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

V. Cvetkovic (✉) · D. Prelević
Faculty of Mining and Geology, University of Belgrade, Đušina 11,
11000 Belgrade, Serbia
e-mail: cvladica@rgf.bg.ac.rs

S. Schmid
Institut für Geophysik ETH, Zürich, Switzerland

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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

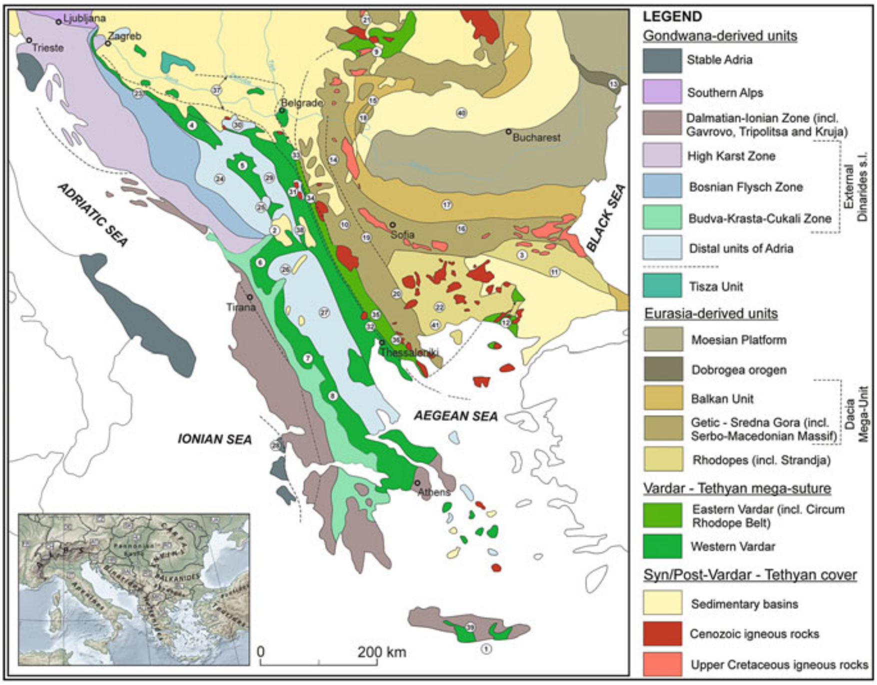

Fig. 1 A simplified geological sketch of South–Eastern Europe. The sketch is a modified compilation of the Geological Atlas of Serbia 1:2.000.000 (Dimitrijević 2002), the International Geological Map of Europe and Adjacent Areas (Ash et al. 2004), the Geological map of the Carpatho–Balkanides between Mehadia, Oravița, 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* Mureș 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.

Syn-Vardar–Tethyan Geology of SEE

This geological evolution is characterized by the formation of ophiolitic rock masses during the opening of the Vardar Tethys in mid-Triassic time until its final closure in the late Mesozoic. These ocean-derived rocks presently occur within the mega-suture either as parts of mostly allochthonous sequences, reworked during collision and afterwards, or as predominantly autochthonous series that overlie the pre-Mesozoic basements of the Gondwana and European margins. We begin with the mega-suture itself, because this is the area which hosts all the remnants of the Mesozoic Vardar Tethys.

Syn-Vardar–Tethyan Geology of the Mega-Suture

The Vardar–Tethyan mega-suture consists of lithologies that physically record the former existence of Mesozoic oceanic lithosphere. In general, they are represented by ophiolites and trench/accretionary wedge (mélange) assemblages. Although it is a highly heterogeneous rock association, all its lithological members have in common that they either originated or were reworked/displaced during the life-span of the Vardar Tethys, including its closure via subduction, obduction and collision processes.

