (cross-polarized light) of a metagranite with a weak metamorphic foliation defined by the preferred orientation of small, elongated quartz (qz) and feldspar (kfs, pl) grains as well as unevenly distributed white mica (wm) and biotite (bt) flakes (sample SG-8-2, location in Fig. 2b); **e** — amphibolites and a thin metagranitoid sheet-like body (Topolnitsa River Valley north of Koprivshtitsa); **f** — photomicrograph (plane-polarized light) of a biotite-amphibole gneiss with a distinct metamorphic foliation defined by the preferred orientation of elongated amphibole (hb), biotite (bt) and quartz-feldspar aggregates (same location as for d).


a
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500 µm

from mafic to intermediate igneous protoliths. The gneisses are medium-grained, with distinct foliation defined by the preferred orientation of amphibole-biotite aggregates and thin quartz-feldspar lenses. The lineation is defined by amphibole-biotite aggregates. The main rock-forming minerals are amphibole and biotite in varying proportions, but reaching up to 80 % of the rocks. Subordinate phases are plagioclase, quartz, ±K-feldspar; accessory phases are apatite, zircon, ±titanite, ±magnetite. Amphibole and biotite commonly form elongated domains, while quartz and feldspars are present as isolated grains or lens-shaped aggregates aligned parallel to the metamorphic foliation (Fig. 3f).

A common feature of the Koprivshtitsa Unit is a distinct E-W striking and steeply-dipping (60–80°) predominantly to the south foliation fabric (Fig. 2, sp2). The mineral lineation is weakly developed, plunging gently to the west-southwest or east-northeast.

Locally, bodies of coarse-grained, K-feldspar porphyroclastic *biotite metagranites* and *metagranodiorites* crop out. They show similar south-dipping foliation, but the coarser texture as well as the presence of well-preserved K-feldspar porphyroclasts allows us to distinguish them from the fine-to medium-grained two-mica metagranitoid sheets.

Contacts

The Koprivshtitsa Unit has a tectonic contact with the migmatitic Pirdop Unit and intrusive relations with the Koprivshtitsa Granite. South of the granite, the high-grade metamorphic basement is dominated again by migmatitic gneisses, which are structurally above the unmigmatized Koprivshtitsa Unit (Fig. 2, cross-section A–A′). During our research we focused on a characterization of the tectonic contact (Fig. 2b), the Chuminska Shear Zone (ChSZ).

The ChSZ is a generally narrow (up to 100–120 m), E-W trending and south-dipping structure, exposed along strike for nearly 15 km (Fig. 2b). It has sharp boundaries with the host gneisses. The footwall is built up by migmatitic two-mica paragneisses (Fig. 4a) and subordinate orthogneisses of the Pirdop Unit. In the hanging wall, the Koprivstitsa Unit consists of unmigmatized orthometamorphic rocks. The shear zone is better developed in the footwall migmatitic paragneisses, although several sub-parallel zones splay north and south from the main zone into both metamorphic units. Along the ChSZ and its splays, the gneisses are transformed to greenschist facies mylonites with well-developed mylonitic foliation and C′ shear bands (Fig. 4c). The mylonitic foliation (S_{my}) trends E–W to NE–SW and dips moderately to steeply (45–80°) to the south. It is generally parallel to the high-grade metamorphic fabric of the host gneisses (Fig. 2, sp1 and sp2). S_{my} is defined by a subparallel arrangement of dark, fine-grained phyllosilicate aggregates and quartz ribbons. In a number of outcrops an unequivocal lineation fabric did not form. Where the lineation is well developed it is defined by the alignment of elongated aggregates of white mica and chlorite or by fibrous quartz striae. The lineation has a moderate to steep down-dip plunge. The quartz linear fabric has the characteristics of a low-temperature stretching lineation. The C′ shear bands are defined by synkinematic white mica and chlorite (Fig. 4c) as well as by trails of mica fragments and by deflected strain-shadows of large feldspar grains. The acute angles with the mylonitic foliation are in the range of 20 to 30°.

