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Mineral and Thermal Waters of Southeastern Europe

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Mineral and Thermal Waters of Southeastern Europe

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Preface

During the International Multidisciplinary Conference on Mineral Waters: Genesis, Exploitation, Protection, and Valorization, in Karlovy Vary from September 8–11, 2014, the Commission on Mineral and Thermal Waters (CMTW) held two meetings. Thanks to the chairman Dr. Jim LaMoreaux, the Commission accepted my offer to edit a book titled "Mineral and Thermal Waters of Southeastern Europe." This book, published by Springer, is a part of the Environmental Earth Sciences Book Series.

The book is organized into nine chapters. It discusses the geology of SE Europe, mineral and thermal water potential, and physical and chemical properties, as well as the utilization of thermal and mineral waters in Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Macedonia, Montenegro, Romania, and Serbia.

In my capacity as editor, I have included nearly 30 colleagues from eight neighboring countries, who are engaged in the fields of mineral water and geothermal energy. Some of them are young doctoral students who specialize in hydrogeology and hydrogeochemistry.

I am especially grateful to Dr. Jim LaMoreaux, for giving me the opportunity to be the editor, and to Dr. Annett Büttner, the publishing editor from Springer. I am indebted to all the authors who contributed to this book, including my doctoral students Ms. Maja Todorović and Ms. Marina Ćuk, who also helped with the layout and graphics and to Ms. Dubravka Miladinov for proofreading of the papers. My personal thanks go to Professor Dr. Miroslav M. Vrvić, from the Faculty of Chemistry, University of Belgrade, and to Mr. Petar Dopuđ from the mineral water bottling company "Dia Petra."

I trust that the book will be useful not only to those who specialize in mineral waters, but also for other professionals as well.

Belgrade
September 2015

Petar Papić

Contents

Geology of South-Eastern Europe

Vladica Cvetkovic, Dejan Prelević and Stefan Schmid

Abstract The region of South-Eastern Europe (SEE) occupies an important segment of the Alpine–Himalayan collisional orogenic belt and consists of several Phanerozoic mobile belts. The SEE region inherits its geology from the evolution of the Vardar Tethys ocean, which existed in-between the Eurasian (Europe) and Gondwana (Africa) continental plates and which relicts presently occur along the Vardar–Tethyan mega-suture. This synthesis, therefore, consists of (1) pre-, (2) syn- and (3) post-Vardar–Tethyan geology of SEE. Pre-Vardar–Tethyan geology on the European side is reflected by geological units formed from Precambrian to Mesozoic times and include the Moesian platform, the Dacia mega-unit and the Rhodopes. On the Gondwana side, it is represented by the External Dinarides, the Dalmatian-Ionian Zone and Stable Adria (Apulia), all principally formed from Paleozoic to Mesozoic times. The Syn-Vardar–Tethyan units encompass the bulk of the geological framework of SEE. They are a physical record of the former existence of the Mesozoic oceanic lithosphere, being represented dominantly by ophiolites and trench/accretionary wedge (mélange) assemblages, which originated and were reworked during the life-span of the Vardar Tethys. The Post-Vardar–Tethyan geological evolution refers to the time period from the final closure of the Vardar Tethys until present. It comprises all rocks that stratigraphically overlie the Vardar–Tethyan mega-suture and seal the contacts between the mega-suture and the surrounding geological units. This is the time characterized by rapid extension coupled with exhumation of the lower crustal material, high heat flow, both intrusive and extrusive magmatism and considerable lithosphere thinning.

Keywords Geodynamics · Gondwana · Europe · Mesozoic · Tethys

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Introduction

The Synthesis' Approach

The current understanding of the geological evolution of South-Eastern Europe (SEE) is associated with still many open questions. This is due to either the lack of data or because the existing data are of variable quality in different regions. This volume is primarily designed to be of use for applied geologists, whose main interest is remote from geological and geodynamical details, in particular from interpretations that are surrounded by large controversy. In this context, the ultimate aim of this synthesis is to provide the hydrogeological and engineering geological community with a solid understanding about the present geological framework of SEE and about how it formed throughout the geological history, without addressing in detail still debated questions.