In terms of geographic distribution, at least three subparallel ophiolite belts are distinguished, each spatially associated with their mélanges. The easternmost ophiolitic sub-belt is known as Eastern Vardar (also called Main Vardar by some authors, see Dimitrijević 1997). In Serbia and FYR of Macedonia it occurs as a narrow and N-S elongated ophiolite belt and it widens from the Belgrade area north–eastwards into Romania. In the east, it is in direct contact with the Serbo–Macedonian Massif, and in the west it is often delineated by overlying Senonian flysch sediments, as well as by the contact with the above described parts of the distal Adria (e.g. Kopaonik Mts. and Paikon unit). The Eastern Vardar comprises small occurrences near Kragujevac and Kuršumlija in Serbia and larger masses near Demir Kapija and Guevgelia in FYR of Macedonia and those of the easternmost Hellenic ophiolites in the Thessaloniki area. The northern continuation of this zone is covered by the Pannonian sediments (Čanović and Kemenci 1999), but the belt crops out again as part of Transylvanian nappes in the Apuseni Mts. (Săndulescu 1984; Balintoni 1994). Further to the south, this unit grades into the so-called Circum–Rhodope Belt (Kockel et al. 1971; Michard et al. 1994; Meinhold and Kostopoulos 2013)—a belt that consists of a mixture of ophiolitic rocks and rocks of the European continental margin. This belt is called Circum–Rhodope because it surrounds the Rhodopes in the west (Thessaloniki area), south (NE Greece) and in the east (easternmost Bulgaria), where it links with the Strandja orogen. Structurally, Strandja overlies the Rhodope unit. The Eastern Vardar consists of igneous ophiolite members, mainly basalt, diabase and gabbro, whereas peridotites are remarkably rare. The rocks possess the strongest supra-subduction zone (SSZ) affinity of all the ophiolites from this region (Brown and Robertson 2004; Šarić et al. 2009; Božović et al. 2013), indicating that large parts of them formed in the upper plate of an intra-oceanic subduction zone. The age of formation of the ophiolites is mid-Jurassic and their final emplacement age is constrained as uppermost Jurassic by both stratigraphic (Bortolotti et al. 2002; Săsăran 2006; Kukoč et al. 2015) and radiometric evidence (Anders et al. 2005; Božović et al. 2013). Although, some authors (e.g. Schmid et al. 2008) argue that the Eastern Vardar ophiolites are the structurally highest tectonic entity within the Dacia mega-unit and that they were probably obducted onto the European Margin, its original emplacement is still a matter of debate (Petrović et al. in press).

Going westward, the next ophiolite belt encountered is the Western Vardar ophiolite belt and even further west one finds the Dinaride-Mirdita-Pindos ophiolite belt (e.g. Jones and Robertson 1991; Lugović et al. 1991; Beccaluva et al. 1994; Shallo 1995; Bazylev et al. 2009). These two belts occupy gradually more external positions with respect to the main axis of the Balkan Peninsula and are geographically separated by the outcrops of Drina–Ivanjica–Korab–Pelagonia Paleozoic basement of distal Adria, and its Mesozoic cover. The Western Vardar ophiolites comprise large predominantly ultramafic massifs in Serbia (Maljen, Stolovi, Kopaonik Mts., etc.) and smaller masses in FYR of Macedonia and Greece (e.g. Almopya). The most prominent peridotites massifs of the Dinaride–Mirdita–Pindos ophiolite belt are the Krivaja–Konjuh massif of Bosnia and Herzegovina, the Mirdita–Tropoja, Kukes, Bulquiza massifs of Albania and the Pindos and Vourinos massifs of Greece. As already mentioned, these two ophiolite belts are best regarded as parts of the same piece of the Vardar Tethys oceanic lithosphere, which was more or less uniformly obducted towards the west, i.e. onto the passive margin of the Gondwana continent. Hence, we agree with the view of Schmid et al. (2008) that these ophiolites should be collectively named Western Vardar to distinguish them from the Eastern Vardar ophiolites. The view of a single Western Vardar ophiolite belt is supported by the following observations: (a) these ophiolites are predominantly represented by large ultramafic bodies, whereas pillow basalts, diabases and gabbros are subordinate, (b) the ultramafic slices were emplaced as hot plates that produced so-called 'metamorphic sole assemblages' at their base, some of them displaying classical inverted P-T gradients (e.g. Brezovica; Karamata 1968), (c) the metamorphic sole rocks exhibit similar age ranges (Lanphere et al. 1975; Okrusch et al. 1978; Spray et al. 1984; Dimo-Lahitte et al. 2001; Bazylev et al. 2009), and (d) the ophiolites show a continuous change in composition, going from west to east, from a mid-ocean-ridge- (MOR) to a supra-subduction zone (SSZ) geotectonic affinity (Maksimović and Majer 1981; Bortolotti et al. 2002). Some of the westernmost ophiolite occurrences, such as parts of the Krivaja-Konjuh massif in Bosnia and Herzegovina and Ozren in SW Serbia exhibit an extremely fertile geochemical signature typical of subcontinental lithospheric mantle (Bazylev et al. 2009; Faul et al. 2014). Thus, when also including the Eastern Vardar into consideration, it is clear that all SEE ophiolites show a general compositional shift from west to east: from the least-depleted subcontinental mantle-like peridotites, through typical MORB ophiolites and transitional MORB–SSZ ones up to those that exhibit a pronounced SSZ affinity.