The microscale observations of the sheared two-mica gneisses of the Pirdop Unit give important information about deformation mechanisms and metamorphic conditions. Less deformed migmatitic gneisses (Fig. 4b) are medium-grained rocks composed of plagioclase, K-feldspar, synmetamorphic quartz, muscovite, biotite, ±garnet, and accessory apatite, zircon and rutile. They have a distinct high-temperature metamorphic foliation defined by the preferred orientation of feldspars and elongated large mica flakes (Fig. 4b). The retrograde shearing within the ChSZ led to the formation of chlorite-white mica-quartz (syndeformational) mylonites (Fig. 4d,e). Their distinct mylonitic foliation is generally subparallel to the initial high-grade planar metamorphic fabric of the gneisses. The mylonites are characterized by variably sized and often fragmented porphyroclasts of feldspar, synmetamorphic quartz and mica, surrounded by a fine-grained synmylonitic white mica-chlorite-quartz matrix (Fig. 4d,e,f). The porphyroclasts are brittlely deformed and rotated by a cataclastic flow along the mylonitic foliation or C′ shear bands (Fig. 4d,e). Most of them show strong undulose extinction (Fig. 4e,f) and have tails ("strain shadows") of very fine-grained recrystallized material of sericite-quartz composition (Fig. 4d). A common feature of the large quartz fragments is the development of deformation bands (Fig. 4f).

The synkinematic fine-grained quartz forms thin bands along the S_{my} (Fig. 4d) or occurs along grain boundaries and micro-fractures of the large quartz porphyroclasts (Fig. 4f). Recrystallized, synkinematic and very fine-grained mica is generally observed along both the intragranular micro-fractures and mylonitic planar fabrics. A high fluid activity during mylonitization is indicated by the advanced replacement of feldspars by secondary minerals (clays, fine-grained white mica and quartz) as well as by the phyllosilicates and fibrous quartz in "strain shadows" and overgrowths around porphyroclasts.

Shear sense criteria such as S–C′ fabric, strain shadows (Fig. 4d), synthetic domino fragmentation of muscovite and feldspars, etc. consistently indicate top-to-the-north and northwest direction of the tectonic transport, namely north-vergent reverse-fault kinematics.

LA-ICP-MS geochronology

We sampled a metagranite sheet-like body from the felsic part of the Koprivshtitsa Unit. Our aim was to constrain the time of emplacement of this abundant rock variety within the section as well as to compare the results with the recently obtained ages of 502.8 ± 3.2 Ma for a hornblende-biotite gneiss of the Pirdop Unit north of Koprivshtitsa (Peytcheva & von Quadt 2004) and 493.8 ± 9.8 Ma for a metagabbro west of Pirdop (Antonov et al. 2010). More than 30 zircons were recovered from the metagranite sample SG-8-2 (sample locality in Fig. 2b). Grains with lengths between 100 and 250 µm were selected for analysis. Most of them are slightly rounded but still have preserved prismatic and bi-pyramidal morphologies, characteristic for a magmatic population. On the

