Evolution and dynamics of the Cenozoic tectonics of the South Balkan extensional system

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ABSTRACT

The South Balkan extensional system consists of normal faults and associated sedimentary basins within southern Bulgaria, Macedonia, eastern Albania, northern Greece, and northwestern Turkey. Extensional tectonism began during the final convergence across the Vardar, Intra-Pontide, and Izmir-Ankara suture zones, where oceanic regions closed between continental Europe and continental fragments that make up the Pelagonian, Sakar, and western Anatolian tectonic units. Earliest extension of latest Cretaceous–middle Eocene age appears to have occurred within a regional convergent tectonic setting and may be related to an increase in gravitation potential energy within a thickening continental lithosphere. Following diachronous closure across the suture zone, from the middle Eocene to late Oligocene, the transition from a regionally convergent to a regionally extensional tectonic setting occurred and was associated with abundant magmatism and formation of sedimentary basins. Extension was associated with lithospheric thinning probably related to changes in geometry of the subducted slab, dynamics of the mantle wedge, and beginning of slab rollback along the Hellenic subduction zone. A short period of local and diachronous (?) shortening (during latest Oligocene–early Miocene time) occurred in the Thrace basin of northwestern Turkey and in some basins in western Bulgaria and eastern Macedonia. Regional extension began in middle Miocene time and was related to the regional extensional tectonic setting that has dominated the Aegean extensional region to the present. Trench rollback was the dominant dynamic process, but during late Miocene time it was modified by the formation of the western part of the North Anatolian fault zone that partially decoupled the South Balkan extensional system from the Aegean extensional region. During late Cenozoic time, east-west–striking normal faults and associated sedimentary basins in the eastern part of the South Balkan extensional system propagated westward in tandem with westward migration of north-south–striking normal faults and sedimentary basins from western Bulgaria into eastern Albania. This migration was caused by evolution of the Hellenic subduction zone

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as it increased its curvature during trench rollback and clockwise and counterclockwise rotation of crustal fragments in the west and east, respectively. After formation of the western part of the North Anatolian fault zone, extension within the eastern part of the South Balkan extensional system was related to southward movement of its lithosphere at a slower rate than the extension within the Aegean extensional region. Active extension and basin formation show two provinces of extension that are nearly at right angles to one another and their overlap in the central South Balkan extensional system: east-west extension in central Albania to eastern Macedonia and north-south extension from northwestern Greece and eastern Macedonia to eastern Bulgaria and northwestern Turkey.

INTRODUCTION

The Cenozoic South Balkan extensional system is within southern Bulgaria, Macedonia, eastern Albania, northern Greece, and northwesternmost Turkey (Fig. 1). Extension within this region began in Paleogene or possibly latest Cretaceous time during the final closure of the Vardar Ocean and subsequent postcollisional deformation. There is a long history of Mesozoic tectonic activity in the Vardar, Pindus, and Izmir-Ankara oceanic regions (e.g., Dilek et al., 2005, 2007, and references therein) that is not considered here because the focus of this study is on the Cenozoic extension in the southern Balkans that leads to the formation of the modern Aegean regime. The South Balkan extensional system was part of the more regional Aegean extensional realm before the formation of the North Anatolian fault zone in late Miocene–Pliocene time (Şengör et al., 2004). Since the development of the North Anatolian fault zone the South Balkan extensional system has been largely or partially decoupled from the Aegean extensional realm to the south. The Cenozoic tectonic evolution of the South Balkan extensional system was associated with the development of the numerous sedimentary basins in the region and much of the timing of faulting can be determined from the sedimentary history of the basins (Fig. 2). During the past decade we have conducted geological, geodetic, and seismological studies within Bulgaria and Macedonia; here we summarize our results and include observations from northern Greece, Albania, and northwestern Turkey to try and present a more complete, but still preliminary, tectonic interpretation of the South Balkan extensional system as we understand it today. Most of the interpretations presented here are taken from our previous work (Tzankov et al., 1996; Burchfiel et al., 2000, 2005, 2008; Nakov et al., 2001; Dumurdzanov et al., 2004, 2005; Kotzev et al., 2001, 2005, 2008) plus an extensive body of literature by other scientists.

The deformation in the South Balkan extensional system exhibits several changes in its development that are gradual but can be tentatively divided into four loosely defined periods: (1) latest Cretaceous and early Paleogene extension within a regional convergent tectonic setting; (2) middle Eocene–late Oligocene (possibly extending into earliest Miocene) extension associated with abundant magmatic activity within a complex transitional tectonic setting that changed from regional compression to the beginning of regional extension; (3) a short period of local (?) shortening, strike-slip faulting, and lack of basin formation during latest Oligocene and early Miocene time; and (4) middle Miocene to present regional extension that affected not only the South Balkan extensional system, but also the Aegean Sea area. The change from a regional compression to regional extension in the Paleogene (periods 1 and 2 above) was related to the termination of subduction within the Vardar zone. During late Miocene time the formation of the North Anatolian fault system caused significant diachronous and progressive changes in extensional tectonism within the South Balkan extensional system, suggesting that at that time there was only a weak coupling between the deformation in the Aegean and the South Balkan extensional system.

TECTONISM IN LATEST CRETACEOUS AND PALEOGENE TIME AND CLOSING OF THE VARDAR OCEAN

Closing of the Vardar Ocean

In latest Cretaceous and earliest Cenozoic time the region of the South Balkan extensional system was on the European plate, separated from continental fragments to the west and south by

