3.3. STRUCTURE AND GEODYNAMICS OF THE BALKAN REGION: A REVIEW

Christo Dabovski

3.3.1. Introduction

The Balkan region has an extremely complex geological structure that is dominated geologically by a system of fold-and-thrust belts and associated foreland and back-arc basins. These belts are products of long-lasting interactions between Eurasia and Gondwana, with successive episodes of continental break-up and oceanic development, subduction, continental collision and orogeny. Tectonic activity here spans from the Panafrican orogeny to the destructive present-day seismicity along the North Anatolian Fault.

3.3.2. Alpine orogenic belts

Since the pioneering studies of Cvijiи (1904), the Alpine orogenic belts on the Balkans have been for a long time traditionally subdivided into two systems (branches): (i) a northern, dominantly E- to N-verging (Carpathians and Balkanides) and (ii) a southern, SW- to S-verging (Dinarides and Hellenides). The Rhodope and Serbo-Macedonian massifs were understood as stable blocks separating the two orogenic systems. More recent studies have shown that these massifs were repeatedly deformed and involved in the tectonic processes that generated the Balkan orgenic belts (e.g. Burg et al., 1996) and in fact should be included in the orogenic architecture. Thus, if we accept the notion of two orogenic systems of opposite vergence, then the boundary between them can be placed along the Vardar zone, one of the main ophiolite sutures on the Balkans (Fig. 3.3.1).

The Carpathians **form an arcuate fold-and-thrust belt that merges to the west with the Alps and to the south with the Balkanides through a complex system of N-S strike-slip faults. The tectonic zonation of the East and South Carpathians in Romania (Sandulescu, 1984, 1994) is schematically shown on Fig. 3.3.1. The Inner Dacides outcrop in the Apuseni Mts. as a system of N-verging thrust sheets of pre-Mesozoic metamorphic rocks and Mesozoic, mainly carbonate platform sequences. The Transylvanides are likewise an N-verging thrust complex of Lower-Middle Jurassic ophiolite and island-arc assemblages, which override the Inner Dacides. This unit is interpreted as the suture zone of a Jurassic ocean that opened during the Early Jurassic and closed in Mid-Cretaceous time. The Median Dacides (Supragetic and Getic nappes) comprise pre-Mesozoic metamorphic–magmatic basement complexes and Mesozoic sedimentary sequences. The Outer Dacides (Severin and Ceahlau nappes) are a thrust sheet complex of Jurassic-Lower Cretaceous turbidites and minor ophiolites. The Marginal Dacides (Danubian), exposed in a tectonic window below the Getic nappes, are composed of Precambrian and Paleozoic basement rocks, covered by a relatively thick succession of Mesozoic shallow- to deep-marine sediments. The Moldavides comprise**

mainly Hauterivian-Barremian to Mid-Sarmatian flysch sediments, thrust towards the foreland