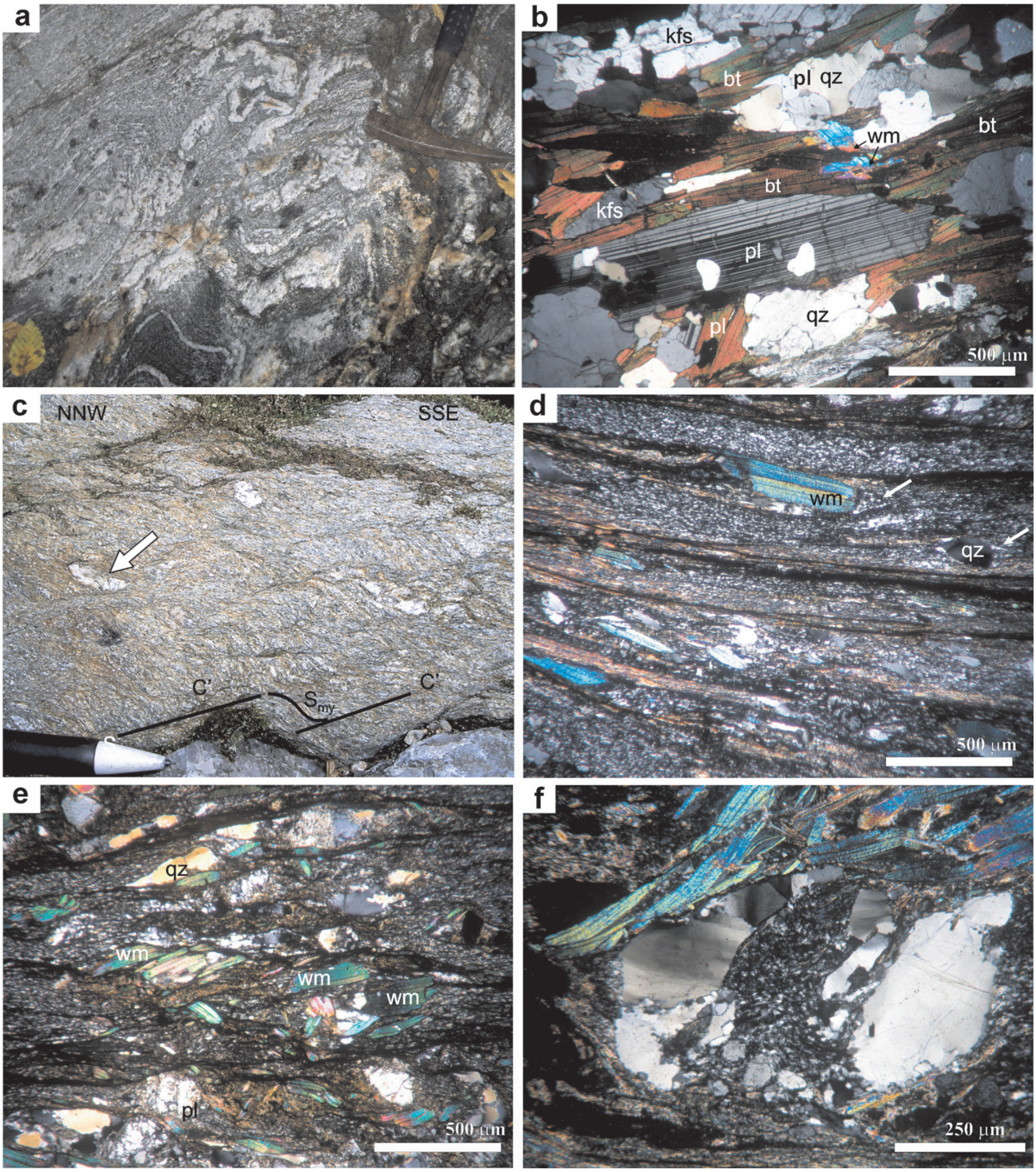

Fig. 4. Field and microscale characteristics of the Pirdop Unit. **a** — two-mica migmatitic gneiss with leucosome material along the metamorphic foliation planes, and within the hinges and along axial planes of small-scaled folds; pavement outcrop; ca. 7.5 km northwest of Koprivshtitsa; **b** — photomicrograph of a two-mica gneiss with a distinct high-grade metamorphic foliation defined by a preferred orientation of main rock-forming minerals — biotite (bt), white mica (wm), plagioclase (pl), K-feldspar (kfs) and quartz (qz); **c** — greenschist facies S–C′ mylonite in the ChSZ; the white arrow points to a lens of a sheared leucosome from the parental migmatitic gneiss; **d** — photomicrograph of a fine-grained mylonite with a distinct "banding" defined by an alternation between thin phyllosilicate-rich domains and thicker bands of fine-grained synkinematic quartz; porphyroclasts of white mica and synmetamorphic quartz are common; strain shadows (white arrow) of the porphyroclasts point to a sinistral (top to the NW) shearing; **e** — photomicrograph demonstrating the brittle deformation behaviour of feldspars, quartz and mica porphyroclasts and abundant microfractures parallel to the mylonitic foliation; **f** — fragmented quartz porphyroclast with strong, undulose extinction and deformation bands; the large microfracture separating the porphyroclast into two parts is filled with fine-grained aggregate of synkinematic phyllosilicates and quartz; weak bulging recrystallization is revealed along the boundaries of the quartz fragments and along fine microfractures. All photomicrographs are with crossed polarizers. Mineral abbreviations as in Fig. 3.

backscattered electron (BSE) images (Fig. 5a), fractures are visible in almost all of the zircon grains. Cathodoluminescence (CL) images (Fig. 5a) reveal a preserved magmatic oscillatory zoning and fine metamorphic rims. The magmatic origin of the grains is further confirmed by the Th/U ratio >0.5 (Table 1). The solid-state recrystallization and fracturing of the zircon grains most probably reflect the high-grade metamorphic overprint. This event is clearly indicated by the consistently younger ages of the rims (Pb-loss).

