GEOLOGICA BALCANICA 52 (1), Sofia, April 2023, pp. 65–86.

# Lower Paleozoic low-grade metamorphic units from the Central Balkan Zone, Bulgaria: tectonic relationships, framework and geodynamic significance

*Ianko Gerdjikov[1], Alexandre Kounov[2], Anna Lazarova[3], Stoyan Georgiev[3], Dian Vangelov[1]*

*[1] Sofia University "St Kliment Ohridski", 15 Tsar Osvoboditel Blvd, 1504 Sofia, Bulgaria; e-mails: janko@gea.uni-sofia.bg (corresponding author); dedo@gea.uni-sofia.bg*
*[2] Department of Environmental Sciences, Basel University, 4056 Basel, Switzerland; e-mail: a.kounov@unibas.ch*
*[3] Geological Institute, Bulgarian Academy of Sciences, Acad. G. Bonchev Str., Bl. 24, 1113 Sofia, Bulgaria; e-mails: alazarova@geology.bas.bg; kantega@abv.bg*

*(Received: 18 November 2022; accepted in revised form: 03 April 2023)*

*Abstract.* The Central Balkan Zone belongs to the north-vergent fold-and-thrust belt of the Alpine Balkan orogen. In this zone, pre-Permian low-grade rocks, metamorphosed during the Variscan orogeny, were later reworked at two main stages of the Alpine compressional tectonics. Several tectono-stratigraphic subdivisions of these metamorphic rocks were previously presented, based on a purely stratigraphic approach in the absence of detailed structural studies and, most importantly, of reliable paleontological and geochronological records. In this study, we propose a new framework of the low-grade metamorphic rocks from the Central Balkan Zone, applying a critical analysis of the existing data combined with new geochronological data and detailed lithological and structural observations. Based on the structural relationships and geochronological constraints, several new entities, such as the Korduna, Bilo and Zvezdets units, were established together with a reassessment of the previously recognized Diabase-Phyllitoid Complex (DPC). Both DPC and the Bilo Unit are now defined as Cambrian–Lower Ordovician (?) mélange complexes part of an accretionary wedge and/or forearc basin formed along the north Gondwanan margin. In the Bilo, Murgash and Etropole mountains, a tectonically uninterrupted Cambrian–Upper Ordovician section, characterized by a normal metamorphic gradient from low-grade to non-metamorphosed terrigenous rocks, is recognized. The deposition of these sediments is related to the subduction of the Prototethys and the early evolution of the Rheic Ocean. An inverted metamorphic gradient recognized along the southern slopes of the Etropole and Zlatitsa-Teteven mountains through the Korduna and Zvezdets units is related to Variscan syn-metamorphic deformation in the Stargel-Bulovanya Tectonic Zone.

Gerdjikov, I., Kounov, A., Lazarova, A., Georgiev, S., Vangelov, D. 2023. Lower Paleozoic low-grade metamorphic units from the Central Balkan Zone, Bulgaria: tectonic relationships, framework and geodynamic significance. *Geologica Balcanica* 52 (1), 65–86.

*Keywords*: Stara Planina Low-Grade Metamorphic Complex, Diabase-Phyllitoid Complex, Central Balkan Zone, Cambrian, Ordovician, Variscan and Alpine tectonics.

## INTRODUCTION

The Central Balkan Zone, best exposed within the central parts of the Stara Planina mountain chain of Bulgaria, is part of the Alpine Balkan orogen (Fig. 1). The zone is an element of the Balkan fold-and-thrust belt, overriding the Moesian Platform to the north and overthrust by the Sredna Gora Zone to the south (*e.g.*, Boyanov *et al.*, 1989; Dabovski *et al.*, 2002; Ivanov, 2017, and references therein).


https://doi.org/10.52321/GeolBalc.52.1.65

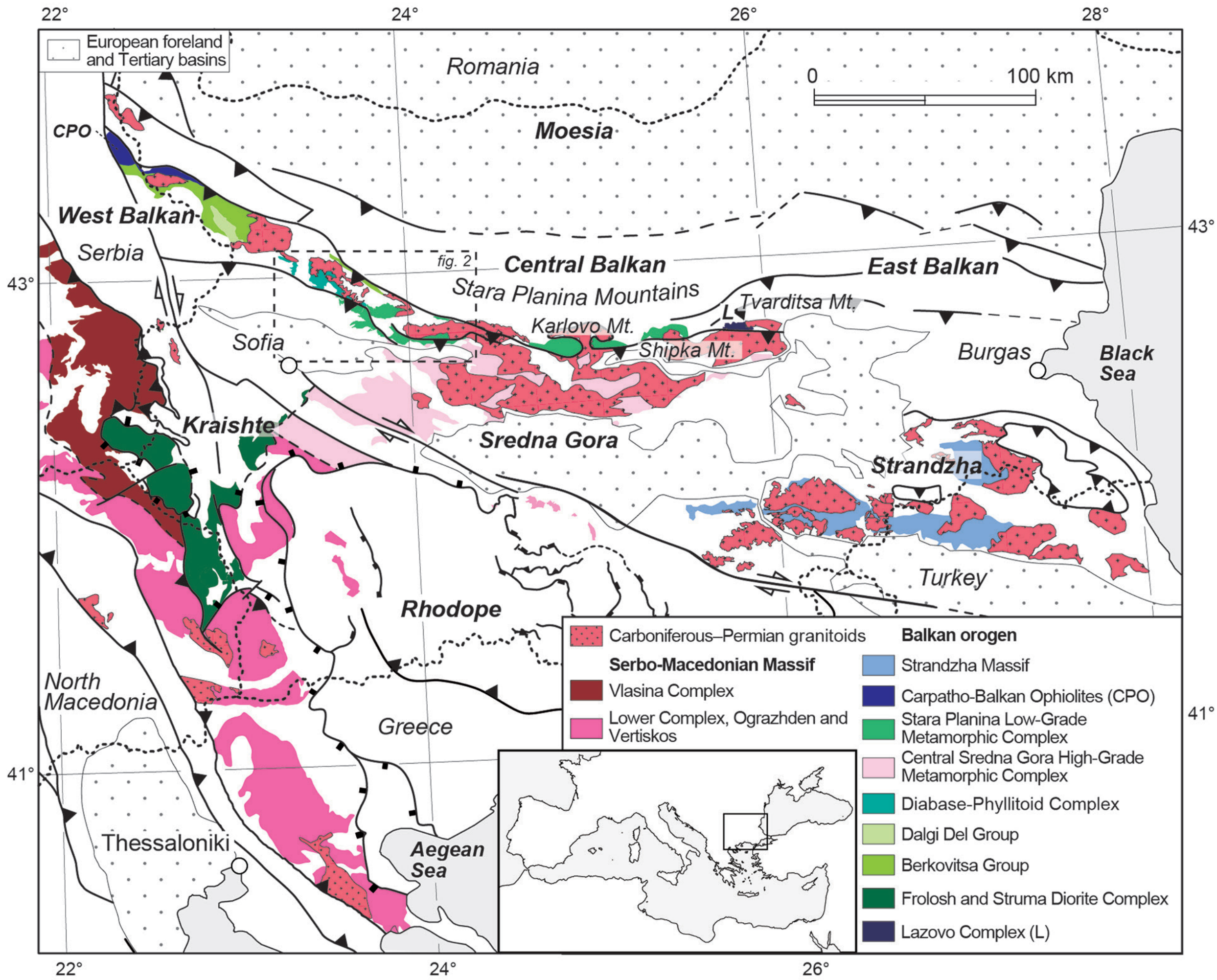


**Fig. 1.** Tectonic map of the central part of the Balkan Peninsula showing the main Ediacaran–Lower Paleozoic metamorphic units and the Carboniferous–Permian plutons that were variably metamorphosed and deformed during the Variscan and Alpine orogenies. Highly reworked and metamorphosed Ediacaran–Lower Paleozoic rocks from the Rhodope Metamorphic Complex are excluded for simplicity. Map compiled from various sources (Basic geological maps of Yugoslavia 1:100 0000; Geological maps of Bulgaria 1:100 000 and 1:50 000; Geological map of Greece 1:500 000; and Okay *et al.*, 2001; Sałacińska *et al.*, 2022). The box outlines Fig. 2.

Despite the strong Alpine overprint, some exclusively low-grade remnants of the pre-Permian basement are preserved in the western and central parts of the Balkan orogen (Fig. 1). In the Central Balkan Zone, along the Iskar River gorge as well as in the Murgash, Bilo, Etropole and Zlatitsa-Teteven mountains, several pre-Permian low-grade metamorphic units with differing lithologies and tectonic positions crop out (Fig. 2). These units were first described as the Diabase-Phyllitoid Complex (Dimitrov, 1939), whereas later several tectono-stratigraphic subdivisions were presented, attributing Ediacaran to Ordovician age of these sedimentary sequences (Fig. 3; Haydoutov *et al.*, 1979; Ivanov *et al.*, 1987; Angelov *et al.*, 1992; Cheshitev *et al.*, 1994a, b; Angelov *et al.*, 2010a–e; Antonov *et al.*, 2010a). The first subdivision follows the model of Haydoutov *et al.* (1979), introduced initially for the low-grade rocks of the Western Balkan Zone and later adopted for all pre-Permian rocks in the whole Balkan Zone. According to this model, three main units were established: i) Cherni Vrah ophiolites; ii) Berkovitsa volcano-sedimentary; and iii) Dalgi Del olistostrome complexes (Angelov *et al.*, 1992; Cheshitev *et al.*, 1994a, b). Later, Ivanov *et al.* (1987) considered part of the DPC, exposed along the Iskar River gorge and the Gabrovnitsa River valley (Fig. 2), as an olistostrome sequence deposited in an epicontinental basin and containing ophiolitic debris. The most recent stratigraphic framework of

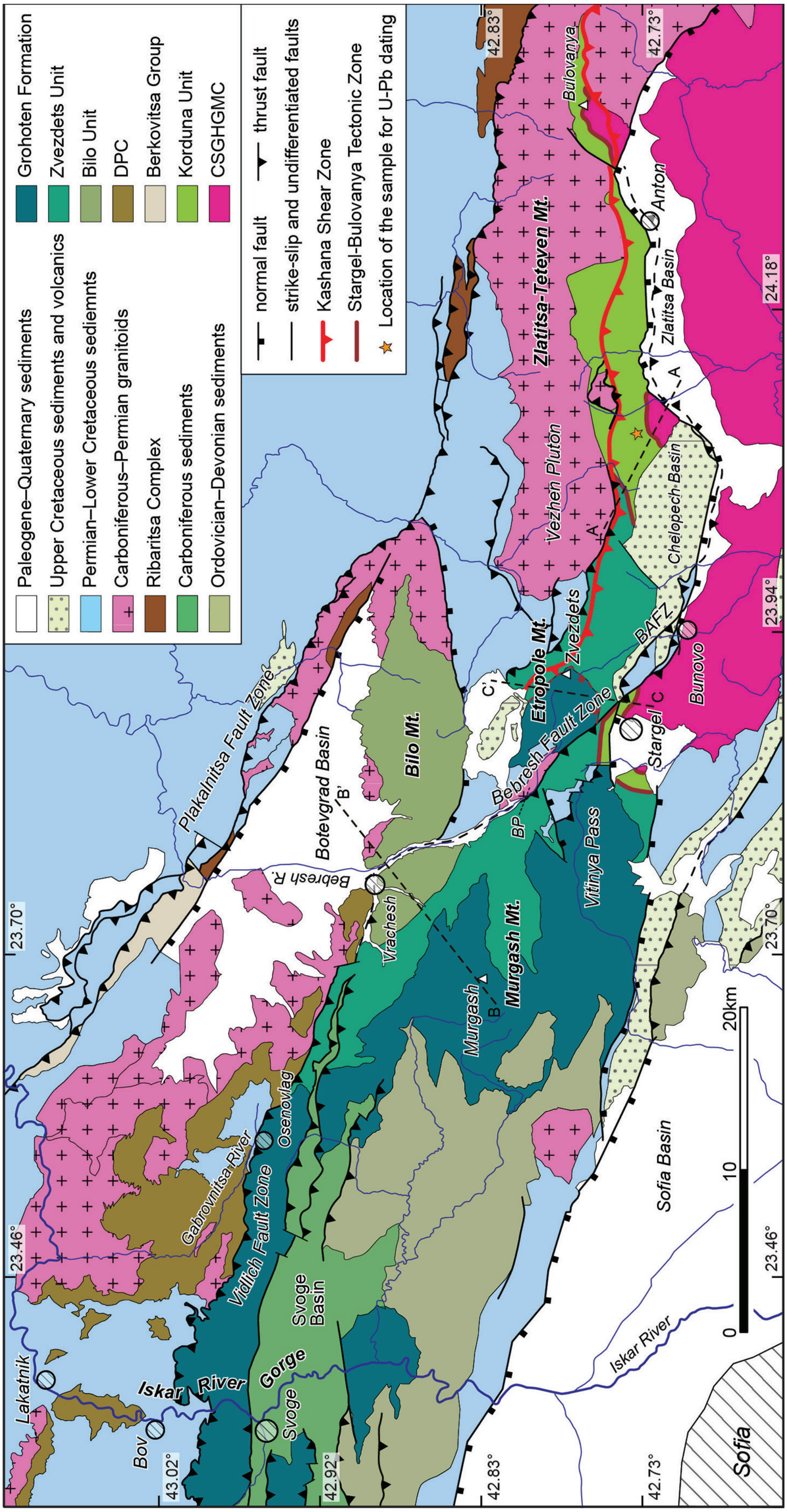


**Fig. 2.** Simplified geological map of the eastern part of the Central Balkan Zone. Map compiled from Geological maps of Bulgaria 1:50 000 (Angelov *et al.*, 2009, 2010a–e). BAFZ – Bunovo-Anton Fault Zone; BP – Bebresh Pluton.