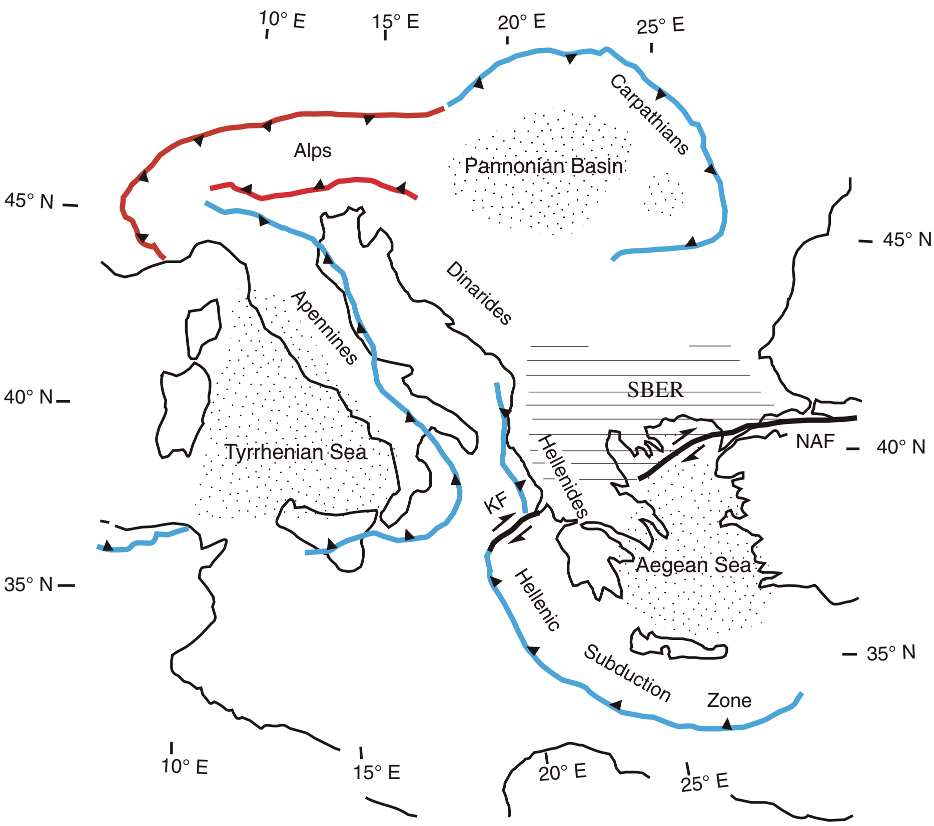

Figure 1. Location of the South Balkan extensional system (SBER) within the eastern European region. The system today is within the southern Balkan region north of the North Anatolian fault (NAF), shown by the horizontal line pattern. Retreating subduction zones and related backarc extensional areas for the Mediterranean region are shown in blue, and advancing subduction zones and related areas of backarc shortening are shown in red (see Royden and Burchfiel, 1996). Backarc extensional regions are shown by dotted pattern. KF—Kefalonia fault zone.

the Vardar Ocean (Brown and Robertson, 2004). With closure of the Vardar Ocean in the west and its two eastern branches, the Intra-Pontide and Izmir-Ankara zones, the Pelagonian, Sakarya, and Anatolide-Tauride continental fragments were accreted to the Balkan area, loosely a part of the European plate at the time. The time of closure of the Vardar zone is not well defined, and was a progressive and diachronous process. There is general agreement that the Vardar Ocean closed in earliest Cenozoic time, and its remnants are preserved within central Macedonia, northern Greece, and northwestern Turkey, but many parts of it are largely covered by the northern Aegean Sea (Fig. 3). The nature of the closing of the Vardar Ocean is necessary to understand its relations to the tectonic development not only in the South Balkan extensional system, but also in areas of Greece and Turkey, to the west and south, respectively, of the suture. Closure of oceanic regions is never instantaneous, but it is progressive, as gradually thicker continental lithosphere is drawn into the subduction zone, and convergent motion, often oblique, may continue following final subduction of oceanic lithosphere. Such a progression has important dynamic effects that change with time, and such changes are manifested in the early history of the South Balkan extensional system.

There is only general agreement on the time of closure and suturing of continental fragments along the Vardar suture zone, but the timing is important, however poorly known. Closure of the Vardar Ocean in Macedonia occurred between latest Cretaceous (possibly Paleocene) and Priabonian time (Dumurdzanov et al., 2005). Brown and Robertson (2004) indicated that deformation in northern Greece within the Vardar zone was active into the early Tertiary, but overlapping strata are not well-enough dated to yield a well-defined time for closure. Farther east in western Turkey, the relations are more complex, because the oceanic area separated into two branches, the northern Intra-Pontide and southern Izmir-Ankara (Fig. 3).

The Intra-Pontide branch, identified by Şengör and Yilmaz (1981), is the more complicated of the two because in northwestern Turkey outcrops of these rocks are rare and scattered; in fact, its existence is even doubted by some workers, who argue that the oceanic remnants assigned to this branch are fragments emplaced by Late Cretaceous or younger strike-slip displacement from a single Izmir-Ankara ocean. The work by Robertson and Ustamor (2004) on the Intra-Pontide zone in the Armautlu Peninsula east of the Sea of Mamara supports the existence of the Intra-Pontide ocean, but its trace to the west is located in different places by different workers. One option places it through the Gulf of Saros (Şengör and Yilmaz, 1981); a second, modified by later north-south strike-slip faults (see Okay et al., 1994), places the trace northward from the Sea of Mamara into the Srednagorie zone of central Bulgaria (see Yilmaz et al., 1997); a third option places it along an ill-defined north-northeast trace in the central part of the Biga Peninsula (Okay et al., 2001). We accept the position of the Intra-Pontide suture through the Gulf of Saros as correct based on all the geological evidence. All these options leave some data unexplained. In particular, the two other optional positions for the sutures to the north and south are not marked by suture zone rocks and leave the rocks related to the suture through the Gulf of Saros unexplained. Along our accepted branch of the Intra-Pontide suture in the southern part of the Thrace basin, late Lutetian–late Eocene strata unconformably overlie ophiolitic mélange that has yielded Paleocene, early Eocene, and early Lutetian ages in northwestern Turkey (Senturk and Okay, 1984; Sumengen and Terlemez, 1991), supporting the earlier interpretation of Şengör and Yilmaz (1981) for the location of the suture and the closure of the Intra-Pontide suture in middle Eocene time. The studies by Robertson and Ustamor (2004) and Okay et al. (2001) suggest that even though oceanic crust may have disappeared in the latest Cretaceous or Paleocene time, folding and thrusting continued at least into the early-middle Eocene, and the crust within the South Balkan extensional system was within a region of convergence during the early part of Paleogene time.

There is some uncertainty about the vergence of the subduction along the Intra-Pontide suture, where the Sakarya continental fragment was sutured to the continental crust of the South Balkan extensional system. Where the data are most abundant just east of the Sea of Mamara and in the eastern Rhodope Mountains (Fig. 3), deformation indicates north vergence along the suture. Robertson and Ustamor (2004) interpreted the local and regional structural and magmatic relations to indicate the major subduction was to the north, but modified by postsuturing convergence that produced shallow crustal north-vergent structures.