Besides the above described remnants of the bottom of the Vardar Tethys, represented by pieces of lithospheric mantle (ultramafics) and overlying oceanic crust (gabbro-diabase-basalt), the syn-Vardar–Tethyan geology is recorded by rocks of subduction trench and accretionary wedge assemblages. In the Serbian literature, this series is commonly named Diabase–Hornstein-, Diabase–Chert or Diabase–Radiolarite Formation (Kossmat 1924; Ćirić and Karamata 1960) and we here refer to it as ophiolitic mélange. The main substrate of the mélange is represented by Upper Jurassic terrigenous sediments deposited in a tectonically active subduction trench. They consist of a non-metamorphosed to slightly metamorphosed silty material mostly derived from volcanic rocks and basalts, which encloses up to several meters long lenses or boudin-like blocks of sandstones (±conglomerates). This terrigenous matrix hosts blocks (olistoliths) with sizes varying from several meters up to a few tens of meters, which show variable lithologies, such as pillow-, massive- and hyaloclastic basalt and radiolarite (both Triassic and Jurassic), gabbro-diabase, serpentinite, and rare granitoids. At some places, this heterogeneous association also comprises several tens of km long masses of Triassic limestone. These are either products of gravitational gliding into the trench in which case are named olistoplaques (Dimitrijević and Dimitrijević 1973) or, alternatively, they were tectonically sliced off the Gondwana margin during obduction (Schmid et al. 2008). At a late stage during obduction the trench sediments and ophiolitic mélanges were obducted by the large and still hot ultramafic bodies of the Western Vardar oceanic lithosphere and this produced the already mentioned contact-metamorphic rocks known as metamorphic soles.

Syn-Vardar–Tethyan Geology of the European Side

During most of the Mesozoic the European continental margin predominantly acted as the eastern passive margin of the Vardar Tethys. In the Early Triassic continental red beds were deposited over the basement of the Dacia mega-unit. In Middle to Late Triassic, this sedimentation gradually evolved into the deposition of shallow marine limestones, and deposition of terrestrial sandstones continued throughout the Early Jurassic (‘Gresten facies’). Later on, the basin suddenly deepened, giving way to Middle Jurassic deposition of radiolarite and Late Jurassic/Early Cretaceous deposition of pelagic sediments. The main phase of east-directed (in present-day coordinates and in Eastern Serbia) nappe stacking formed during the mid-Cretaceous (so-called “Austrian” phase). This is evident from the age of a post-tectonic cover composed of Albian to Cenomanian Molasse-type deposits that are widespread in the Romanian Carpathians. Locally, however, this part of the European continent was also affected by Late Cretaceous deformation (“Laramian” phase), as pointed out by Săndulescu (1984). Due to late uplifts of the more distal (more frontal) parts of the European margin, such sedimentary record is rare in the Serbo–Macedonian Massif and in the Rhodopes.

The record of active subduction processes along the western margin of the European continent is found in the Eastern Vardar Zone. It was related to the formation of the Paikon arc (Brown and Robertson 2004) in the mid-Jurassic. This arc is considered to be a short-lived feature, because soon after its formation, it was influenced by slab rollback and spreading behind the arc. This led to the formation of the oceanic crust preserved in the Demir Kapija and Guevgelia ophiolites in FYR of Macedonia (Božović et al. 2013).