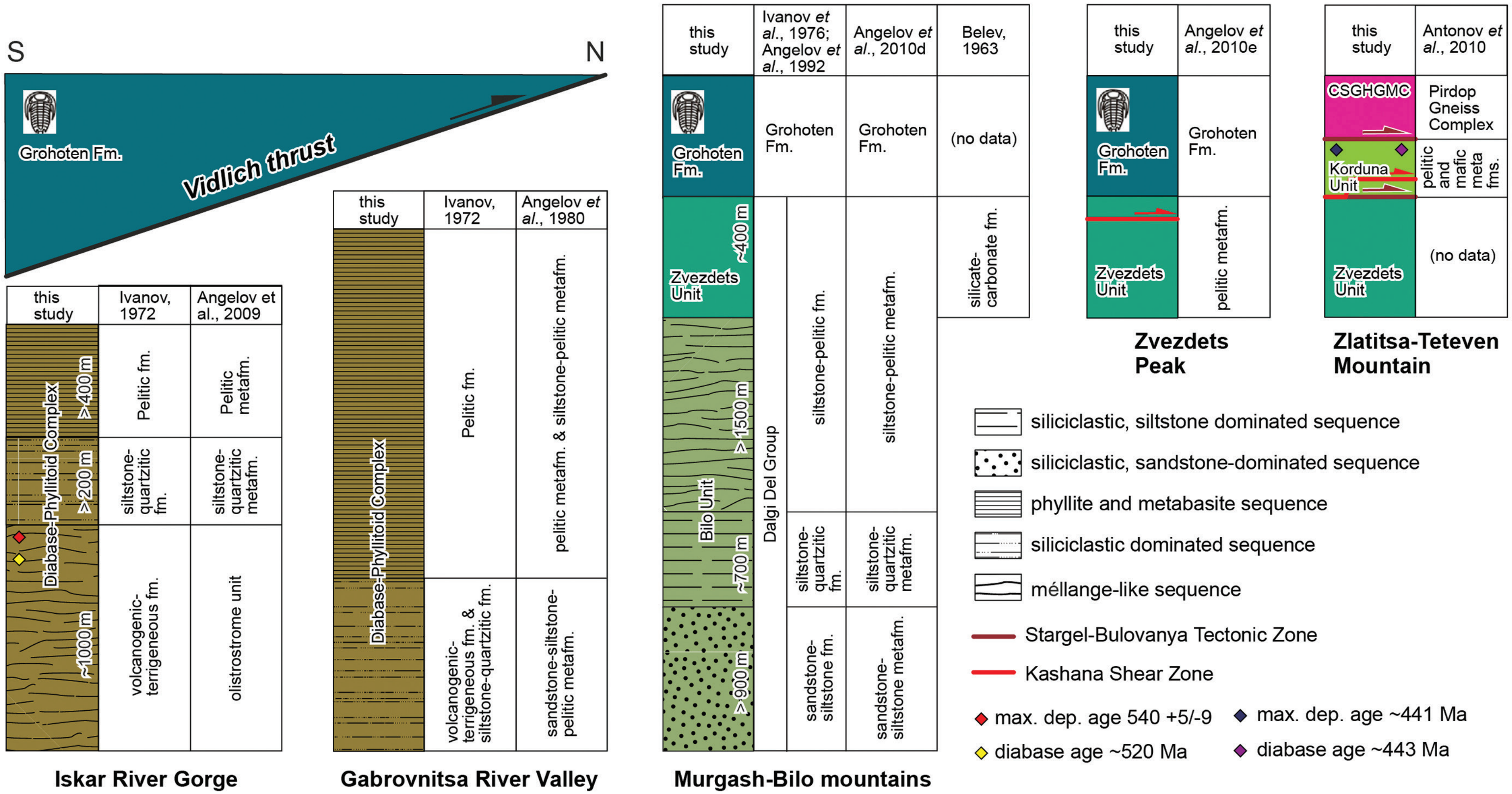


**Fig. 3.** Lithological sequences and unit superposition in the studied areas. Comparison between previous tectonostratigraphic subdivisions for the main Ediacaran–Lower Paleozoic units and the distinguished herein lithological subunits. Thickness data is after Belev (1963) and Ivanov *et al.* (1976, 1987).

the low-grade metamorphic rocks of the Central Balkan Zone is presented on the geological map of Bulgaria in scale 1:50 000 (Angelov *et al.*, 2010a–e; Antonov *et al.*, 2010a, b). On the map, Angelov *et al.* (2010c–e) distinguished several tectonically juxtaposed metamorphic units: i) the Berkovitsa Group; ii) the Lakavitsa and Trudovets metamorphic complexes, situated in the hanging wall of the Plakalnitsa Fault Zone (Fig. 2); and iii) several terrigenous low-grade metamorphic units exposed in the Bilo Mountain and in the area between the Quaternary Botevgrad Basin and the Iskar River gorge (Fig. 2), interpreted as a chaotic mélange (Fig. 3). Additionally, the low-grade metamorphic rocks exposed in the Etropole and Zlatitsa-Teteven mountains and previously attributed to the Neoproterozoic–Cambrian Berkovitsa Group (Angelov *et al.*, 1992) were defined as independent Mafic, Pelitic and Siltstone-Shaly metamorphic formations (Fig. 3; Angelov *et al.*, 2010e; Antonov *et al.*, 2010a, b). All these tectono-stratigraphic subdivisions were based on very little structural studies and, most importantly, on poor paleontological and geochronological records (*e.g.*, Kalvacheva, 1982). Assessment of the relative age of these rocks was further hampered by the fact that most of their contacts with the younger non- to only weakly metamorphosed Paleozoic rocks are tectonic (*e.g.*, Angelov *et al.*, 1992). The oldest well-dated transgressive cover of the low-grade metamorphic rocks known in the Central Balkan Zone is Carboniferous in age (Fig. 2; Cheshitev *et al.*, 1994a). Recently, Gerdjikov and Balkanska (2013) and Balkanska *et al.* (2021) introduced the term Stara Planina Low-Grade Metamorphic Complex to describe the low-grade metamorphic rocks of different age and tectonic position from the Central Balkan Zone (Fig. 1).

At present, a number of new geochronological analyses (*e.g.*, Georgiev *et al.*, 2016; Kiselinov *et al.*, 2017; Žák *et al.*, 2021) have allowed a significant reassessment of the previous stratigraphic subdivisions of the Stara Planina Low-Grade Metamorphic Complex to be made. The incorporation of the geochronological data in the newly presented tectonic models is crucial for their accuracy and reliability, as recently was emphasized by the re-evaluation of the age and geodynamic evolution of the Lower Devonian Carpatho-Balkan Ophiolites (Fig. 1; Zakariadze *et al.*, 2012; Balica *et al.*, 2014; Kiselinov *et al.*, 2017; Plissart *et al.*, 2017), including the Cherni Vrah ophiolites, previously considered Ediacaran (Haydoutov, 1989; von Quadt *et al.*, 1998). The further attempts to decipher the Paleozoic geodynamic evolution of these rocks are closely related to the integration of the geochronological constraints with good knowledge of their lithological and structural features.

Our contribution is based on a critical analysis of the existing data combined with new geochronology and detailed mapping in the area of the Murgash, Etropole, Bilo and Zlatitsa-Teteven mountains, as well as along the Iskar River gorge and the Gabrovnitsa River valley (Fig. 1). This allows us to present a new tectono-stratigraphic framework of the low-grade metamorphic rocks from the western parts of the Central Balkan Zone, where the following units are distinguished: Korduna, Bilo, Zvezdets and Diabase-Phyllitoid Complex. Their tectonic relationships, metamorphic evolution and geodynamic significance is considerably re-evaluated, which allowed some correlations to be made with other Lower Paleozoic units from the Balkan orogen also elucidating some aspects of the poorly studied Early Paleozoic geodynamics of the Balkan Peninsula.

## GEOCHRONOLOGY

### Zircon U-Pb analysis

To constrain the time of the main metamorphic event in the low-grade rocks of the Zlatitsa-Teteven Mountain, we have applied a U-Pb analysis on a sample collected from metamorphic quartz vein concordant to the foliation in the host schists (Fig. 4*a*). The location of the sample is given in Fig. 2 and the selected cathodoluminescence (CL) and BSE images and analytical data in Fig. 5*a*, *b*. Appendix A presents a comprehensive table with results from the U, Th and Pb isotopic measurements, while the CL images of analyzed zircon grains are provided in Appendix B.

### Methodology

The zircon fraction was extracted, using conventional procedures, including crushing and sieving, followed by Wilfley table, magnetic and heavy liquids separations. Cathodoluminescence images were taken prior to zircon analyses aiming to identify inherited cores, cracks and inclusions, using SEM JSM-259 6610 LV at the University of Belgrade. U-Pb isotope analyses of particular zircon zones were carried out, using a New Wave Research (NWR) Excimer 193 nm laser-ablation system attached to a Perkin-Elmer ELAN DRC-e inductively coupled plasma mass spectrometer (LA-ICP-MS) at the Geological Institute, Bulgarian Academy of Sciences. The spatial resolution was 35 μm at a fre-

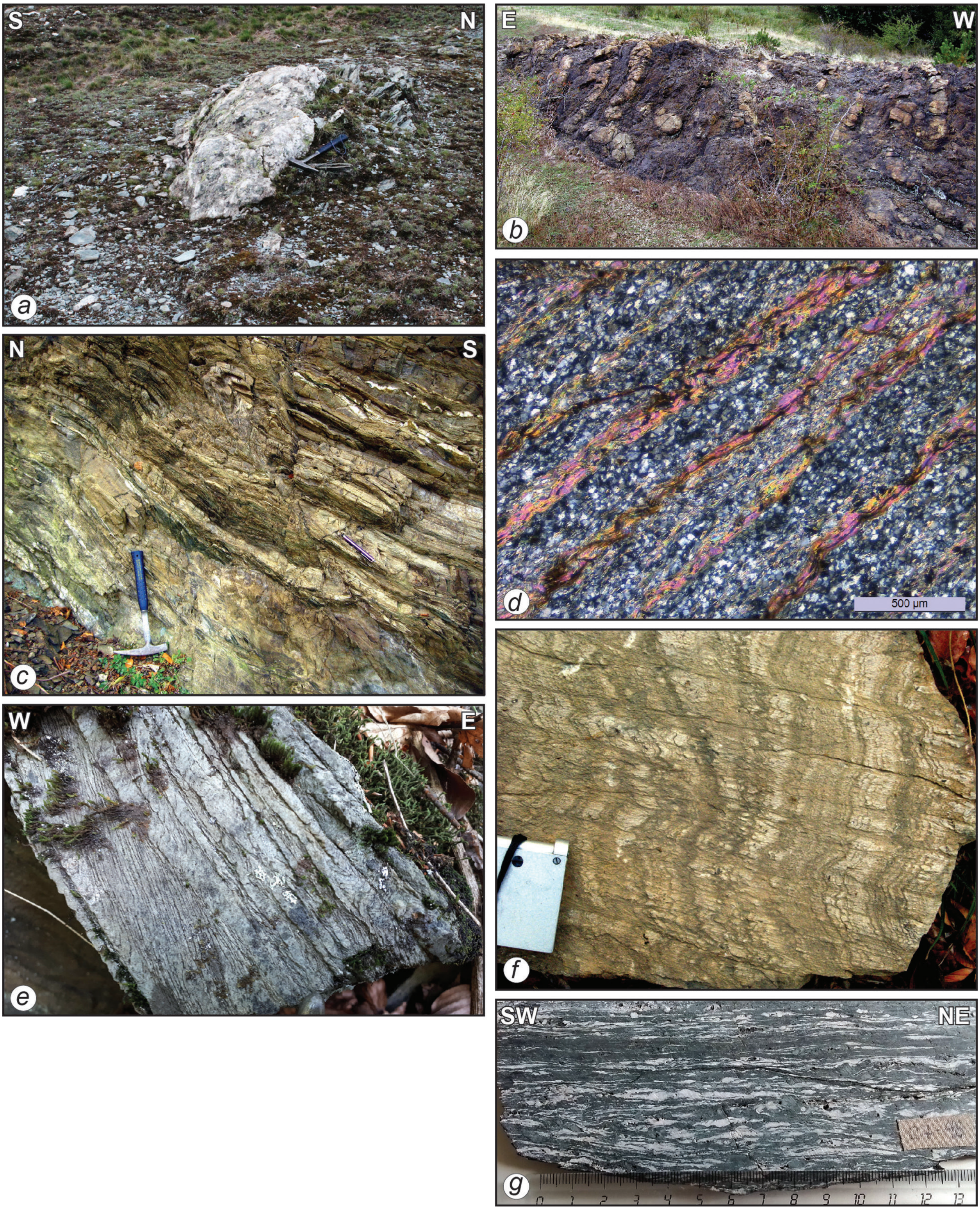


**Fig. 4.** Photographs of the studied low-grade metamorphic units: *a*) sampled quartz veins from the lower structural level of the Korduna Unit (*Sample locality*: N 42°44'13.164"; E 24°3'39.132"); *b*) dismembered greywacke beds in a chlorite-sericite schist matrix, NW of Anton; *c*) high-strain fabric in the uppermost structural levels of the Korduna Unit, marked by isoclinal folds and stretched quartz veins; *d*) fully recrystallized siltstone from the lower structural levels of the Bilo Unit; *e*) centimeter-scale isoclinal folds transposing the main foliation in the lower levels of the Bilo Unit; *f*) cleaved siliciclastic sediments from the Zvezdets Unit; *g*) mylonitic gabbro from lowermost parts of Central Sredna Gora High-Grade Metamorphic Complex.

quency of 8 Hz. Measurement procedure involved calibration against an external zircon standard (≈604±3 Ma; Jackson *et al.*, 2004) at the beginning, middle and end of the analytical block. This technique allows suitable effects. Raw data were processed using Iolite software (Paton *et al*., 2011); $^{207}Pb/^{206}Pb$, $^{208}Pb/^{232}Th$, $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ratios were calculated and the time-resolved ratios for each analysis were then carefully examined. Optimal signal intervals for the background and ablation data were selected for each sample and automatically matched with the standard zircon analyses. U-Pb Concordia ages were calculated and plotted, using ISOPLOT 4.15 (Ludwig, 2003).