In general, the SEE region consists of several mobile belts that formed during the youngest geological history of the Eurasian continent when Alpine–Himalayan belt originated. There is a general consensus that this region evolved during Phanerozoic geodynamic events controlled by sea floor spreading, plate convergence and collision, which occurred between the Eurasian and African (Gondwana) continental plates (e.g. Blundell et al. 1992). This geodynamic regime—which is still active today in the southernmost part of the region, i.e. in the Hellenide trench —was particularly important during the last 200 m.y. It was directly associated with the opening and closure of a branch of the Mesozoic Tethys that separated the Eurasian continent and a promontory of Africa, referred to as Adria plate. We consider the evolution of this part of the Mesozoic Tethys, hereafter named the Vardar Tethys, a pivotal point for the explaining the geological history of the entire SEE region. This synthesis, therefore, consists of three major parts, in which (1) pre-, (2) syn- and (3) post-Vardar–Tethyan geology of SEE are explained. These parts refer to geological entities and rock masses that formed before this ocean opened, those that originated during its life-span and those formed after it had been closed, respectively.

In this geological presentation we compile the information from relevant geological and geotectonic syntheses of various parts of the SEE region. For the Dinarides-Albanides-Hellenides we mainly use the interpretations provided by Karamata (2006), Robertson and Shallo (2000), Schmid et al. (2008) and Robertson et al. (2009), for the Carpathians and the Balkanides we apply the views of Mahel (1973), Ivanov (1988), Săndulescu (1994), Kräutner and Krstić (2006) and Schmid et al. (2008), whereas for the Balkan orogen in Bulgaria and the Rhodopes we use the syntheses of Dinter and Royden (1993), Burchfiel et al. (2003), Burchfiel and Nakov (2015) and Burg (2011), among many others.

Definition of the Research Area

The boundaries of South-Eastern Europe may differ because of various geographic and political reasons. Here SEE comprises the area that generally coincides with the Balkan Peninsula (Fig. 1). The north-westernmost border of this area is located