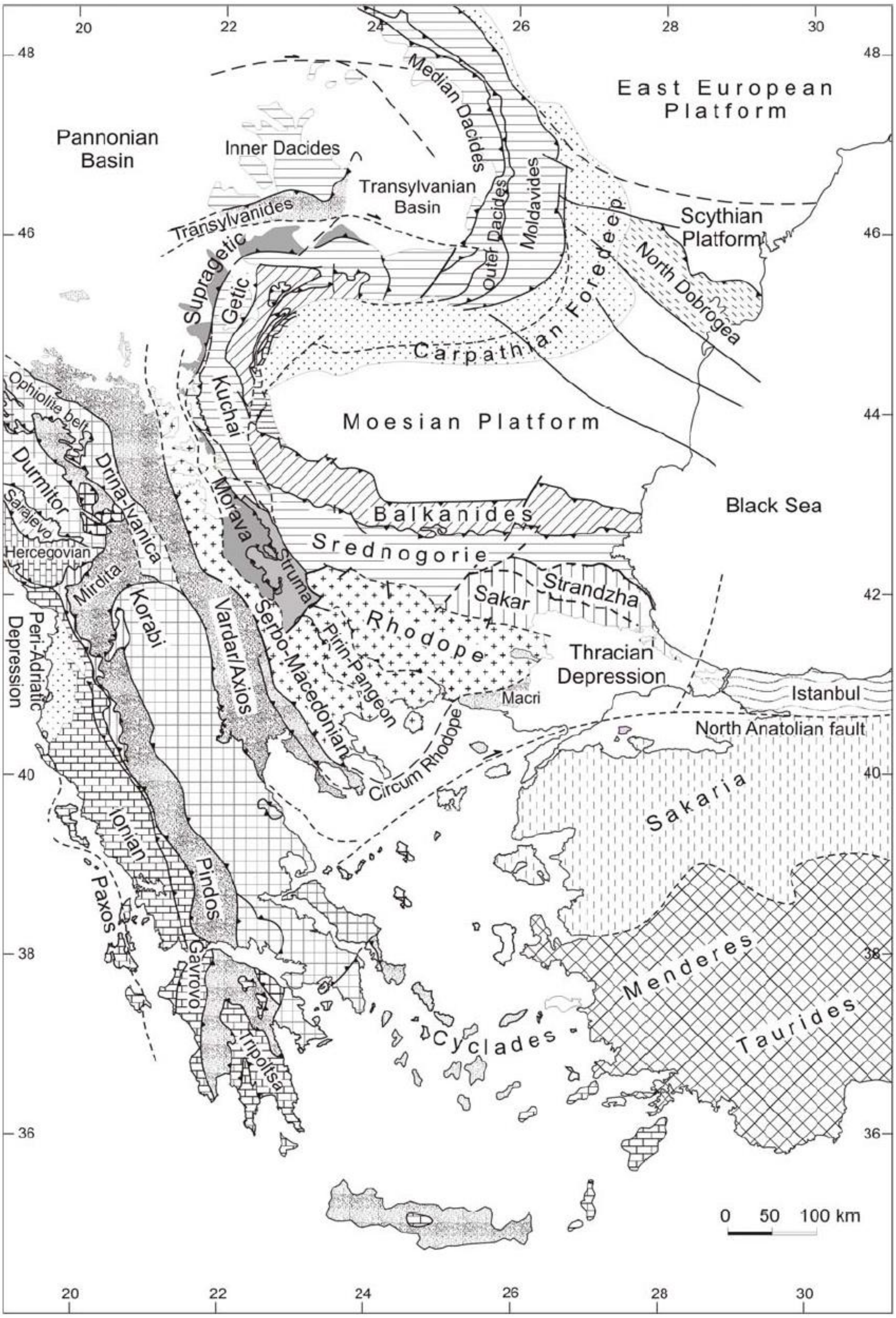

Fig. 3.3.1. Orogenic belts and major tectonic units on the Balkans (based on Sandulescu, 1994, Dimitrijevиc, 1999, Kräutner, Krstiи, 2003, Bornovas, ed., 1983, Papanikolaou et al., 2004, Carminati et al., 2004, Dabovski et al., 200,; Okay, Tüysüz, 1999)

(Scythian and Moesian platforms) and partly overriding the shallow-marine Upper Miocene to lowermost Pleistocene molasse deposits of the Carpathian foredeep.

Major compressional events and thrusting in the Carpathians are recorded toward the end of the Early Cretaceous (Transylvanides, all Dacidic units), the end of the Late Cretaceous (Median, Outer and Marginal Dacides) and during the Late Oligocene-Miocene (Moldavides).

***The Balkanide orogenic belt* is a gently curved, NW-SE to W-E-trending, generally N-verging fold-and-thrust system, located between the Moesian platform to the north and the Vardar zone to the south (Fig. 3.3.1.). From north to the south, four major tectonic zones can be recognized (Dabovski et al., 2002). Typical of the external Balkan zone are Jurassic-Lower Cretaceous to Early Tertiary flysch sequences and almost total lack of Mesozoic and Tertiary magmatic activity. The Srednogorie zone, interpreted as the remnant of an Upper Cretaceous volcanic island arc (Boccaletti et al., 1974), comprises an over 5 km thick pile of volcanics and sediments of the same age. The Strandzha-Sakar zone includes two tectonic units: a lower, autochthonous (Precambrian-Paleozoic basement covered by Triassic-Jurassic shallow-marine sediments); and an upper, allochthonous unit (Paleozoic greenschists and Triassic deep-marine metasediments) that was thrust over the lower in Late Jurassic or Mid-Cretaceous time. The Morava-Rhodope zone is a complex thrust system of five tectonic units (Strouma, Morava, Rhodope, Pirin-Pangeon and Serbo-Macedonian). Characteristic features of all units are: widely exposed high-grade metamorphic basement and Eocene-Oligocene volcanosedimentary sequences; almost total lack of Mesozoic cover (except for Strouma and Serbo-Macedonian units), main Mid-Cretaceous compressional deformations and thrusting; Late Cretaceous-Early Tertiary crustal thickening, exhumation and related growth of metamorphic core complexes, accompanied by Tertiary magmatic activity (e.g. Ivanov, 2000; Khroe, Mposkos, 2002) in the southern units (Rhodope, Pirin-Pangeon, Serbo-Macedonian).**

The Alpine evolution of the Balkanide belt has been described (Georgiev et al., 2001, Dabovski et al., 2002) as a series of successive episodes of extensional and compressional deformations along the south-facing convergent margin of the European plate. Major compressional events are recorded toward the end of the Late Triassic, the end of the Middle Jurassic, the end of the Early Cretaceous, and during the Mid-Eocene – the time of main structuration of the belt. Extensional regime is dominating from the Late Eocene to present days.