## U-Pb zircon data

Fifty-five spot analyses of different zones (rims and cores) of zircon crystals from the sample were made. Most of the analyzed zircons exhibit inherited cores and magmatic oscillatory peripheries (Fig. 5). Some crystals have undergone metamic-

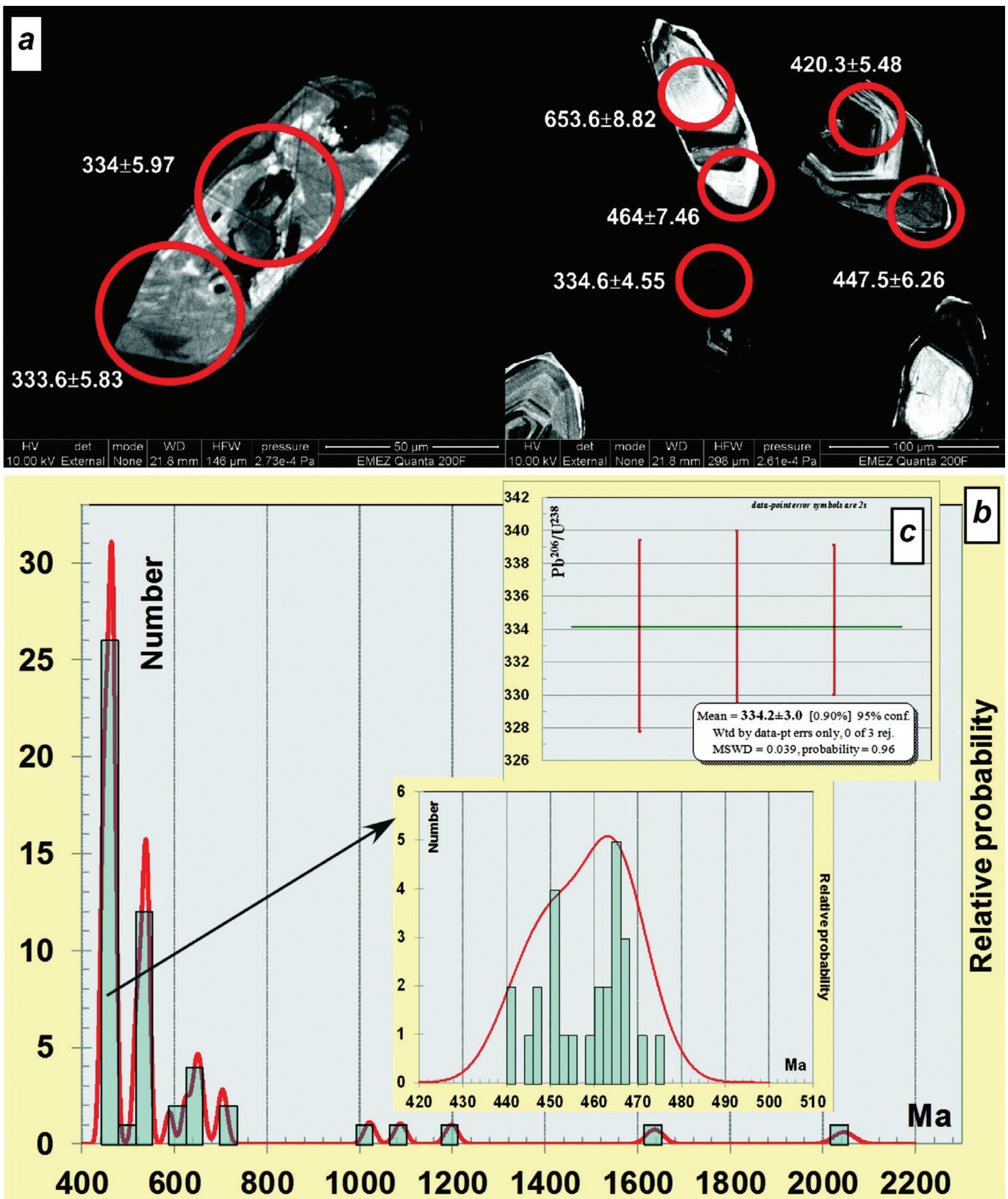


**Fig. 5.** LA-ICP-MS zircon geochronology results for the hydrothermal quartz vein from the Korduna Unit: *a*) CL and BSE images of selected zircon grains; *b*) probability density plot diagram; *c*) weighted average diagram of recrystallized zircons.

tization along the peripheries, other show evidence of fluid-assisted recrystallization (Appendix B). Most of the zircons yield ages falling in several intervals (Fig. 5*a*): 441–474 Ma (the most abundant); 517–541 Ma; 622–657 Ma (3 grains); 700 Ma (1 grain); 1020–1673 Ma (3 grains); and 2045 Ma (1 grain). These grains are considered as xenocrysts trapped from the Lower Paleozoic host sediments during the fluid circulation and quartz vein formation. Three analyses from two recrystallized crystals give weighted average $^{206}Pb/^{238}U$ age of 334.2±3 Ma (Fig. 5b). This age is considered as related to a Variscan metamorphic event, corresponding to the hydrothermal activity and vein formation. The Th/U ratio of the xenocrystic magmatic zircons is in the range of 0.01–0.59, suggesting a magmatic origin of most of the crystals. In the metamict and recrystallized zircons, the ratio decreases to 0.008 probably due to the fluid-assisted trace-elements' redistribution.

## NEW TECTONO-STRATIGRAPHIC FRAMEWORK OF THE STARA PLANINA LOW-GRADE METAMORPHIC COMPLEX

The Stara Planina Low-Grade Metamorphic Complex embraces all the low-grade pre-Permian terrigenous successions intercalated with volcanic and volcaniclastic rocks and tectonically imbricated with various magmatic rocks from the Central Balkan Zone (Fig. 1). The absence of reliable paleontological data, the imposed intense deformation and internal tectonic imbrications rendered the previously used purely stratigraphic approach to establish a framework of this complex rather inadequate. Therefore, in this study, we use structural relationships and new geochronological data to distinguish several independent units characterized by their age, lithology, structural frame and tectonic position. In the following text, we present lithological and structural descriptions of the newly distinguished units together with their lateral extent and boundaries (Fig. 2). The new framework is based not only on the detailed lithological studies but also on estimations of the strain gradients, syn-metamorphic fabric and sense of shear. While parts of the Zlatitsa-Teteven and Etropole mountains were mapped in detail, most of the observations in the Bilo Mountains, Iskar River gorge and Gabrovnitsa River valley were made along key profiles. Beyond the scope of this study remain the metamorphic rocks exposed along the Plakalnitsa Fault Zone north of the Botevgrad Basin, considered as part of the Berkovitsa Group and Lakavitsa complex (Fig. 2, Angelov *et al.*, 2010d).

### Korduna Unit

The unit is exposed along the southern slopes of the Zlatitsa-Teteven Mountains, east of the Late Cretaceous Chelopech Basin (Fig. 2). During the latest mapping of the area (Antonov *et al.*, 2010a, b), these rocks were considered as a part of the Pelitic and Mafic metamorphic formations (Fig. 3). Our arguments to distinguish a new unit in this area are the newly obtained geochronological data and redefinition of its tectonic relationships with the neighboring rocks. To the south, the Korduna Unit is overthrust by the Central Sredna Gora High-Grade Metamorphic Complex (CSGHGMC; Gerdjikov *et al.*, 2013) along the Variscan Stargel-Bulovanya Tectonic Zone (SBTZ, Figs 2, 6; Gerdjikov *et al.*, 2007, 2009; Lazarova *et al.*, 2010). To the north, it is underlain by the Zvezdets Unit (Figs 2, 6).

The Korduna Unit consists of phyllites, amphibole and mica schists, intercalated with lens-like bodies of metabasites, metagranites and quartzites. Similar rocks occur as a narrow sliver within the SBTZ north of Stargel (Fig. 2). The unit represents a tectonic mélange of sedimentary and igneous rocks with a different origin, brought together and affected by an intense syn-metamorphic deformation related to the SBTZ (Fig. 4*b*). The penetrative foliation is moderately dipping to the south, parallel to the contact with the gneissic CSGHGMC of the hanging wall of the SBTZ (Fig. 6*a*). In the Korduna Unit, two structural levels, differing by their metamorphic degree and specific lithologies, could be distinguished. The upper structural level, situated immediately below the high-grade gneisses of the CSGHGMC, consists mostly of coarse-grained schists with mineral assemblages pointing to a high greenschist facies metamorphism. Metabasite, metagranite and metasandstone lenses hosted in the schists are abundant. The thickness of this upper level varies considerably along the strike, reaching few hundreds of meters in some places. Rootless and drag folds, together with highly stretched and boudinated metamorphic quartz veins (Fig. 4*c*), are indicative of a high shear strain. The lower structural level is phyllite-dominated, including bodies of metabasites and quartzites with various dimensions. Here, the rocks are fine-grained, composed mostly of sericite and chlorite and minor quartz and plagioclase. Due to a primary fine-grained texture of the dominant lithologies, estimation of the intensity of the ductile shearing based on a grain-size reduction

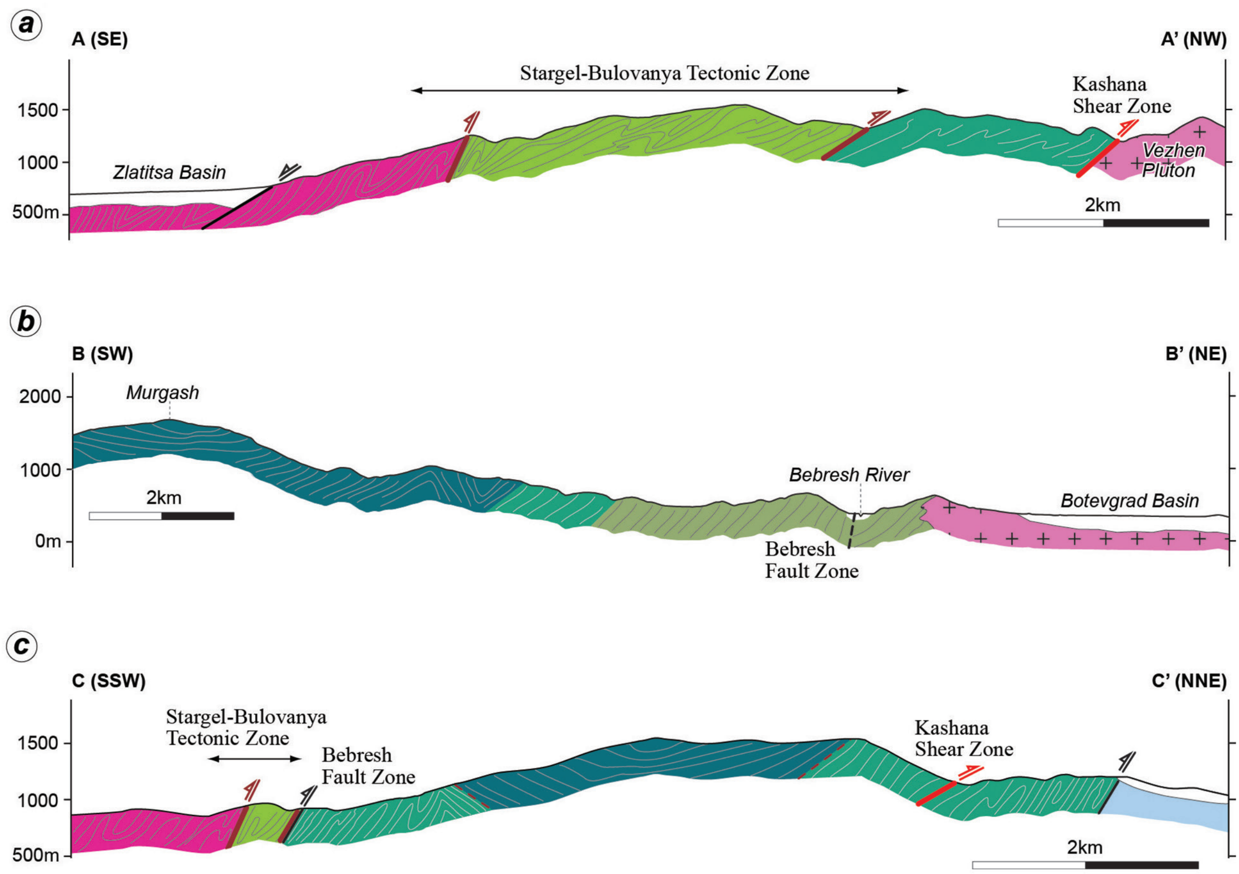


**Fig. 6.** Geological sections AA′, BB′ and CC′ (Fig. 2). Lithological key as in Fig. 2. Scale V = H.

of the rock-forming minerals was not possible. All structural observations show that the Korduna Unit represents a gently southward-dipping and strongly sheared complex, exhibiting an inverted metamorphic gradient from a high- to mid-greenschist facies in the uppermost levels to low-greenschist facies metamorphism in its lowermost parts (below 400 °C).

There are no paleontological age constraints of the Korduna Unit. We assume an Early Ordovician–Early Silurian maximum age for the sediments of this unit, as suggested by the dominant younger xenocrystic zircon population of 474–441 Ma from the syn-metamorphic quartz vein parallel to the foliation in the low-grade metasedimentary rocks (Fig. 4*a*). We consider these xenocrystic zircons as representing a detrital input in the host sediments later trapped in the metamorphic vein. Intermediate to acid magmatic rocks were the most probable source of these detrital zircons (Georgiev *et al.*, 2020). These data are consistent with the Early Silurian U-Pb zircon age of 443.0±1.5 Ma reported for a diabase from the upper structural level of the Korduna Unit (Peytcheva and von Quadt, 2004). The newly obtained U-Pb age of 334.2±3 Ma (Fig. 5) yielded by the hydrothermal vein (Fig. 4*a*) from the Korduna Unit is interpreted as related to the Variscan metamorphism in these rocks. This age is indistinguishable from the muscovite $^{40}Ar/^{39}Ar$ age of 333.9±0.2 Ma obtained from the gneiss of the overthrusting CSGHGMC and interpreted as related to the greenschist facies retrogression in these rocks (Gerdjikov *et al.*, 2010).

## Bilo Unit

The Bilo Unit represents another mélange-like low-grade metamorphic unit, largely exposed to the south of the Quaternary Botevgrad Basin in the Bilo Mountain and the north-easternmost parts of the Murgash Mountain (Fig. 2). Initially, it was subdivided into several terrigenous formations (Ivanov *et al.*, 1976), which were later described as the following metamorphic formations: Sandstone-Siltstone, Siltstone-Quartzitic and Siltstone-Shaly (Fig. 3; Angelov *et al.*, 2010d). The same unit was also assigned to the Dalgi Del Group (Kalvacheva, 1982). The lower contact of the unit is not exposed, and it is overlain by the Zvezdets Unit (Fig. 2).

The Bilo Unit consists mainly of chlorite-sericite schists, phyllites and quartzites derived from siltstone, mudstone and sandstone protoliths. Varying in size bodies and lenses of metamorphosed ultrabasites, gabbro, gabbro-dolerites and dolerites, are largely presented in the sedimentary sequences (Angelov *et al.*, 2010d). Manganese-rich spessartine-bearing quartzites, known as coticules/gondites, are typical for the unit (Ivanov *et al.*, 1976).

Syn-sedimentary structures and primary stratigraphic succession is difficult to be reconstructed due to the strong syn-metamorphic deformation (Fig. 4*d*). The north–south trending syn-metamorphic foliation is steeply dipping to the west at odds with the generally northwest–southeast trending foliation in the neighboring metamorphic units (Fig. 6*b*). The most strongly deformed are the eastern domains of the Bilo Unit, which represent the lowermost structural levels relative to the dip of the penetrative foliation. The entire section is intensely foliated and later folded in generally north–south trending folds (Ivanov *et al.*, 1976). At the outcrop scale, the foliation is isoclinally folded and an axial planar cleavage, defined by new growth of chlorite and sericite (Fig. 4*e*), was developed. Kalvacheva (1982) reported a normal metamorphic gradient based on the size of the metamorphic minerals in the Bilo Unit. This progressive gradient is marked by a transition from coarse-grained schists in the lower part of the section to low-grade schists to very low-grade phyllites in the upper part. The metamorphic gradient is also closely related to an upward gradual decrease in the syn-metamorphic structural overprint of the rock section, which is capped by the very low-grade rocks of the Zvezdets Unit (Fig. 6*b*). The contact with the overlying Zvezdets Unit is difficult to be clearly defined in the field and is generally marked by the disappearance of both the coticule horizons and the metabasite lenses.