The U-Pb isotope ages (Table 1) are summarized in Fig. 5b. The obtained age data range between 400 and 700 Ma. Two analyses concordant at ca. 600 and another two at ca. 700 Ma correspond to inherited zircon cores (e.g. grain 1, Fig. 5a) and point to a Neoproterozoic source contribution. CL images reveal that a group of several concordant to slightly discordant analyses yielding ages between ca. 400 and ca. 470 Ma correspond to zones of recrystallization and certain Pb-loss or rejuvenation (e.g. grain 3, Fig. 5a). The main group of 11 concordant analyses corresponding to zircon grains with fine magmatic oscillation (e.g. grain 2, Fig. 5a) were used to calculate a concordia age of 491.5±7.6 Ma (Fig. 5c). This date is considered the best approximation of the crystallization age of the granite.

Discussion

The Koprivshtitsa Unit — structure and ages

Field data show that the Koprivshtitsa Unit represents a small but from a geodynamic point of view important, unmigmatized domain of the Central Sredna Gora Complex.

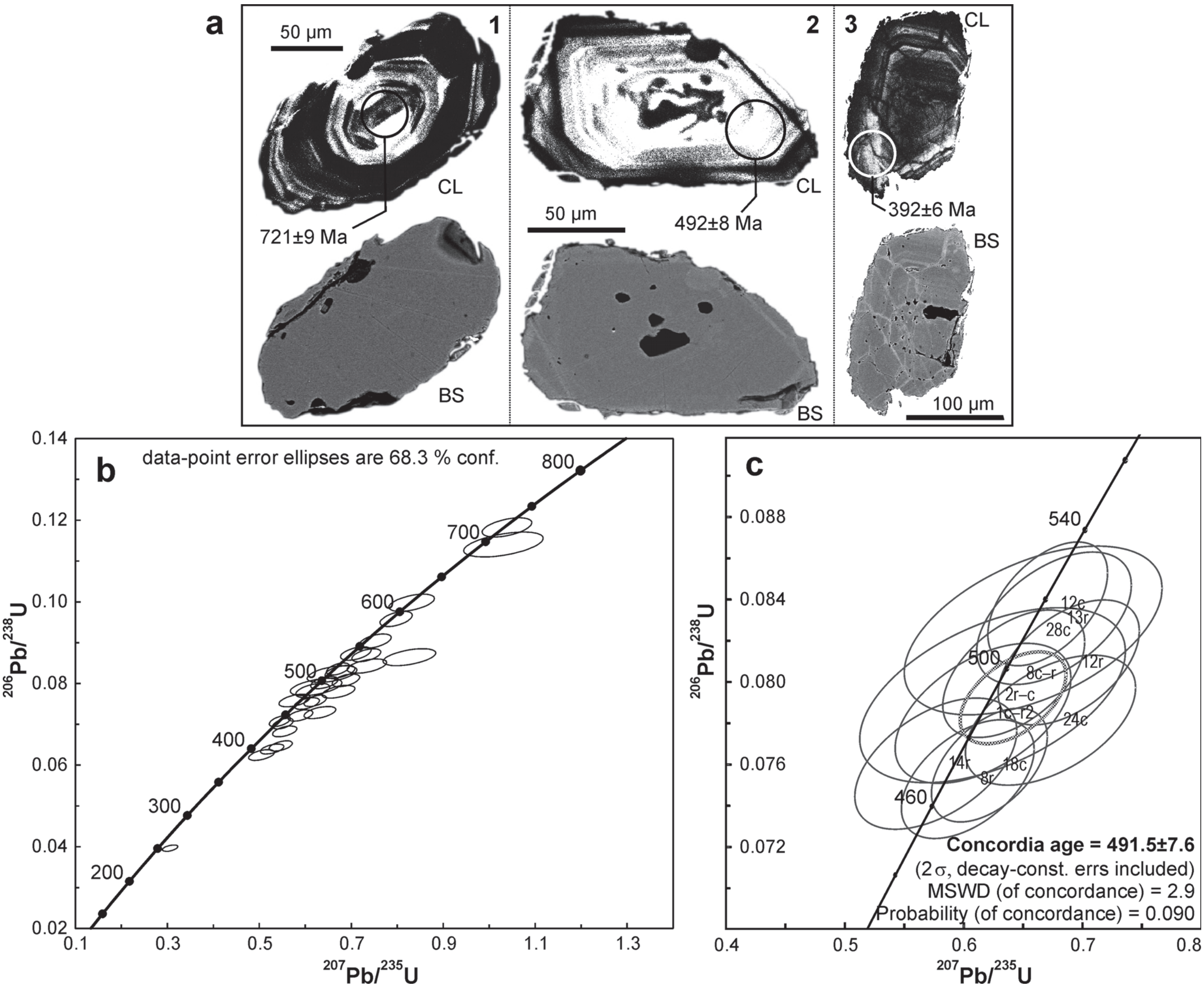

Fig. 5. LA-ICP-MS U-Pb geochronology results for metagranite sample SG-8-2 (sample location in Fig. 2). **a** — selected cathodoluminescence (CL) images (upper row) and backscattered electron (BSE) images (lower row) of analysed zircon grains with position of the laser ablation craters (circles) and corresponding ages. Grain 1 — inherited Neoproterozoic magmatic core, grain 2 — large grain with fine oscillatory zonation (analysed area) and thin metamorphic rim (black on the CL image), grain 3 — fractured and largely recrystallized zircon with analysed metamorphic rim; **b** — concordia plot of all LA-ICP-MS analyses; **c** — concordia crystallization age excluding inherited cores and metamorphic rims. Data calculations and plots were carried out in ISOPLOT 3.0 (Ludwig 2003).

Table 1: Results of U-Pb LA-ICP-MS zircon geochronological analyses on sample SG-08-2. **Abbreviations:** c — zircon core, r — zircon rim, Rho — correlation coefficient, 1SE — 1 sigma error, 2SE — 2 sigma error.