Syn-Vardar–Tethyan Geology of the Gondwana Side

The rock record of the Permian to Triassic intracontinental rifting phase, by which the Vardar Tethys formed, is abundant on the Gondwana side of the mega-suture. In addition to many places in the mega-suture itself, from NW Bosnia and Herzegovina to Greece, these rocks crop out throughout the External Dinarides *s.l.* in Croatia, Bosnia and Herzegovina and Montenegro. These are mostly autochthonous rock sequences that consist of shallow-water marine/lagoonal limestones, often with gypsum layers, and continental siliciclastic sediments. They are associated with predominantly mid-Triassic volcanic and volcaniclastic rocks that range widely in composition from tholeiitic to calc-alkaline and from basalt to rhyolite (Pamić 1984). The Triassic of the proximal parts of the Gondwana margin was characterized by deposition of thick shallow-water carbonate sediments (Rampnoux 1970), whereas at more distal places continental slope facies or even basinal facies deposited, for instance Ladinian/Carnian siliceous limestones (Dimitrijević and Dimitrijević 1991; Schefer et al. 2010). This deposition continued into the Jurassic and produced thick radiolarite sequences in Bosnia and SW Serbia (Rampnoux 1970; Pamić 2000; Vishnevskaya and Đerić 2005).

In the Late Jurassic, huge masses of ophiolites were obducted to the west and covered large parts of the eastern distal margins of the Gondwana continent. By later out-of-sequence trusting these obducted ophiolites were deformed and at places also dismembered and these tectonic and subsequent erosion processes left parts of the underlying basement exposed. This post-obduction thrusting also affected narrow deep-water intervening basins. One such basin is, for instance, the Budva Zone in Montenegro, Krasta–Cukali Zone in Albania and the Pindos–Olonos Zone in Greece (Robertson and Shallo 2000; Schmid et al. 2008). Some of these basins, such as the "Flysch Bosniaque" (Aubouin et al. 1970) continue to be active from the latest Jurassic into the Cenozoic, although varying both along and across strike with respect to paleotectonic conditions and source areas (see explanations in Schmid et al. 2008).

Post-Vardar–Tethyan Geology of South-East Europe

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 mega-suture and seal the contacts between the suture and the surrounding geological units. The oldest unconformable cover of the mega-suture is represented by Tithonian reef limestones and Lower Cretaceous flysch-like clastic sediments. From this, one could theoretically infer that all geological formations that are younger than the Lower Cretaceous would naturally belong to the post-Vardar–Tethyan geology. However, this is not so simple because not all the elements of the mega-suture closed in Late Jurassic to Early Cretaceous. Therefore, we must face a still open question, namely: did the entire Vardar Tethys close by uppermost Jurassic/lowermost Cretaceous times or, alternatively, did some of its realms floored by oceanic crust remain still open throughout the Late Cretaceous or even later? In other words, at what time does the post-Vardar–Tethyan geology really start?

The Late Cretaceous, Its Magmatism and the Problem of the Sava Zone

Late Cretaceous time was a period of formation of widespread flysch sediments, whose remnants are mostly preserved in the Serbian and Macedonian part of the Balkan Peninsula. They were deposited within deep and elongated troughs that post-date obduction. Some of these flysch sediments are only slightly deformed, others are strongly deformed and they all passively overlie the ophiolites, ophiolitic mélange and basement rocks of the Adria distal margin, as already noticed by Kossmat (1924). One narrow belt called Sava– or Sava–Vardar zone (Pamić 2002) begins south of Zagreb and stretches WNW-ESE towards Belgrade, and then apparently inflects and continues as a very narrow strip further southward to FYR of Macedonia (Fig. 1). Its continuation can be further traced in the Izmir area of Western Turkey (Bornova flysch of Izmir Ankara suture Zone; Okay et al. 2012). The southward narrowing and almost disappearance of the Sava zone may have resulted from substantial compression and uplift of the southern parts of the Balkan Peninsula in latest Cretaceous to Paleocene times. The Sava zone is younger and locally more metamorphosed than other Cretaceous flysch belts overlying the Jurassic mélanges, particularly in Northern Bosnia where upper greenschist to lower amphibolite facies metamorphism of late Cretaceous age was reached (Ustaszewski et al. 2010). Because it contains blocks of Late Cretaceous ophiolite-like basalt–diabase(±gabbro) complexes (Karamata et al. 2005; Ustaszewski et al. 2009; Cvetković et al. 2014), some authors believe that the Sava zone is the last suture that records the former presence of a Tethyan oceanic realm throughout Late Cretaceous times (Karamata 2006; Schmid et al. 2008; Robertson et al. 2009).