The age of the low-grade sedimentary rocks in the Bilo Mountain, now attributed to the Bilo Unit, was previously poorly defined as Middle Ordovician, based on some findings of coalified and strongly fragmented palynomorphs (Kalvacheva, 1982).

### Zvezdets Unit

This unit represents a lower greenschist facies succession of phyllites exposed mainly in the Murgash and Etropole mountains (Fig. 2). Generally, it coincides with the previously distinguished Silicate-Carbonate Formation (Belev, 1963), Zvezdets Formation (Spasov, 1989) or Pelitic and Siltstone-Shaly metamorphic formations (Fig. 3; Angelov *et al.*, 2010e; Antonov *et al.*, 2010a). The metamorphic succession is covered by the Middle to Upper Ordovician Grohoten Formation (Fig. 2). West of the Bebresh River valley, the contact with the underlying Bilo Unit is gradual, marked by a downward increase in the metamorphic grade (Fig. 2). North of the Late Cretaceous Chelopech Basin, the Zvezdets Unit is overlain by the metamorphic rocks of the Korduna Unit (Fig. 2).

The Zvezdets Unit represents a monotonous finely laminated (centimeter-thick layers) alternation of phyllites and chlorite-sericite schists, which protoliths are siltstones and mudstones. Quartzite and metabasite lenses are rare. The metamorphic transformations took place at ~300–350 °C as was suggested by Belev (1963). The syn-metamorphic planar fabric is often weak, and the primary stratification is frequently preserved (Fig. 4*f*). Several generations of folds, related to polyphase Variscan and Alpine tectonics, were distinguished (Nanov *et al.*, 2016). Due to the consequent brittle-ductile faulting, the foliation planes are variously trending (Fig. 6*c*).

No paleontological or geochronological data are reported from this unit, and a Cambrian–Ordovician age was previously assumed since it is overlain by the Middle to Upper Ordovician Grohoten Formation (Fig. 2; Angelov *et al.*, 2010e).

### Diabase-Phyllitoid Complex

The DPC is a greenschist facies mélange-like association of sedimentary and igneous rocks, first introduced by Dimitrov (1929), whose type sections, exposed along the Iskar River gorge between Bov and Lakatnik and the Gabrovnitsa River valley (Fig. 2), were previously precisely described (Dimitrov, 1929; Ivanov, 1970, 1972; Pristavova *et al.*, 2003; Angelov *et al.*, 2009). Ivanov *et al.* (1987) presented the DPC as an olistostrome sequence, relating the mélange structure to sedimentary phenomena. Despite the long history of research (including a large amount of data reported in numerous exploration reports), important questions as the exact superposition of the constituent sub-units, the origin of the mélange structure (for example primary or tectonic) and the age are still unresolved (*e.g.*, Bonchev, 1986).

Our observations along several profiles show that structures indicative of an olistostrome origin are in fact missing and most of the contacts between the different lithologies are tectonic. This feature points to a considerable similarity between the strongly deformed mélange DPC and the Bilo Unit, as the only notable difference is the presence of manganese-rich sandstones (coticules) in the latter. The upper age limit for the metamorphism in the DPC is provided by the cross-cutting Late Carboniferous magmatic rocks (Angelov *et al.*, 2008). The oldest transgressive cover of the DPC are the terrigenous sedimentary rocks of an Early Triassic age. The contacts with the other low-grade metamorphic units and non-metamorphosed Paleozoic sediments are tectonic (Fig. 2). The lower contact of the unit is not observed.

The lower levels of the DPC are exposed between Bov and Lakatnik (Fig. 2), and consist of irregularly distributed igneous bodies, mainly of mafic composition, tectonically intercalated with phyllites and metasandstones (Ivanov, 1970). This is the typical rock association exemplifying the original (according to Dimitrov, 1929) description of the unit. Although preserved ophiolitic successions are missing in the DPC, the presence of ultramafic rocks and pillow lavas in the section suggests of an oceanic origin of part of the igneous rock fragments (Ivanov *et al.*, 1987). Upwards, the succession continues with metasandstones and sporadic metaconglomerates, topped by metapelites and metasiltstones intercalated with chlorite schists (metamorphosed basic tuffs) and lenticular mafic bodies (Ivanov *et al.*, 1987). Along the Gabrovnitsa River valley, the basal part of the section is not exposed (Fig. 3; Pristavova *et al.*, 2003).

The entire DPC is strongly foliated to mylonitized, as weakly deformed are only some low-strain lenses of massive igneous rocks. Linear fabric is not observed. The foliation shows variable orientations, most probably due to the presence of large-scale folds (Ivanov, 1970; Pristavova *et al.*, 2003).

Until recently, only poorly defined micropaleontological data were available. Kalvacheva (1972) reported some Middle to Upper Ordovician acritarch fauna from the upper part of the DPC. However, these determinations must be taken with caution as all the reported subgroups and species actually have their first occurrence already in the Early Ordovician (Servais *et al.,* 2014). The triangle acritarchs presented as proving the Middle and Late Ordovician age of the DFC sediments in fact appeared on the Gondwanan margin since at least the late Tremadocian (Servais *et al.*, 2014), whereas some genera are even placed now in the Cambrian (Raevskaya and Servais, 2009).

More robust constraints are provided by recently obtained geochronological data. From the lower part of the unit, two basalt bodies (pillow lavas) were dated at 519.9±3.6 Ma and 519.8±3.5 Ma (Georgiev *et al.*, 2016), and for the overlying metasandstones an Early Cambrian maximum depositional age is suggested based on detrital zircon U-Pb geochronology (Žák *et al.*, 2021). Therefore, we can conclude that an Early Cambrian–Early Ordovician (?) age of the DPC is more plausible.

## Ordovician to Devonian non-metamorphic succession

A continuous, paleontologically well-dated Middle Ordovician to Devonian sedimentary section is documented in detail in the eastern part of the studied area along the Murgash Mountain and in the region of Svoge (Fig. 2; overview in Boncheva *et al.*, 2010, and Sachanski, 2015). It covers conformably the Zvezdets Unit and is transgressively covered by the Upper Carboniferous (Namurian–Westphalian) sedimentary rocks of the Svoge Basin (Fig. 2; Angelov *et al.*, 2010a). The non-metamorphosed rocks of the Ordovician to Devonian succession are folded but any signs of an intense penetrative deformation and recrystallization are absent. Below, we describe in detail only the Middle–Upper Ordovician part of the section referred to the Grohoten Formation (Spasov, 1960), as it represents an important age constraint of the underlying metamorphic units.

### *Grohoten Formation*

The Grohoten Formation is the lowermost stratigraphic unit of the Paleozoic non-metamorphosed succession in the Central Balkan Zone (Angelov *et al.*, 2010a, c, and references therein). It overlies the Zvezdets Unit in the Murgash Mountain and is covered by the Upper Ordovician Tseretsel Formation in the Iskar River gorge (Fig. 2; Sachanski, 2015).

The Grohoten Formation consists of generally non-metamorphic, weakly cleaved siltstones and mudstones intercalated with quartzarenites in its lower levels. Igneous rocks are absent unlike the underlying Lower Paleozoic low-grade units. Only Kalvacheva and Nedjalkov (1976) reported the occurrence of mafic lenses in the sedimentary section west of the Vitinya Pass (Fig. 2). However, our attempts to find these mafic rocks were unsuccessful.

The Darriwilian–Sandbian age of the Grohoten Formation is defined based on palynological data as well as graptolite and trilobite fauna (Kalvacheva, 1978; Gutiérrez-Marco *et al.*, 2003). Georgiev *et* *al.* (2021) reported an Early Ordovician maximum age based on Tremadocian youngest detrital zircon population in these rocks.

### Relationships between the low-grade metamorphic units and the non-metamorphic Lower Paleozoic sediments

Deciphering the true nature of the contact between the low-grade metamorphic units and the overlying non-metamorphic Lower Paleozoic sediments is crucial for the assessment of not only the age of the metamorphic succession but also their tectonic position and evolution. Unfortunately, most of the actual contacts represent Alpine tectonic zones, which give very little, if any, information about the Paleozoic evolution of these units (see the next section for details).

Previously, in some localities (*e.g.*, the Vitinya Pass and the summits of the Etropole Mountain; Figs 2, 6), a lack of structural break (Belev, 1963; Spasov, 1989) and even a transgressive contact between the Grohoten Formation and the Zvezdets Unit were reported (Chunev and Kozhoukharov, 1968; Angelov *et al.*, 2010d, e). Our field observations support the idea of the primary stratigraphic contact between these units, which was probably consequently tectonically reactivated. In the Murgash Mountain, as well as along the southern slope of Zvezdets Peak (Figs 2, 6*b*, *c*), although the contact is not directly exposed, the rocks of the Grohoten Formation clearly occupy hypsometrically higher position than those of the Zvezdets Unit. In this area, the lowermost part of the Grohoten Formation is often occupied by poorly stratified and strongly silicified arenitic sandstones considered analogous to the Armorican Quartzite of Early to Middle Ordovician age well known from Western European sections of the Rheic Ocean (*e.g.*, Gutiérrez-Alonso *et al.*, 2007). Southwest of Vrachesh (Fig. 2), the foliation of the Zvezdets Unit is conformably oriented to the bedding and cleavage in the Grohoten Formation. Similar relationships are observed also northeast of Stargel near Zvezdets Peak (Fig. 2).

### Main Variscan and Alpine tectonic zones

The prolonged Variscan and Alpine tectonic evolution has significantly modified and obliterated the primary relationships and tectonic position of the low-grade metamorphic units from the Central Balkan Zone. Bellow, the major tectonic zones and their significance for the evolution of the studied units, as well as their recent position in the orogen, are discussed in detail.

#### *Variscan tectonic zones*

The Stargel-Bulovanya Tectonic Zone (Fig. 2), defined as the main Variscan structure in the studied area (*e.g.*, Gerdjikov *et al.*, 2010), represents a kilometers-thick, south-dipping ductile shear zone following the southern slopes of the Zlatitsa-Teteven Mountain. Previously, Haydoutov (1989) referred to the zone as part of the Variscan Thracian suture, separating two peri-Gondwanan terranes: Thracian and Balkan. Along the SBTZ, the gneiss-dominated section of the CSGHGMC, affected by a mid-Carboniferous (~336 Ma, Carrigan *et al.*, 2006) partial melting during the thermal peak of metamorphic conditions, is emplaced over the low-grade metamorphic rocks of the Korduna Unit (Fig. 2). The east–west striking foliation within the shear zone dips generally to the south (Fig. 6*a*) and the rarely observed lineation is southeast- to southwestward plunging. Shear-sense criteria as porphyroclast systems, shear bands and asymmetric boudins indicate general top-to-the-north tectonic transport (Fig. 4*g*). Ductile shearing along the SBTZ led to the inversion of the metamorphic gradient of a pre-existing right-way-up metamorphic sequence in the footwall Korduna Unit. The observed steep metamorphic field gradient over only ~400 m thick rock section from high- to sub-greenschist facies metamorphic conditions suggests a substantial internal stretching and shearing, leading to telescoping of the metamorphic isograds across the SBTZ. Continuous exhumation of the hanging wall led to the greenschist facies retrogressive overprint in the CSGHGMC. Muscovite $^{40}Ar/^{39}Ar$ geochronological data suggest an age of ~334 Ma for this shearing-related retrogression (Gerdjikov *et al.*, 2010). The herein reported 334.2±3 Ma old metamorphic quartz vein from the upper level of the Korduna Unit (Fig. 2) is most probably related to the fluid circulation associated with the syn-tectonic metamorphism.

The contact between the Korduna and Zvezdets units could also be considered as a part of the shear domain related to the SBTZ (Figs 2, 6*a*). The apparent difference in the metamorphic grade and strain magnitude between the penetratively foliated and recrystallized phyllites of the Korduna Unit and the underlying structurally concordant but weakly deformed phyllites of the Zvezdets Unit suggests the existence of a syn-metamorphic tectonic contact separating both entities. The inverted metamorphic grade suggests overthrusting of the higher-grade onto the lower-grade unit. The similarity in orientation, kinematics and deformation style between this zone and the SBTZ evidences a possible kinematic link.

Variscan age of the SBTZ is also confirmed by the fact that the syn-metamorphic fabric of the Korduna Unit is sealed by the Late Carboniferous Vezhen Pluton (Fig. 2; Gerdjikov *et al.*, 2007; Georgiev *et al.*, 2020). The ductile shear zone separating the Korduna and Zvezdets units was partially reactivated by the Alpine low-grade Kashana Shear Zone (Fig. 2).

### *Alpine tectonic zones*

The present-day structural frame of the Central Balkan Zone is a result of two compressional phases related to north-vergent thrusting and folding (*e.g.*, Vangelov *et al.*, 2013). In the Bulgarian geological literature, these two phases are referred to as Early (Late Jurassic–Early Cretaceous) and Late Alpine (Paleogene). However, the attribution of the main tectonic zones of the study area to one or the other compressional phase is still questionable due to the lack of reliable age constraints. The following main Alpine structures were defined in the study area: Plakalnitsa, Vidlich, Bebresh and Bunovo-Anton fault zones and Kashana Shear Zone (Fig. 2).

The Plakalnitsa Fault Zone is a complex northwest–southeast trending zone of north-vergent thrusts and minor south-vergent back-thrusts (Fig. 2). In fact, it represents the thick-skinned westernmost limit of the Central Balkan Zone along which the pre-Alpine basement rocks override the Mesozoic sedimentary cover (*e.g.*, Vangelov *et al.*, 2013). In the hanging wall of the zone, various Carboniferous granites and locally their high-grade metamorphic host rocks are exposed (Lazarova *et al.*, 2007; Antonov *et al.*, 2010b).

The Vidlich Fault Zone is another major north-vergent thrust zone, which in the studied area stretches between the Iskar River gorge and the Bebresh River valley (Fig. 2). In the Iskar River gorge, where the Grohoten Formation is emplaced over the Mesozoic cover, the thrust character is best expressed with the presence of imbricate fans in the immediate footwall (Fig. 2). Eastwards, where the Grohoten Formation overlies mainly the DPC (Fig. 2), the contact is still not well studied and therefore primary transgressive relationships could not be excluded. Farther east, between Osenovlag and the Bebresh River valley (Fig. 2), where the translation amount along the Vidlich Fault Zone most probably decreased, only few small high-angle thrusts and reverse faults were recognized (Angelov *et al.*, 2010c). Our field observations support the idea of general lack of a major thrust structure inducing considerable translations in this area.