Analysis #	Zircon	Isotope ratios								Rho	Age/Ma				Concentrations (ppm)			Ratio
		$^{206}Pb/^{238}U$	1SE	$^{207}Pb/^{235}U$	1SE	$^{208}Pb/^{232}Th$	1SE	$^{207}Pb/^{206}Pb$	1 SE		$^{206}Pb/^{238}U$	2SE	$^{207}Pb/^{235}U$	2SE	Th	U	Pb	Th/U
12ma12a04	1c–r	0.08710	0.00110	0.7326	0.0208	0.0285	0.0013	0.0610	0.0018	0.59	538.44	13.04	558.10	24.09	643	909	88.62	0.707
12ma12a05	1c–r2	0.07848	0.00112	0.6163	0.0244	0.0292	0.0015	0.0570	0.0023	0.57	487.13	13.38	487.57	30.31	400	706	60.78	0.567
12ma12a06	5c	0.07102	0.00088	0.5450	0.0151	0.0262	0.0013	0.0557	0.0016	0.59	442.39	10.59	441.79	19.75	347	749	56.44	0.464
12ma12a07	5r	0.07034	0.00087	0.5511	0.0151	0.0260	0.0013	0.0568	0.0016	0.59	438.30	10.47	445.76	19.61	318	748	55.21	0.424
12ma12a08	7c	0.08754	0.00112	0.7102	0.0217	0.0286	0.0015	0.0588	0.0018	0.58	541.06	13.27	544.90	25.44	525	987	92.08	0.532
12ma12a09	2r	0.08667	0.00138	0.8267	0.0374	0.0293	0.0017	0.0692	0.0032	0.57	535.90	16.36	611.83	40.85	195	322	30.77	0.604
12ma12a10	2r–c	0.07936	0.00140	0.6243	0.0369	0.0265	0.0016	0.0570	0.0035	0.56	492.38	16.71	492.60	45.31	155	223	19.77	0.696
12ma12a13	3c	0.09598	0.00120	0.7975	0.0231	0.0305	0.0019	0.0602	0.0018	0.58	590.90	14.11	595.46	25.83	433	911	91.50	0.476
12ma12a14	8r	0.07529	0.00095	0.6034	0.0184	0.0249	0.0016	0.0581	0.0018	0.58	468.03	11.39	479.45	23.14	1195	1946	159.86	0.614
12ma12a15	8c–r	0.08040	0.00102	0.6421	0.0197	0.0267	0.0019	0.0579	0.0018	0.58	498.61	12.17	503.66	24.14	190	905	70.70	0.210
12ma12a16	9r	0.07238	0.00092	0.5900	0.0181	0.0262	0.0019	0.0591	0.0019	0.58	450.57	11.06	470.93	22.85	610	1288	99.17	0.474
12ma12a17	9c	0.06270	0.00085	0.5047	0.0184	0.0266	0.0020	0.0584	0.0022	0.57	392.12	10.31	414.94	24.58	537	1194	80.92	0.450
12ma12a18	13r	0.08309	0.00106	0.6760	0.0215	0.0163	0.0013	0.0590	0.0019	0.58	514.60	12.61	524.41	25.75	1552	1240	116.40	1.252
12ma12a19	14r	0.07604	0.00105	0.5766	0.0225	0.0230	0.0019	0.0550	0.0022	0.57	472.52	12.57	462.29	28.66	592	798	67.19	0.742