***The Vardar (Axios) zone* is a complex stack of thrust sheets emplaced to the SW over the Internal Hellenide platform (Papanicolaou, 1996-1997) as rootless ophiolite slices. Most authors agree that this unit traces one of the main suture zones on the Balkans, resulting from the closure of a Jurassic ocean (Vardar/Axios). The time of closure of this ocean is controversial – during the Late Jurassic-Early Cretaceous or during the Eocene (discussion in Brown, Robertson, 2004). The northern parts of Vardar zone merge into the Circum Rhodope belt of Kockel et al. (1971). In NW Greece, this belt is similar in rock composition to Vardar zone and, due to complex tectonic interrelations, is not well defined. In NE Greece and Bulgaria (Eastern Rhodope), a possible equivalent (Mandritsa-Makri) of this belt has been recently described (Bonev, Stampfli, 2003) as a Late Jurassic-Mid Cretaceous nappe over the Rhodope high-grade metamorphics, later reactivated as a Tertiary detachment fault. The section comprises greenschists at the base, overlain by a melange-like Jurassic-Lower Cretaceous volcano-sedimentary sequence and Upper Cretaceous sediments and volcanics.**

The Hellenides **are a SW- to S-verging thrust belt (Fig. 3.3.1.) that extends across continental Greece and the Aegean islands to the Turkish coast, merging to the east into the Pontides, Sakaria and the Taurides. Several major tectonic units are distinguished from northeast to the southwest (Papanicolaou, 1996-1997, Papanicolaou et al., 2004). The internal Hellenides platform (roughly equivalent to the Pelagonian zone of other authors) is composed of pre-Mesozoic basement, Middle Triassic to Late Jurassic platform carbonates, overthrust by ophiolites of the Vardar unit, and a transgressive cover of Maastrichtian carbonates and Maastrichtian-Danian flysch. The Pindos-Cyclades unit is a SW-verging system of thrust sheets over the External Hellenides platform that comprises pelagic Upper Triassic to Cretaceous sediments, Jurassic ophiolite slices and Maastrichtian-Danian flysch. HP/LT blueschists, metamorphosed in Early Tertiary time, are characteristic of the Cyclades. The Pindos-Cyclades unit is interpreted as the suture zone of a Jurassic (Pindos) ocean that opened during the Late Triassic-Early Jurassic and closed in latest Cretaceous to Eocene time. The External Hellenides platform (Paxos, Ionian and Gavrovo-Tripolitsa) is a fragment of Gondwana (Apulia), composed of a thick Triassic to Eocene carbonate platform with a pelagic basin (Ionian) in the axial part.**

The Alpine history of the Hellenides is governed by the opening, subduction and closure of a series of oceanic basins, followed by microcollisions and accretion of continental terranes along the European margin (Papanicolaou et al., 2004). Major orogenic events, related to terrane accretion, are recorded in Late Triassic (Cimmeride orogeny), Late Jurassic-Early Cretaceous (paleo-Alpine orogeny) and Eocene-Miocene time (main Alpine orogeny).

The Dinarides **are a SW-verging thrust belt between the Adriatic (Apulian) platform and the Vardar zone, merging into the Hellenides to the SE and the Southern Alps to the NW (review in Dimitrijevič, 1995, 2001, Karamata et al., 1996-97). The section of the innermost Drina-Ivanica tectonic unit, located immediately SW of the Vardar zone (Fig. 3.3.1.), comprises Paleozoic low-grade metamorphic rocks at the base, followed upward by Triassic clastics and platform carbonates, Upper Cretaceous sediments and Senonian flysch. The Dinaride ophiolite belt is the hypothetical suture zone of a former oceanic domain that opened in the Early-Middle Triassic, separating Drina-Ivanica from Bosna-Durmitor domain, and closed during the Late Jurassic. Typical components of this unit are huge olistoplakas of Triassic carbonates, gravitationally transported from NE (form Drina-Ivanica), and large bodies of ultramafics and ophiolites embedded in an ophiolitic melange. The East Bosna-Durmitor unit is a complex pile of several large SW-verging thrust sheets, composed of Paleozoic and Mesozoic (Triassic to Lower-Middle Jurassic) sequences and ophiolitic melange. The Sarajevo Sigmoid comprises a series of nappes (dominantly Senonian flysch) thrust to the SW over the Dalmatian-Hercegovian unit – a thick Upper Triassic to Paleocene carbonate platform. The Budva zone comprises a rather condensed Mesozoic section covered by thick Oligocene flysch.**