The Izmir-Ankara branch of the Vardar suture is marked by abundant remnants of oceanic crust, associated sedimentary deposits, and blueschist metamorphism, indicating northward subduction along its arcuate trace in northwestern Turkey (Fig. 3). Along this suture the Anatolide-Tauride continental fragment was accreted to the Sakarya fragment to the north. The northern margin of the Anatolide-Tauride fragment shows

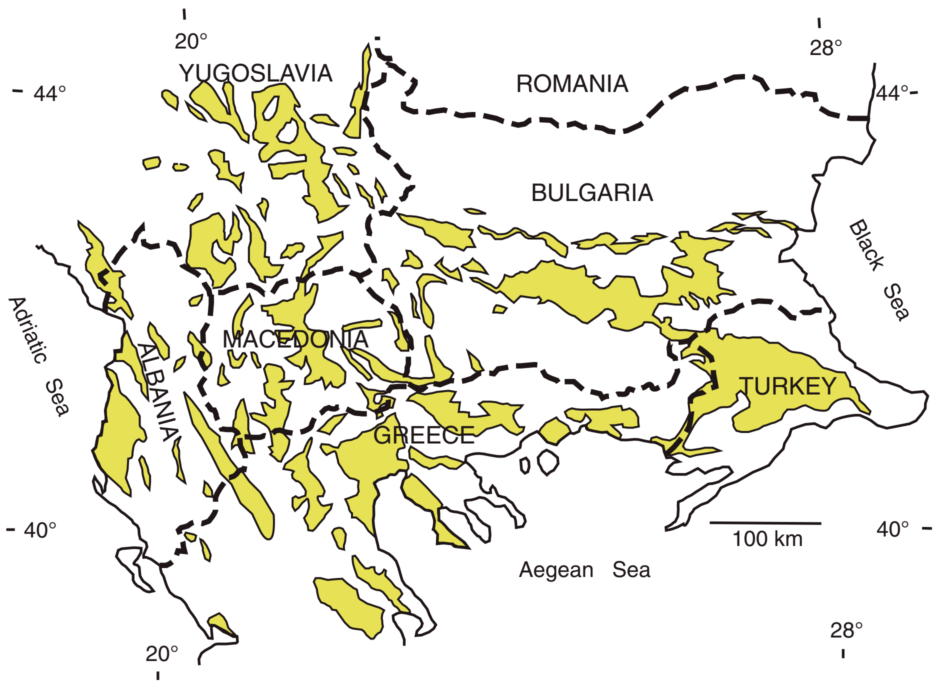

Figure 2. Cenozoic sedimentary basins in the South Balkan extensional system. Most of the basins are directly related to extensional faulting; however, some are related to shortening (e.g., along coastal Albania) or are outside the area we include within the South Balkan extensional system (e.g., basins in eastern Yugoslavia, although some of these are related to extension).

a blueschist event during Campanian time (80 ± 5 Ma), but most of the crustal fragment is covered by deposition of pelagic carbonate strata from the Campanian to Maastrichtian; deformation and flysch deposition starting in latest Maastrichtian and Paleocene time mark a time of southward obduction of ophiolitic rocks (Okay et al., 2001). As discussed by Okay et al. (2001, 2006), flysch deposition continued and the final suturing of the Anatolide-Tauride fragment occurred in middle Eocene time with extensive development of blueschist and deformation of suture zone sedimentary rocks; they suggested that intracontinental convergence and deformation probably continued into the early Miocene.

Following subduction of the Vardar oceanic lithosphere, the Pelagonian, Sakarya, and Anatolide-Tauride crustal fragments were accreted to the European continental crust and tectonism in the South Balkan extensional system and the accreted fragments became intracontinental. The dynamic setting of the intracontinental tectonism needs to be examined carefully because it is during Paleogene and possibly latest Cretaceous time that the earliest extensional structures formed and the transition from a convergent to an extensional tectonic setting took place.

Tectonic Setting during Closing of the Vardar Ocean

Shortening associated with generally north and northeastward subduction and subsequent postcollisional convergence along the Vardar zone produced a thickened crust north of the suture in southern Bulgaria, eastern Macedonia, northern Greece, and northwesternmost Turkey. The thickened crust crops out within the Rhodope Mountains and extends westward into western Bulgaria and eastern Macedonia, where it forms part of the Serbo-Macedonian zone (Fig. 3). Metamorphism, plutonic activity, and low-angle faults and shear zones formed within this thickened crust. Metamorphic ages are difficult to interpret because evidence suggests that metamorphism occurred during the transition from compressional to extensional tectonism in Late Cretaceous (pre-Vardar closure) and Paleogene time (post-closure), and most radiometric ages are hybrids. Most of the magmatism within this thickened crust is dated as latest Cretaceous and late Eocene–Oligocene, and it is probably related to subduction processes, postcollisional melting of thick crust, continued convergence following the initial closure of the Vardar Ocean, and heating due to decompression melting related to the earliest extension, or at times some combination of all these.

The earliest extension in the South Balkan extensional system is recognized within the metamorphic terranes north of the Vardar Ocean and its continuation to the east in northwestern Turkey. These rocks, now exposed in eastern Macedonia, western and southern Bulgaria, northern Greece, and northwesternmost Turkey, were in the hanging wall of the north-vergent Vardar subduction zone. The orientation of the