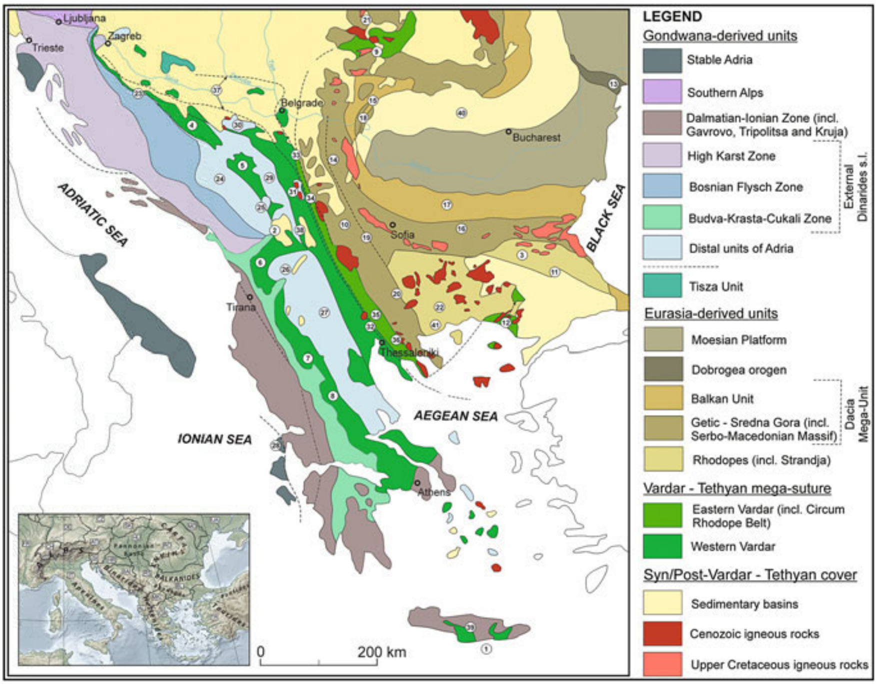

Fig. 1 A simplified geological sketch of South–Eastern Europe. The sketch is a modified compilation of the Geological Atlas of Serbia 1:2.000.000 (Dimitrijević 2002), the International Geological Map of Europe and Adjacent Areas (Ash et al. 2004), the Geological map of the Carpatho–Balkanides between Mehadia, Oraviţa, Niš and Sofia (Kräutner and Krstić 2006), and the Tectonic map of the Carpathian–Balkan mountain system and adjacent areas (Mahel 1973). Geotectonic and geological sketches of some parts of SEE by Schmid et al. (2008), Dimitrijević (1997), Karamata (2006), Robertson and Shallo (2000), and von Quadt et al. (2005) were also used. Explanations (by the order of appearance in the text): *1* Hellenic trench, *2* Metohija depression, *3* Maritsa valley, *4* Krivaja–Konjuh ultramafics, *5* Zlatibor ultramafics, *6* Mirdita ophiolitic massif, *7* Pindos ophiolitic massif, *8* Othrys ophiolitic massif, *9* Mureş valley (Transylvanian nappes), *10* Serbo–Macedonian Massif, *11* Strandja, *12* Circum–Rhodope belt, *13* North Dobrogea orogen, *14* Getic unit, *15* Danubian nappes, *16* Sredna Gora, *17* Balkan unit (Stara planina), *18* Ceahlău–Severin ophiolite belt, *19* Morava unit, *20* Vertiskos unit, *21* Biharia nappes, *22* Drama unit, *23* Sana–Una unit, *24* Central Bosnian Schist Mts. unit, *25* Lim Paleozoic unit, *26* Korabi unit, *27* Pelagonian unit, *28* Levkas island, *29* Jadar unit, *30* Drina–Ivanjica unit, *31* Kopaonik Mts. unit, *32* Paikon unit, *33* Kragujevac ophiolite complex, *34* Kuršumlija ophiolite complex, *35* Guevgelia–Demir Kapija ophiolite, *36* Eastern Hellenic ophiolites, *37* Sava Zone, *38* Kosovska Mitrovica Flysch, *39* Crete, *40* Dacic basin (Eastern Paratethys), *41* Mesta half– graben

south of Ljubljana and north of Istria, and its northern boundary is delineated by the Sava River, from Zagreb until its junction with the Danube, and further by the Danube River, all the way from Belgrade down to the Black Sea. The other borders of the SEE to the east, south and west are delineated by the coastal areas of the Black, Aegean, Ionian and Adriatic Seas, respectively. Politically, this region comprises the southern parts of Slovenia and Croatia, central and southern Serbia (including Kosovo), south-easternmost Romania (Dobrogea), the European part of Turkey, and the entire territories of Bosnia and Herzegovina, Montenegro, Albania and Greece.

In terms of present day geomorphology, the SEE region begins along the junction between the south-eastern Alps and the north-western Dinarides and encompasses the entire Dinaride–Albanide–Hellenide, Carpatho–Balkan and Rhodope mountain belts (see inset in Fig. 1). This rather complex orogenic realm contains a few smaller depressions, such as, for instance, the Metohija depression and the Maritza valley, whereas several lowlands occurring along the coastal areas are directly related to the above mentioned Seas. These recent depositional systems stay beyond the scope of this presentation.

Terminology

The specialists in applied geology usually face problems when acquiring a solid knowledge of the regional geological framework of a given area. This is so, because they are often bewildered by unnecessarily detailed geodynamic explanations or by too complicated and incomprehensible stratigraphic and lithological divisions. We think that a more simplified approach that follows a simple motto: 'geology through geodynamics', can be of use for those who may not be entirely familiar with recent developments in basic geo-disciplines. Therefore, we first briefly summarize essential theoretical aspects and explain the most important elements of the terminology used. This will surely strengthen the capability of future readers to follow our interpretations.