The Bebresh Fault Zone is another important Alpine tectonic structure in the studied area, traced along the Bebresh River valley from Vrachesh to Stargel, where it is probably linked with the Bunovo-Anton Fault Zone (Fig. 2). The fault zone is poorly studied and detailed structural data are still missing. Along the Bebresh River valley southeast of Vrachesh, it is loosely defined and there is no clear evidence of a major displacement (Fig. 2). Farther southeast, the zone is described as steep thrust fault along which the low-grade metamorphic rocks of the Zvezdets Unit override the Late Carboniferous Bebresh Pluton (~310.0±6.4 Ma; Angelov *et al.*, 2010e) and the sedimentary rocks of the Grohoten Formation (Fig. 2; Antonov *et al.*, 2010a). In this area and farther southeast in the surroundings of Stargel, the fault zone represents a system of northwest–southeast trending, mainly steeply dipping to the southwest, faults (Fig. 2). Bonchev (1986) was the first who suggested the presence of a significant strike-slip component along the Bebresh Fault Zone. The steep dips of particular faults and their anastomosing geometry, as well as the relatively small vertical translations, indeed suggest the strike-slip nature of the zone. In fact, the Bebresh Fault Zone could be regarded as a transform zone with limited compressional component, linking the Vidlich and Bunovo-Anton thrusts (Fig. 2).

The Bunovo-Anton Fault Zone follows the northern margin of the Zlatitsa Basin and is largely covered by its Neogene–Quaternary sediments (Fig. 2). The zone partially reactivated the Variscan SBTZ and is cut by the system of normal faults bordering the Zlatitsa Basin (Fig. 2). The north-vergent translations along the zone led to the deformation of the Upper Cretaceous sequences of the Chelopech Basin (Fig. 2; *e.g.*, Kounov and Gerdjikov, 2020).

The Kashana Shear Zone is the main tectonic structure attributed to the Early Alpine evolution of the area (Fig. 2; *e.g.*, Gerdjikov and Georgiev, 2005, 2006; Lazarova *et al.*, 2006; Lazarova and Gerdjikov, 2008). The north-vergent thrust tectonics along the ridge of the Etropole and Zlatitsa-Teteven mountains was first suggested by Trashliev (1961) from drill-hole data. Later, Antonov and Jelev (2002) described the zone as a system of compressional brittle faults. More recent studies proved that this zone represents an Early Alpine low-grade brittle-ductile to ductile thrust (*e.g.*, Gerdjikov and Georgiev, 2005, 2006; Lazarova *et al.*, 2006; Lazarova and Gerdjikov, 2008; Nanov *et al.*, 2016).

The Kashana Shear Zone is east–west trending and generally shallowly dipping to the south. The observed shallowly plunging to the south lineation and shear-sense indicators point to the top-to-the-north tectonic transport. The zone cuts the original Variscan tectonic contact between the Korduna and Zvezdets units, imposing a partial reworking of the earlier fabrics (Fig. 2).

## PALEOZOIC GEODYNAMIC SIGNIFICANCE AND CORRELATIONS

The new structural and geochronological data clearly show that the Stara Planina Low-Grade Metamorphic Complex, initially collectively described as DPC, in fact incorporates a number of units differing in age and Paleozoic geodynamic evolution. Below, we discuss the tectonic relationships between the studied units together with their geodynamic significance and correlations with other low-grade metamorphic units from the Balkan orogen and more distant parts of the Rheic Ocean in Central and Western Europe.

### Diabase-Phyllitoid Complex and similar units

The DPC is the only Paleozoic unit in Bulgaria from which Early Cambrian pillow lavas are reported (Georgiev *et al.*, 2016). The other unit, where remnants of an Ediacaran–Upper Cambrian oceanic crust are geochronologically proven is the Frolosh Complex of the Kraishte Zone (Fig. 1; Zagorchev *et al.*, 2011; Kounov *et al.*, 2012). However, a straightforward correlation between both units is not possible due to several major differences. Unlike DPC, the Frolosh Complex lacks an important terrigenous part and is strongly tectonically intercalated with the Ediacaran–Lower Cambrian calc-alkaline magmatic rocks with an arc signature (the Struma Diorite Complex – Stephanov and Dimitrov, 1936; Haydoutov *et al.*, 1994). If the Struma Diorite and Frolosh complexes are regarded as a magmatic arc and obducted ophiolitic suite, respectively (Kounov *et al.*, 2012; Antić *et al.*, 2016), the DPC mélange-like unit was described as part of an accretionary wedge and/or forearc basin (Žák *et al.*, 2021).

Correlations were also made between the DPC and another mélange-like unit – the Dalgi Del Group of the Western Balkan Zone (Fig. 1; Angelov *et al.*, 1992). The latter, representing a terrigenous low-grade complex containing numerous fragments of ophiolite and calc-alkaline magmatic rocks, is considered as a transgressive cover of the low-grade volcano-sedimentary sequences of the Berkovitsa Group (Fig. 1; Haydoutov, 1989). The age of the Dalgi Del terrigenous sediments is loosely defined as Early Silurian–Devonian on the basis of relics of porous dry-land plant tissue findings (Ercegovac *et al.*, 2011). This age, together with the fact that the Carpathian-Balkan Ophiolites (Fig. 1, CBO, Haydoutov, 1989) are now well dated as Early Devonian (Zakariadze *et al.*, 2012; Balica *et al.*, 2014; Plissart *et al.*, 2017; Kiselinov *et al.*, 2017), put some doubts on the previously suggested CBO provenance of the ophiolitic fragments in the Dalgi Del sediments. On the other hand, if they indeed belong to the latter, this suggests a post Early Devonian age for the Dalgi Del Group, which partially confirms the paleontological findings.

For the sediments of the Berkovitsa Group, a Cambrian age is suggested based on the youngest detrital zircon population (~500 Ma) and the age of the oldest magmatic rocks intruding them (493±6.6 Ma zircon U-Pb age of gabbroic sill, Carrigan, 2005). Previously, all these low-grade volcano-sedimentary complexes from the Balkan Zone (DPC, Dalgi Del and Berkovitsa groups), together with the Frolosh and Vlasina complexes from the Kraishte Zone, were considered as part of a single terrane (Fig. 1; *e.g.*, Haydoutov, 1989; Haydoutov and Yanev, 1997). In the last ten years, however, an increasing number of studies have highlighted several differences between these units (*e.g.*, Kounov *et al.*, 2012; Antić *et al.*, 2016; Georgiev *et al.*, 2016; Žák *et al.*, 2021). Additionally, to the above-mentioned differences, we should add the fact that the Vlasina Complex must be older than the DPC and the Berkovitsa Group, as it is intruded by Ediacaran granites (*e.g.*, Kounov *et al.*, 2012; Antić *et al.*, 2016) and a maximum depositional age of 577 +5/–6 Ma is reported (Žák *et al.*, 2021). Furthermore, although of similar age, the DPC and the Berkovitsa Group differ in their lithologies. The latter represents a volcano-sedimentary, probably arc related, complex containing not only mafic but also a large amount of acid volcanic rocks and some marbles. Recently, detrital zircon U-Pb geochronological analysis suggested that, although tectonically juxtaposed during the Alpine and probably already during the Variscan orogeny (*e.g.*, Kounov *et al.*, 2012; Antić *et al.*, 2016), these units occupied different positions along the northern margin of Gondwana – eastern for the Sredna Gora and Stara Planina complexes and western for the Vlasina Complex (Žák *et al.*, 2021).

Due to similar lithologies and tectonic position, the Berkovitsa Group sequences were correlated with those of the Eşelniţa Formation of south Romania (Plissart *et al.*, 2017), whereas the latter was interpreted as formed in a rifting environment during Early Palaeozoic times (Iancu *et al.*, 2005). At the scale of the western and central European Rheic Ocean (*e.g.*, Nance *et al.*, 2010), the lithological characteristics of the Berkovitsa Group make it very similar to the Cambrian volcano-sedimentary successions of the Ossa-Morena Zone (Southwest Iberia) and Vesser Complex (Saxo-Thuringian Zone of the Bohemian Massif) characterized by a bimodal felsic and mafic volcanic activities and MOR-related rocks from an early stage of the Rheic Ocean evolution (Linnemann *et al.*, 2007; Sánchez-García *et al.*, 2010).

Alternatively, the DPC and the Berkovitsa Group could be regarded as different parts of an accretionary wedge/forearc basin system (Žák *et al.*, 2021; Žák *et al.*, in review) related to the Prototethys subduction. This basin(s) might represent an equivalent of the Late Cambrian Chamrousse oceanic domain developed along the southern Gondwana margin and which became a part of the Variscan belt of Western Europe (*e.g.*, von Raumer and Stampfli, 2008).

## Lower Paleozoic sections from the Bilo and Murgash mountains and Zvezdets Peak

An uninterrupted section of low-grade terrigenous rocks could be followed in the Bilo and Murgash mountains and in the area of Zvezdets Peak (Figs 2, 6). Apart from the evident lack of major tectonic zones along their contacts, a normal metamorphic gradient is observed from the lowermost Bilo coarse-grained schists through the Zvezdets phyllites to the non-metamorphosed siltstones and mudstones of the Grohoten Formation. Up until now, there are no reliable geochronological and paleontological constraints from the metamorphosed part of this section and its age is considered as pre-Middle Ordovician (pre-Darriwilian) as it is covered by the Middle–Upper Ordovician sediments of the Grohoten Formation (Fig. 2). Apparent lithological and structural similarities between the Bilo Unit and DPC allow some correlations to be made between these two mélange units.

Despite the lack of an apparent angular and structural unconformity between the Zvezdets Unit and the overlying Grohoten Formation, there is, however, an apparent difference in metamorphic grade and deformation between both units. Therefore, it could be tentatively suggested that a primary transgressive contact was consequently reactivated as a post-Variscan extensional decollement running at the base of the Grohoten quartzarenites and leading to the exhumation of the relatively older and higher-grade rocks of the Zvezdets Unit. A relatively larger amount of Late Variscan exhumation east of this contact is well evidenced by the fact that, in the Zlatitsa-Teteven Mountain, deeply eroded Carboniferous granitoids, intruding the Lower Paleozoic formations, are covered by Permian–Lower Triassic sedimentary rocks (Fig. 2). In contrast, in the Bilo and Etropole mountains, these sedimentary rocks transgressively cover only the Lower Paleozoic sediments and Carboniferous volcanic rocks (Fig. 2).

The subduction of the Prototethys in the Balkan area continued until the Early–Middle Ordovician (*e.g.*, Balintoni *et al.*, 2010; Antić *et al.*, 2016) and the oldest known sediments associated with the Rheic Ocean in Bulgaria are of a Middle Ordovician age (*e.g.*, Spassov, 1973; Sachanski *et al.*, 2005; Boncheva *et al.*, 2010). Furthermore, from the Lower Complex of the Serbo-Macedonian Massif (Fig. 1), Middle Ordovician rifting-related tholeiitic dykes were reported (Antić *et al.*, 2016). Therefore, the mélange-like Bilo Unit and DPC of probable Cambrian–Early Ordovician age could represent parts of an accretionary wedge/forearc basin system formed along the Gondwanan margin, which was later transgressively covered by the Middle Ordovician deposits of the newly formed, in this part of Europe, Eastern Rheic Ocean. Linnemann *et al.* (2008) already suggested rift propagation from the west in the area of the Ossa-Morena Zone towards the east to the Saxo-Thuringian Zone and more easterly situated areas of Europe during the Cambrian. In Western and Central Europe, since the Early Ordovician, a new phase of extension related to the Rheic Ocean evolution is observed, accompanied by a large-scale volcanic activity, erosion of the rift shoulders and deposition of the Armorican Quartzite (*e.g.*, von Raumer and Stampfli, 2008). As it was mentioned before, the thick quartzarenite layers at the base of the Grohoten Formation could be correlated with the Armorican Quartzite of the Western European part of the Rheic Ocean. The apparent lack of a major unconformity between the pre- and post-Middle Ordovician sequences in the Balkan area suggests that they have probably escaped the Cadomian arc-continental collision, and the newly formed during the Early Ordovician in the west Rheic Ocean propagated eastward into a still open oceanic realm. Recently, Žák *et al.* (in press) have envisaged a possible absence of a true seafloor spreading related to the Rheic Ocean in the Balkan area, where the northern Gondwanan margin represented an extended shelf.

Another possibility, which could not be fully excluded for the time being, is that the discussed-above contact between the Middle–Upper Ordovician sediments and the underlying low-grade metamorphic rocks represents in fact a diachronous breakup unconformity marked in other parts of the Rheic Ocean by a transgressive quartzarenite correlative with the Lower Ordovician Armorican Quartzite (*e.g.*, Noblet and Lefort, 1990; Gutiérrez-Alonso *et al.*, 2007; Nance *et al.*, 2010). This would imply that the Cambrian–Lower Ordovician Bilo Unit, DPC and even the Berkovitsa Complex were not parts of a back-arc and/or forearc basin(s) related to the Prototethys subduction as suggested before (Kounov *et al.*, 2012; Žák *et al.*, 2021), but rather represent volcano-sedimentary sequences related to the rifting of the Rheic Ocean.

For the Kraishte area, to the southwest (Fig. 1), where an apparent discordance between the greenschist Ediacarian–Lower Cambrian Vlasina Complex and the overlying Lower Ordovician sediments, as well as the low-grade to non-metamorphosed Silurian–Devonian sedimentary sequences of the Vlasina-Morava Unit, are also missing, Kounov *et al.* (2012) suggested a continuation between the Ediacaran–Early Cambrian backarc Vlasina Basin and the Rheic Ocean. The metamorphic difference between the distinct sedimentary sequences Antić *et al.* (2016) related to a telescoping of a Variscan normal gradient metamorphic section during the late Early Cretaceous shortening and northeast-directed thrusting.

## Paleogeographic affinities of the Lower Paleozoic section

When discussing Lower Paleozoic sedimentary sequences in Europe, it is inevitable to raise the question concerning their eventual affinity to the Gondwanan margin or the Avalonian Plate during the Rheic Ocean evolution. For the Ordovician–Devonian section of the western part of the studied area, it has already been suggested that these sediments were deposited along the Gondwanan margin (*e.g.*, Gutiérrez-Marco *et al.*, 2003; Boncheva *et al.*, 2007; Chatalov, 2017; Georgiev *et al.*, 2022). From this section, Chatalov (2017) reported Hirnantian glaciomarine deposits typical also for other peri-Gondwana terranes and not known from the Avalonian shelf (*e.g.*, Kroner and Romer, 2013). Recently, detrital zircon U-Pb geochronology analyses on middle Darriwilian sandstone from the lower part of the Grohoten Formation designate the Trans-Saharan Belt as most probable source area for these sediments (Georgiev *et al.*, 2022). All these results are consistent with the paleobiogeographic data from the Ordovician System of the Balkan Zone. The Middle Ordovician benthic faunas (brachiopods and trilobites) and acritarchs from this zone are closely related to peri-Gondwanan provinces (Kalvacheva, 1990; Gutiérrez-Marco *et al.*, 2003).