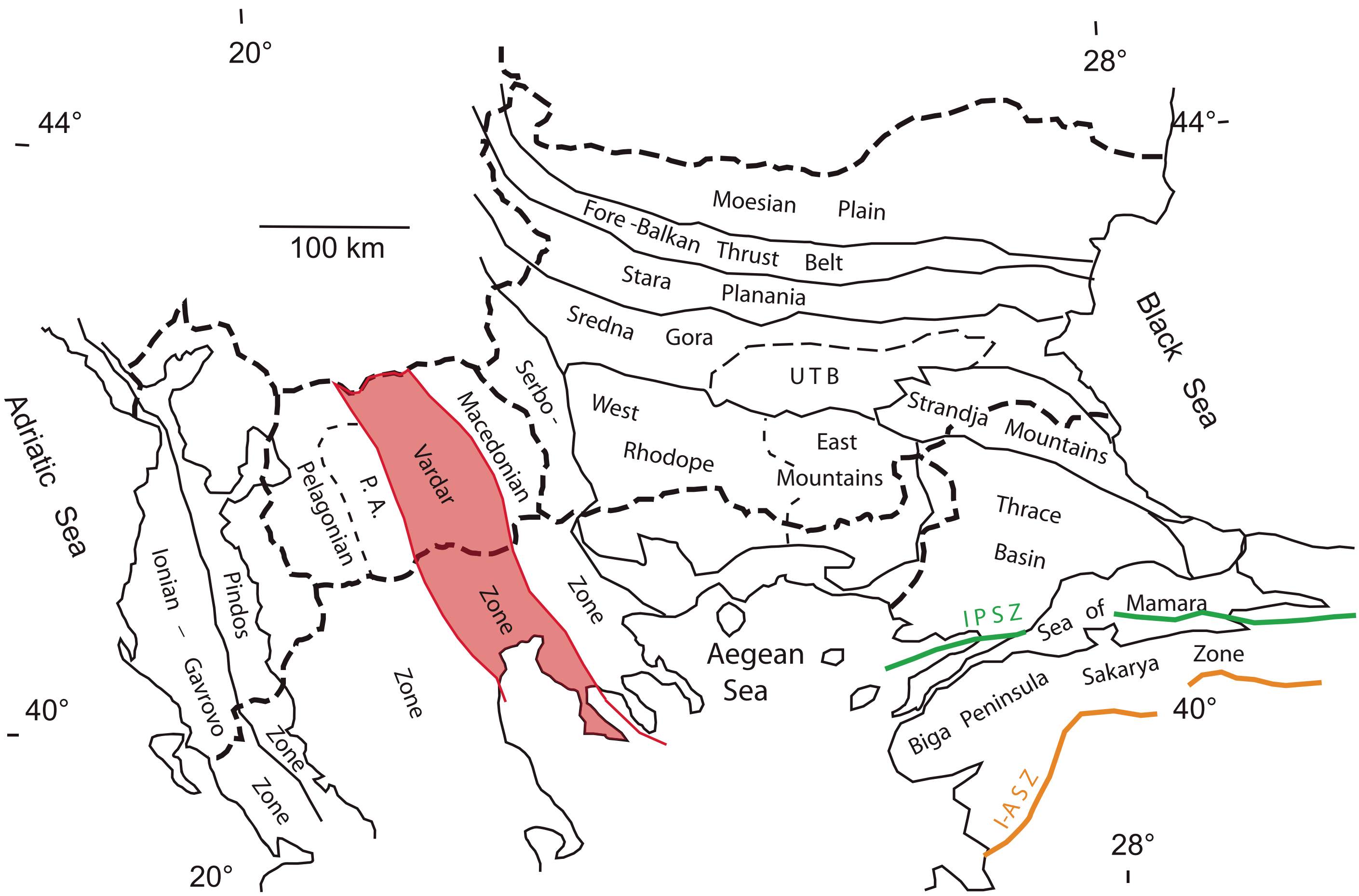

Figure 3. Topographic and tectonic units mentioned in the text. The location of the Vardar suture zone (orange) and its eastward continuation in the Intra-Pontide suture zone (IPSZ—green) and Izmir-Ankara (I-A SZ—orange line) suture zones of northwestern Turkey are also shown. P. A.—Pelagonian antiform; UTB—Upper Thracian basin.

subduction zone was probably east-west– to northwest-trending, but straighter than at present, as indicated by the paleomagnetic results of Kissel et al. (1986, 2003) and Kissel and Laj (1988). The subduction system produced characteristic rock assemblages and structures in the area of the South Balkan extensional system that are, from south to north, an ophiolitic mélange belt within the subduction zone, a belt of metamorphic rocks formed in pre-Cenozoic basement rocks intruded by magmatic rocks of Late Cretaceous and earliest Paleogene age, and a north-vergent antithetic (or retroarc) thrust belt in central Bulgaria (Fig. 4; Boyanov et al., 1989). All these features are characteristic of a convergent, Andean-type margin for the South Balkan extensional system from latest Cretaceous to approximately middle Eocene time, but the timing of the formation of structures may be very diachronous. It is within this tectonic setting that the earliest extensional features in the South Balkan extensional system developed. The tectonic setting changed to one of regional extension by middle Miocene time, but the timing