The geotectonic significance of the Sava zone is crucial for elucidating the entire post-Vardar–Tethyan geological history. Many authors (see Gallhofer et al. 2015) invoke that Late Cretaceous subduction of Sava zone oceanic lithosphere was responsible for the formation of well-known Late Cretaceous Banatite–Timok–Srednjegorje magmatic and metallogenetic belt (Berza et al. 1998; von Quadt et al. 2005). This is a presently curved but originally straight (Fügenschuh and Schmid 2005) belt that developed within the Dacia-derived basement of the European margin. It is part of a global subduction belt along the Eurasian active margin, which can be further traced to the Pontide magmatic arc in Anatolia, and the Somkheto–Karabakh arc in Lesser Caucasus (e.g. Ciobanu et al. 2002; Georgiev et al. 2009; Mederer et al. 2013, and references therein). It consists of volcano-sedimentary complexes formed during Turonian to Campanian times within elongated rift-like basins (Kräutner and Krstić 2006). The predominant rocks are andesite to basaltic/andesite volcanics and volcaniclastics associated to rare plutonic counterparts. This magmatism produced some of the largest porphyry copper systems in Europe, such as Bor, Majdanpek and Veliki Krivelj in Serbia and Assarel, Chelopech and Elatsite in Bulgaria, and some of them are related to significant epithermal gold deposits (e.g. Neubauer and Heinrich 2003). The magmatism shows a strong subduction geochemical affinity and that is explained by an eastward subduction under the European continent (Kolb et al. 2013; Gallhofer et al. 2015). This view is supported by the well-established across-arc age pattern that shows a gradual trenchward younging, in present-day coordinates westward in East Serbia and southward in Bulgaria (von Quadt et al. 2005; Kolb et al. 2013). In this context, if the Sava zone indeed hosts remnants of a wide Late Cretaceous oceanic bottom, then it is a suitable candidate for subduction and formation of the above mentioned magmatic and metallogenetic belt.

Cenozoic: Period of an Unstable Orogen, Widespread Magmatism and Formation of Extensional, Sedimentary Basins

The last chapter of the geological history of SEE involves the final consumption of Tethyan oceanic remnants and the still ongoing shaping of the global Alpine–Himalayan orogenic belt. The large amount of information ensures that the youngest geology is well-known, but this does not necessarily mean that the Cenozoic geological interpretation is simple. On the contrary, there are many controversies about this geological era as well, and, in keeping with our general approach, we will base our interpretation only on the issues upon which most authors agree.

Geotectonic Regime in the Cenozoic

During the Cenozoic, the just consolidated Dinaride–Albanide–Hellenide–Carpathian–Balkan section of the Alpine–Himalayan orogenic belt underwent remarkable tectonic reworking. The tectonics was controlled by various factors, ranging from global and regional to purely local in character. The essential tectonic control is the ongoing N- to NW-directed movement of the Adria microplate as an

