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Amphibolite-facies metamorphic complexes in Bulgaria and Precambrian geodynamics: controversies and "state of the art"

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И. Загорчев — Метаморфические комплексы амфиболитовой фации в Болгарии и прекамбрийская геодинамика: противоречия и состояние вещей. Эволюция идей о комплексах фундамента на Балканском полуострове развивалась из начальной концепции о едином и единственном прекамбрийском комплексе к дифференциации и признании разных протолитов которые перетерпели полиметаморфическую и полидеформационную историю. Корреляцию между метаморфическими комплексами обнаруженными в отдельных альпийских и/или герцинских тектонических зонах надо делать только когда была бы получена детальная характеристика всех основных оссобеностей протолитов и наложенных метаморфических и деформационных событий. Настоящая петрологическая информация недостаточна чтобы полно понять и обрисовать комплексную тридименсионную историю региона.

Abstract. The evolution of the ideas about the basement complexes on the Balkan Peninsula has developed from the initial attribution to a single and uniform Precambrian complex towards differentiation, and recognition of different protoliths that underwent polymetamorphic and multideformational histories. Correlation between metamorphic complexes distinguished in different Alpine and/or Hercynian tectonic zones should be made only when a detailed knowledge were obtained on all significant features of the protoliths and the superimposed metamorphic and structural events. The now available petrologic information is still insufficient to fully understand and outline the complex 3D history of the region.

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Evolution of ideas

The eightieth anniversary of the first published *Geology of Bulgaria* (Златарски, 1927) and the sixtieth anniversary of the Geological Institute at the Bulgarian Academy of Sciences are a good occasion to throw a retrospective glance over the development of the ideas on the origin, structure and evolution of the "crystalline rocks", "high-grade metamorphics" (metamorphics of medium pressure and moderate temperature), or more precisely formulated, the amphibolite-facies metamorphic rocks and complexes. The historic part of such study should begin with the first scientists who started the study of the metamorphics of European Turkey (Ami Boué and Auguste Viquesnel), with the basic studies of J. Cvijić, G. Zlatarski and G. Bonchev, for to come to our days of wide and multi-faceted knowledge and varied ideas.

The early ideas about the metamorphic complexes of the Balkans consisted in the recognition of two groups ("series") of metamorphic rocks, of higher (amphibolite facies) and of lower (greenschist facies) grade, respectively. Two assumptions have been made.

The first one may be summarized as "higher grade, older age". Secondly, it was believed that the amphibolite-facies complexes were of very old (Archean, and Algonkian or Palaeozoic, respectively) age, and that their primary position was of normal superposition. There has been always some confusion (e.g., s. Димитров, 1939, 1946, 1955) about the exact nature of the "younger" complexes. Thus, very low-grade to greenschist facies Palaeozoic complexes, the diabase-phyllitoid formation (complex) and the "upper series of the Rhodope crystalline" have been often all referred to the upper "series".

In more modern times, Dimitrov (Димитров, 1939) distinguished the diabase-phyllitoid formation as a volcano-sedimentary complex of Palaeozoic (according to him, most probably Devonian?) age, most of the Palaeozoic and Mesozoic formations previously ascribed to the "upper series" being successfully detached from it. It should be emphasized again that a confusion originated in the implicit assumption that only one complex of diabase-phyllitoid composition had ever existed on the Balkans. Now we know that several such complexes are exposed, and three of them are of Neoproterozoic-Cambrian, Devonian and Mesozoic (Triassic-Jurassic) age.

At their turn, and following the detailed mapping by the Russian Complex Geological Expedition, two series of upwards decreasing grade (but always within the amphibolite facies of Barrovian type) have been distinguished within the high-grade metamorphics of the Rhodope massif: lower (ultrametamorphic, called also Archean) and upper ("Rhodope series"), of supposed Proterozoic age (Димитров, 1955; Вергилов и др., 1963). Further studies (Кожухаров, 1968, 1984; Иванов и др., 1984; Kozhoukharov et al., 1974, 1978; Kozhoukharov in Zoubek et al., eds., 1988; Kozhoukharov, 1986) developed the lithostratigraphy and introduced in the formal lithostratigraphic nomenclature a number of formations.

Although the opinions about the Precambrian age of most of the high-grade metamorphics (with the exception of the Sakar-type Triassic) have been always dominant, some authors have insisted on a much younger, Mesozoic and Palaeogene age for the amphibolite-facies metamorphism, and a Mesozoic (and/or Palaeozoic) age, for the protoliths. This opinion, first expressed by Yanishevski (Янишевски, 1947), has found its followers even in latest times (Ricou et al., 1998) although the Precambrian age has been proven at least for a part of the metamorphic rocks and complexes.

Many of the high-grade metamorphics have been continuously referred (s. Khain, ed., 1981; Zoubek et al., eds., 1988; Rudakov, 1992; Zagorchev, 1998a) to the Precambrian (and partially, even to the Archean) based mostly on presence of a presumably unconformable Palaeozoic cover. In many cases acceptance of a Precambrian age was made by intuition rather than based on strict evidence. However, new evidence obtained by modern methods during the last years has shown that most of the assumptions made in Zoubek et al., eds. (1988) remain valid in our days.

Indications for the presence of Neoproterozoic granitoids in the Precambrian basement of the Serbo-Macedonian massif have been reported by G. Deleon, who applied for the first time in that area the Rb-Sr method (s. Zoubek et al., eds., 1988). Cadomian reworking events have been supposed to be of major importance for the formation of the high-grade metamorphic basement (core complexes) in South Bulgaria on the basis of Rb-Sr data (s. Lilov et al., 1983; Zagorchev, Moorbath, 1986; Zagortchev, 1994). S. Moorbath (personal communication, 1981) considered the Cadomian metamorphism as the first metamorphic event in the Ograzhdenian complex on the basis of the comparatively low initial $^{87}Sr \backslash ^{86}Sr$ ratio obtained. These evidence and interpretations remained underestimated mostly due to preconceived ideas (s. criticism by Zagorchev, 2000), and only recently, studies by the U-Pb method (Graf, 2001; Carrigan et al., 2006) confirmed our previous data and ideas. The new radiogeochronological and petrological data allow for a new synthesis to be made.

The present paper aims to expose the basic evidence about the Precambrian amphibolite-facies complexes in the central and eastern parts of the Balkan Peninsula. The new insight is also adding new elements in the ideas about the pre-Cadomian and Cadomian palaeogeodynamics of the Peri-Gondwanan Balkan regions.

A "new" approach

A serious flaw of previous research has been the tendency to correlate all Precambrian (or referred to the Precambrian) rock entities in Bulgaria and on the Balkans to a small number of formal units often underestimating seemingly negligible differences. The latter could be in fact related to different geologic histories.

A modest attempt to accentuate on such differences has been made by Kozhoukharov et al. (1978) and D. Kozhoukharov, E. Kozhoukharova, C. Dabovski and I. Zagorchev (in Zoubek et al., eds., 1988). Informal units (complexes) have been independently described and later formalized as supergroups for the Rhodope massif [two complexes: lower ultrametamorphic (Prerhodopian) and upper varied (Rhodopian)], the Serbo-Macedonian massif and the Strouma unit [lower ultrametamorphic Ograzhdenian complex (Supergroup) and Osogovo "Formation"], the Srednogorie zone ["Precambrian metamorphic rocks in the Ihtiman block"; "Precambrian metamorphic rocks in the Sredna Gora block" (subdivided into amphibolitic Koprivshtitsa "Group" and gneissic Pirdop "Group")] and the Sakar-Strandzha zone. Further on, Ivanov (1989) formulated the idea about the presence of two types of metamorphic complexes: Rhodope type (exposed in the Rhodope massif s.s.) and Balkanide type (exposed in the internal Balkanides, i.e., in the Srednogorie, Kraishtids and the Ograzhden block). These ideas have been recently developed (Герджиков, 2004) with the distinction between 5 types of amphibolite-facies metamorphics (metamorphic units): Sakar, Srednogorie, Osogovo-Lisets, Serbo-Macedonian and Rhodopian (the latter uniting the Prerhodopian and Rhodopian Supergroups of D. Kozhoukharov). Suggestions for a new lithostratigraphic approach to the metamorphic complexes have been recently made by Krischev (Хрисчев, 2005).