12ma12b04	11c	0.09057	0.00115	0.7529	0.0231	0.0270	0.0015	0.0603	0.0019	0.58	559.01	13.59	569.98	26.47	98	490	42.78	0.201
12ma12b05	12c	0.08379	0.00099	0.6707	0.0166	0.0233	0.0013	0.0581	0.0015	0.59	518.79	11.77	521.19	20.05	820	1302	116.32	0.630
12ma12b06	12r	0.08095	0.00100	0.6884	0.0196	0.0276	0.0016	0.0617	0.0018	0.58	501.89	11.92	531.88	23.36	338	936	77.47	0.361
12ma12b07	16c	0.11841	0.00158	1.0387	0.0358	0.0360	0.0023	0.0636	0.0022	0.58	721.51	18.20	723.30	34.99	27	178	20.16	0.154
12ma12b08	18c	0.07597	0.00091	0.6216	0.0161	0.0230	0.0014	0.0594	0.0016	0.59	472.11	10.90	490.91	20.00	891	1479	120.66	0.603
12ma12b09	20c	0.11418	0.00202	1.0313	0.0573	0.0335	0.0023	0.0655	0.0037	0.56	697.07	23.35	719.60	55.74	46	83	10.00	0.551
12ma12b10	21r–c	0.03989	0.00053	0.3064	0.0111	0.0144	0.0011	0.0557	0.0021	0.57	252.26	6.57	271.40	17.17	224	2154	80.86	0.104
12ma12b13	22r	0.06414	0.00082	0.5282	0.0170	0.0255	0.0020	0.0597	0.0020	0.58	400.85	9.93	430.67	22.33	453	1674	108.12	0.270
12ma12b14	22c	0.06495	0.00081	0.5476	0.0164	0.0240	0.0020	0.0611	0.0019	0.58	405.75	9.80	443.46	21.37	757	1926	130.36	0.393
12ma12b15	25r	0.06845	0.00087	0.5556	0.0174	0.0221	0.0019	0.0589	0.0019	0.58	426.89	10.49	448.73	22.47	1292	1858	141.27	0.696
12ma12b16	25c	0.08444	0.00117	0.7339	0.0280	0.0299	0.0028	0.0630	0.0025	0.57	522.65	13.90	558.90	32.34	309	474	44.83	0.652
12ma12b17	24c	0.07815	0.00104	0.6731	0.0236	0.0301	0.0029	0.0625	0.0022	0.57	485.16	12.43	522.63	28.36	595	1302	108.94	0.457
12ma12b18	24r	0.07307	0.00098	0.6323	0.0229	0.0281	0.0029	0.0628	0.0023	0.57	454.71	11.77	497.59	28.12	825	1608	128.11	0.513
12ma12b19	28c	0.08250	0.00135	0.6585	0.0358	0.0340	0.0038	0.0579	0.0032	0.56	511.13	16.07	513.73	43.08	30	111	9.23	0.269
12ma12b20	29c	0.09995	0.00140	0.8324	0.0326	0.0337	0.0038	0.0604	0.0024	0.57	614.19	16.40	614.98	35.59	409	518	59.56	0.789