African promontory. This is the major factor of compressive forces in the region, which led to substantial shortening in the coastal areas of Montenegro, Albania and Greece. However, since the beginning of the Cenozoic, this general compression has been associated by numerous regional-scale plate reorganizations and changes in local tectonic conditions. This made possible that a region undergoing a constant northward push from the south was able to evolve into local strike-slip or even purely extensional tectonic regimes, for instance in the Pannonian basin and the Aegean. These extensional episodes also involved differential rotations of some tectonic blocks along stable indenters and this primarily shaped the present day configuration of the SEE orogenic system. As the consequence of the opening of the Pannonian basin, the orogen split into two branches west and northwest of Belgrade—the Dinarides and the Carpathians including the Apuseni Mountains. Parts of the orogenic system exhibit remarkable curvatures due to oroclinal bending around Moesia and Adria as stable indenters, in the east and west, respectively (e.g. Fügenschuh and Schmid 2005). The (micro)plate re-organizations were also responsible for establishing regional to local geotectonic regimes, which ranged from pure compression to transpression in some regions, and transtension to pure extension in others.

The above mentioned controlling factors and resulting regional to local tectonic regimes were of supreme importance for the SEE Cenozoic geological evolution. In the area west of the Vardar–Tethyan mega-suture and along the Adriatic and south-Aegean coasts (e.g. Crete) the post-Vardar–Tethyan evolution was dominated by constant crustal shortening and westward and southward out-of sequence thrusting (see also above). This thrusting was associated with the formation of flexural foreland basins that likely existed from Middle/Late Eocene to Quaternary (Tari 2002; Merlini et al. 2002). This is corroborated by the evidence of compression tectonics in the SE continuation in Albania and in the Adriatic Sea (Carminati et al. 2004; Picha 2002). On the other hand, along the Vardar–Tethyan mega-suture and eastwards from it different tectonomagmatic conditions prevailed. They gave rise to widespread magmatism and formation of continental depositional systems. In the following text we illuminate only these two latter aspects of the SEE geology.

Cenozoic Sedimentary Basins

The formation of the Cenozoic sedimentary basins in SEE was primarily related to transtension and extension-related deformations that occurred from the Paleogene onwards. This was generally associated to a constant westward to southward retreat of E-, NE- to N-dipping subduction fronts, either as true oceanic plate subductions (subduction *s.s.*) or as deep underthrustings of thinned continental lithosphere (subduction *s.l.*). In response to this retreat, the respective suprasubduction/backarc areas underwent gravitational collapse and local spreading of previously thickened continental crust segments. In spite of this generally uniform tectonic framework, these extensional or extension-like pulses developed diachronously in different SEE regions, and these variations were controlled by the nature of the retreating subduction (oceanic vs continental lithosphere) and by local crustal anisotropy of the pre-Cenozoic basement. In this context, we distinguish the Cenozoic Dacic basin, and North and Southern Balkan Extensional Sectors (Rögl 1999; Burchfiel et al. 2003, 2008).

The Cenozoic Dacic basin is the western part of what is generally known as Eastern Paratethys (Rögl 1999). It was a wide sedimentary area, which was left behind from the much larger Vardar Tethys and since the Oligocene it acted as an isolated basin floored by continental crust. Most parts of the Eastern Paratethys occur outside of the northern boundary of SEE as defined in this article, and it will not be further addressed.

The Balkan Extensional Sector also created the Metohija depression and going north, encompasses much of the territories of Bosnia and Herzegovina and Serbia. It formed during the phase of opening of intramontane basins in the Dinarides, within a NNW-SSE wrench corridor associated to steeply dipping normal faults (Marović et al. 1999). The main tectonic cause for this event was a dual one: (1) the westward, and in Greece southward, retreat of the subduction front, associated to underthrusting of thinned continental crustal slices in the External Dinarides and Hellenides, which gave rise to gravitational subsidence in the overlying plate, and (2) retreat of the European slab underneath the Carpathians and opening the Pannonian basin. The same tectonic conditions were responsible for more or less contemporaneous magmatism (discussed below). The Northern Balkan Extensional Sector that underwent a strong tectono-sedimentary and magmatic overprint by the influence of the Pannonian extension led to exhumation processes and the formation of metamorphic core complexes along low-angle normal faults (Marović et al. 2007; Schefer et al. 2010; Matenco and Radivojević 2012).