In the Rhodope massif itself, another approach (Саров и др., 2004) is now adopted in the geological mapping on the scale 1:50 000. It is based upon the assumption about a single-cycle model with two (compressional and extensional) stages that developed in Alpine times and have been related to the Alpine collision and following extension and exhumation (Burg et al., 1996; Ricou et al., 1998). Unfortunately, the authors cited have not followed the basic geologic principles, and have consequently fabricated a number of “extensional shear zones” and “regional detachments” for to distinguish between “lithotectonic units”.

A new approach should be based on clearly formulated principles. Many of the existing controversies come from different meaning implied in the terminology used by different authors. Hence, the necessity to find the basic features for to obtain sound geological definitions.

The basic features discussed may be as follows: 1. Protoliths (how many within the complex?; data for interrelations, ages, primary character, etc.); 2. First metamorphism (type and time); first exhumation; 3. New burial (cover formations); superimposed metamorphic events leading to tectonometamorphic amalgamation or to other types of superimpose metamorphism (new migmatization, metasomatism, etc.); 4. New exhumation (geological data, exhumation age by isotopic data, etc.).

The elucidation of all these features for the metamorphic rocks and complexes is a difficult task, and some of the features cannot be firmly recognized due to incompleteness of the geological record. For some of the complexes the available information is scarce and very old (40–45 years). A very schematic attempt to summarize the evidence is done hereafter.

Basic features of some of the metamorphic complexes (Fig. 1)

Metamorphic complexes of the Sredna gora crystalline block (Sashtinska Sredna gora and Sarnena Sredna gora mountains) (based on Загорчев и др., 1973; Dabovski in Zoubek et al., eds., 1988)

Two complexes are distinguished: Koprivshtitsa amphibolitic complex and Pirdop gneiss-migmatitic complex.

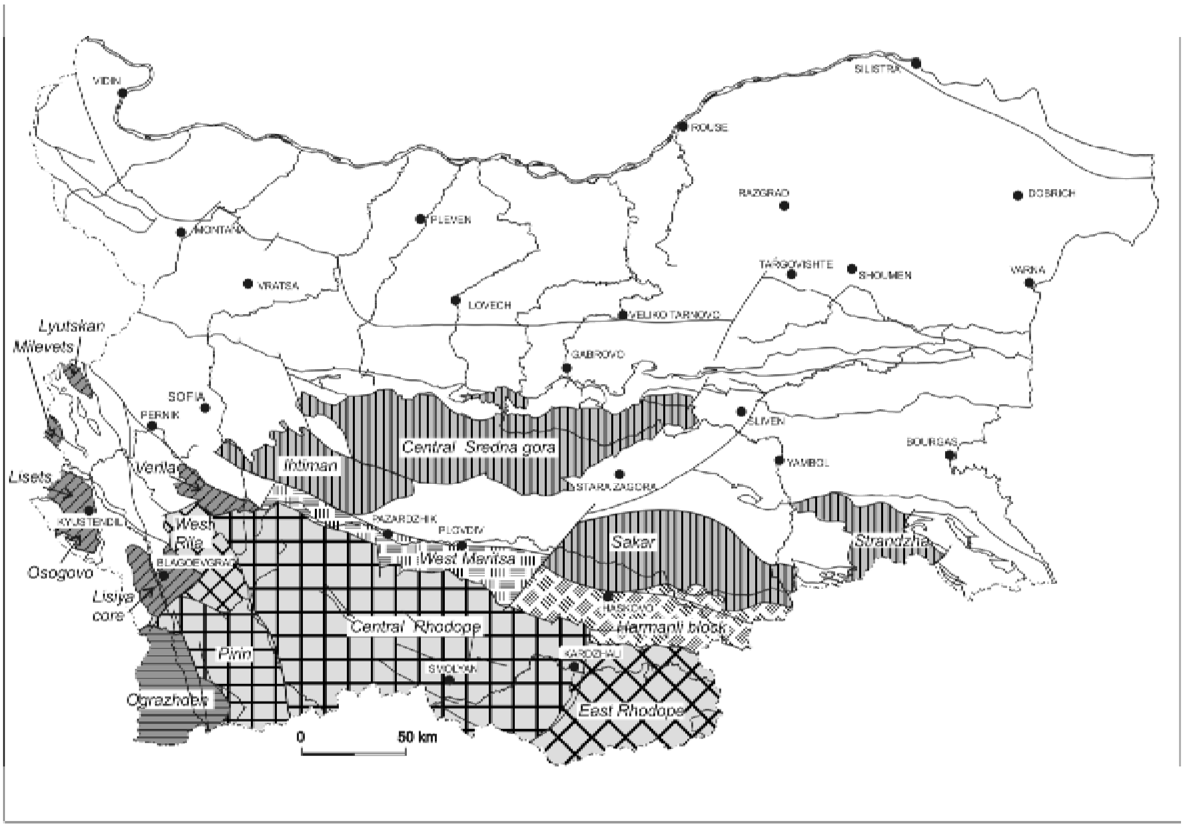

Fig. 1. Schematic map of the Alpine tectonic zones (after Dabovski et al., 2002) and the position of the amphibolite-facies Precambrian complexes

The Koprivshtitsa amphibolitic complex consists of amphibolites and biotite gneisses, and interbedding of biotite and two-mica schists, quartzo-feldspathic gneisses, sillimanite-biotite and garnet-sillimanite-biotite schists, quartzites (muscovite- and magnetite-bearing), quartzitic schists. Quartzites form in some places particularly thick layers and packets. Amongst the comparatively rare rock layers and bodies, marbles (a single layer observed), plagioclase-garnet-pyroxene calciphyres (containing also hornblende, zoisite and titanite) and amphibolites and garnet amphibolites (sometimes with pyroxene or quartz) are present. The protolith is most probably a Precambrian sedimentary terrigenous formation with rare limestone beds and basic volcanics. The Cadomian metamorphism is of Barrovian type. Precambrian (dated at c. 617 Ma, Carrigan et al., 2006) leucocratic granites (Bobevitsa granite) are foliated in the peripheral parts. Superimposed metamorphic (including contact metamorphism with andalusite and cordierite) and deformation events are related to the Cadomian and Hercynian granites and deformations. The contacts with the Pirdop gneiss complex are sharp (the primary character is not determined) but younger? migmatization events pass through these boundaries.