A considerable part of the unit represents an alternation of metagranitoid and metabasic rocks. Their initial relationships were obliterated during the high-grade metamorphic overprint, but the sheet-like geometry of the metagranitoids and their small thickness suggest dyke- or sill-like emplacement within the mafic host rocks. The new U-Pb geochronological data indicate a Late Cambrian (491.5 ± 7.6 Ma) crystallization age of the metagranites (Fig. 5). The results overlap within the analytical error with the protolith crystallization age of 493.8 ± 9.8 Ma reported for a metagabbro lens within the migmatitic gneisses of the Pirdop Unit (Antonov et al. 2010) (Fig. 2a). Similar, although not very precise due to large discordance of the analyses, is the lower intercept age of 502.8 ± 3.2 Ma of a hornblende-biotite gneiss from the Pirdop Unit (Fig. 2a) north of Koprivshtitsa (Peytcheva & von Quadt 2004). These data suggest an approximately contemporaneous Late Cambrian emplacement of the mafic and felsic melts within the Central Sredna Gora Complex.

Considering the amphibolite facies overprint of the Koprivshtitsa Unit, concordant ages obtained from some of the zircons (mainly from rims but also from inner zones with fractures) which cluster around 400 Ma are important (Table 1). These ages probably reflect the time of a high-grade metamorphic event. They correlate well with the age of 398 ± 5.2 Ma interpreted as an amphibolite facies re-equilibration of mafic eclogites south of the studied area (Gaggero et al. 2009). There is a substantial difference with the time of the migmatization in the Pirdop Unit, estimated by Carrigan et al. (2006) at 336.5 ± 5.4 Ma, but at this stage of research our results and previously published data are insufficient to thoroughly address this issue. Although scattered and incomplete, the geochronological data for the Central Sredna Gora Complex (Velichkova et al. 2004; Carrigan et al. 2006; Gaggero et al. 2009) are in agreement with the prolonged and complicated metamorphic evolution suggested for the Variscan Belt in Central and Western Europe. It is generally characterized by an Early Variscan subduction and high-pressure metamorphism at ca. 400 Ma, a Mid to Late Variscan high-temperature event at ca. 340–330 and late-to-post-tectonic granitoids emplacement between ca. 330–300 Ma (e.g. Kroner et al. 2008; Kroner & Romer 2013 and references therein).

The mylonitic contact of the Koprivshtitsa Unit

The Chuminska Shear Zone represents a mylonitic boundary between the Koprivshtitsa and Pirdop units. The syndeformational mineral assemblage of quartz, chlorite and white mica, the generally brittle behaviour of the feldspar porphyroclasts as well as the quartz recrystallization fabrics within the mylonites suggest a greenschist facies fluid-assisted deformation along the zone at temperatures most probably in the range of 300–350 °C. The observed sense-of-shear criteria indicate reverse kinematics along the north vergent zone thus supporting the earlier interpretation of Dabovski et al. (1966) and Iliev & Katskov (1990).

Initially, a Late Alpine time of shearing was suggested (Dabovski et al. 1966), whereas Antonov et al. (2010) assumed a Variscan deformation. The sole indirect age indicator is the fact that the Chuminska Shear Zone cuts the migmatitic gneisses of the Pirdop Unit in which the leucosome has been dated to 336.5 ± 5.4 Ma (Carrigan et al. 2006). Thus, the deformation clearly postdated the ca. 336 Ma high-temperature metamorphic event. In regional scale, similarities in terms of geometry, deformation style and kinematics are found between the Chuminska Shear Zone and several Early Alpine north-vergent thrusts in the Stara Planina Mountain area adjacent to the north (for details see Gerdjikov et al. 2007; Lazarova & Gerdjikov 2008 and references therein). Therefore, a kinematic and temporal correlation with these structures can be made. Furthermore, south of the Koprivshtitsa area, low-temperature (greenschist facies) shear zones deforming the high-grade Variscan metamorphic rocks have been dated at 105–100 Ma ($^{40}Ar/^{39}Ar$ mica ages — Velichkova et al. 2004). However, at this stage of research an unequivocal time constraint of the activities along the Chuminska Shear Zone cannot be given.