On the other hand, the spessartine-rich quartzites (coticules), as those from the Bilo Unit (Ivanov *et al.*, 1976), were exclusively reported from the Early Paleozoic Avalonian shelf (*e.g.*, Kroner and Romer, 2013). The only exception is the manganese-rich rocks occurring in the greenschist-facies volcano-sedimentary complex of the Ossa-Morena Zone, in the Iberian Massif of southwestern Spain (Jiménez Millan and Velilla, 1998). However, the existence of coticules in the Bilo Unit could not be used as reliable evidence of a possible Avalonian affinity. The apparent lack of any significant tectonic boundary, representing a Rheic suture between this unit and the rest of the Lower Paleozoic sedimentary sequences with proven Gondwanan provenance, clearly reject such a possibility.

The available tectonostratigraphic, paleontological, and geochronological data from the Moesian Platform suggest that it was part of the Avalonian Plate, which was separated from North Gondwana and accreted to Baltica (Laurussia) during the Late Ordovician–Early Devonian (*e.g.*, Oczlon *et al.*, 2007; Kalvoda and Babek, 2010; Balintoni *et al.*, 2014; Okay and Nikishin, 2015; Okay and Topuz, 2017). Therefore, the main Rheic suture must be positioned between the Moesian Platform and the Lower Paleozoic rocks from the Balkan Zone. This suture is not recognized yet, probably being covered by the thick Mesozoic and Neozoic sediments of the Moesian Platform or strongly sheared and displaced by the Variscan wrench tectonics (*e.g.*, Žák *et al.*, 2021).

## Korduna and Zvezdets units

The recognition of the Zvezdets phyllites as an independent tectonostratigraphic unit is one of the key elements that helped to resolve the complicated evolution (including Variscan and Alpine tectonic events) of the rocks along the southern slopes of the Etropole and Zlatitsa-Teteven mountains (Figs 2, 6*a*). The lower metamorphic grade, lower strain intensity and almost complete lack of magmatic rocks in the Zvezdets Unit clearly differentiate it from the mélange-like and intensively deformed Korduna Unit. These major differences between both units, together with their age difference, define their contact as a major Variscan tectonic zone, which was partially reactivated by the Alpine Kashana Shear Zone (Figs 2, 6*a*).

One of the other major breakthroughs is the recognition of the inverted metamorphic gradient in the Korduna Unit, which allows attributing it to the Variscan Stargel-Bulovanya Tectonic Zone. All this also suggests a possible affinity of the Korduna Unit to the CSGHGMC rather than to the SPLGMC. The Lower Silurian basic volcanic rocks reported from the Korduna Unit (Peytcheva and von Quadt, 2004) have no correspondent in any of the other known Silurian sediments, not only in the Balkan Zone but also in the neighboring zones of the Balkan orogen. This let us consider the Korduna Unit as an exotic entity, which obviously has arrived from a part of the Rheic Ocean up until now unknown in the Balkans.

### Correlations with other Early Paleozoic units from the Central Balkan Zone

Farther east, in the central parts of the Stara Planina Mountains, several other Early Paleozoic metamorphic units, part of the Central Balkan Zone, are exposed (Fig. 1). In the Karlovo Mountain (Fig. 1), the SPLGMC is presented by a volcano-sedimentary sequence containing scarce lenses of metabasic rocks, all metamorphosed in low-grade greenschist facies conditions (*e.g.*, Milanov *et al.*, 1971; Cheshitev *et al.*, 1994a, b). This complex, for which an Ediacaran–Early Cambrian maximum age was suggested (Žák *et al.*, 2021), is intruded by Early Cambrian granitoids (Balkanska *et al.*, 2021). It correlates well, in terms of rock composition and protolith ages, with the Berkovitsa Group (Haydoutov, 1991), although the latter contains larger amount of volcanic and magmatic rocks and an apparent Cambrian age is suggested (Žák *et al.*, 2021; Žák *et al.*, in press).

In the Shipka Mountain (Fig. 1), part of the pre-Permian basement of the Central Balkan Zone consists of limestones covered by rhythmic terrigenous sediments, to which a Devonian age was attributed (Kalvacheva and Prokopov, 1988). These sediments are similar to the Devonian deposits in the Kraishte Zone (Boncheva *et al.*, 2010), although the upper part of the complex could also be correlated with the Upper Devonian turbiditic sequences of the Iskar River gorge (Fig. 2).

The Devonian from the Shipka Mountain differs from the other Devonian sedimentary sections of the Balkan Zone by the presence of limestones and mafic volcanic rocks. Similar rocks have been described in the low-grade Lower Paleozoic sequences in the Strandzha Zone of southeast Bulgaria (Fig. 1; Dabovski *et al.*, 1994, 2002), whereas the Devonian age is reported for the carbonate turbidites (Lakova *et al.*, 1992; Boncheva and Chatalov, 1998) and diabases (Lilov and Maliakov, 2001). Devonian mafic volcanic rocks have also been recognized in the terrigenous sequences in the Kraishte Zone in Bulgaria (Zagorchev and Boncheva, 1988) and in the Paleozoic of Central Serbia (Krstić *et al.*, 2002). Farther west in Central Europe, similar Devonian sequences, consisting of mafic volcanics intercalated with terrigenous sediments and covered by carbonates, have been reported from the Rhenohercynian and Moravo-Silesian zones (*e.g.*, von Raumer *et al.*, 2017).

The easternmost unit, which is attributed to the metamorphic basement of the Balkan Zone, is the Lazovo Complex exposed in the Tvarditsa Mountain (Fig. 1; Ivanov *et al.*, 1974), described as one of the rare remnants of a Cadomian metamorphic basement in Bulgaria (Gerdjikov *et al.*, 2013). The complex comprises intermediate, mafic and ultramafic igneous rocks and metasedimens, all metamorphosed at high-grade amphibolite facies conditions (Georgiev *et al.*, 2006; Statelova, 2006). A protolith zircon U-Pb age of ~600 Ma is obtained from orthogneisses in the eastern part of the complex (Statelova *et al.*, 2011). The Lazovo Complex is juxtaposed along a ductile shear zone with the Shivachevo orthogneisses, which were recently dated at 319–315 Ma (Dörr *et al.*, 2021). The Shivachevo orthogneisses were correlated with the similarly deformed and metamorphosed in medium- to high-grade greenschist facies Carboniferous (zircon U-Pb age of 313.1±4.6 Ma, Antonov *et al.*, 2010b) Ribaritsa granitoids from the Central Balkan Zone (Fig. 2; Dörr *et al.*, 2021). This correlation suggests that, although metamorphosed at a higher degree than the other pre-Permian units of the Balkan Zone, the Lazovo Complex most probably is part of this lithotectonic unit and not of the high-grade basement of the Sredna Gora Zone (Dörr *et al.*, 2021).

## CONCLUSIONS

In this study, we propose a new framework for the low-grade metamorphic rocks from the Central Balkan Zone, applying a critical analysis of the existing data combined with new geochronological analysis and detailed lithological and structural observations. Based on their structural relationships and new geochronological constraints, several new units such as the Korduna, Bilo and Zvezdets units were established together with a reassessment of the previously recognized Diabase-Phyllitoid Complex.

In spite of the still poor time constraints and intense deformation, which led to the obliteration of the primary stratigraphic relationships and probable omission of large amount of the sedimentary record, several hypotheses are developed concerning the geodynamic evolution of the studied rocks.

The Diabase-Phyllitoid Complex and the Bilo unit are now defined as Cambrian–Lower Ordovician (?) mélange complexes, probably representing parts of an accretionary wedge and/or forearc basin formed along the Gondwanan margin during the subduction of the Prototethys. In the Bilo, Murgash and Etropole mountains, an apparently conformable Cambrian–Upper Ordovician section, characterized by a normal metamorphic gradient from low-grade to non-metamorphosed terrigenous rocks, is recognized. The deposition of these sediments is related to the subduction of the Prototethys and the early evolution of the Rheic Ocean, whereas their metamorphism and deformation is attributed to the Variscan orogeny.

An inverted metamorphic gradient recognized along the southern slopes of the Etropole and Zlatitsa-Teteven mountains through the Korduna and Zvezdets units is related to a Variscan syn-metamorphic shearing in the crustal-scale Stargel-Bulovanya Tectonic Zone. Along this zone, the Stara Planina Low-Grade Metamorphic Complex is overthrust by the Central Sredna Gora High-Grade Metamorphic Complex, to which the rocks of the Korduna Unit probably also belong.

### *Acknowledgments*

Initial work was supported by grant VU-13/06 by the Ministry of Education and Science. Due to the contracts with Elatsite Med and Geoins and their logistic support, it was possible to be realized a detail-scale mapping in the Zlatitsa-Etropole Mountain. The fieldwork of Ianko Gerdjikov and Dian Vangelov in the Zlatitsa Mountain has been carried out in the framework of the National Science Program "Environmental Protection and Reduction of Risks of Adverse Events and Natural Disasters", approved by Resolution of the Council of Ministers No 577/17.08.2018 and supported by the Ministry of Education and Science (MES) of Bulgaria (Agreement No D01-230/06.12.2018). The final analysis is funded by a project of Sofia University "St Kliment Ohridski" 80-10-17/2021. In the period 2008–2011, Rafael Ferreiro Mählmann participated in field studies and greatly helped with the determination of the metamorphic grade. We are grateful to Jiří Žák for joint fieldwork and fruitful discussions. Our thanks go also to Polina Pavlishina for her expert assistance in deciphering some of the problems of the palynomorph record from the studied units. The late Nikolay Markov, a very close friend and colleague, supported us in our endeavors and helped in their realization. We would like to thank also the reviewers Antoneta Seghedi and Valeri Sachanski, whose valuable comments and suggestions helped improve the quality of the manuscript.

## APPENDICES

**Appendix A.** LA-ICP-MC isotope data (U, Th and Pb) of zircons from the sample measured in this study. (These data are available online at https://www.geologica-balcanica.eu/sites/default/files/supplementary/Gerdjikov_Geol_Balc_52-1_2023_Appendices.zip).

**Appendix B.** CL and BSE images of all dated zircons. (These data are available online at https://www.geologica-balcanica.eu/sites/default/files/supplementary/Gerdjikov_Geol_Balc_52-1_2023_Appendices.zip).

## REFERENCES

Angelov, V., Iliev, K., Haydutov, I., Yanev, S, Dimitrova, R., Sapunov, I., Tchoumatchenko, P., Tzankov, T., Chunev, D., Rusanov, I. 1992. *Geological map of the Republic of Bulgaria in scale 1:100 000, Botevgrad map sheet.* Committee of Geology, Geology and Geophysics, Sofia.

Angelov, V., Antonov, M., Gerdzhikov, S., Petrov, P., Kiselinov, H., Aidanlijsky, G., Valev, V. 2008. *Geological map of Bulgaria in scale 1:50 000, K-34-35-G (Lakatnik).* Ministry of Environment and Water, Bulgarian Geological Survey, Sofia.

Angelov, V., Antonov, M., Gerdzhikov, S., Petrov, P., Tanatsiev, S., Kiselinov, H., Marinova, R., Valev, V. 2010a. *Geological map of Bulgaria in scale 1:50 000, K-34-48-V (Elin Pelin) map sheet*. Ministry of Environment and Water, Bulgarian Geological Survey, Sofia.

Angelov, V., Antonov, M., Gerdzhikov, S., Sirakov, V., Tanatsiev, S., Sachanski, V., Valev, V. 2010b. *Geological map of Bulgaria in scale 1:50 000, K-34-47-B (Svoge) map sheet.* Ministry of Environment and Water, Bulgarian Geological Survey, Sofia.

Angelov, V., Antonov, M., Gerdzhikov, S., Petrov, P., Kiselinov, H., Tanatsiev, S., Valev, V. 2010c. *Geological map of Bulgaria in scale 1:50 000, K-34-48-A (Litakovo) map sheet*. Ministry of Environment and Water, Bulgarian Geological Survey, Sofia.

Angelov, V., Antonov, M., Gerdzhikov, S., Petrov, P., Kiselinov, H., Tanatsiev, S., Valev, V. 2010d. *Geological map of Bulgaria in scale 1:50 000, K-34-48-B (Botevgrad) map sheet.* Ministry of Environment and Water, Bulgarian Geological Survey, Sofia.

Angelov, V., Antonov, M., Gerdzhikov, S., Petrov, P., Kiselinov, H., Tanatsiev, S., Valev, V. 2010e. *Geological map of Bulgaria in scale 1:50 000, K-34-48-G (Etropole SW) map sheet.* Ministry of Environment and Water, Bulgarian Geological Survey, Sofia.

Antić, M., Peytcheva, I., von Quadt, A., Kounov, A., Trivić, B., Serafimovski, T., Tasev, G., Gerdjikov, I., Wetzel, A. 2016. Pre-Alpine evolution of a segment of the North-Gondwanan margin: Geochronological and geochemical evidence from the central Serbo-Macedonian Massif. *Gondwana Research* 36, 523–544, https://doi.org/10.1016/j.gr.2015.07.020.

Antonov, M., Gerdjikov, S., Metodiev, L., Kiselinov, H., Sirakov, V., Valev, V. 2010a. *Geological map of Bulgaria in scale 1:50 000, K-35-37-B (Pirdop) map sheet*. Ministry of Environment and Water, Bulgarian Geological Survey, Sofia.

Antonov, M., Gerdjikov, S., Metodiev, L., Kiselinov, H., Sirakov, V., Valev, V. 2010b. *Geologic Map of the Republic of Bulgaria in Scale 1:50 000, K-35-37-G (Klisura) map sheet*. Ministry of Environment and Water, Bulgarian Geological Survey, Sofia.

Antonov, M., Jelev, V. 2002. Ductile shear zone and brittle faults in the southwestern slope of Zlatitsa-Teteven Mountain (Central Bulgaria). *Annual of the University of Mining and Geology* 45 (1), 13–20.

Balica, C., Balintoni, I., Berza, T. 2014. On the age of the Carpathian-Balkan pre-Alpine ophiolite in SW Romania, NE Serbia and NW Bulgaria. *Proceedings of XX Congress of the Carpathian-Balkan Geological Association, Tirana, Albania.* Buletini i Shkencave Gjeologjike, Special Issue 1, 196–197.

Balintoni, I., Balica, C., Ducea, M.N., Hann, H.P., Şabliovschi, V. 2010. The anatomy of a Gondwanan terrane: the Neoproterozoic–Ordovician basement of the pre-Alpine Sebeş–Lotru composite terrane (South Carpathians, Romania). *Gondwana Research* 17 (2–3), 561–572, https://doi.org/10.1016/j.gr.2009.08.003.

Balintoni, I., Balica, C., Ducea, M.N., Hann, H.-P. 2014. Peri-Gondwanan terranes in the Romanian Carpathians: A review of their spatial distribution, origin, provenance, and evolution. *Geoscience Frontiers* 5 (3), 395–411, https://doi.org/10.1016/j.gsf.2013.09.002.