The Pirdop gneiss complex is built of biotite gneisses and gneiss-schists. Locally they are muscovite-bearing (passing to two-mica gneisses), garnet- and sillimanite- bearing (to garnet-sillimanite-biotite and sillimanite-biotite gneisses). Amphibolites and hornblende-biotite gneisses are rarely observed. Lenticular bodies of amphibolite and garnet amphibolite (eclogite-amphibolite?) are rare in the lower parts. The protoliths are not proven — possibly, a Precambrian terrigenous sequence with scarce volcanics. A metaserpentinite complex is represented by rootless bodies of serpentinized peridotites (harzburgites) and pyroxenites. Presence of eclogites has been indicated, too. Thus, it may be inferred that two different protoliths (of continental and of oceanic-crust origin, respectively) have been amalgamated. The age of the first metamorphism (Barrovian type) is pre-Carboniferous (pre-dating the first c. 340 Ma old granitoid complex; some c. 450 Ma old zircons have been reported from the gneisses), most probably Cadomian or pre-Cadomian. The contacts with the Cadomian(?) greenschist-facies diabase-phyllitoid complex are tectonic or tectonized. Multiple superimposed tectonic and metamorphic (including migmatization) events in Cadomian and Hercynian times; Late Cretaceous intrusions, Alpine deformations, locally intense.

Metamorphic complexes in the Ihtiman and Verila blocks (based on Кожухаров и др., 1980; Dabovski in Zoubek et al., eds., 1988)

Two complexes ("groups") are distinguished (Garvanitsa and Plana complexes).

The Garvanitsa complex consists of biotite gneisses, interbedded with amphibolites, muscovite- and two-mica schists, gneiss-schists and gneisses, kyanite schists and gneisses, biotite schists. The protolith is probably a predominantly sedimentary formation of terrigenous composition. Rootless bodies (some of them of considerable size) of serpentinized peridotites are abundant. Metamorphism of Barrovian type: pre-Hercynian, most probably Cadomian. Probable Cadomian amalgamation of continental and oceanic crust products. Superimposed Cadomian?, Hercynian and Alpine tectonic events; contact metamorphism due to Hercynian intrusions.

The Plana complex consists of two-mica gneisses interbedded with biotite gneisses, muscovite (often garnet-bearing) gneisses, hornblende-biotite gneisses and amphibolites. Very rarely, kyanite-staurolite schists and lenticles of metamorphosed serpentinites are encountered. Amphibolitized eclogite lenses have been found in layers of quartz amphibolites (Димитрова, Белмустакова, 1982). The pre-Hercynian (Cadomian?) metamorphism is of Barrovian type (amphibolite facies). Possible Cadomian amalgamation of continental and oceanic crust products. Superimposed Cadomian?, Hercynian and Alpine tectonic events. Alpine deformations are most intense at the boundaries (strike-slip faults) of the Ihtiman block where locally superimposed Late Cretaceous schistosity may develop in greenschist- to amphibolite-facies conditions (recorded in Late Cretaceous intrusive bodies along shear zones).

Special attention should be dedicated to the interrelations between the Plana complex and the younger formations: the Neoproterozoic-Cambrian? greenschist-facies diabas-phyllitoid complex, the Ordovician and the Upper Carboniferous. The latter (locally missing — direct cover by Permian and/or Lower Triassic) is clearly sealing all previous complexes. The Ordovician sediments cover the diabase-phyllitoid complex with a depositional unconformity. The principal problem concerns the boundary between the diabase-phyllitoid complex and the Plana metamorphic complex, and it will be specially discussed later.

Very similar composition (a complex similar to the Plana complex) and relations (without presence of Ordovician) exist in the Verila block

Metamorphic complexes in the Strouma unit (after Zagorchev in Zoubek et al., eds., 1988; Zagorchev, 2001; Graf, 2001; Kounov, 2002, and other sources)

These complexes (Fig. 1) are exposed in several cores of Alpine structures, usually of Mid-Cretaceous age. The formations sealing with depositional unconformable contact the pre-Alpine structure are of Permian, Lower Triassic or Middle Jurassic age depending on the depth of the post-Hercynian denudation.

Two amphibolite-facies metamorphic cores crop out in the northern part of the Strouma unit but they are of small (horizontally and vertically) dimensions and are poorly studied. Two large cores are exposed in the southern parts of the Strouma unit, and namely, in the Osogovo-Lisets and the Vlahina (Lisiya) domes.

The Osogovo-Lisets dome is cored by biotite and two-mica gneisses interbedded with amphibolites and hornblende-biotite gneisses (Osogovo "Formation", Lisets gneisses). Some parts of the section are almost devoid of amphibolites, the latter being concentrated in one (middle) member. Orthoamphibolites are also exposed, amongst them a large body consisting of metagabbroids. Metagranites are often found, one body being dated at c. 520 Ma by U-Pb studies on zircon. Extensive bodies of granitoids ("Lisets diorites", Bosilegrad granite) have pre-Ordovician age (covered with depositional contact by Ordovician metasandstones). The first metamorphism is probably of Cadomian or pre-Cadomian age – Sm-Nd studies suggest an age of the protolith of about 1400–1100 Ma; the metagabbrodiorite is dated at c. 548 Ma, and the orthogneiss, at c. 544 Ma (Graf, 2001). These data are consistent with a Cadomian amalgamation of pre-Cadomian continental crust with mantle-derived gabbroids, and a first late Cambrian exhumation followed by Early Ordovician transgression. A Hercynian greenschist-facies metamorphic event of c. 343 Ma is roughly coincident with the upper intercept (c. 346 Ma, U-Pb zircon studies) of the Osogovo granite. The Palaeozoic history is not yet enlightened (dry land or covered by Palaeozoic sequence later totally eroded during late Hercynian exhumation), and the basement has been afterwards covered with sediments during the Triassic transgression. The Mid-Cretaceous (Austrian) compressional deformations led to the thrusting of the Morava over the Struma unit, and are partially documented in c. 119 Ma old white micas in Permian and Triassic very low-grade metamorphics. The last exhumation is referred to the Palaeogene uplift: c. 46–30 Ma (Graf, 2001).

The Lisiya dome (core of the Vlahina block) consists of two complexes: the Troskovo amphibolitic complex (Troskovo Supergroup) and a gneiss-migmatitic complex considered to be a correlate of the gneiss-migmatitic complex ("Maleshevska Group") of the Ograzhdenian complex (Supergroup). The polymetamorphic and polydeformational character of the two complexes has been documented by Zagorchev (1976, 2001; Zagorchev in Zoubek et al., eds., 1988). The Troskovo complex is built up mostly of amphibolites, the majority being of ortho-origin (basic metavolcanics), and contains also some rootless lenses of metagabbroids, metapyroxenites and metaserpentinites. The volcano-sedimentary character of the protolith is shown by rare thin marble lenses (ignored by Machev, Kenkmann, 2001). The gneiss-migmatitic complex is also of a volcano-sedimentary origin (layered or lenticular amphibolites) but is dominated by acid metasedimentary rocks (now two-mica and biotite schists and gneisses) with a few isolated lenses of metaserpentinites, and possible participation of metagranites (gneiss-granites). Cadomian tectonometamorphic amalgamation is considered as most probable process for the formation of the mixture of petrologies typical for continental crust and for oceanic crust (and/or upper mantle) protoliths.