Correlations and tectonic context

Southwest of the studied area, the Central Sredna Gora Complex is similarly subdivided into two high-grade metamorphic units (Kouzhoukharov et al. 1980; Dabovski 1988; Zagorchev 2008) — one is dominated by migmatitic gneisses (the Plana Unit) and the other is composed of partially migmatized or non-migmatized biotite gneisses, amphibolites and eclogite lenses (the Garvanitsa Unit). They lack a direct connection with the Pirdop and Koprivshtitsa units, being separated by a several kilometers wide strip of Mesozoic and Cenozoic sedimentary and magmatic rocks (Fig. 2a). Nevertheless, based on the similar lithology and the grade of the metamorphic overprint a correlation between the Pirdop and Plana units and between the Koprivshtitsa and Garvanitsa units might be suggested.

In the context of the Paleozoic geodynamic evolution of the Balkans, a number of crustal "pieces" now composing the Variscan high-grade metamorphic complexes belonged to the northern peri-Gondwanan realm most probably until the Devonian and Early Carboniferous (Yanev 1993, 1997, 2000; Lakova 1995; Gutierrez-Marco et al. 2003; Boncheva et al. 2010 and references therein). The most recent regional (Nance & Linnemann 2008; Nance et al. 2010, 2012; Stampfli et al. 2011, 2013; von Raumer et al. 2013) and local (Kounov et al. 2012; Balintoni et al. 2014; Antic et al. 2014) geodynamic reconstructions suggest that during the time span between the Late Neoproterozoic and mid Paleozoic, several events of an enhanced magmatic activity took place: i) late Ediacaran–early (to mid?) Cambrian subduction, accretion and arc magmatism linked to the evolution of the Prototethys Ocean; ii) late Cambrian–Early Ordovician rifting related to the opening of the Rheic Ocean; iii) Mid Ordovician–Early Devonian magmatic arc magmatism. According to this scheme, and considering the newly obtained ca. 500 Ma protolith ages for both metagranitoids (this study) and metamafic rocks (Peytcheva & von Quadt 2004; Antonov et al. 2010), we could suggest that the mafic and the felsic igneous rocks in the northern flank of the Central Sredna Gora Complex are most probably related to the initial opening stages of the Rheic Ocean or a related basin in the late Cambrian. They intruded a Late Neoproterozoic (Carrigan et al. 2006) crust, which in the studied area is presented by the Bobevitsa-type orthogneisses.

Conclusions

The Koprivshtitsa Unit is an unmigmatized, orthogneiss-dominated part of the Variscan high-grade section of the Central Sredna Gora Complex in Bulgaria. The unit represents a fragment of a metamorphosed magmatic complex that includes metagranitoids and metabasites. The newly obtained crystallization age for the protoliths of the metagranites is 491.5 ± 7.6 Ma. The similar ages of 493.8 ± 9.8 Ma from a metagabbro (Antonov et al. 2010) and of 502.8 ± 3.2 Ma from a hornblende-biotite gneiss (Peytcheva & von Quadt 2004) from the migmatitic Pirdop Unit suggest a contemporaneous Late Cambrian emplacement of mafic and felsic melts. They intruded a Cadomian crustal fragment (the Bobevitsa-type orthogneisses) dated to ca. 616.9 ± 9.5 and 595 ± 23 Ma (Carrigan et al. 2006).

The age of ca. 400 Ma obtained from zircon rims shows that most probably an Early Devonian high-grade metamorphic event affected these basement rocks. A similar age is obtained from eclogites southwest of the studied area. These data are an important contribution to the further reconstructions of the P-T-t metamorphic evolution of the Balkan part of the Variscan belt.

The contact of the Koprivshtitsa Unit with the migmatitic Pirdop Unit is a greenschist facies mylonitic zone, postdating the high-temperature metamorphic overprint of the gneiss section. An Alpine age of the shearing or reactivation of preexisting structure could be assumed based on structural similarities with shear zones from the terranes adjacent to the study area.

According to published Paleozoic geodynamic schemes, we can suggest that the igneous rocks from the northern flank of the Sredna Gora Complex intruded Ediacaran crustal fragments most probably during the initial opening stages of the Rheic Ocean in the late Cambrian.

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