In a most simplistic way, the evolution of an orogen involves that two lithospheric plates, each having different stratigraphic and tectonic histories, approach each other and, finally, weld by collision (see Skinner et al. 2003). The process of 'approaching' occurs via subduction, by which usually oceanic areas in-between the converging continental plates often become totally consumed. After collision and welding the two once separated plates stick together, and this means that no intervening ocean exists anymore. What remains are relicts of the vanished ocean: different parts of the ocean's bottom (mainly peridotites and basalts) and overlying sediments (cherts, various siliciclastic sediments, sometimes carbonates, etc.). Some of the originally intervening oceans do not disappear entirely via subduction but are obducted as huge ophiolitic sheets onto continental realms. Obduction means that the oceanic plate overrides the continent and during this process a mix of exotic rock masses that may represent any lithology derived from the margins of the colliding oceanic and continental plates is preserved. Such tectono-stratigraphically very complex mixed units underneath the obducted oceanic plates are referred to as 'ophiolitic mélange', whereas obducted peridotites are usually named 'ophiolite'. An ophiolite basically represents a section of the Earth's oceanic lithosphere that has been uplifted and exposed above sea level and often emplaced onto continental crust.

The above described orogen (i.e., a mountain belt) forming processes are commonly followed by post-orogenic phases, during which the earlier compression tectonics are replaced by strike-slip or purely extension regimes. This tectonic switch is mostly controlled by local changes in relative plate motions, and commonly evolves into gravitational (isostatic) instability and orogen collapse. The major driving force for the lithospheric extension is rapid advective thinning of the shortened thermal boundary conduction layer, which occurs beneath an orogen and causes a rapid uplift (Dewey 1988). In some places, the extension involves the formation of steeply dipping, crustal- to lithospheric-scale fractures, whereas in other places low-angle detachment faults substantially stretch the former orogen, exhuming deeper parts of the crust to the Earth's surface. These exhumed parts are called 'metamorphic core complexes'. These processes usually produce sedimentary basins and magmatism within transtensional/transpressional wrench corridors or within larger extensional areas.

In accordance to the explanations given above, the geology of SEE will be simply presented in terms of the formation of a complex mobile belt via disappearance of an earlier ocean. The term 'orogen' is used to delineate parts of this complex mobile belt, and always also has a geographical connotation (e.g. Dinaride orogen, Carpatho–Balkanide orogen, etc.). By the term 'unit' (or sometimes 'mega-unit') we delineate a geological entity formed during a similar time-span that has similar geotectonic and stratigraphic characteristics, but without implications whether that unit represents an earlier microcontinent or an erosion/tectonic window. In a similar way the terms: 'mass', 'massif', 'block', 'belt' or 'zone' are used. The notion 'terrane', however, is applied in the sense of Keppie and Dallmeyer (1990) and denotes a microplate that via subduction of a consuming oceanic was welded to (or docked to) another microplate or 'terrane'. Note that the term 'suture zone'—which normally represents a narrow belt located in-between two terranes, we here use in a wider sense, i.e. as 'mega-suture' for delineating the area that comprises all remnants of the Vardar Tethys. The main collision described below occurred between two large continental plates often also referred to as 'Eurasia' and 'Gondwana' (Fig. 1). The former is also named 'European continent', or simply 'Europe', whereas the parts of the latter present in SEE are referred to as Africa or its promontories, known as Adria or Apulia.

Geology of South-East Europe

Time-Space Framework of the Vardar Tethys Ocean

Geological development of the Vardar Tethys is still a matter of an ongoing debate (Karamata 2006; Robertson et al. 2009; Dilek and Furnes 2011). Therefore, we must first agree upon the most salient and widely accepted features of its evolution. For instance, there are conflicting opinions about how many oceans did exist in the SEE area. Some authors argue in favour of the existence of more than one ocean, suggesting that each left behind its own suture zone, whereas others believe that there was only one ocean and, consequently, only one suture. The latter consider many occurrences of ophiolites and ophiolitic mélanges as representing pieces of obducted oceanic lithosphere rather than suture zones. There are also disagreements with respect to the life-span of the ocean(s). Some authors suggest that the ocean (or more) opened in early- to mid-Triassic, others think that the Vardar Tethys' oceanic crust was present in SEE as early as in Paleozoic times. Most authors think that an oceanic realm of the Vardar Tethys was still open in the Late Cretaceous, whereas a minority still believes that the closure finished in Upper Jurassic/Early Cretaceous times. The above mentioned controversies are the subject of many papers (e.g.: Bernoulli and Laubscher 1972; Smith and Spray 1984; Săndulescu 1988; Robertson and Karamata 1994; Channell and Kozur 1997; Dimitrijević 2001; Golonka 2004; Haas and Pero 2004; Stampfli and Borel 2004; Bortolotti and Principi 2005; Schmid et al. 2008; Robertson et al. 2009, among many others). In these papers many different names appear for oceans and/or related ophiolites/ophiolite mélanges and suture zones, for instance: Neotethys (±Mesozoic Tethys), Vardar (±Axios), Dinaride (±Mirdita ±Pindos), Maliak-Meliata, Hallstadt, etc., and this adds to confusion and makes the comprehension of the already complex geology of this region even more difficult.