The southeastern domains of the Dinarides in Albania are known as Albanian Dinarides. They are traditionally divided into Internal and External units (e.g. Frasheri et al., 1996; Carminati et al., 2004), which are comparable to most of the Dinaride units in the neighboring Serbia and Macedonia. The external units of the Albaian Dinarides are thrust to the SW over a foredeep basin (the Peri-Adriatic Depression), filled by Eocene-Quaternary turbiditic sediments.

The Alpine evolution of the Dinarides started with Permian-Triassic extension and rifting, followed by Late Jurassic-Early Cretaceous compression as a result of the

closure of Vardar Ocean and SW obduction of oceanic crust. The main structuration of the belt occurred progressively from the latest Maastrichtian onward, with climax between the Oligocene and the Earliest Miocene, concurrent with the convergence between the Adriatic (Apulian) and European plates. This process continued during the Neogene and is still active.

3.3.3. Mesozoic and Tertiary geodynamics

During the last 25 years, numerous alternative paleotectonic reconstructions and models for the geodynamic evolution of the Tethyan, and in particular the Mediterranean domain, have been proposed. Controversial and contradicting in many details, they are founded on a common basic concept and develop in plate tectonic context the idea of Suess (1901) about a Tethyan ocean that closed in Late Mesozoic-Tertiary time and generated the Alpine-Himalayan fold-and-thrust belt.

One popular concept is that of a single Tethys (e.g. Ricou, 1994) – a closed Mesozoic ocean of equatorial direction that divided the continents into northern and southern. Tethys opened towards the end of the Permian and the beginning of the Triassic during the break-up of Pangea, reached its maximum width during the Early Cretaceous, separating entirely Laurasia from Gondwana, and closed in Late Eocene time, leaving the Alpine-Himalayan orogen as a suture zone of the closed ocean.

According to another alternative concept (Stöklin, 1974, Sengör, 1979, 1984, Sengör, Yilmaz, 1981), the Alpine-Himalayan orogen was generated during the closure of two Tethyan oceans. The earlier (Paleotethys) opened after the Hercynian orogeny and closed in the period Triassic-Early Jurassic as the result of northward drift of a long and narrow fragment of Gondwana ("Cimmerian continent"). This continent moved to the north, rotating counterclockwise around a pole in the domain of the present-day Carpathians, and opened another ocean or several oceanic basins to the south along the Gondwana margin, known under the collective name of Neotethys. Neotethys opened during the Triassic and continues to close today. During the closure of the two oceanic basins, subduction was mainly or entirely northwards at least from the Permian onwards. Thus, Sengör introduced the concept that the Alpine-Himalayan fold-andthrust belt ("Tethysides" in his terminology) is composed of two independent, superimposed orogens – Cimmerides, resulting from the closure of Paleotethys, and Alpides – a product of Neotethys.

Recently, new plate tectonic models have been proposed based on multidisciplinary approach to plate tectonic reconstructions (Ziegler et al., 2001, Stampfli et al., 2001, Stampfli, Borel, 2004). According to these models, the present-day geological configuration of the Mediterranean region is the result of the opening and subsequent consumption of two major oceanic basins (Paleotethys and Neotethys) and of additional smaller back-arc basins behind subduction zones within an overall regime of prolonged interaction between the Eurasian and the African-Arabian plates. The closure of these heterogenous oceanic domains produced a system of discrete orogenic belts of diverse tectonic setting, timing of deformation and internal architecture. From this point of view, the Mediterranean fold-and-thrust belts cannot be interpreted as the end product of a single "Alpine" orogenic cycle but instead are the result of different tectonic events spanning from the late Triassic to the Quaternary.