The Southern Balkan Extensional Sector comprises Albania, FYR of Macedonia and the south–western parts of Bulgaria and north-western Greece. Post-orogenic sedimentary basins in this sector began to form in the late Eocene, when numerous NW-striking lacustrine basins formed. They were associated to extensional half-graben structures that originated in the eastern part in the FYR of Macedonia. Roughly simultaneously, similar basins formed in Bulgaria along NW-striking and W-dipping detachments, such as, for instance the large Mesta half-graben (Burchfiel et al. 2003; Kounov et al. 2004). This extensional phase produced several kilometers thick piles of Priabonian (Late Eocene) to Oligocene clastic and volcaniclastic deposits. Evidence of earlier extensions further east in the eastern Rhodopes is not entirely certain (Dimov et al. 2000). The second period started in Middle Miocene, after a short-lived compression event when the earlier sedimentary strata deformed by west-vergent structures (Dumurdzanov et al. 2005; Nakov et al. 2001), and also partly uplifted and eroded. Further to the west the Middle Miocene sedimentary phase produced heterogeneous types of basins, with the predominance of N-W-trending grabens. From the Late Miocene to the present day, in eastern FYR of Macedonia and adjacent Bulgaria E-W stretching normal faults and half-graben structures originated.

Cenozoic Magmatism

The immense subduction system of Eurasian continental active margin (e.g. Richards et al. 2012) entered its waning stage by the end of the Cretaceous. In the Upper Cretaceous occurred slab retreat and arc migration to the south and this, first changed fore-arc areas into arc regions (Kolb et al. 2013; Gallhofer et al. 2015; Gülmez et al. 2015) and then the entire arc system terminated by collision. During Cenozoic times this process continued to be the major mechanism of accommodating most of the shortening of an accretionary wedge of stacked nappes. These nappes represent the crustal portions decoupled from the underthrusting oceanic or continental lithospheric slab (Faccenna et al. 2003; Ricou et al. 1998; Schmid and Kissling 2000). The rolling-back of this slab, sometimes combined with its break-off and/or tear, produced rapid extension coupled with exhumation of the lower crustal material and high heat flow, which, in several areas ultimately gave rise to intrusive and extrusive magmatism (Bird 1979).

This magmatism is derived from both the mantle and the crust, and the rocks produced are geochemically extremely heterogeneous. In general, there is a roughly expressed age shift towards the west and south in Serbia and Bulgaria and Greece (and further in Western Anatolia), respectively. However, this shift is at many places obliterated because of magmatic events that were apparently controlled by regional- to local tectonic pulses. Additionally, there are substantial differences between this part of the Alpine–Himalayan orogenic magmatism and the classical active-margin or island-arc plate-tectonic models. It is so because in the former case the lithospheric slab(s) involved in subduction and roll-back processes was comprised of lithospheric mantle usually accompanied by lower crustal material generated by decoupling from the rest of the overlying crustal segments. Such subducting "lithospheric slab" is not simply a "wet oceanic lithosphere" that dehydrates and releases water necessary for melting of the overlying subarc asthenospheric mantle wedge. By contrast, in case of a delaminated slab melting is triggered when the asthenospheric mantle directly invades into the subcontinental lithosphere previously enriched in hydrous minerals or even into lower continental crust. Such complex geodynamic settings provided conditions for activation of different mantle and crustal sources and generation of wide spectra of mafic and intermediate to acid post-collisional magmas in the SEE region.

The above tectonomagmatic conditions resulted in formation of a large and diffuse zone of Eocene to Oligocene, subordinately Oligocene-Miocene igneous rocks. It stretches from the Periadriatic Province of the Alps up to the easternmost parts of the Macedonian–Rhodope–North Aegean Belt (Marchev et al. 2013). The belt continues further to East in the Thrace and Pontides volcanism in Turkey, and has its continuation in northwest Anatolia. The rocks are compositionally very heterogeneous, but there is apparent predominance of granitoid intrusives and associated acid to intermediate volcanic rocks.