One of the most important and still pending problems concerns the boundaries between the gneiss-migmatitic complex and the Neoproterozoic–Cambrian diabase-phyllitoid Frolosh Formation. Haydoutov (1989, 2002 and elsewhere) insists on a subduction of the Balkan (Frolosh Formation) under the Thracian (gneiss-migmatitic complex) terrane and a tectonic contact between the two whereas Zagorchev (1974, 1998a,b, 2001 and elsewhere) describes the opposite primary relations (Frolosh Formation over the gneiss-migmatitic complex) and inclusion of gneissic inliers as slices into the Frolosh Formation during common synmetamorphic (grenschist-facies) folding of the two complexes, most probably in Cadomian times. The Frolosh Formation itself is a volcano-sedimentary complex dated at c. 557 Ma (Razhdavitsa gabbro) that contains besides the abundant basic metavolcanics, also metatuffs, metaconglomerates, metasandstones, calcareous schists and impure marbles. A few metalherzolite lenticular bodies are present, and they are considered to be fragments from oceanic crust (Хайдутов, 1991, 1994). The Strouma diorite formation has been formed partially at the expense of the metavolcanics of the Frolosh Formation, and is regarded as a volcanic arc product. According to the present author (Zagorchev, 1998a), the Neoproterozoic-Cambrian Frolosh Formation is formed by considerable mantle contribution in conditions of a volcanic arc formed by rifting of pre-Cadomian continental lithosphere, crustal fragments and Neoproterozoic-Cambrian volcanics, intrusives (with ultrabasic cumulates) and sediments being jointly deformed and amalgamated in late Cadomian times. Palaeozoic exhumation has been followed by deep denudation, coverage by Permian and Triassic sediments, and a new exhumation in Palaeogene times.

Metamorphic complexes in the Morava and Ograzhden units (after Zagorchev, 1976, 2001; Zagorchev in Zoubek et al., eds., 1988; Zidarov, Nenova, 1995; and other sources)

The metamorphic complexes of these units are considered as parts of the Serbo-Macedonian massif.

The metamorphic complex (Dragoychintsi complex, Dragoychintsi "Formation") in the Morava unit is similar to that of the Osogovo-Lisets core of the Strouma unit. Pre-Cadomian gneisses and amphibolites have been intruded by the Cadomian (c. 557 Ma — Graf, 2001) Milevets granite (orthogneiss), and later subject to late Cadomian deformations and metamorphism (greenschist to lower amphibolite facies). The interrelations with the Cheshlyantsi complex ("Formation") built of metasedimentary rocks (marbles, schists, some lydites and metasandstones; a few basic metavolcanics?; unknown age, probably Cambrian or Ordovician) are not yet clear. After the Mid-Cretaceous thrusting of the Morava over Strouma unit (probable Palaeozoic and Mesozoic erosion and denudation; oldest cooling age of c. 112 Ma), K-Ar and Ar-Ar data point at a Palaeogene exhumation (Graf, 2001; Kounov, 2002).

The metamorphic complexes of Maleshevska and Ograzhden Mountains (Ograzhden unit; for the time being, we will refrain from considering the Belasitsa block) have been described as one complex (Ograzhdenian complex, or supercomplex; Ograzhdenian "Supergroup") consisting of 3 groups. The latter should be probably described as separate complexes. Later studies by N. Zidarov and collaborators (now in course) will throw additional light over a number of pending problems. Here only the upper "Maleshevska Group" (gneiss-migmatitic complex) will be discussed. The gneiss-migmatitic complex consists of two-mica and biotite gneisses interlayered with mica schists, hornblende-biotite gneisses and amphibolites. Some layers of gneisses and schists contain graphite, garnet, kyanite, sillimanite or tourmaline, often in considerable amounts. The protoliths of these rocks are mostly terrigenous sedimentary rocks of pelitic, psammitic and psephytic character. Amphibolite layers are concentrated in packets (members), and are most probably of basic metavolcanic origin. Larger metabasic bodies (metapyroxenites, metagabbroids) occur independently or in relation to the metavolcanic layers, and often are eclogitized (Zidarov, Nenova, 1995). Several layer-parallel medium-sized bodies of serpentinized harzburgites are known, too. The sequence contains also bodies of diatexitic quartz-diorites and of metagranitoids formed mostly in Cadomian times (according to Rb-Sr whole-rock data, about 540 Ma BP), and numerous concordant layers of quartzo-feldspathic gneisses and pegmatoid gneisses that in many cases are proven as former aplites and pegmatites affected by late Cadomian deformations and metamorphism. Thus, the whole Ograzhdenian gneiss-migmatitic complex is considered to be a product of Cadomian tectonometamorphic amalgamation of pre-Cadomian continental crust with oceanic crust fragments. The pre-Cadomian and Cadomian tectonometamorphic history is complicated by the presence of pre-Cadomian or early Cadomian basic intrusions (well-preserved norite to troctolite with amphibolitization along shear zones — s. Zagorchev, 1976, 1996), followed by the second (Cadomian) migmatization event. Cadomian and post-Cadomian shear zones and foliation-parallel extensive shear transpose the initial pre-Cadomian and early Cadomian structures. The complex is intruded by late Hercynian (300–250 Ma) granites. The whole Ograzhden unit has been thrusted (greenschist-facies mylonites) over the Pirin (Pirin-Pangaion) unit of the Rhodope massif along the Strymon thrust and its ramifications, and further on, intruded by Late Cretaceous (c. 88 Ma) granitoids and Palaeogene (c. 34 Ma) subvolcanic bodies. The last exhumation is considered to be pre-Palaeogene or early Palaeogene.

Metamorphic complexes of the Rhodope massif (western part) (after published data of D. Kozhoukharov, E. Kozhoukharova and other authors)

The western part of the Rhodope massif consists (Fig. 1) of several Alpine tectonic units (Burg et al., 1996) bounded by thrusts with mylonites formed in very low-grade to greenschist-facies conditions. As eastern boundary of this large composite unit the Kurdzhali fault is considered. This is a large composite fault with extensive mylonitization in greenschist-facies conditions.

Two metamorphic complexes (supergroups) have been distinguished (s. Kozhoukharov in Zoubek et al., eds., 1988): Prerhodopian (ultrametamorphic) and Rhodopian. The composition of the complexes is well-known (s. also Иванов и др., 1984; Кожухаров, 1984). Having in mind some considerations presented by Kozhoukharov (in Haydoutov et al., 1997) as well as the practice in the adjacent areas of the Greek Rhodope, the groups of the Prerhodopian Supergroup described by Kozhoukharov could be regarded as independent complexes, too. Thus, four complexes are distinguished, and namely, the ultrametamorphic (Prerhodopian, Arda) complex, Roupchos varied complex (corresponding to the Kimi complex in Greece — s. Mposkos, 2002), Bachkovo gneiss complex (Greek equivalent: the Sidironero albite-gneiss complex) and Asenovgrad calcareous complex (Greek equivalent: Falakron/Pangaion Marbles). Extensive descriptions have been made by the authors cited, as well as in many other publications. Here only some interpretative considerations will be given.

The Arda complex is exposed in the cores of three domal structures lately interpreted as Tertiary extensional domes: the Vucha, Shiroka-luka and Madan-Davidkovo domes. It consists of biotite and two-mica gneisses and schists interlayered with amphibolites and hornblende-biotite gneisses. The protoliths belonged to a volcano-sedimentary association. Eclogites and metabasic and metaultrabasic rocks are present in the Madan-Davidkovo dome, and a polymetamorphic and polydeformational evolution is proven (published and unpublished data of D. Kozhoukharov; s. Zoubek et al., eds., 1988). Most probably, two or more Precambrian tectonometamorphic cycles or composite events finished with a Cadomian amalgamation of crustal material with mantle or oceanic-crust products. No isotopic evidence has been obtained up to now in support of this hypothesis. Scarce data indicate a possible Hercynian overprint, and a very strong Alpine overprint is dated with U-Pb and K-Ar studies on aplite and granite veins along late shear zones. The youngest ages of c. 32 Ma are interpreted as exhumation ages of metamorphic core complexes (in the domes mentioned above) along detachments (e.g., Burg et al., 1996). The alternative interpretation considers these domes as thermal domes that remained at relatively high-temperature conditions because being deeply buried within the thickened crust (during multiple thickening events, last time during the Austrian compressional phase), and due to heating by increased heat flow during the extensive latest Eocene — Early Oligocene volcanic activity (e.g. Zagortchev, 1994).