Although some of the above explained problematic issues will be addressed later (see section Syn-Vardar–Tethyan Geology of SEE), it is important to clearly state which scenario of the origin and evolution of the Vardar Tethys is adopted here. This starting point has important bearings to the entire division and organization of further geological presentation.

We base our simplified geological interpretation on a piece of information upon which most authors agree, namely on the view that there formerly existed *at least one ocean* in the region of present day SEE. It is generally referred to as Neotethys, and was distinguished from the Paleotethys whose remnants in Turkey and eastwards are uncontested by all authors. Furthermore, most authors agree that parts of the Neotethys Ocean remained *open during most of Mesozoic time*. Hence, our simple approach has similarities with the 'single ocean scenario', first proposed by Bernoulli and Laubscher (1972) and Baumgartner (1985), and recently refined and reformulated by Schmid et al. (2008). This scenario assumes that the (geographically) multiple belt of ophiolites and ophiolitic mélanges—stretching all the way from north-western Dinarides to Southern Greece (and further to Turkey and Iran), encompasses remnants of a single ancient oceanic realm—Neotethys, hereafter named Vardar Tethys. In this sense, this entire ophiolite-bearing complex orogenic belt can be considered a single very wide Vardar–Tethyan mega-suture. The western margin of this mega-suture is marked by the westernmost occurrences of the Jurassic ophiolites and ophiolitic mélanges in Bosnia (Krivaja–Konjuh), west Serbia (Zlatibor), east Albania (Mirdita) and central Greece (Pindos and Othris). The western margin terminates in the north-west at around Zagreb, whereas the eastern margin is buried beneath the thick cover of Pannonian sediments and reappears in the Mures valley, as part of the Transylvanian nappes (Balintoni 1994). This entire and very wide mega-suture zone crosses the Aegean Sea and outcrops again in Asia Minor of Turkey.

Summarizing, the geological division which follows invokes that: (1) all Mesozoic geological units located within the Vardar–Tethyan mega-suture are rock masses that formed during the life-span of this Mesozoic ocean, (2) all pre-Mesozoic geological entities that primarily occurred on both sides of the ocean record parts of the Pre-Vardar–Tethyan geological history, and (3) all geological units that seal the contacts of the mega-suture and its shoulders are results of post-Vardar–Tethyan geology. In the presentation that follows these three time periods are ordered chronologically.

Pre-Vardar–Tethyan Geology of SEE

Pre-Vardar–Tethyan geological record is predominantly found in the areas west and east from the main mega-suture. These two broad continental margins underwent different geological evolutions during Paleozoic and pre-Paleozoic times. In the division below, the pre-Mesozoic geological entities located eastward from the mega-suture represent relicts of the southern margin of the ancient European continent (Eurasia), whereas the units outcropping on the western/south–western side of the mega-suture are parts of the northern margin of Gondwana or its promontories (Adria or Apulia). In addition, several pre- to early Mesozoic geological units presently outcrop within the mega-suture itself. Some authors (see Robertson et al. 2009 and references therein) interpret these units as terranes—i.e. as microcontinents, which once separated different oceanic realms. As already mentioned above, we here adopt a scenario in which these basement units are considered distal parts of the Gondwana margin, i.e. distal parts of Adria (see section Pre-Vardar–Tethyan geology of the Gondwana continent and Fig. 1).

It needs to be stressed that the pre-Vardar–Tethyan geological history of both sides of the major mega-suture is difficult to discern, because the geological records are only fragmentarily exposed and because they were later subject to different periods of tectonic and sedimentary reworking. This is especially valid for the Gondwana margin, because during the syn- and post-Vardar–Tethyan time, this area underwent deposition of platform carbonates and locally siliciclastic sediments. Although also partly obscured, the pre-Vardar–Tethyan geological record on the European side is better exposed and it provides evidence that this area evolved through geodynamic processes similar to those related to the SEE geological evolution, characterized by the disappearance of oceanic realms and collisional accretion of continental units to the European mainland.