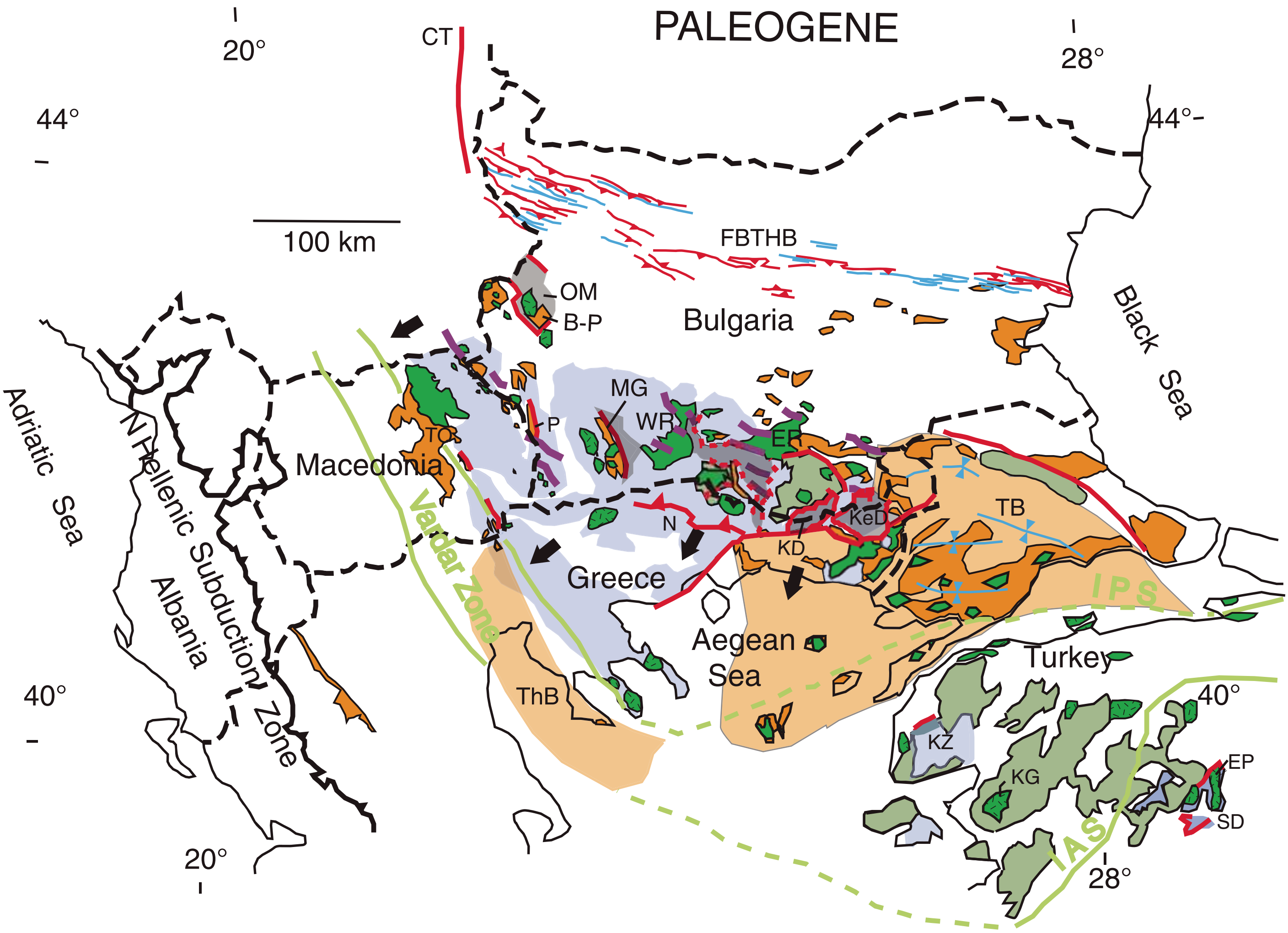

Figure 4. Latest Cretaceous–Paleogene (largely middle Eocene–late Oligocene) tectonic setting and related structures in the South Balkan extensional system. Sedimentary rocks are shown in orange (faded orange in the Gulf of Thermikos, Thrace basin [TB], and adjacent Aegean Sea areas where they are covered by younger sediments or water); magmatic rocks, both intrusive (patterned) and extrusive are shown in green; and mixed sequences of volcanic and sedimentary rocks are shown in pale green. Mylonitic metamorphic rocks, where they are below low-angle detachment faults, are shown in dark gray. Distribution of pre-Cenozoic metamorphic rocks—Rhodope, Serbo-Macedonian, and equivalent rocks north of the Vardar zone shown in light gray. Thick red lines, solid where well established and dashed where suspected, represent normal faults, and where surrounding metamorphic areas (dark gray), the faults are low angle and are interpreted to be detachment faults. Thin barbed red lines in north Bulgaria are thrust faults and thin blue lines are fold axial traces, both of which form the Fore-Balkan fold-and-thrust belt (FBTHB) of Lutetian age. Thick purple lines are trends of dikes within the magmatic belt. Blue lines within the Thrace basin show the axes of greatest sediment thickness. The boundaries of the Vardar zone and traces of the Intra-Pontide (IPS) and Izmir-Ankara (IAS) suture zones are shown in green. The Paleogene position of the North Hellenic subduction zone following the closure of Vardar zone is shown. Large arrows show the direction of relative extension. Locations: B-P—Bobov dol-Persink basin; CT—Cerni-Timok fault, ER—Eastern Rhodope Mountains, EP—Egrigoz pluton, KD—Kardamos dome, KeD—Kechros dome, KG—Kozak granodiorite, KZ—Kazdag metamorphic rocks, MG—Mesta graben, N—Nestos thrust, OM—Osogovo Mountains, P—Padesh graben, SD—Simav detachment, ThB—Thermikos basin, TO—Tikvis-Ovche basin, WR—Western Rhodope Mountains.

and the nature of the tectonic transition from dominantly regional shortening to dominantly regional extension are not easy to decipher. The transition took place approximately during late Eocene–late Oligocene time. By early (?) or middle Miocene time regional extension was dominant in the South Balkan extensional system and southward into the area of the Aegean Sea (Le Pichon and Angelier, 1979, 1981; Pe-Piper and Piper, 2006).

Within the latest Cretaceous–early Paleogene convergent environment, subduction and subsequent postcollisional convergence produced a thickened crust north of the suture in southern Bulgaria, eastern Macedonia, and northern Greece. Crustal thickening was associated with regional metamorphism of latest Cretaceous–early Paleogene age (Bonev, 2006; Bonev et al., 2006; Krohe and Mposkos, 2002; Fig. 4). Metamorphism, plutonic activity, and low-angle faults and shear zones formed within this thickened crust, and our most recent understanding of these features comes from two areas: (1) the Kardomos and Kechros domes in the eastern part of the Rhodope Mountains in Bulgaria and Greece (Bonev, 2006: Bonev et al., 2006; Krohe and Mposkos, 2002), and (2) the Osogovo Mountains of western Bulgarian (Kounov et al., 2004) (Figs. 3 and 4).

Rhodope Mountains

The Rhodope Mountains contain the most extensive areas of rocks and structures that developed during the late precollisional and early postcollisional closing of the Vardar Ocean (Figs. 3 and 4). These areas are characterized by metamorphism and deformation of latest Cretaceous and early Paleogene age. Metamorphic ages are difficult to interpret because many of the ages are hybrids related to development of thickening crust where both shortening and extensional structures are present. Evidence suggests that eclogite and amphibolite metamorphism occurred during crustal thickening in Late Cretaceous and Paleogene time, and is as young as 53 Ma (Ypresian–early Eocene) during pre-Vardar closure (Krohe and Mposkos, 2002; Bonev, 2006: Bonev et al., 2006). Most of the plutons within this thickened crust are dated as Late Cretaceous, and one post-tectonic pluton yielded a 53 Ma (U/Pb zircon and monazite) age (Ovtcharova et al., 2003). Late Eocene–Oligocene magmatism is widespread, but is considered to have occurred within the tectonic transition period (discussed below) related to postcollisional melting of thick crust, continued subduction following the initial closure of the Vardar Ocean, heating due to decompression melting related to regional extension, or some combination of all three.

Within the metamorphic region of the Rhodope Mountains are numerous low-angle shear zones and faults that formed at the time of the high-grade metamorphism (Ivanov, 1988, 2000). The Nestos thrust in northern Greece is well known (Papanikolaou and Panagopoulos, 1981) and places higher grade over lower grade rocks (Papanikolaou, 1984, 1988, 1997; see also discussion in Dinter, 1998). Some of these structures are generally southwest- to south-southeast–vergent thrust faults related to crustal thickening, but at shallower levels some low-angle faults are interpreted to be south- or north-vergent normal faults (Krohe and Mposkos, 2002; Bonev et al., 2006). Overlying both structurally and stratigraphically are Maastrichtian–Paleocene to lower Eocene strata that contain coarse debris derived from some of the metamorphic units, indicating that they were at least partly exhumed by early Paleogene time (Bonev, 2006; Bonev et al., 2006). These strata were displaced by detachment faults during their deposition or at a later time (Bonev et al., 2006). The strata currently have limited distribution and their original depositional setting remains difficult to decipher (Boyanov and Goranov, 2001).

These metamorphic, magmatic, and tectonic events are coeval with thrusting in north and central Bulgaria. The Fore-Balkan fold-and-thrust belt trends generally east-west across central north Bulgaria, containing several periods of folding and thrusting dating from the Jurassic, but events most relevant to this discussion have been dated as Late Cretaceous–Paleocene to middle Miocene (Boyanov et al., 1989). Dating of the youngest middle Eocene shortening is poorly constrained as rocks of middle Eocene age are not abundant, and unconformably overlying strata, usually early Micoene and more commonly middle Miocene age, are also rare. Upper Eocene and younger strata north of the fold-thrust belt are fine-grained brackish-water sediments, suggesting that topographic relief developed during middle Eocene deformation was no longer an important source of sediments by late Eocene time (Nakov et al., 2001b). Along the southern margin of the fold-and-thrust belt are late Eocene–Oligocene strata that were deposited in extensional half-grabens (Nakov et al., 2001b), indicating that shortening in the fold-and-thrust belt had ceased and extension had begun by that time. In drill holes in the Black Sea, the continuation of structures in the fold-and-thrust belt deform middle Eocene strata, and they are overlain unconformably by younger middle Eocene deposits (Dachev et al., 1988; Botzov and Dikova, 1969). Thus the coeval latest Cretaceous–middle Eocene events from northern Greece to northern Bulgaria are consistent with the South Balkan extensional system region being within a regionally convergent system with the north-vergent fold-and-thrust belt being antithetic (in a retroarc position) to the northward subduction within the Vardar zone.