The other three complexes (groups) are grouped (Kozhoukharov in Kozhoukharov et al., 1978; Кожухаров, 1984) into the Rhodopian Supergroup (supercomplex). They represent a sequence of thick (over 2 km each) pile of originally volcano-sedimentary and sedimentary formations, this sequence being comparatively stable over the Western Rhodope massif. This correlation is doubtful in respect of the East Rila unit, and for some scientists, also for the Pirin-Pangaion unit. Although locally of high intensity, synmetamorphic deformations have not transposed the sequence but in the marginal Pirin-Pangaion unit the whole section is found in overturned position and subject of several intense folding events (Zagorchev, 1994). It is also highly tectonized near the Bulgarian/Greek border in the Madan-Davidkovo dome where a deep Rhodope thrust is proposed to explain the position of the marbles under the ultrametamorphic complex (Ivanov, 1981).

In the geometric section of the Central Rhodope, the three complexes outlined follow from bottom to top in believed-to-be normal superposition. The protolith of the Roupchos complex represented a volcano-sedimentary association that contains also typical ophiolites. In the midst of the complex (group), the Bogoutevo Formation has a predominantly "granitic" composition but with some amphibolite and rare marble layers, and rootless bodies of amphibolitized eclogites dated (Arkadakskiy et al., 2003) as Neoproterozoic (between 700 and 600 Ma). Having in mind the probable Mesoproterozoic age of the sedimentary protolith (determinations by B. Timofeyev and M. Konzalova, s. Kozhoukharov, 1986, Zoubek et al., eds., 1988, and later publications), we should again suggest a Cadomian collision with amalgamation of continental (gneisses, etc.) and oceanic (eclogites, serpentinites) crustal products. It is also very important U-Pb studies on zircons (believed-to-be detrital) of the Kimi complex yielded a high proportion (more than 25%) of Archean and Proterozoic ages situated between 3200 and about 560 Ma (Liati, Gebauer, 2001). Another possible explanation would be that the oldest part of these zircons (3.2–1.6 Ga) are really detrital and coming from closely-situated protolith source of Archean to Palaeoproterozoic age whereas the Neoproterozoic zircons correspond to a Cadomian tectonometamorphic amalgamation.

Considerable controversies exist in respect of the protolith of the Bachkovo (= Sidironero) complex (in our understanding, grouping the Dobraluk/Boykovo and the Bachkovo Formations, both consisting of biotite banded gneisses to massive leucocratic (quartzo-feldspathic) gneisses often garnet-bearing. Marble and/or amphibolite interbeds are rarely observed. The Dobroluk/Boykovo Formation is subject of intense shear at low angle to the foliation (primary bedding?) giving the aspect of pencil gneisses or wooden gneisses. The Bachkovo Formation (leptynites or aplitoid gneisses) bears traces of considerable granitization (K and Si metasomatosis, studied in detail by V. Vergilov) and partial melting. Small skialiths or restites of micaceous rocks ("Glimmerites") are observed. The protoliths of the two formations are subject of discussions: from metasedimentary rocks (arkosic sandstones; E. Kozhoukharova in Zoubek et al., eds., 1988) and rhyolitic metavolcanics and metatuffs (V. Vergilov) to metagranites (Z. Cherneva and others). The metasedimentary origin hypothesis is supported by the constancy of the position in the section over a considerable region (although with thickness variations) impossible in case of metagranitoid origin. If the complex would be proven to be of metasedimentary (metaconglomerates and mature metasanstones) origin, its base may be an important boundary (sedimentation break and wash-out) within the whole Rhodopian sequence.

The parametamorphic character of most of the Asenovgrad Group (complex) is without doubt, being mostly built of calcareous rocks (marbles and calcareous schists). In the original scheme of Kozhoukharov, the varied Loukovitsa Formation is referred to the underlying "Sitovo Group" (here Bachkovo complex). However, the transitional character towards the Dobrostan Marble Formation of the upper parts of the Loukovitsa Formation, and the fast decrease of volcanogenic component in the lower parts (to total disappearance in Northern Pirin) are arguments for to refer it to the Asenovgrad complex. Thus, the Asenovgrad complex (Falakron/Pangaion complex in Greece) is a thick predominantly carbonatic complex of Neoproterozoic age (determinations by B. Timofeyev and M. Konzalova, s. Kozhoukharov, 1986, and elsewhere) similar to many other thick Neoproterozoic complexes around the world. The age has been confirmed on Problematica determined by P. Tchoumatchenco and I. Sapunov, and the isolated find of W. Meyer of a "fossil similar to tetracoral" could be in fact a single stromatolite.

The timing of the amphibolite-facies metamorphism (Barrovian type) of the three complexes is subject of controversies. There is no firm evidence about it, and speculative hypotheses vary: from polymetamorphic events of Cadomian age and Hercynian and Alpine overprint, to a single Alpine process of several events of Mid-Cretaceous to Oligocene age. The present author is in favour of the first option (first Cadomian metamorphism with some Cadomian amalgamation, and Hercynian overprint), with a strong compressional Mid-Cretaceous episode (coeval to Austrian thickening, about 90–100 Ma BP), and prolonged extension and erosional exhumation in Palaeogene times.

Metamorphic complexes of the Rhodope massif (eastern part) (after published data of D. Kozhoukharov, E. Kozhoukharova and other authors; s. also Bonev et al., 2006)

Kozhoukharov (in Zoubek et al., eds., 1988; Кожухаров, 1987; Kozhoukharov, 1992) referred the metamorphic rocks of the Eastern Rhodopes (Kesebir-Kardamos and Byala-reka–Kechros domes) to the Prerhodopian Supergroup and the Roupchos Group of the Rhodopian Supergroup. The presence of the Roupchos Group (complex) seems without doubt, and is confirmed by the continuation (Kimi complex) in Northern Greece, although a much greater occurrence of huge ultramafic (serpentinites) bodies is recorded here when compared to the Central Rhodope. Substantial differences appear in respect of the "Prerhodopian Supergroup", and here we propose to treat its three "groups" as independent complexes. The three complexes are clearly superposed one upon the other in the Byala-reka dome, a detailed lithostratigraphy being established there by Kozhoukharov (Кожухаров, 1987).

The lower complex (Strazhets Group) is characterized by widespread leucocratic muscovite, two-mica and biotite gneisses. Quartzo-feldspathic gneisses and Augengneisses are dominant although interbeds of schists and amphibolites are present, too. Some of the amphibolite layers are interpreted as strongly sheared metabasic dykes with contacts transposed parallel to the foliation. The protolith (yet of unknown age; upper intercept for U-Pb data on bipiramidal zircons from one "metagranite" sample from the complex is c. 2250 or 1700–1800 Ma – Peytcheva, Von Quadt, 1995) is deduced to be a terrigenous sequence with predominance of graywackes and arkosic sandstones. A part of the granite-gneisses may be of ortho-origin (metagranites) of different ages. Barrovian type amphibolite-facies metamorphism is referred to the Precambrian. Granitization phenomena are widespread but migmatization is not typical. Hercynian metagranites identified both in the Byala-reka and the Kesebir domes were dated at c. 310–330 Ma (Peytcheva, Von Quadt, 1995; Von Quadt, Peytcheva, 1995; Peytcheva et al., 1998), and these data and the presence of superimposed schistosity gave grounds to Von Quadt, Peytcheva (1998) to consider the Rhodope region as a Hercynian orogenic edifice.