***The Mesozoic geodynamics* of the Mediterranean region is shown on Fig 3.3.2 as an illustration of the model of Stampfli and Borel (2004).**

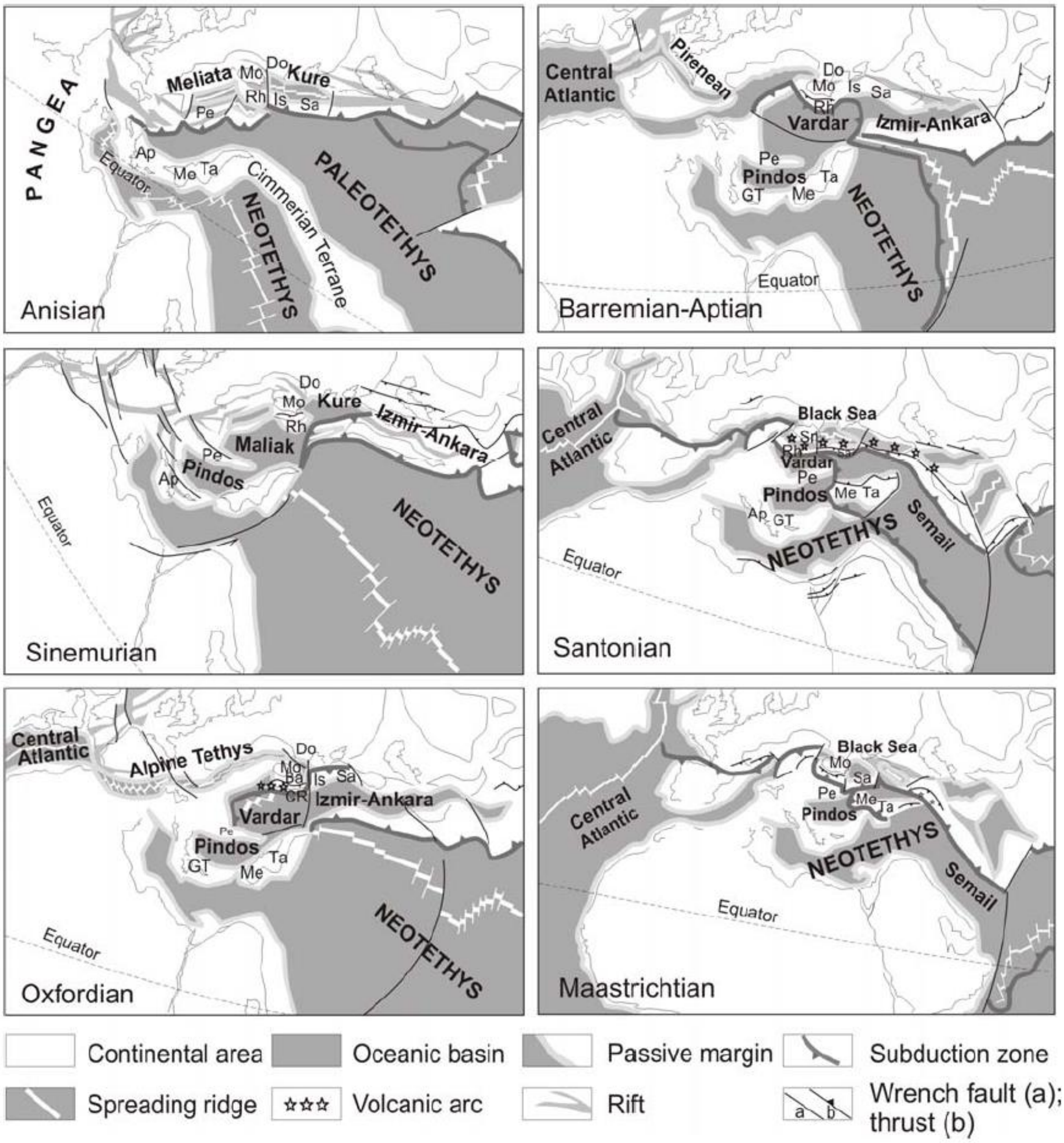

Fig. 3.3.2. Paleogeographic reconstructions of the Western Tethys region during the Mesozoic (after Stampfli, Borel, 2004, simplified and slightly modified) Abbreviations of some major tectonic units: Ap - Apulia; Ba - Balkan; GT -Gavrovo-Tripolitsa; Do - Dobrogea; Is - Istanbul zone; Mo - Moesia; Me - Menders; Rh - Rhodopes; Sa - Sakaria; Sr - Srednogorie; Ta - Taurides; CR – Circum Rhodope.