Balkanska, E., Gerdjikov, I., Georgiev, S., Lazarova, A., Dörr, W., Kounov, A. 2021. Structural and geochronological constraints on the magmatic and tectonic events in the pre-Alpine basement of the central parts of the Balkan fold–thrust belt (Central Stara Planina Mountains, Bulgaria). *International Journal of Earth Sciences* 110, 1181–1211, https://doi.org/10.1007/s00531-021-02011-1.

Belev, S. 1963. Über die Petrographie und Stratigraphie der Gesteine von der Diabas-Phyllitoid Serie im Balkangebirge. *Annuel de l'Institut des Mines et de la Géologie* 9, 241–259 (in Bulgarian, with German abstract).

Bonchev, E. 1986. *The Balkanides, geotectonic position and evolution*. Bulgarian Academy of Sciences, Sofia, 273 pp. (in Bulgarian, with English abstract).

Boncheva, I., Chatalov, G. 1998. Palaeozoic conodonts from the Dervent Heights and the Strandzha Mountain. *Comptes rendus de l'Académie bulgare des Sciences* 51 (7–8), 45–48.

Boncheva, I., Lakova, I., Sachanski, V., Koenigshof, P. 2010. Devonian stratigraphy, correlations and basin development in the Balkan Terrane, western Bulgaria. *Gondwana Research* 17 (2–3), 573–582, https://doi.org/10.1016/j.gr.2009.11.012.

Boncheva, I., Sachanski, V., Lakova, I., Yaneva, M. 2007. Facial transition and biostratigraphic correlation of the Upper Silurian and Lower Devonian in West Bulgaria. *Geological Quarterly* 51 (4), 7–17.

Boyanov, I., Dabovski, C., Gocev, P., Harkovska, A., Kostadinov, V., Tzankov, T., Zagorchev, I. 1989. A new view of the Alpine tectonic evolution of Bulgaria. *Geologica Rhodopica* 1, 107–121.

Carrigan, C.W. 2005. Gondwana-derived terranes and the Variscan orogeny in Bulgaria: Zircon geochronology and thermobarometry. PhD Thesis, Ann Arbor, University of Michigan, 181 pp.

Carrigan, C., Mukasa, S., Haydoutov, I., Kolcheva, K. 2006. Neoproterozoic magmatism and Carboniferous high-grade metamorphism in the Sredna Gora Zone, Bulgaria: An extension of the Gondwana-derived Avalonian-Cadomian belt?. *Precambrian Research* 147 (3–4), 404–416, https://doi.org/10.1016/j.precamres.2006.01.026.

Chatalov, A. 2017. Sedimentology of Hirnantian glaciomarine deposits in the Balkan Terrane, western Bulgaria: Fixing a piece of the north peri-Gondwana jigsaw puzzle. *Sedimentary Geology* 350, 1–22, https://doi.org/10.1016/j.sedgeo.2017.01.004.

Cheshitev, G., Milanova, V., Sapunov, I., Tchoumatchenko, P. 1994a. *Geological map of the Republic of Bulgaria in scale 1:100 000, Teteven map sheet*. Committee of Geology, Geology and Geophysics, Sofia.

Cheshitev, G., Nikolov, T., Milanova, V., Chontova, T. 1994b. *Geological map of the Republic of Bulgaria in scale 1:100 000, Troyan map sheet*. Committee of Geology, Geology and Geophysics, Sofia.

Chunev, D., Kouzhukharov, D. 1968. Diabas-philitoidna Formatsiya (Diabase-Phyllitoid Formation). *In*: Tzankov, V., Spasov, Ch. (Eds), *Stratigraphy of Bulgaria*. Nauka i Izkustvo Publishing House, Sofia, 63–70 (in Bulgarian).

Dabovski, C., Savov, S., Chatalov, G., Shiliafov, G. 1994. *Geological map of Bulgaria scale 1:100 000, Map sheet Elhovo*. Sofia, Committee of geology and mineral resources, Geology and Geophysics Corp.

Dabovski, C., Boyanov, I., Khrischev, K., Nikolov, T., Sapunov, I., Yanev, Y., Zagorchev, I. 2002. Structure and Alpine evolution of Bulgaria. *Geologica Balcanica* 32 (2–4), 9–15, https://doi.org/10.52321/GeolBalc.32.2-4.9.

Dimitrov, S. 1929. Die Diabasgesteine im Iskerdurchbruch zwischen den Eisenbahnhaltestelle Bow und Lakatnik. *Annuaire de l'Université de Sofia, Faculté Physique-Mathématique* 25 (3), 175–237.

Dimitrov, S. 1939. Ergebnisses und Probleme der petrographische Forschungen in Bulgarien. *Annuaire de l'Université de Sofia, Faculté Physique-Mathématique* 35 (3), 225–253.

Dörr, W., Lazarova, A., Gerdjikov, I. 2021. Pre-Mesozoic basement of Tvarditsa Stara Planina Mountain, Central South Bulgaria: U-Pb geochronology and regional implication. *Review of the Bulgarian Geological Society* 82 (3), 84–86, https://doi.org/10.52215/rev.bgs.2021.82.3.84.

Ercegovac, M., Krstić, B., Kiselinov, H., Zagorchev, I., Kalenic, M. 2011. New data on the age of the low-grade metamorphic complexes in Stara planina Mts., NW Bulgaria and Eastern Serbia. *Bulgarian Geological Society, National Conference with International Participation "Geosciences 2011", Abstracts*, 85–86.

Georgiev, N., Gerdjikov, I., Statelova, J. 2006. Ductile to brittle-ductile shear zones from the Pre-Mesozoic basement of Tvarditsa Stara Planina area: preliminary field and mesostructural data. *Bulgarian Geological Society, National Conference with international participation "Geosciences 2006", Abstracts*, 94–97.

Georgiev, S., Gerdjikov, I., Peytcheva, I, Makaveev, P. 2020. Time frame of the Carboniferous tectonic and magmatic activity in the area of Vezhen pluton, Bulgaria. *Review of the Bulgarian Geological Society* 81 (3), 72–74.

Georgiev, S., Popov, M., Balkanska, E., Gerdjikov, I., Vangelov, D. 2016. First U-Pb zircon geochronology data of the diabases from the Lower Paleozoic section along Iskar and Gabrovnitsa River valleys. *Bulgarian Geological Society, National Conference with International Participation "Geosciences 2016", Abstracts*, 55–56.

Georgiev, S., Sachanski, V., Andreeva, P., Kiselinov, H., Balkanska, E., Lakova, I., Tanatsiev, S. 2021. Paleogeographic position of the Ordovician rocks from the Svoge Unit, Western Balkan – preliminary results. *Review of the Bulgarian Geological Society* 82 (3), 49–51, https://doi.org/10.52215/rev.bgs.2021.82.3.49.

Georgiev, S., Sachanski, V., Andreeva, P., Kiselinov, H., Balkanska, E., Lakova, I., Tanatsiev, S. 2022. Trans-Saharan belt provenance: A potential source for the Ordovician succession of the Balkan Terrane (Svoge Unit) – clues from LA-ICP-MS detrital zircon dating analysis. *Comptes rendus de l'Académie bulgare des Sciences* 75 (2), 237–247, https://doi.org/10.7546/CRABS.2022.02.09.

Gerdjikov, I., Balkanska, E. 2013. Kalofer granitoid suite. A Late Variscan stitching pluton. *Comptes rendus de l'Académie bulgare des Sciences* 66 (5), 709–716.

Gerdjikov, I., Georgiev, N. 2005. Spectacular fabric but little displacement: Early Alpine shear zones from Zlatishka Stara Planina, Central Balkanides. *Bulgarian Geological Society, National Conference with International Participation "Geosciences 2005", Abstracts*, 35–38.

Gerdjikov, I., Georgiev, N. 2006. The Svishti Plaz Allochthon (Central Balkanides). Position and associated fabric. *Comptes rendus de l'Académie bulgare des Sciences* 59 (6), 631–638.

Gerdjikov, I., Georgiev, N., Dimov, D., Lazarova, A. 2007. The different faces of supposedly single thrust: a reevaluation of the Vezhen thrust, Central Balkanides. *Bulgarian Geological Society, National Conference with International Participation "Geosciences 2008", Abstracts*, 24–26.

Gerdjikov, I., Kounov, A., Lazarova, A., Bonev, K. 2009. The Thracian Suture – does it exist?. Bulgarian Geological Society, National Conference with International Participation "Geosciences 2009", Abstracts, 93–94.

Gerdjikov, I., Lazarova, A., Kounov, A., Vangelov, D. 2013. High-grade metamorphic complexes in Bulgaria. Part I. Geology and geophysics. *Annual of the University of Mining and Geology* 56, 47–52 (in Bulgarian, with English abstract).

Gerdjikov, I., Ruffet, G., Lazarova, A., Vangelov, D., Balkanska, E., Bonev, K. 2010. 40Ar/39Ar geochronologic constrains of a Variscan transpression in Central Stara Planina Mountain. *Bulgarian Geological Society, National Conference with International Participation "Geosciences 2010", Abstracts*, 109–110.

Gutiérrez-Alonso, G., Fernández-Suárez, J., Gutiérrez-Marco, J.C., Corfu, F., Murphy, J.B., Suárez, M. 2007. U–Pb depositional age for the upper Barrios Formation (Armorican Quartzite facies) in the Cantabrian zone of Iberia: implications for stratigraphic correlation and paleogeography. *In*: Linnemann, U., Nance, R.D., Zulaf, G., Kraft, P., Zulauf, G. (Eds), *The Evolution of the Rheic Ocean: From Avalonian–Cadomian Active Margin to Alleghanian–Variscan Collision*. Geological Society of America Special Paper 432, 287–296, https://doi.org/10.1130/2007.2423(13).

Gutiérrez-Marco, J.C., Yanev, S., Sachanski, V., Rabano, I., Lakova, I., San Jose Lancha, M.A., Diez Martínez, E., Boncheva, I., Sarmiento, G. 2003. New biostratigraphical data from the Ordovician of Bulgaria. *In*: Albanesi, G.L., Beresi, M.S., Peralta, S.H. (Eds), *Ordovician of the Andes*, INSUGEO, Serie Correlación Geologica 17, 79–85.

Haydoutov, I. 1989. Precambrian ophiolites, Cambrian island-arc, and Variscan suture in the South Carpathian-Balkan Region. *Geology* 17 (10), 905–908, https://doi.org/10.1130/0091-7613(1989)017<0905:POCIAA>2.3.CO;2.

Haydoutov, I. 1991. *Origin and Evolution of the Precambrian Balkano-Carpatian Ophiolite Segment*. Bulgarian Academy of Sciences Publishing House, Sofia, 179 pp. (in Bulgarian, with English abstract).

Haydoutov, I., Yanev, S. 1997. The Protomoesian microcontinent of the Balkan Peninsula – a peri-Gondwanaland piece. *Tectonophysics* 272 (2–4), 303–313, https://doi.org/10.1016/S0040-1951(96)00264-8.

Haydoutov, I., Kolcheva, K., Daieva, L. 1994. The Struma Diorite Fm from Vlahina block, SW Bulgaria. *Review of the Bulgarian Geological Society* 55, 9–35.

Haydutov, I., Tenchov, Y., Yanev, S. 1979. Lithostratigraphic subdivision of the Diabase-Phyllitoid Complex in the Berkovica Balkan Mountain. *Geologica Balcanica* 9 (3), 13–25.

Iancu, V., Berza, T., Seghedi, A., Mărunţiu, M. 2005. Paleozoic rock assemblages incorporated in the South Carpathian Alpine Thrust Belt (Romania and Serbia): a review. *Geologica Belgica* 8, 48–68.

Ivanov, Z. 1970. Sur le caractère et la succession des déformations précoces des terrains anciens du Balkan – entre la vallée de l'Iskăr et du passage d'Etropole. *Bulletin of the Geological Institute, Series Geotectonics* 19, 29–59 (in Bulgarian, with French abstract).

Ivanov, Z. 1972. Structure du terrain Paléozoïque entre les gares Bov et Lakatnik. *Annuaire de l'Université de Sofia "St Kliment Ohridski", Faculté de Géologie et Géographie* 64 (1), 83–96 (in Bulgarian, with French abstract).

Ivanov, Z. 2017. *Tectonics of Bulgaria*. Kliment Ohridski University Press, Sofia, 331 pp. (in Bulgarian, with English abstract).

Ivanov, Z., Kolcheva, K., Moskovski, S. 1974. Édification géologique d'une partie du noyau de l'anticlinal de Tvarditsa. *Annuaire de l'Université de Sofia "St Kliment Ohridski", Faculté de Géologie et Géographie* 65 (1), 245–277 (in Bulgarian, with French abstract).

Ivanov, Z., Kolceva, K., Cholakov, P., Kirov, K. 1976. On the geology of the low Paleozoic from the Bilo Mountain (Botevgrad District). *Review of the Bulgarian Geological Society* 37 (3), 283–295 (in Bulgarian, with English abstract).

Ivanov, Z., Kolceva, K., Moskovski, S., Dimov, D. 1987. Des particularités et du caractère de la "formation diabaso-phyllithoide". *Review of the Bulgarian Geological Society* 48 (2), 1–24 (in Bulgarian, with French abstract).