The Botourche Group (complex) has features of an ophiolite association: huge serpentinite lenticular bodies flowing into a mass of micaschists with typical white mica of phengitic type. Two formations have been distinguished by Kozhoukharov (Кожухаров, 1987), the basal Zhultichal Formation being clearly of parametamorphic or metavolcano-sedimentary character: wide presence of kyanite-staurolite-garnet muscovite schists, graphite- and magnetite quartzites, amphibolites and quartzo-feldspathic gneisses. However, in some of the sections serpentinites and orthoamphibolites typical for the next Gnezdare Formation are reported to occupy also most of the Zhultichal Formation. Serpentinites and amphibolites have undergone a complex geologic history as reported by Kozhoukharova (Кожухарова, 1985). After serpentinization, increasing pressure and temperature progressively have apparently led to amphibolite-facies and eclogite-facies metamorphism, and metasomatic formation of gabbroids along former foliation (path 4 at Fig. 2*A*).

Although primarily designated as a Tintyava "Group", the next Tintyava complex has been referred by D. Kozhoukharov to the Arda Group of the Prerhodopian Supergroup. However, Kozhoukharov (in Тенчов, ред., 1993, pp. 36, 90–91, 317) introduced 3 formations special for the East Rhodopes (Gorsko, Tintyava and Belopoltsi Formation, from bottom to top) evidently appreciating the differences between the Arda complex (in our designation here) of the Central Rhodope and the Tintyava complex. The latter is built mostly of two-mica gneisses and granite-gneisses, with participation of garnet-bearing gneisses, schists and amphibolites. The protolith has according to Kozhoukharov a predominantly metasedimentary character whereas other authors favourize the hypothesis about predominant metagranitoids.

The late tectonometamorphic history of the Eastern Rhodopes may be illustrated with the sequence of events proposed for the Kesebir-Kardamos dome by Bonev et al. (2006): crustal shortening and thickening (mostly Late Cretaceous, 119–65 Ma), crustal extension (65–53 Ma), exhumation and doming (42–39 Ma). The limited space and the complexity of the problems do not allow a discussion on some dubious aspects of this interpretation. Due to the same reasons and to lack of sufficient personal experience, other metamorphic complexes (in Sakar and Strandzha Mountains, in particular) are omitted in this review.

Some aspects of the metamorphism in the amphibolite-facies complexes

A number of authors have discussed during the last twenty years different aspects of the metamorphism of the Bulgarian and Balkan high-grade metamorphic complexes. Great differences exist in respect of the age and P-T conditions of the metamorphism. A summary compilation (Zagortchev, 1994, Text-Fig. 6) of the scarce data existing in that time schematized for the Precambrian basement of parts of the Rhodopes a progressive Barrovian metamorphic path reaching the boundary area of amphibolite and eclogite facies, migmatization and granite formation in Palaeozoic times due to decompression, a new burial triggered by Mid-Cretaceous (Austrian) deep thrusting, new decompression with crustal melting and formation of Late Cretaceous granites, and Alpine retrograde metamorphism related to shear zones and faulting. Abundant new data obviously have to change this very simplified picture. When speculating on possible metamorphic paths we should cer-