Pre-Vardar–Tethyan Geology of the European Continent

Pre-Vardar–Tethyan geology on the European side is reflected by geological units formed from Precambrian to Mesozoic times. These complex units occur within three mega tectonic continental blocks: the Moesian platform, the Dacia mega-unit (including the Serbo–Macedonian Massif) and the Rhodopes (including Strandja). These individual units represent huge and more or less complex nappe piles, which differ in their age and geological evolution and whose remnants discontinuously appear below a Mesozoic and younger cover. Note, however, that the Circum–Rhodope Belt (Kauffmann et al. 1976), which fringes part of the Serbo-Macedonian Massif and the Rhodopes in northern Greece, is not considered here as part of the European margin but as an element of the main mega-suture (see further below).

The Moesian Platform in SEE comprises the regions of northern Bulgaria and South Dobrogea in Romania. It is now largely covered by younger sediments and its basement is reconstructed on the basis of scarce exposures as well as by boreholes and seismic data. Moesia is the only tectonic unit of the present SEE, which was part of the European continent during significant portion of Paleozoic and Mesozoic times (Seghedi 2001). It has acted as the margin of stable Europe since Jurassic Cimmerian orogeny that only marginally affected it and whose remnants presently occur in north Dobrogea. With respect to Vardar–Tethyan geology, the Moesian Platform can be regarded as 'undeformed foreland' (Schmid et al. 2008). It is composed of Neoproterozoic ('Panafrican') metamorphic rocks that only locally record a Variscan overprint (Seghedi et al. 2005; Oczlon et al. 2007). Most of the deformation of the South Carpathians and the Balkanides has occurred along the boundaries of the stable Moesian platform (Fügenschuh and Schmid 2005).

In contrast to predominantly covered Moesia, the metamorphic basement of the Dacia mega-unit outcrops in many places. In Serbia, this unit corresponds to the area between the eastern border of the mega-suture (i.e. Eastern Vardar) and the Moesian Platform, which integrates two systems of nappes: the Serbo-Macedonian Massif and the East Serbian Carpatho–Balkanides. Towards the south they form two branches: one goes directly southwards, as the continuation of the Serbo–Macedonian Massif in the Former Yugoslav Republic (FYR) of Macedonia and Greece, and the other continues south-eastwards, and merges with the composite Balkan unit in Bulgaria (Burchfiel and Nakov 2015). Across the Danube, the Dacia mega-unit continues to the north–east into the South Carpathians of Romania, whereas in the north it is bordered by another European mega-unit named Tiszia (e.g. Csontos and Vörös 2004). The Tiszia unit is outside of the SEE region and will not be addressed in this study.

The internal part of Dacia consists of the East Serbian Carpatho–Balkanides—often referred to as the Getic unit and the Danubian nappes, according to Romanian nomenclature, and by their lateral counterparts in Bulgaria—the Sredna Gora unit and the Balkan unit (or Stara Planina). More eastern analogues of these units can be found in the Pontides of NW Anatolia. These individual geological entities are, in fact, poorly exposed collages of Paleozoic units and/or terranes that have a Gondwana affinity. The units often have local names, for instance: Median Dacides—Danubian (Vrška Čuka–Miroč)—central/pre-Balkan or Infrabucovinian—Getic (Kučaj)—Kraishte–Sredna Gora units, etc. The contacts between them are obscured by later compressive tectonics and by deposition of a younger Mesozoic and Cenozoic sedimentary cover. The largest preserved suture-like belt is the one composed of Iuti–Donji Milanovac–Deli Jovan–Zaglavak–Černi Vrah gabbro-diabase (±peridotite) complexes. The Deli Jovan complex is dated to Early Devonian (Zakariadze et al. 2012), which suggests that these so-called "Danubian Ophiolites" represent relicts of an Ediacarian-Early Cambrian ocean and magmatic complex (Kounov et al. 2012). Where exposed, the Dacia-derived basement is represented by medium- to high-grade Neoproterozoic ('Panafrican') to Early Paleozoic gneiss and Paleozoic greenschist to sub-greenschist metabasic rocks. The basement is unconformably overlain by Late Carboniferous to Permian fluvial sediments (Iancu et al. 2005), with detrital material derived from the European continent. The basement is also intruded by Variscan plutons that crop out at many places in Serbia (e.g. Neresnica, Gornjani, Ziman, etc.; Šarić et al. 2014) and Bulgaria (e.g. Vezhen, Hisara, Smilovene, etc.; Carrigan et al. 2005). Large parts of the Dacia mega-unit were separated from the European continent along the Ceahlau-Severin oceanic rift which extends from Ukraine into north-westernmost Bulgaria. The closure of this basin in the Lower Cretaceous was followed by later phases of emplacement of these nappe systems from the Late Cretaceous to Miocene times (Săndulescu 1984; Kräutner and Krstić 2006; Burchfiel and Nakov 2015).