Jackson, S.E., Pearson, N.J., Griffin, W.L., Belousova, E.A. 2004. The application of laser ablation-inductively coupled

plasma-mass spectrometry to in situ U/Pb zircon geochronology. *Chemical Geology* 211 (1–2), 47–69, https://doi.org/10.1016/j.chemgeo.2004.06.017.
Jiménez Millan, J., Velilla, N. 1998. Mn-Fe spinels and silicates in manganese-rich rocks from the Ossa-Morena Zone, southern Iberian Massif, southwestern Spain. *The Canadian Mineralogist* 36 (3), 701–711.
Kalvacheva, R. 1972. Preliminary results from palynological studies of the Lower Palaeozoic in the Iskur Gorge. *Review of the Bulgarian Geological Society* 33 (2), 242–250 (in Bulgarian, with English abstract).
Kalvacheva, R. 1978. Acritarch stratigraphy of Lower Paleozoic formation in the West Balkan Mountains, Bulgaria. *Palinologia* 1, 303–311.
Kalvacheva, R. 1982. Palynology and stratigraphy of the Diabase-Phyllitoid Complex in the Western Balkan Mountains. *Review of the Bulgarian Geological Society* 43 (1), 8–24 (in Bulgarian, with English abstract).
Kalvacheva, R. 1990. Review on microfossil dating of low metamorphic rocks in Stara Planina and Vakarel hills. *In*: Nikolov, T. (Ed.), *Microfossils in Bulgarian Stratigraphy*. Bulgarian Academy of Sciences Publishing House, Sofia, 13–22 (in Russian).
Kalvacheva, R., Nedjalkov, S. 1976. Diabase body in the Ordovician sediments in the Western Balkan Mountains (Bulgaria). *Comptes rendus de l'Académie bulgare des Sciences* 29 (10), 1519–1522.
Kalvacheva, R, Prokopov, R. 1988. Fossil evidence (Devonian crinoids) for the age of metamorphic rocks in Sipka Balkan Mountains, Bulgaria. *Comptes rendus de l'Académie bulgare des Sciences* 41 (2), 91–94.
Kalvoda, J., Bábek, O. 2010. The margins of Laurussia in central and southeast Europe and southwest Asia. *Gondwana Research* 17 (2–3), 526–545, https://doi.org/10.1016/j.gr.2009.09.012.
Kiselinov, H., Georgiev, S., Vangelov, D., Gerdjikov, I., Peytcheva, I. 2017. Early Devonian Carpathian-Balkan ophiolite formation: U–Pb zircon dating of Cherni Vrah gabbro, Western Balkan, Bulgaria. *Bulgarian Geological Society, National Conference with International Participation "Geosciences 2017", Abstracts*, 59–60.
Kounov, A., Gerdjikov, I. 2020. The problems of the post-Cenomanian tectonic evolution of the central parts of the Sredna Gora Zone. The wrench tectonics – how real is real?. *Geologica Balcanica* 49 (2), 39–58, https://doi.org/10.52321/GeolBalc.49.2.39.
Kounov, A., Graf, J., von Quadt, A., Bernoulli, D., Burg, J-P., Seward, D., Ivanov, Z., Fanning, M. 2012. Evidence for a "Cadomian" ophiolite and magmatic-arc complex in SW Bulgaria. *Precambrian Research* 212–213, 275–295, https://doi.org/10.1016/j.precamres.2012.06.003.
Kroner, U., Romer, R.L. 2013. Two plates — Many subduction zones: The Variscan orogeny reconsidered. *Gondwana Research* 24 (1), 298–329, https://doi.org/10.1016/j.gr.2013.03.001.
Krstić, B., Maslarević, L., Ercegovac, M., Đajić, S. 2002. Devonian of the Serbian Carpatho-Balkanides. *Proceedings of XVII Congress of CBGA, VEDA, Bratislava*.
Lakova, I., Gocev, P., Yanev, S. 1992. Palynostratigraphy and geological setting of the Lower Paleozoic allochthon in Dervent Heights, SE Bulgaria. *Geologica Balcanica* 22, 71–88.
Lazarova, A., Gerdjikov, I. 2008. Structures of sheared granitoids from the Zlatishka Stara Planina Mountain: indicators for the deformation at frictional-viscous transition. *Review of the Bulgarian Geological Society* 69 (1–3), 7–20 (in Bulgarian, with English abstract).
Lazarova, A., Georgiev, N, Dimov, D. 2007. Preliminary structural data on the Stara Planina high-grade metamorphic series, Teteven Stara Planina Mountains. *Bulgarian Geological Society, National Conference with International Participation "Geosciences 2007", Abstracts,* 11–13.
Lazarova, A., Gerdjikov, I., Georgiev, N., Dimov, D. 2006. The Anton shear zone (Central Stara planina Mountains). Temporal relations, extent and significance. *Comptes rendus de l'Académie bulgare des Sciences* 59 (6), 639–644.
Lazarova, A., Gerdjikov, I., Vangelov, D., Georgiev, N. 2010. Variscan transpression and related voluminous magmatism in Central Stara Planina Mountain, Bulgaria. *Geologica Balcanica* 38 (1–2), 226–227.
Lilov, P., Maliakov, Y. 2001. K/Ar datations de métadiabases du Strandja. *Comptes rendus de l'Académie bulgare des Sciences* 54 (10), 95–98.
Linnemann, U., Gerdes, A., Drost, K., Buschmann, B. 2007. The continuum between Cadomian orogenesis and opening of the Rheic Ocean: Constraints from LA-ICP-MS U-Pb zircon dating and analysis of plate-tectonic setting (Saxo-Thuringian zone, northeastern Bohemian Massif, Germany). *In*: Linnemann, U., Nance, D., Kraft, P., Zulauf, G. (Eds), *The Evolution of the Rheic Ocean: From Avalonian–Cadomian Active Margin to Alleghenian–Variscan Collision*. Geological Society of America 423, 61–96, https://doi.org/10.1130/2007.2423(03).
Linnemann, U., Pereira, M.F., Jeffries, T., Drost, K., Gerdes, A. 2008. The Cadomian Orogeny and the opening of the Rheic Ocean: the diachrony of geotectonic processes constrained by LA-ICP-MS U-Pb zircon dating (Ossa-Morena and Saxo-Thuringian Zones, Iberian and Bohemian Massifs. *Tectonophysics* 461 (1–4), 21–43, https://doi.org/10.1016/j.tecto.2008.05.002.
Ludwig, K. 2003. User's manual for Isoplot 3.00. *A Geochronological Toolkit for Microsoft Excel*. Berkeley Geochronology Center Special Publication 1a, Berkeley, 74 pp.
Milanov, L., Kuikin, S., Gercheva, Y., Christov, S., Chunev, V. 1971. Geology of east Troyan Stara Planina Mountain. *Bulletin of the Committee of Geology* 18, 201–221 (in Bulgarian).
Nance, R.D., Gutierréz-Alonso, G., Keppie, J.D., Linnemann, U., Murphy, J.B., Quesada, C., Strachan, R.A., Woodcock, N.H. 2010. Evolution of the Rheic Ocean. *Gondwana Research* 17 (2–3), 194–222, https://doi.org/10.1016/j.gr.2009.08.001.
Nanov, Z., Naydenov, K., Georgiev, N., Vasileva, V. 2016. Structural evolution of the greenschist basement of Zlatishka Stara Planina – an example from the Elatsite mine area. *Bulgarian Geological Society, National Conference with International Participation "Geosciences 2016", Abstracts*, 93–94.
Oczlon, M., Seghedi, A., Carrigan, C. 2007. Avalonian and Baltican terranes in the Moesian Platform (southern Europe, Romania, and Bulgaria) in the context of Caledonian terranes along the southwestern margin of the East European craton. *In:* Linnemann, U., Nance, R.D., Kraft, P., Zulauf, G. (Eds), *The Evolution of the Rheic Ocean: From Avalonian–Cadomian Active Margin to Alleghenian–Variscan Collision*. Geological Society of America, Special Paper 423, 375–400, https://doi.org/10.1130/2007.2423(18).
Okay, A.I., Nikishin, A.M. 2015. Tectonic evolution of the southern margin of Laurasia in the Black Sea region. *International Geology Review* 57 (5–8), 1051–1076, https://doi.org/10.1080/00206814.2015.1010609.

Okay, A.I., Topuz, G. 2017. Variscan orogeny in the Black Sea region. *International Journal of Earth Sciences* 106, 569–592, https://doi.org/10.1007/s00531-016-1395-z.

Okay, A., Satır, M., Tüysüz, O., Akyüz, S., Chen, F. 2001. The tectonics of the Strandja Massif: Late-Variscan and mid-Mesozoic deformation and metamorphism in the northern Aegean. *International Journal of Earth Sciences* 90, 217–233, https://doi.org/10.1007/s005310000104.

Paton, C., Hellstrom, J., Paul, B., Woodhead, J., Hergt, J. 2011. Iolite: Freeware for the visualisation and processing of mass spectrometric data. *Journal of Analytical Atomic Spectrometry* 26 (12), 2508–2518, https://doi.org/10.1039/C1JA10172B.

Peytcheva, I., von Quadt, A. 2004. The Palaeozoic protoliths of Central Srednogorie, Bulgaria: records in zircons from basement rocks and Cretaceous magmatites. *5th International Symposium on Eastern Mediterranean Geology, Thessaloniki, Greece, Conference Volume*, T11-9.

Plissart, G., Monnier, C., Diot, H., Mărunţiu, M., Berger, J., Triantafyllou, A. 2017. Petrology, geochemistry and Sm-Nd analyses on the Balkan-Carpathian Ophiolite (BCO – Romania, Serbia, Bulgaria): Remnants of a Devonian back-arc basin in the easternmost part of the Variscan domain. *Journal of Geodynamics* 105, 27–50, https://doi.org/10.1016/j.jog.2017.01.001.

Pristavova, S., Antonov, M., Janeva, M. 2003. Petrological and structural characteristics of the low-grade metamorphic rocks from the valley of Gabrovnitsa River, Western Stara planina. *Annual of the University of Mining and Geology* 46 (1), 163–170.

Raevskaya, E.G., Servais, T. 2009. Ninadiacrodium: a new Late Cambrian acritarch genus and index fossil. *Palynology* 33 (1), 219–239, https://doi.org/10.2113/gspalynol.33.1.219.

Sachanski, V. 2015. The Silurian in the West Balkan Mts. (Svoge Unit, Srednogorie Zone) – 110 years later. *Geologica Balcanica* 44 (1–3), 3–15, https://doi.org/10.52321/GeolBalc.44.1-3.3.

Sachanski, V., Boncheva, I., Lakova, I. 2005. A continuous section across the Silurian–Devonian boundary in the Kraishte region: graptolite and conodont biostratigraphy. *Bulgarian Geological Society, National Conference with International Participation "Geosciences 2005", Abstracts*, 18–20.

Sałacińska, A., Gerdjikov, I., Kounov, A., Chew, D., Szopa, K., Gumsley, A., Kocjan, I., Marciniak-Maliszewska, B., Drakou, F. 2022. Variscan magmatic evolution of the Strandja Zone (Southeast Bulgaria and northwest Turkey) and its relationship to other north Gondwanan margin terranes. *Gondwana Research* 109, 253–273, https://doi.org/10.1016/j.gr.2022.04.013.

Sánchez-García, T., Bellido, F., Pereira, M.F., Chichorro, M., Quesada, C., Pin, C., Silva, J.B. 2010. Rift related volcanism predating the birth of the Rheic Ocean (Ossa-Morena Zone, SW Iberia). *Gondwana Research* 17 (2–3), 392–407, https://doi.org/10.1016/j.gr.2009.10.005.

Servais, T., Li, J., Molyneux, S.G., Rubinstein, C.V., Vecoli, M., Yan, K. 2014. The palaeobiogeographical spread of the acritarch Veryhachium in the Early and Middle Ordovician and its impact on biostratigraphical applications. *GFF* 136 (1), 234–237, https://doi.org/10.1080/11035897.2014.893255.

Spasov, C. 1960. Stratigraphie des Ordoviziums und Silurs im Kern der Svoge-Antiklinale. *Travaux sur la géologie de Bulgarie, Série stratigraphie et tectonique* 1, 161–202 (in Bulgarian, with German abstract).

Spassov, C. 1973. Stratigraphie des Devons in Südwest-Bulgarien. *Bulletin of the Geological Institute, Series Stratigraphy and Lithology* 22, 5–38.

Spasov, H. 1989. Lithostratigraphy of the Ordovician–Silurian deposits in Bulgaria. *In*: Zhelyaskova-Panayotova, M., Bozhilova, L., Zacharieva, M., Stoichev, Z., Wachev, W. (Eds), *Extended Abstracts of XIV Congress CBGA*. Bulgarian Academy of Sciences, Sofia, 648–651 (in Russian).

Statelova, J. 2006. Variscan high-grade metamorphic rocks in Lazovo complex, Central Stara Planina Mountain. *Bulgarian Geological Society, National Conference with International Participation "Geosciences 2006", Abstracts*, 189–192.

Statelova, J., von Quadt, A., Machev, P, Georgiev, S. 2011. Cadomian igneous rocks from Europe's Variscan belt, Lazovo complex. *Goldschmidt Conference 2011 Abstracts*, Mineralogical Magazine, 1930.

Stephanov, A., Dimitrov, Z. 1936. Geologische Untersuchungen im Kustendiler Gebiet. *Review of the Bulgarian Geological Society* 8, 1–28.

Trashliev, S. 1961. On the genesis and age of the barite locality "Kashana", District of Pirdop. *Review of the Bulgarian Geological Society* 22 (3), 245–252 (in Bulgarian, with English abstract).

Vangelov, D., Gerdjikov, I., Kounov, A., Lazarova, A. 2013. The Balkan Fold-Thrust Belt: an overview of the main features. *Geologica Balcanica* 42 (1–3), 29–47, https://doi.org/10.52321/GeolBalc.42.1-3.29.

von Quadt, A., Peytcheva, I., Haydoutov, I. 1998. U-Pb zircon dating of Tcherny Vrah metagabbro, the West Balkan, Bulgaria. *Comptes rendus de l'Académie bulgare des Sciences* 51 (1–2), 81–84.

von Raumer, J.F., Stampfli, G.M. 2008. The birth of the Rheic Ocean – Early Palaeozoic subsidence patterns and subsequent tectonic plate scenarios. *Tectonophysics* 461 (1–4), 9–20, https://doi.org/10.1016/j.tecto.2008.04.012.

von Raumer, J.F., Nesbor, H.-D., Stampfli, G.M. 2017. The north-subducting Rheic Ocean during the Devonian: Consequences for the Rhenohercynian ore sites. *International Journal of Earth Sciences* 106, 2279–2296, https://doi.org/10.1007/s00531-016-1425-x.

Zagorchev I., Boncheva, I. 1988. Indications of Devonian basic volcanism in Southwest Bulgaria. *Geologica Balcanica* 18 (4), 55–63.

Zagorchev, I., Balica, C, Balintoni, I., Kozhoukharova, E., Dimitescu, R., Săbău, G., Negulescu, E. 2011. New isotopic data on the metamorphic rocks in SW Bulgaria. *3rd International Symposium Geology of the Black Sea Region, October 2011*, Bucharest, Romania, 223–225.

Žák, J., Svojtka, M., Gerdjikov, I., Kounov, A., Vangelov, D. 2021. The Balkan terranes: a missing link between the eastern and western segments of the Avalonian-Cadomian orogenic belt?. *International Geological Review* 64 (17), 2389–2415, https://doi.org/10.1080/00206814.2020.1861486.

Žák, J., Svojtka, M., Gerdjikov, I., Vangelov, D.A., Kounov, A., Sláma, J., Kachlík, V. (in press). In search of the Rheic suture: detrital zircon geochronology of Neoproterozoic to Lower Paleozoic metasedimentary units in the Balkan fold-and-thrust belt in Bulgaria. *Gondwana Research*.

Zakariadze, G., Karamata, S., Korikovsky, S., Ariskin, A., Adamia, S.A., Chkhotua, T., Sergeev, S., Solov'eva, N. 2012. The early-middle Palaeozoic oceanic events along the southern European Margin: The Deli Jovan Ophiolite Massif (NE Serbia) and Palaeo-oceanic zones of the Great Caucasus. *Turkish Journal of Earth Sciences* 21 (5), 635–668, https://doi.org/10.3906/yer-1011-2.