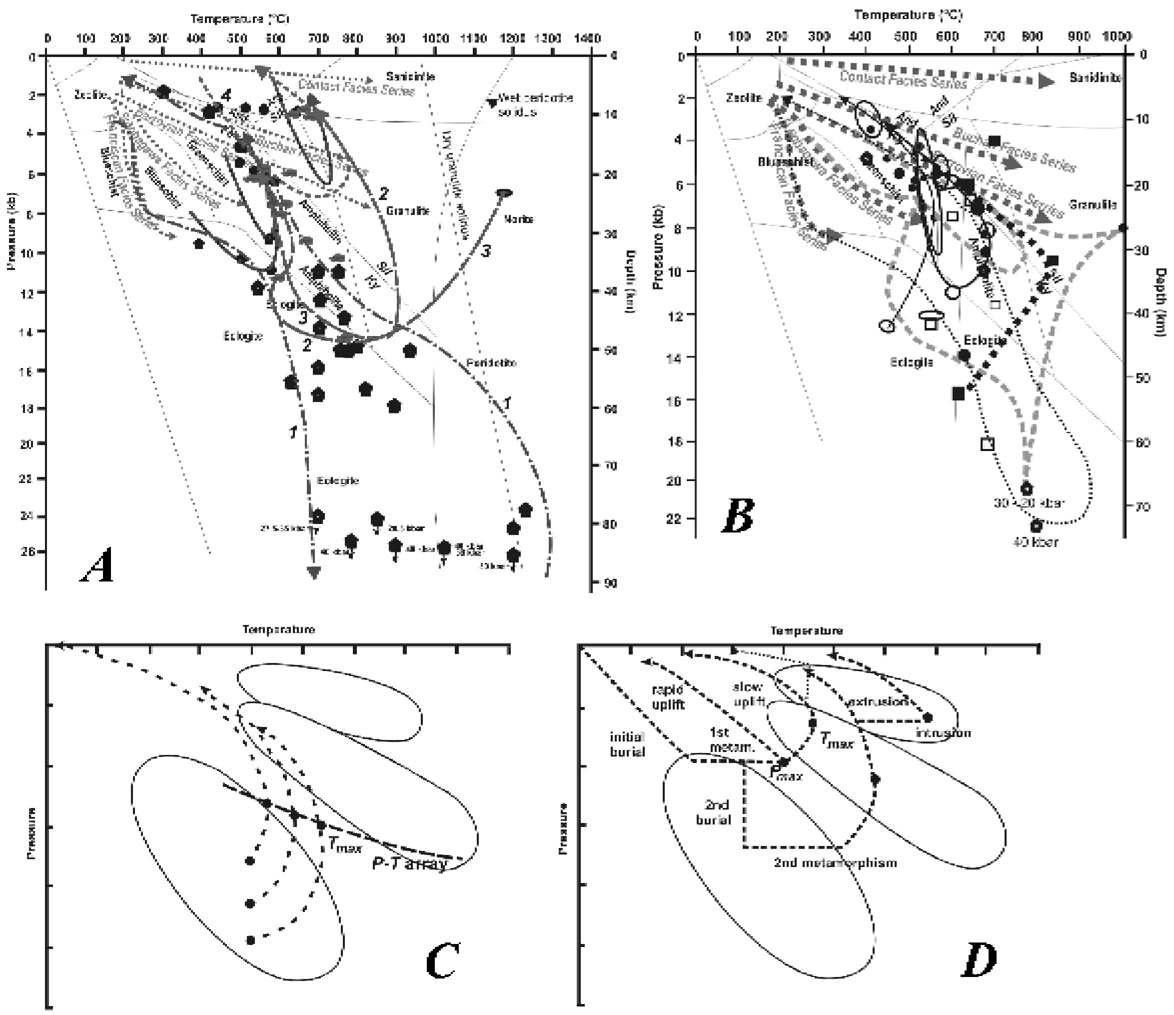

Fig. 2. Schematic diagrams for the P-T paths of the Precambrian complexes in Bulgaria and Greece (Rhodope massif — *A*, Sredna gora and Ograzhden units — *B*) and cartoons (after Thompson, Ridley, 1987) demonstrating possible P-T paths after a single thickening event (*C*; example of coeval rocks buried to different depths) and in polymetamorphic conditions (*D*). After published data of Z. Cherneva, K. Kolcheva, E. Kozhoukharova, A. Liati, F. Machev, L. Macheva, E. Mposkos, S. Pristavova; diagram setting after Winter (2001) and other sources. Supposed metamorphic paths with dashed lines. Metamorphism of basic and ultrabasic rocks (*A*): 1 — subduction of oceanic crust (Franciscan facies series to eclogites) to depths exceeding 80–100 km (HP to UHP), or tectonometamorphic amalgamation of mantle and crustal material; 2 — crustal subsidence (Barrovian to Sambagawa facies series) to the upper mantle, formation of eclogites near the amphibolite-eclogite facies boundary; 3 — eclogitization of norites and/or ultramafics (subsidence from lower crustal to upper mantle conditions); 4 — formation of metasomatic gabbroids (Kozhoukharova, 1999) at lower depths (upper crust). Metamorphic paths in Sredna gora and Ograzhden units: Barrovian facies series, amphibolite-facies conditions (dominant); possible eclogitization of basic and ultramafic rocks through subsidence, or tectonometamorphic amalgamation of mantle and crustal material.

tainly take into account several feeble points in our data: i) the imperfectness of the thermobarometers, especially in respect to the pressure determination — for some thermobarometers pressures determined for a very narrow temperature range may vary between 3 and 9 kilobars; ii) the incompleteness of the geological record — intense younger events may greatly obliterate the traces of earlier events; iii) the comparatively small number of reliable radiogeochronological data obtained by different methods. Different metamorphic P-T paths are predicted (Thompson, Ridley, 1987, Figs. 2, 3) for rocks buried to different depths (Fig. 2*C*) during crustal thickening, and for superimposed metamorphic events during a polymetamorphic history (Fig. 2*D*).

Even with the new data, the general trend of the metamorphism remains the path (Fig. *2A, B*) of rapid burial (Barrovian Facies Series near the transitional boundary to Sambagawa Facies Series: greenschist facies to amphibolite facies and entering the field of eclogitic facies, path *2* on Fig. 2*A*); exhumation with decreasing pressure still retaining higher temperature, decompression leading to formation of sillimanite (transition to the Buchan Facies Series) and/or partial melting and granitoid formation. Another complication is introduced when basic magma has been intruded between two tectonometamorphic cycles (e.g., Zagorchev, 1976): then, burial of a norite body (path *3* on Fig. 2*A*) would lead to its partial eclogitization and amphibolitization without necessarily reaching ultra-high pressure conditions. A mechanism (path *4*, Fig. 2*A*) of formation of gabbroic rocks by metasomatism of serpentinites at low pressures has been proposed by Kozhoukharova (1999). Most important new developments concern the discovery of ultrahigh-pressure (UHP) minerals (diamond, coesite) in some of the HP rocks of the Greek Rhodopes (s. Mposkos, 2002; review in Герджиков, 2002а,б). The corresponding pressures reach 30–70 kbars that correspond to depths of more than 100 km. The explanation given refers to a fast subduction (path *1* on Fig 2*A*) of oceanic crust (Fransiscan Facies Series) to deep eclogitic facies conditions, and when rising towards the surface (possibly together with mantle peridotites), amalgamation with the material in the basal parts of the thickened continental crust. These events are up to now referred (Liati et al., 2004) to Cretaceous times possibly coinciding with the Mid-Cretaceous crustal thickening in the Rhodope region (e.g., Zagortchev, 1994; Bonev et al., 2006), and the subduction of the Vardar ocean under the Rhodope.

Geodynamic aspects and conclusions

The finding of relics from HP- to UHP-metamorphism in the Rhodope and Serbo-Macedonian massifs opens new prospects for the geology of the amphibolite-facies complexes of the Balkan Peninsula. Special emphasize should be put on the further studies of the basic and ultrabasic rocks that originate from different sources (subducted oceanic crust, mantle slices, intrusions of mantle origin, metasomatic layers into older ultramafics), have different ages, and have undergone different metamorphic histories.

Previous correlations between the metamorphic complexes exposed in different Hercynian and Alpine tectonic units should be reconsidered in the light of new evidence. Extensive and more precise new petrologic and radiogeochronological data are needed.

The available evidence, both geological and isotopic, points at a pre-Cadomian age of the metamorphic complexes in the Serbo-Macedonian massif, the Strouma unit, and the Ihtiman and Central Sredna-gora units of the Srednogorie. Geological evidence (akritarchs, Problematica) point at Neoproterozoic (possibly also Mesoproterozoic) age for different parts of the Asenovgrad and the Roupchos complex, respectively. Cadomian deformations and metamorphism seem to be the major factor in the principal shaping of all Precambrian metamorphic complexes on the Balkans.

Although severely criticized, the lithostratigraphic subdivision of most of the complexes (especially those of predominant parametamorphic or mixed character) has no alternative for the moment. Recently introduced complexes on Greek territory (Mposkos, 2002, and elsewhere) coincide with equivalents in Bulgaria established, subdivided and studied in details (e.g., Zoubek et al., eds., 1988). Following the rules of priority the names of formations and groups (complexes) should be preserved as introduced, and with indication of their equivalents on Greek territory.

The presence of a high percentage of very old (Mesoarchean to Palaeoproterozoic) zircons in the supposedly Meso- to Neoproterozoic Roupchos Group (Kimi complex) in the Rhodopes indicated a sedimentary origin of the protoliths of that complex in marine basins in or at the periphery of Hudsonland (existing between 1.83 and 1.5–1.25 Ga). The ophiolitic sequences in the varied formations of the Rhodopian supercomplex (mostly, the Roupchos Group and partially, the Loukovitsa Formation) is usually related to oceanic-crust environments; however, the high amount of metacarbonatic rocks could be more appropriate for volcanic arc environments. Such environments probably had existed also in the Strouma unit, the Serbo-Macedonian massif and the Pelagonian massif. Tholeiitic basalts of the Cumpana Group (South Carpathians) dated at c. 1.57 Ma are also related to volcanic arc environments (Draguşanu, Tanaka, 1999).

The formation of the next supercontinent (Rodinia) is usually related to continental collision at 1.1–1.0 Ga, i.e., at the Mesoproterozoic/Neoproterozoic boundary. The composition and extent of Rodinia is subject of strong discussion and criticism even in respect of huge shield areas, and we could hardly believe to make serious conclusions about the strongly reworked in Cadomian, Hercynian and Alpine times peri-Gondvanan fragments on the Balkan Peninsula and Asia Minor. Some authors suppose the presence of a Cadomian microcontinent (Cadomia) at the periphery of Rodinia in the times of disintegration of the latter. Probably East of that microcontinent and North of the future Arabian shield several fragments of continental crust have already existed (Fig. 3), and they gave the beginning of the peri-Gondvanan fragments Pelagonia, Dardania and Thracia (Zagorchev in Cavazza et al., eds., 2004). It should be also noted that Rudakov (1992) suggested a Neoproterozoic evolution of the Alpine, Carpathian and Balkan peri-Gondvanan fragments that regarded the European Prototethys as narrow seaway with oceanic crust formed in early to middle Neoproterozoic times (1000–850 Ma BP). This basin developed as “a mature ocean before the Cadomian events”, i.e. during rifting in the southern parts of the Aegir Sea about 750 Ma BP (Meert, Torsvik, 2003) that was related also to the disintegration of Rodinia. The whole history of the Panafrican (Assyntian, Baikalian, Cadomian) cycle is outlined as follows: assembling of Rodinia after the Grenvillian phase (1100–1000 Ma BP); first rifting events (800–700 Ma BP); late rifting (650–550 Ma BP); collisional events (580–540 Ma