During the Triassic, northward subduction of Paleotethys induced back-arc extension, rifting and opening of small oceanic basins (Meliata-Maliak, Küre), followed by Late Triassic closure of Paleotethys and collision of Cimmerian terranes with the southern margin of Eurasia (Cimmerian orogeny). Northward subduction of Neotethyan oceanic crust started in Early Jurassic time with a new back-arc extensional regime along the Eurasian margin, associated rifting and opening of new oceanic basins (Pindos, Vardar, Izmir-Ankara). Towards the end of the Jurassic, intra-oceanic subduction of Meliata-Maliak beneath the spreading Vardar ocean generated a Jurassic volcanic island arc. The collision of this arc with the Serbo-Macedonian-Rhodope Massif in Barremian-Aptian time initiated compression, northward-propagating thrusting and basin inversion (Mid-Cretaceous orogeny). This major compressional event on the Balkans

was followed by continuous subduction of Vardar oceanic crust beneath the Serbo-Macedonian-Rhodope Massif, initiation of the Late Cretaceous Banat-Srednogorie-Pontide volcanic arc and the Black Sea as a back-arc basin. During the Maastrichtian, Vardar closed and Pelagonia collided with the Serbo-Macedonian-Rhodope, inducing Late Cretaceous thrusting, basin inversion and crustal thickening in the Rhodope area.

***The Tertiary geodynamics*, still not well constrained, records the final structuration of the fold-and-thrust belts on the Balkan Peninsula. After the Late Cretaceous closure of the Vardar Ocean, the region experienced a series of changes from extensional to compressional tectonics, related to continuous subduction of the Apulian plate beneath the southern Eurasian margin and closure of Pindos Ocean in Late Eocene to Miocene times.**

3.3.4. Present-day geodynamics

The present-day geodynamics of the Balkan region is controlled by the active tectonic processes in the Eastern Mediterranean (Fig. 3.3.3.): (i) the subduction of the Adriatic (Apulian) microplate beneath the Dinarides; (ii) the subduction of oceanic Ionian and Levantine lithosphere under the Hellenic arc-and-trench system; (iii) the collision between Eurasia and Arabia with related westward escape of Anatolia along the North Anatolian dextral strike-slip fault. The present-day activity of these processes is indicated by GPS velocity data (Fig. 3.3.3.) and the clustering of seismic epicenters along the two subduction zones and the trace of the North Anatolian fault (Fig. 3.3.4B).

The *Dinaric subduction zone* follows the eastward subducting margin of the Adriatic microplate (Figs. 3.3.3., 3.3.4.). It has a 25-30 km thick continental crust with upper parts composed of a thick succession of Permian-Paleogene platform and basinal carbonates (Cavazza et al., 2004). The subduction zone is fringed to the east by a flexural foredeep basin (the Peri-Adriatic Depression, see Fig. 3.3.1.), filled with several km thick synorogenic Oligocene-Quaternary sediments. Farther east follow the west-verging Dinaride fold-and-thrust belt and an extensional domain in its inner parts, characterized by Neogene and Quaternary extensional basins and associated magmatic activity.

The Dinaric subduction merges to the south into the *Hellenic subduction zone*, where oceanic Ionian and Levantine lithosphere subducts under the Hellenic arc-and-trench system (Fig. 3.3.3.). The following major tectonic elements of the system can be recognized from south to the north (Papanicolaou et al., 2004): (i) the relatively deep (about 5 km) fore-arc basin in the western part of the Hellenic trench; (ii) the uplifted (frontal) island arc from Peloponnesus to Crete and the Dodecanese; (iii) the back-arc basin of the Cretan Sea; (iv) the modern Aegean volcanic arc; (v) the back-arc basin of the Aegean Sea with stretched continental crust (see Fig. 3.3.4.(A)). The East Mediterranean Ridge is located on the lower plate of the subduction zone and forms an accretionary prism of over 8 km thick imbricated sediments detached from the underlying oceanic crust and thrust to the south.