Osogovo Mountains

Kounov et al. (2004) described detachment faults surrounding the Osogovo-Lisets metamorphic complex (Fig. 4) in the Osogovo Mountains, northwestern Bulgaria. The southwest-vergent Eleshnitsa low-angle detachment bounds the core rocks on the west side and is considered the major extensional fault in the area. The northeast-vergent Dragovishitsa detachment on the northeast side of the core rocks is considered a younger and possibly a less important extensional fault. These detachment faults involve sedimentary rocks that are as old as late (?) Eocene, so much of the evolution of these detachments faults occurred within transitional events considered below. However, zircon and apatite fission track ages from the core rocks show fast cooling from 47 to 38 Ma. Because these cooling ages come from the low-temperature end of the spectrum, Kounov et al. (2004) suggested that the cooling must have started earlier, perhaps at 49 Ma or earlier. This would place the initial development of the detachment faults in the early Eocene and may make them coeval with the older period of extensional faulting in the Rhodope Mountains to the east. Most of the data from the Osogovo Mountains are more logically in the younger part of the Paleogene extension considered below, but it leaves the possibility open that earlier extension may also be present here, extending the early Paleogene extension from the eastern Rhodope Mountains to western Bulgaria. It may also suggest a somewhat gradual transition in the tectonic setting of the South Balkan extensional system.

Dynamics of Latest Cretaceous–Early Paleogene Extension

If the latest Cretaceous–middle Eocene extension is within a regional compressional setting, there are several possible mechanisms for contemporaneous shortening and extension. The Rhodope Mountains are an area of thickened crust in the hanging wall of the north-dipping Vardar subduction zone, a crust that was relatively hot, as indicated by the latest Mesozoic–early Paleogene plutonic and prograde metamorphic rocks (Bonev, 2006; Bonev et al., 2006). Within a hot thick crust, lower and middle crust may spread laterally driven by gravitational potential energy, as in other orogens such as the Himalaya (Burchfiel et al., l992; Burchfiel and Royden, 1985) and beneath Tibet (Royden, 1996). Lateral spreading may be accommodated by thrusting at deeper crustal levels but by contemporaneous extension at shallower crustal levels, and faults form that have all the characteristics of detachment faults in regional extensional environments (Burchfiel et al., l992; Lister and Davis, l989). It cannot be excluded that the Osogovo-Lisets core complex and associated Eleshnitsa detachment in western Bulgaria might be related to gravitationally induced extension with possible lateral stretching in a thick and hot crust during oroclinal bending around the Moesian foreland (Kounov et al. (2004) and/or related strike-slip faulting within the southern Carpathians (Fig. 4; Fugenschuh and Schmid, 2005). Such a lateral stretching mechanism offers a partial explanation for the Eleshnitsa detachment in western Bulgaria, but does not appear to be an obvious explanation for the detachments in the Rhodope area.

Regional extension is commonly associated with crustal (or lithospheric) thinning and local basin development, either as structural basins at high or low elevations or broader areas of subsidence and sedimentation. The early extensional faulting within the southern part of the South Balkan extensional system lacked the formation of depositional basins, with the exception of the Maastrichtian–Paleocene to early Eocene strata at the north end of the Kardamos dome in the eastern Rhodope Mountains (Bonev et al., 2006), although these strata do not show a simple relation to the detachment faults (Boyanov and Goranov, 2001). This is not unusual for tectonic settings where extension and contraction are coeval, for example, in the Himalaya (Burchfiel et al., l992). This is in contrast to regional extensional settings, where characteristics include crustal thinning, subsidence, and formation of numerous narrow and/or broad fault-controlled sedimentary basins. In the South Balkan extensional system depositional basins that are related to the regional extensional faulting are much more widespread, began in late-middle Eocene (Bartonian) or early-late Eocene (Prabonian) time, and are characteristic features that distinguish the early Paleogene from the late Paleogene landscape; we suggest that it also signals the change in the tectonic environment.

LATEST-MIDDLE EOCENE TO LATE OLIGOCENE EXTENSION AND ITS TECTONIC SETTING: THE TRANSITION FROM REGIONAL SHORTENING TO REGIONAL EXTENSION

In contrast to the early Paleogene extension, in latest-middle Eocene (Bartonian) or early-late Eocene (Priabonian) time, the widespread development of different types of sedimentary basins began; many of the basins are associated with major extensional faults and abundant volcanic rocks. The Mesta graben in the western Rhodope Mountains is an example of syntectonic sedimentation accompanied by low-angle extensional faults (Fig. 4; Burchfiel et al., 2003). East-dipping nonmarine strata in the Mesta graben show progressively less rotation with decreasing age along the north-striking, west-dipping fault that bounds the east side of the basin. The oldest strata may be Bartonian, but are certainly Priabonian in age, and they unconformably overlie the basement metamorphic rocks along the west side of the basin. They dip up to 70°–80°E at the base of 2.5 km of growth strata that become nearly horizontal at the top. These strata are characteristically very coarse grained deposits, often debris flow deposits, close to the basin-bounding fault. The sedimentary rocks contain abundant volcanic rocks in their upper part and the entire section is intruded by hypabyssal plutons, many of which are related to caldera formation (Harkovska, l983). The strata are cut by numerous moderate- to high-angle normal faults that terminate downward into a west-dipping listric normal fault that must have a very gentle dip at depth, and has a 17°W dip at the village of Ribnovo. Exposed footwall rocks are brittle or locally mylonitic, but were deformed at low temperature, unlike the high-temperature ductile deformation associated with much of the earlier Paleogene extension.