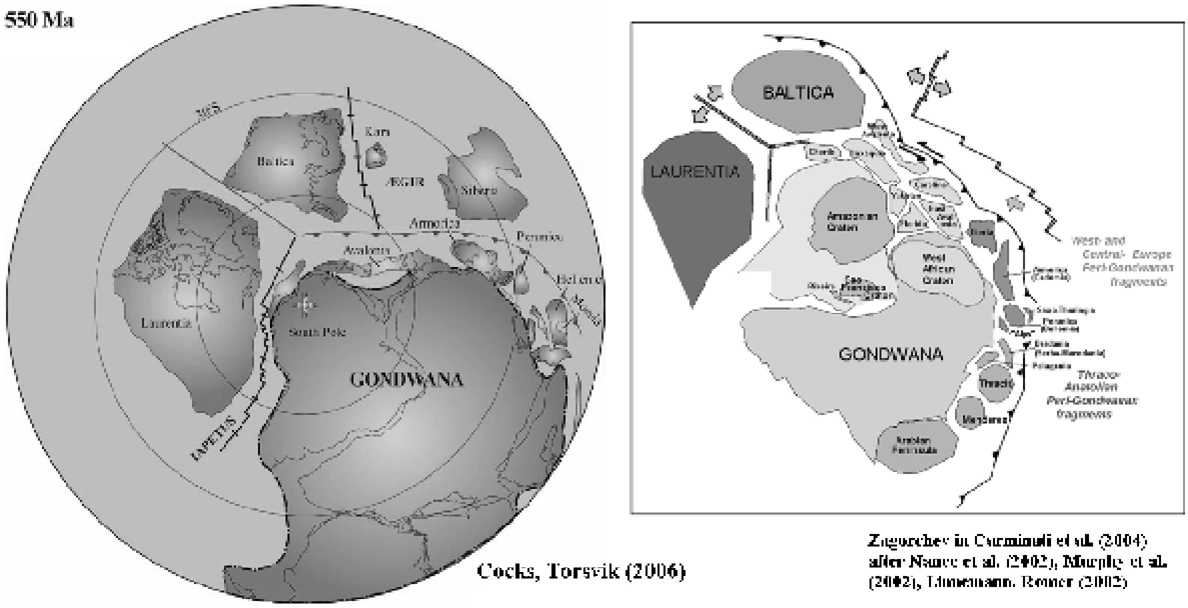

Fig. 3. Cartoon for the possible position of the principal Peri-Gondvanan fragments of SE Europe. Revised after Murphy et al. (2002), Cocks, Torsvik (2006), and other authors

BP); late collisional igneous activity (540–520 Ma BP). The disintegration of Rodinia before about 750 (800) to 600 Ma puts forward the problem about the place of the principal peri-Gondvanan fragments and the evolution of the Neoproterozoic to Palaeozoic terranes outlined (Haydoutov, 1989; Yanev, 1993; Haydoutov et al., 1997; Carrigan et al., 2006). It is clear even from the existing data that the amphibolite-facies complexes described in the eastern parts of the Balkan Peninsula fit well into the Cadomian evolution. The principal phase of Cadomian amalgamation and shaping of these complexes should be referred to the collisional events (580–540 Ma) and the late collisional igneous activity.

Another important problem for the future studies concerns the very young ages obtained for metamorphic minerals and rocks in the Rhodope region. At least partially, these dates are due to the considerable crustal thickening in the Rhodope, the effect of increased heat flow during the collisional Palaeogene volcanism, and the late exhumation and cooling. Detailed research will certainly reveal new sides of the Alpine processes in the Rhodope and the surrounding areas.

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И. Загорчев — Метаморфните комплекси амфиболитов фациес в България и прекамбрийската геодинамика:противоречия и състояние на проблема. Еволюцията на идеите за характера и възрастта на метаморфните комплекси от фундамента на Балканския полуостров се развива от първоначалното причисляване към един единствен прекамбрийски комплекс към диференциация и разпознаване на различни протолити, които са претърпели полиметаморфна и полидеформационна история. Подходът за отделяне на метаморфни комплекси би трябвало да бъде подчинен на ясно определени принципи, тъй като корелациите между разкъсани и отдалечени разкрития могат изкуствено да обединят скали с различно геоложко развитие. Основните особености, на които би трябвало да се основава отделянето на комплексите са: 1) Първичен характер, възраст и взаимоотношения на протолитите; 2) Тип и време на първия метаморфизъм и първата ексхумация; 3) Ново погребване (покриващи формации), наложени метаморфни явления, водещи до тектонометаморфно амалгамиране или други типове наложен метаморфизъм; 4) Нова ексхумация (геоложки данни, възраст по изотопни данни и пр.). Изясняването даже на част от тези особености е трудна задача поради непълнотата на геоложката летопис и остарялата информация.

Въз основа на наличната информация би следвало да различаваме следните основни типове прекамбрийски метаморфни комплекси (амфиболитов фациес).

1) Метаморфни комплекси от Средногорския кристалинен блок (Същинска и Сърнена Средна гора): Копривщенски амфиболитов и Пирдопски гнайсово-мигматитов комплекс.

2) Метаморфни комплекси от Ихтиманския и Верилския блок: Гарванишки гнайсово-амфиболитов и Плански гнайсов комплекс.

3) Метаморфни комплекси от Струмската единица: Осоговски комплекс (в Осоговско-Лисецкото подуване), Тросковски амфиболитов и Малешевски гнайсово-мигматитов (в Лисийското подуване).

4) Метаморфни комплекси в Моравската и Огражденската единица: Драгойчински комплекс (в Моравската единица), Малешевски комплекс (в Огражденската единица, където е възможно отделянето и на други комплекси в рамките на Огражденския суперкомплекс).

5) Метаморфни комплекси от западните части на Родопския масив: Арденски ултраметаморфен комплекс, Рупчоски пъстър комплекс (гръцки еквивалент — комплекс Кими), Бачковски гнайсов комплекс (отговаря на Ситовската група, но без Луковишката свита; гръцки еквивалент — комплекс Сидиронеро) и Асеновградски комплекс (включва в основата Луковишката свита; гръцки еквивалент — мрамори Фалакрон/Пангейон).

6) Метаморфни комплекси от източните части на Родопския масив: Стражецки гнайсов, Ботурченски метаофиолитов и Тинтявски гнайсов комплекс.

Въпреки че в последните години е подложена на сериозна критика, класическата литостратиграфска подялба на тези метаморфни комплекси, които се състоят предимно от параметаморфни и/или смесени скали остава засега без алтернатива. Наскоро въведените комплекси на територията на Северна Гърция съвпадат по обем с вече въведени еквиваленти на българска територия. Поради това не е правомерно пренасянето на нововъведените имена на територията на България.

Протолитите на комплексите са с доказана прекамбрийска (докадомска) възраст, но полиметаморфната история на всеки от тях показва значителни различия. Поради това е необходимо преразглеждане на предишните корелации в светлината на новите данни, както и на бъдещите петроложки и радиогеохроноложки изследвания.

Палеогеодинамичните интерпретации, които са очертани в последните години, засега се основават на твърде малко данни от нашия регион. Поради това различните предложени варианти (включително и този от настоящата статия) са само първи опити по посока на един по-глобален подход към прекамбрийската история.