The Serbo–Macedonian Massif represents the structurally uppermost part of Dacia and a more internal unit with respect to the above described Carpatho–Balkanides and is comparable to the Supragetic nappe of Romania (Schmid et al. 2008). It is a crystalline belt of Paleozoic-age high to medium grade metamorphic rocks that are generally distinguished into the Lower and the Upper Complex (Dimitrijević 1957, 1997). The Lower complex is composed of gneiss, micaschists and subordinate amphibolites, quartzites, marbles and migmatites. They occur as relicts of a Late Neoproterozoic-earliest Cambrian high- to medium-grade metamorphic belt that formed during the Cadomian orogeny and which underwent overprints in Variscan and Alpine times (Balogh et al. 1994). The rocks of the Upper Complex represent a Cadomian volcano-sedimentary sequence, which was only metamorphosed under greenschist facies conditions. They are intruded by Cadomian igneous rocks and are covered by post-Cambrian sedimentary series (Kräutner and Krstić 2002). According to most authors the Bulgarian part of the Serbo–Macedonian Massif in Bulgaria is also known as the Morava unit (Kounov et al. 2004), whereas in Greece this same massif is referred to as Vertiskos Unit (i.e. Kockel et al. 1971, although some authors interpret Vertiskos as being part of the

Rhodopes (Burg 2011). The northern continuation of the Serbo–Macedonian Massif is documented in the drill-cores in the Pannonian basin (e.g. Kemenci and Čanović 1997) and its northern counterparts outcrop again as part of the Biharia nappes of the Apuseni Mountains (sensu Schmid et al. 2008).

The most internal Europe-derived geological units in the south-east are the very complex tectonic units of the Rhodopes and overlying Strandja. In the east, large parts of the Rhodopes are covered by Cenozoic basin sequences. However, due to post-thickening extension of the Rhodopes starting in the Eocene, various originally deep-seated high- to medium-grade metamorphic rocks became exhumed and are now exposed in the mountains of southern Bulgaria and northern Greece (Burg 2011). According to many authors the Rhodope massif comprises a south- to southwestward facing nappe stack. However, north-facing tectonic transport has also been documented in the Rhodopes, particularly in the Eastern Rhodopes (Bonev et al. 2015). There is also an ongoing debate about the origin of thin ophiolitic bodies found within the Rhodopes. According to some (e.g. Froitzheim et al. 2014), these have their origin in the "Vardar Ocean", i.e. in our Vardar–Tethyan mega-suture. Classically, they were attributed to a former Mesozoic Ocean located between the main part of the European continent and a more southerly located continental block named Drama block, which is still of European affinity and is located north of the Vardar–Tethyan mega-suture (e.g. Turpaud and Reischmann 2010).