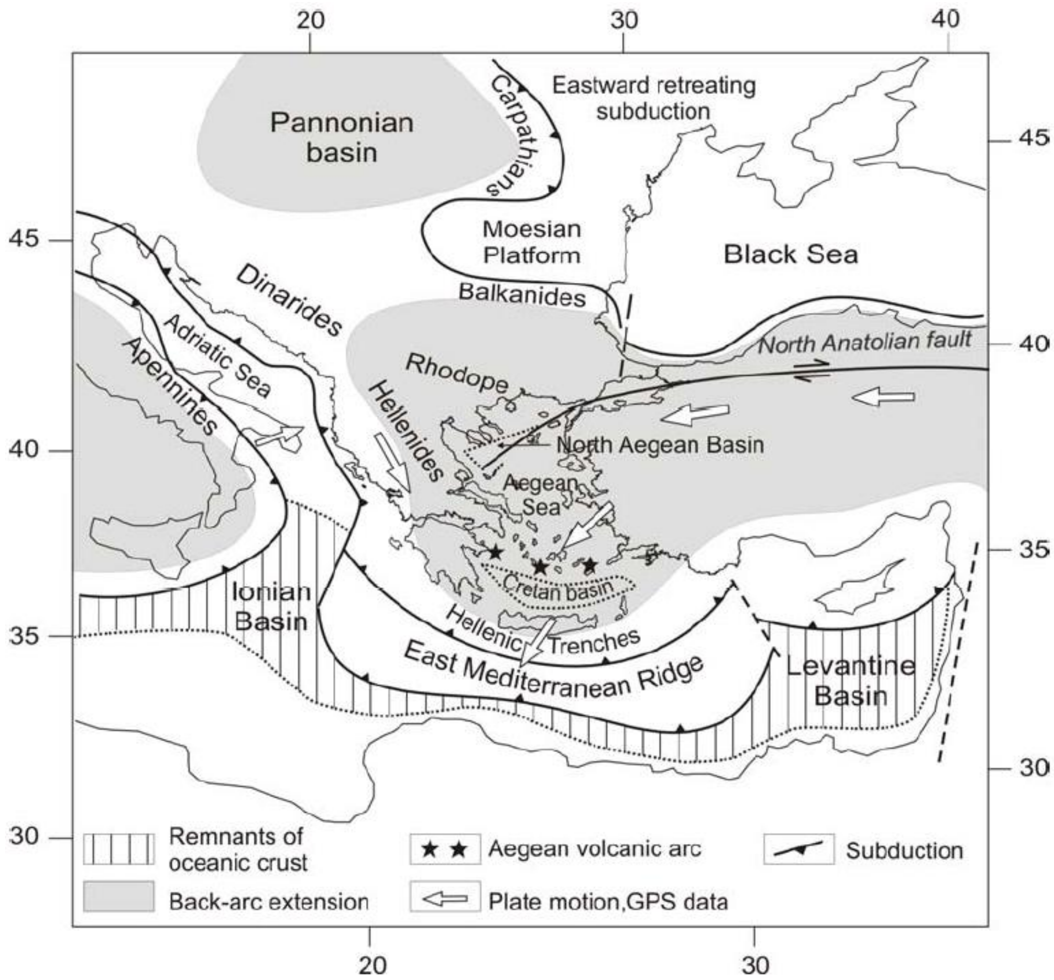

Fig. 3.3.3. Active processes in the Eastern Mediterranean (based on Carminati et al., 2004, Papanicolaou et al., 2004)

The subduction zone is well pronounced on seismic tomographic images and can be followed for several hundreds of km below the Aegean Sea (Wortel, Spakman, 2000). The tomographic evidence suggests the cumulative result of a long-lasting subduction process, which involves continental fragments of a few hundreds of km in width. The present-day activity of the subduction zone is indicated by a relatively shallow (30$_0$) dipping Benioff seismic zone, extending to about 150-200 km in depth. The lack of deeper focal mechanisms has been attributed to slab detachment.

To the north of the subduction zone, the Aegean and peri-Aegean region is dominated by widespread Neogene extensional tectonics (Fig. 3.3.3.), as indicated by thinning of continental crust along low-angle detachment faults (e.g. Durand et al., 1999, Burchfiel et al., 2000). This extensional regime can be attributed to roll-back and progressive retreat of the Ionian and East Mediterranean lithospheric slabs, which allows for southeastward and southwestward extension of the Aegean region (e.g. Royden, 1993).

Stress field studies are in agreement with this geodynamic scenario. The extension direction in the Northern Aegean and surrounding land areas is in general N-S oriented (see Reinecker et al., 2005), i. e. perpendicular to the Hellenic subduction zone, whereas in the Southern Aegean region, the Hellenides and Western Anatolia, the extension direction is roughly parallel to the subduction front and the general trend of the thrust belts.