The granitoid plutons were emplaced at mid-crustal levels, and have been exhumed by extension tectonics. They mostly occur along the Serbo–Macedonian Massif and the Circum–Rhodope Belt (e.g. Kopaonik Mts., Surdulica, Sithonia, Ouranopolis, Ierissos, etc.), within the Rhodope unit (e.g. Vrondou, Pirin, etc.) and smaller masses in the Kraishte and Sredna Gora tectonic units. They are dominantly I-type metaluminous, calc-alkaline to high-K calc-alkaline granites, granodiorites and tonalities, locally adakitic in character. Minor S-type intrusions, mostly Miocene in age, are found in Cyclades and Serbia. The origin of the I-type granitoids involves mixing (±fractional crystallization) between a mafic magma, derived by melting of a subduction-enriched depleted lithospheric mantle, and voluminous crustal felsic magma generated by melting of lower- to mid-crustal amphibolites (Perugini et al. 2003; Christofides et al. 2007, and references therein). The transition from non-adakitic to adakitic compositions is explained by amphibole fractionation of primary mantle-derived melts (Marchev et al. 2013). The origin of S-type magmas is modelled by melting of variable mid-to shallow crustal sources (Altherr and Siebel 2002; Cvetković et al. 2007).

It is widely accepted that the high-heat flow and melting associated to the formation of the Eocene-Miocene I-type intrusives did not result solely from thermal relaxation after tectonic thickening. By contrast, the melting of deep to middle crustal sources was most likely triggered by advective heating from mantle-derived melts. This means that mantle melting processes were essential for the petrogenesis of the origin of the I-type post-collisional granitoids, either by direct producing parental magmas, or by providing an advective heat source for melting of overlying continental crust (e.g. Pe–Piper and Piper 2002). There is a line of evidence for the presence of roughly contemporaneous mafic magmas in most post-collisional granitoid complexes in the SEE region, with omnipresence of mafic enclaves varying in composition from diorite to lamprophyre (Knežević–Đorđević et al. 1994; Prelević et al. 2004).

From the Oligocene to recent times occurred widespread volcanism in the SEE region. This volcanism was associated to the formation of numerous volcanic landforms, including stratovolcanoes, collapsing calderas, lava flows and various volcaniclastic facies and subvolcanic intrusions. The volcanoes occur within the same NW-SE directed belt as do the above described intrusives and host some very large volcanic areas in Serbia (e.g. Rudnik, Kopaonik, Lece, etc.), FYR of Macedonia (Kratovo–Zletovo) and Bulgaria (e.g. Zvezdel, Madzharovo, etc.). Although there is a general southward (westward) younging, there is no simple age-geochemical pattern among volcanic rocks. However, the ignimbrite flare-up is characteristic for the inception of extensional tectonic processes, which occurred in the late Oligocene-early Miocene. This was followed by the formation of a variety of subalkaline, potassic to ultrapotassic magmas, which indicates a progressive dehydration of the subcontinental lithospheric mantle. The youngest magmas were less voluminous, silica-undersaturated and sodic-alkaline in composition, suggesting a transition from lithosphere to asthenosphere melting in the orogenic environment. Generally, the volcanism shows orogenic geochemical features, characterized mostly by (high-K) calk-alkaline acid/intermediate volcanic rocks that are found intimately associated, in space and time with shoshonitic and ultrapotassic rocks.

One important consequence of the general geodynamic processes that triggered widespread volcanism within SEE may be an overall thinning of the lithosphere. As already mentioned above, during the interaction between the asthenosphere and lithosphere driven by rolling back of the delaminating lithosphere, previously metasomatized lithospheric domains hosting geochemically enriched material (with or without lower crustal segments) will be molten and removed due to the heat from the upwelling asthenosphere. In other words, we may expect thinning of considerable part of the lithospheric mantle, as being proposed for Western Anatolia (e.g. Kind et al. 2015) and the Pannonian basin (Horváth 1993; Falus et al. 2008), which resulted in increased heat flow. Available data for the thickness of the modern lithosphere in the central part of the SE Europe (Serbia, FYROM) based on the crustal temperature distribution, implies an approximate lithospheric thickness to be largest under the External Dinarides, where it is up to 260 km, whereas the large-extent thinning has been proposed for the Pannonian Basin and the Serbian–Macedonian Massif, with only 40–50 km (Milivojević 1993).

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