Within eastern Macedonia and western Bulgaria there are numerous similar north-northwest–striking basins with east-dipping strata (Fig. 4) that may be above a deeper west-dipping detachment fault (Nakov et al., 2001a; Dumurdzanov et al., 2005). Most stratigraphic sections are incomplete; however, the Padesh graben in western Bulgaria contains at least 4 km of strata (Zagorchev, l998). In the Osogovo Mountains the first sedimentary deposits filling syntectonic basins are coarse clastics of Bartonian age (Kounov et al., 2004) that are above the major Eleshnitsa detachment fault (that may be of regional extent). They grade upward into marine turbidites and the total thickness of strata may approach 4 km (Bobov dol-Persink basin; Fig. 4; see Nakov et al. 2001a). Although extension, based on thermochronological data, within the Osogovo Mountains probably began before Bartonian time, the first syntectonic sedimentary deposits are Bartonian, suggesting that at least in the Osogovo Mountains pre-Bartonian extension may have been continuous into Bartonian time. The upper part of these strata unconformably overlaps the detachment fault and directly overlies the core metamorphic rocks. Thus, here, like in other places (see following), faulting was outlasted by subsidence and deposition. These extensional basins in eastern Macedonia and western Bulgaria often contain upper Eocene–Oligocene intermediate to felsic volcanic rocks and small intrusive bodies that characterize the extensional terrane from eastern Macedonia to the eastern Rhodope Mountains (Fig. 4).

In the Rhodope Mountains widespread thick successions of upper Eocene–Oligocene volcanic rocks may be interlayered with sedimentary rocks or contain clastic rocks at the base of section, some of which may be as old as Bartonian (Nakov et al., 2001a; Boyanov and Goranov, 2001). They are in fault contact or unconformably overlie metamorphic rocks belonging to the detachment systems of early Paleogene age (Bonev et al., 2006; Ivanov, 2000; Boyanov and Goranov, 2001). Some of the strata contain abundant very coarse clasts suggestive of debris flows or even larger blocks possibly emplaced by landsliding (e.g., see Ivanov, 2000). These deposits are in places strongly tilted and suggest active extensional tectonism of Bartonian (?) to Oligocene age. Their relation to low-angle faults that have been mapped in the area, however, remains controversial. Bonev et al. (2006) began to delineate these relations in the eastern part of the Rhodope Mountains, showing that sedimentary or volcanic rocks are in the hanging walls of brittle detachment faults, but in other areas the sedimentary and volcanic rocks depositionally overlie them and the metamorphic rocks of the Rhodope Mountains. In many places these strata are not strongly tilted or may even remain subhorizontal, suggesting that even though extension may have been active, it did not affect all rocks equally in the eastern Rhodope Mountains. In some places within the eastern Rhodopes, small scattered remnants of strongly tilted fault-bounded coarse clastic strata, the age of which is unknown, lie unconformably below subhorizontal late Eocene–Oligocene sedimentary and volcanic rocks. Some of these strata are related to early Paleogene extension (Bonev, 2006; Bonev et al., 2006), but it is not clear whether other similar strata are related to the early Paleogene tectonism.

South of the Rhodope Mountains in northern Greece, on the island of Thassos, structural and metamorphic evidence suggests that extension has exposed crustal levels as deep as 25 km (Brun and Sokoutis, 2007). Exposures of these rocks are the southernmost outcrops of the Rhodopian metamorphic core, and Wawrzenitz and Krohe (1998) suggested that they were exhumed by major southwest-vergent detachment faulting. There is evidence in older ages obtained from the footwall rocks that earlier structures, Late Cretaceous or early Paleogene, may have been related to shortening deformation (Brun and Sokoutis, 2007). Thus they have a setting that is similar to the main body of the Rhodope Mountains and were a part of it during the early Paleogene. However, where Dinter (1998) and Wawrzenitz and Krohe (1998) related the exhumation to a major detachment fault that evolves into the Strymon Valley detachment (see following), Brun and Sokoutis (2007) related the exhumation to a more complex evolution of detachment faulting and a ramp structure on the Kerdylion detachment, west of the Strymon Valley. Detachment faults evolve through time as the deeper crustal rocks are brought to shallower crustal levels, and incise and excise different parts of the detachment system (e.g., see Lister and Davis, 1989); we suggest that the relations on Thassos are part of such a system, and support the general concept presented by Dinter and Royden (1993) rather than that of Brun and Sokoutis (2007).

A second type of basin formed contemporaneously with the extensional basins in the metamorphic terranes of the South Balkan extensional system. In central Macedonia there is a broad area underlain by late Eocene–Oligocene strata forming the Tikves and Ovche Pole basins described by Dumurdzanov et al. (2004, 2005; Fig. 4). These strata are 3.5–4 km thick with basal coarse clastic rocks overlain by flysch-like strata, followed by limestone and sandstone. The section contains both marine and nonmarine strata that range from Priabonian to Oligocene age, but the basal 600–1200 m of strata are undated. These rocks interfinger northeastward with volcanic rocks. The basin has been eroded and its original lateral extent remains unknown, but the distribution of strata is not obviously related to synsedimentary extensional faults like the basins to the east. It also overlies the eastern part of the Vardar zone rocks. A second similar example is the Thermikos basin in northern Greece. The basin trends north-northwest and is largely covered either by water or younger strata, but overlies the southern extent of the Vardar zone (Figs. 3 and 4). It contains ~3.5 km of marine and nonmarine strata in its thickest part. The oldest strata are assigned a late Lutetian age, but their age is poorly known. Seismic sections show the basin strata to be generally subhorizontal and not obviously rotated by synsedimentary normal faulting. The strata are cut by normal faults, most of which extend upward into late Cenozoic strata; some of the faults may be active. Like the Tikves and Ovche basins to the north, it is not clear how its Paleogene inception and subsidence are related to extensional faulting.

In northwestern Turkey the Thrace basin is on strike and east of the eastern Rhodope extensional area and is filled with more than 7 km of early Cenozoic sedimentary rocks; the basin's structure and subsidence history contrast with the uplift and exposure of mid-crustal rocks within the Rhodope Mountains. Except in its southern part, where the strata overlie ophiolite-bearing mélange that belong to the Intra-Pontide suture (see above), basal strata are characterized by coarse clastics that grade upward into marine limestone, then into thick turbidite deposits that shallow upward into nonmarine and lacustrine strata (Perincek, 1991). Deposition ceased in late Oligocene or earliest Miocene time. Volcanic rocks of calc-alkaline affinity are interbedded with the sedimentary rocks and are mainly exposed in the southern part of the basin (Yilmaz and Polat, 1998). These volcanics are similar to contemporaneous rocks in the Rhodope Mountains to the west and to rocks in northwestern Turkey to the east, although the rocks in northwestern Turkey appear to extend to younger ages (Yilmaz and Polat, 1998; Aldanmaz et al., 2000), and occur in a deep marine and/or nonmarine sedimentary basin. The sedimentary and volcanic rocks in the eastern Rhodopes not only fill both fault-related extensional basins and broad areas not obviously related to extension, but structurally and depositionally overlie high-grade metamorphic rocks in areas exhumed as metamorphic core complexes. In the Thrace basin there is no direct evidence that these strata are on similar core complexes. The basin has a sharply defined northern boundary along a west-northwest–striking normal fault that was active during deposition and separates basinal deposits from the Strandja shelf deposits to the north. The thickness of basinal strata is variable and on basement highs may be only 1–2 km; these basement highs are bounded by normal faults with important strike-slip components (Perincek, 1991). While the basin appears to be related to extensional faulting, there is little in the geometry of the faults that suggests major tilted fault blocks or detachment faults. Similar rocks are exposed on Limnos Island in the northern Aegean.