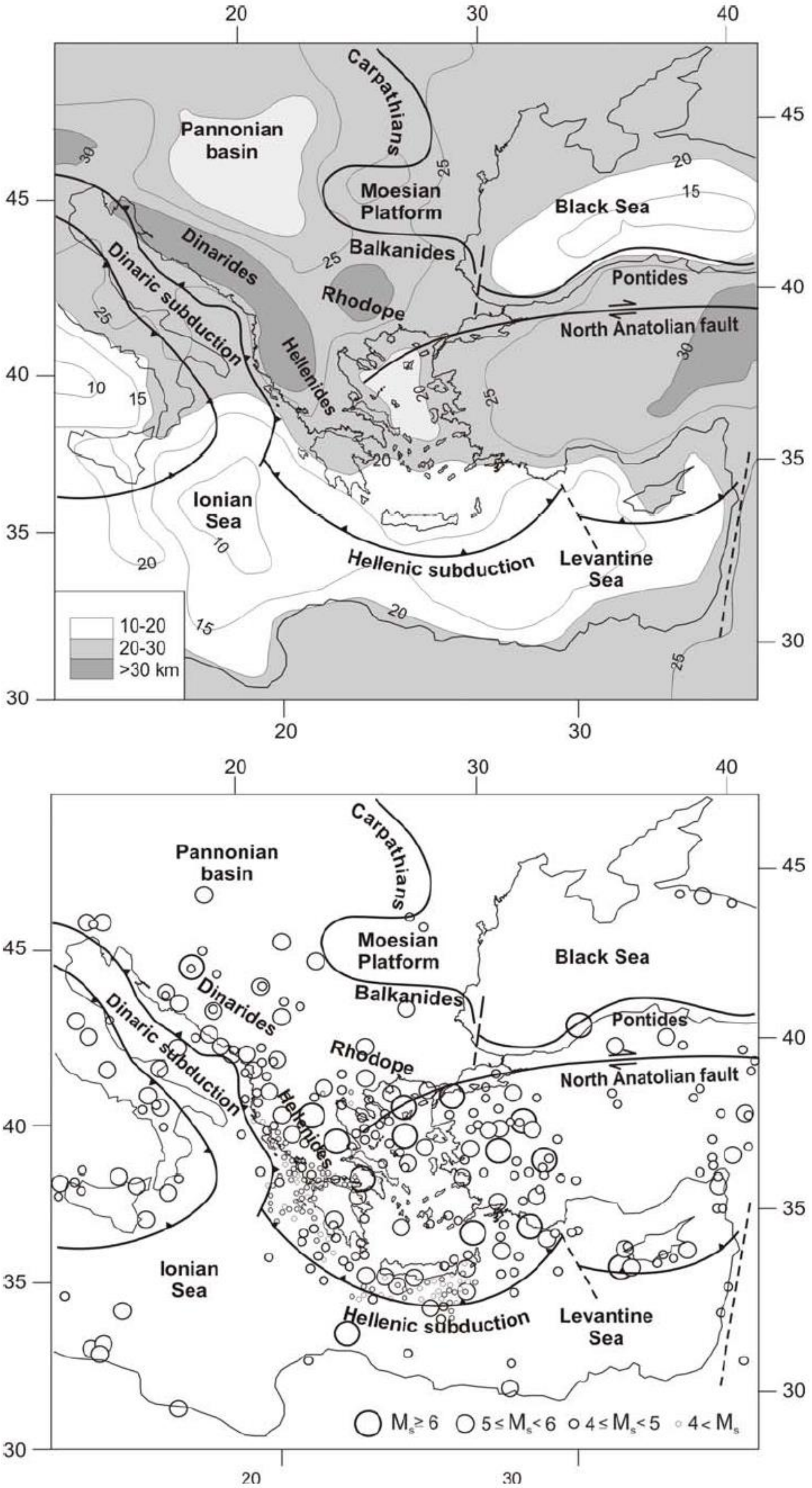

Fig. 3.3.4. Crustal thickness (A) and seismicity (B) in the Eastern Mediterranean (after Cavazza et al., 2004)

The *collision between Eurasia and Arabia* has a not so well pronounced but nevertheless cumulative effect on the overall extensional regime in the Aegean region. GPS velocities (Fig. 3.3.3) indicate that relative to stable Africa, Arabia moves northward at 10 mm/yr; Anatolia rotates counterclockwise and escapes at 20 mm/yr westward from the Arabia-Eurasia collision along the North Anatolian dextral strike-slip fault; the Aegean Sea moves SSW at 40-50 mm/yr (Papanicolaou et al., 2004). North of the North Anatolian fault, however, the southward convergence of Europe relative to Africa is limited to 10 mm/yr. This velocity difference between Europe and Anatolia is accommodated by the oblique opening of the North Aegean basin as a result of combined N-S oriented extension and dextral strike-slip.

This kinematics has been maintained since Late Miocene times, when the subduction of Ionian oceanic crust was initiated, at the same time as the collision between Arabia and SE Eurasia and the subsequent dextral motion along the North Anatolian fault.

3.3.5. References

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