The Rhodope massif underwent high- to ultra-high pressure metamorphism (Liati and Seidel 1996; Mposkos and Kostopoulos 2001; Kostopoulos et al. 2003), supposedly at various times starting in the Jurassic, and was subsequently overprinted by granulite and amphibolite facies (Liati and Seidel 1996; Carrigan et al. 2002; Liati et al. 2002). Similarly to the Carpatho-Balkanides, the Rhodope massif is also pierced by Variscan intrusives (e.g. Arda and Startsevo; Cherneva and Gheorgieva 2005). This suggests that Variscan late- or post-collision granitoid magmatism is a common feature for the European part of the pre-Tethyan basement, as was found in other parts of the Alpine orogen (e.g. Finger et al. 1997). The Rhodopes are separated from the overlying Strandja unit by Jurassic thrusts and often by younger Cenozoic faults (Kilias et al. 1999; Georgiev et al. 2001; Okay et al. 2001; Brun and Sokoutis 2007; Bonev et al. 2015). Strandja is part of the north-verging Cimmerian orogen. This basement-cover unit is formed by northward-verging nappes in Late Jurassic to Early Cretaceous time. From this time onwards, the Strandja belongs to the Balkan part of the complex Alpine–Himalayan mobile belt.

Pre-Vardar–Tethyan Geology of the Gondwana Continent

Pre-Mesozoic outcrops presently occurring westwards from the main mega-suture represent remnants of the northern margin of the ancient Gondwana continent. In this synthesis we distinguish three major tectonic entities, namely: the External Dinarides sensu *lato*, the Dalmatian-Ionian Zone and Stable Adria (Apulia).

The External Dinarides *s.l.* are composed of a system of westward-vergent Mesozoic and younger nappes. Their Paleozoic basement is scarcely exposed, predominantly in form of tectonic or erosion windows. This basement records only weak metamorphism in Variscan times, with again a weak metamorphic overprint in Cretaceous and Cenozoic times (Pamić et al. 2004; Hrvatović and Pamić 2005). It comprises separate Paleozoic units, such as Sana-Una, Central Bosnian Schist Mts. and Lim Paleozoic, which occur from Croatia, through Bosnia and Herzegovina, Montenegro to SW Serbia. The hemipelagic Pindos Zone stretches from Greece to Montenegro, but disappears NW-wards south of Dubrovnik. The more external hemipelagic Ionian Zone, crossing the Adriatic Sea SE-wards from Italy into Albania is only exposed in Albania and Greece. Its pre-Mesozoic basement, however, is completely covered by Mesozoic carbonate platform sediments (Robertson and Shallo 2000). In front of the Ionian Zone one enters the Apulian carbonate platform exposed on Ionian islands (e.g. Levkas). This platform sequence is part of the Adria/Apulia plate, which acted as the main indenter along which the External Dinarides and more internal units, as well as the Alps were deformed (Schmid and Kissling 2000). In this context, the immediate basement of the Ionian zone, which possesses the structurally lowermost position, is represented by Pre-Apulia and Apulia and can be correlated by non-deformed parts of Istria (Stable Adria in Fig. 1).

As noted earlier, several continental blocks are located within the mega-suture itself and they are considered as distal parts of the ancient Gondwana margin. These basement units include (from NNW to SSE): Jadar, Drina-Ivanjica, and Kopaonik Mts. (including the Studenica slice) in Serbia, Korabi in Albania, and Pelagonia in the FYR of Macedonia and Greece. All these units are predominantly composed of non- to low-grade metamorphic Paleozoic clastic sediments overlain by Permian/Triassic carbonates that are often transformed into marbles and intercalated with rift-related igneous rocks (Zelić et al. 2005; Sudar and Kovács 2006; Schefer et al. 2010). The south-eastern counterparts of these units are the Korabi and Pelagonian zones that mostly occur in Eastern Albania and Greece. Both the Korabi and Pelagonian zones record a more pronounced Variscan metamorphic and magmatic overprint and show transitions from an arc to a passive margin setting (Clift and Robertson 1990; Robertson and Shallo 2000). The Pelagonian zone is intruded by Variscan granitoids (Mountrakis 1984), similar outcrops are not present in situ in the Korabi zone. However, granitoids of a similar age are found as allochthonous blocks within the ophiolite mélange sequences in west Serbia or as pebbles in the sequence overlying mélange (e.g. Neubauer et al. 2003). All the above mentioned Paleozoic/earliest Mesozoic basement units were originally overlain by westward obducted ophiolites, but they acquired their present structural setting by later out-of-sequence thrusting, mostly during the Latest Cretaceous to Early Cenozoic.