All these areas of Paleogene strata from Tikvis-Ovche, through the Thermikos basin to the Thrace basin, have some similar characteristics, showing major subsidence that is not obviously related to the type of extensional faulting present in the other adjacent basins to the east or west, respectively. They are also on basement rocks along the southern margin of pre-sutured Europe and on the Vardar–Intra-Pontide suture. In most places they cover either part (Tikves-Ovche, Thrace) or all (Thermikos) of the suture zone rocks, indicating that they are post-suture deposits. Unfortunately, the direct connection between all these deposits cannot be made because of later tectonics, erosion, or cover by younger sediments or water in the north Aegean Sea. They define a major zone of subsidence that is related to crustal and/or lithospheric thinning, but their thickness and structural relations appear to be different from the tectonic setting within the basement areas to the north and east, where crustal thinning can be related to extension and detachment faults whose hanging walls are cut by faults that rotate syntectonic basinal strata. The Thrace basin appears to have some of the characteristics of both basin types. The two types of basins are contemporaneous and should be tectonically related. In the west, most of the major detachment faults are west dipping, and we suggest that the detachment faults extend into crustal and/or lithospheric levels to the west, where extension is accommodated by deeper, more ductile extension with little surface expression (e.g., see Wernicke, 1985). The origin of the Thrace basin appears to be extensional, but the relation of its subsidence to the uplift and formation of core complexes to the west and to the east in northwestern Turkey (Yilmaz et al., 1997) remains unresolved.

The closure of the Vardar, Intra-Pontide, and Izmir-Ankara oceans was marked by the accretion of the Pelagonian, Sakarya, and Anatolide-Tauride crustal fragments to Europe. Following the closure of the intervening oceanic areas, subduction migrated to the Pindus ocean to the west and oceanic tracks south of Anatolian-Tauride fragment to the south (Şengör and Natal'in, 1996). These events occurred during a time period when structural changes took place from crustal thickening and termination of thrusting within the southern Balkan area and in the Fore-Balkan thrust belt to the beginning of regional extension and basin formation in the South Balkan extensional system. These changes were not instantaneous, may have been diachronous, and mark a period of transition within the tectonic setting and dynamic changes within the South Balkan extensional system. We suggest that during crustal heating and thickening in the early Paleogene, gravitational potential energy increased within an increasingly ductile crust, causing lateral crustal flow and associated extension to begin within a regionally convergent tectonic setting. Following closing of the suture the tectonic setting progressively changed from one of intracontinental convergence to regional extension, with crustal and/or lithospheric thinning and subsidence associated with significant basin formation related to detachment faulting in the north and deeper crustal thinning and broader crustal subsidence to the south. This younger dynamic setting may be related to the increase in importance of gravitational potential energy and by a decrease in the magnitude of regional horizontal shortening within and beyond the region of the suture zone, related to the fate of the subducted slab as subduction shifted to the south. The change was not instantaneous nor did it lead to a tectonic setting of continuous regional extension. Events during late Oligocene–middle Miocene time suggest a complex evolution of a dynamic system that did not become continuously regionally extensional until late-middle to late Miocene time.

The evolution of the late Eocene–Oligocene volcanism also contributes to the understanding of the dynamic setting of the transition from regional shortening to regional extension. All studies of the mafic to the more abundant intermediate to felsic volcanic rocks indicate a change from a subduction enriched subcontinental lithospheric mantle source with fractional crystallization and crustal contamination to volcanic rocks that indicate an origin related to decompression melting of an enriched asthenospheric source. Marchev et al. (2004) reported on the mafic volcanic rocks in the Rhodope region, whereas Yilmaz and Polat (1998) included a wider range of rock types in their study of the Thrace basin. Similar conclusions were reached by Aldanmaz et al. (2000) from their study of the volcanic rocks from the western Biga Peninsula in western Anatolia; however, they regarded these rocks as Miocene in age, whereas most maps show them to be mainly Paleogene in age and probably correlative with the rocks in Rhodope and Thrace. The age of all these volcanic rocks needs to be determined more precisely to establish contemporaneity, or whether they show a progressive younging to the east.

Marchev et al. (2004) added important data on the evolution of the latest Eocene–Oligocene volcanism in the eastern Rhodope Mountains and possible dynamics during the transition from compression to extensional tectonism. Basaltic rocks that are generally rare within the thick volcanic sequences of latest Eocene–Oligocene age show an evolution from the oldest volcanics, dated as ca. 34 Ma, that are K-rich trachybasalt and reflect a high degrees of crustal contamination, to the youngest magmatic rocks that form alkaline dikes, dated as 28–26 Ma, cutting the core complexes that are consistent with derivation from an oceanic island basalt–like reservoir contaminated by depleted mantle lithosphere. Marchev et al. (2004) interpreted this change to suggest a progressive removal of lithosphere and upward movement of asthenosphere. Such data begin to link possible mantle dynamics to upper crustal geology that we interpret to indicate that upper crustal extension began during this time period, or perhaps slightly earlier, and shows the progressive thinning of previously thickened crust and lithosphere. These events correlate with the termination of thrusting in the Fore-Balkan region and the beginning of subsidence and preservation of sedimentary and volcanic sequences in extensional basins from the southern flanks of the Stara Planina in the north, south across the entire Balkan region. It is also the time when subduction ended within the Vardar zone and shifted to the west and southwest into the Pindus zone of the central Hellenides. Timing of events in the South Balkan extensional system suggests that these changes may have been diachronous, i.e., older in the west, where regional extension began in the late-middle Eocene, and younger in the east, where it may have begun in latest Eocene time. All these events took place over a period of perhaps several million years. Marchev et al. (2004) interpreted regional extension to have begun in the Late Cretaceous, an interpretation with which we do not agree.

All these studies suggest a change from a thicker subduction-modified lithosphere to a thinner lithosphere and more elevated asthenosphere, and evoke processes of lithospheric stretching, delamination of the thermal boundary layer, or slab detachment as mechanisms for the postcollisional magmatism. Such processes occur within the mantle wedge during the termination of subduction and are probably related to the fate of the subducted slab and/or the dynamic processes that occur within the mantle wedge that are still poorly understood. Model studies by Royden (1999) and Royden and Husson (2006) have shown steepening of slab dip following accretion of continental fragments that might result in stretching of the lithosphere as a normal consequence of subduction dynamics. The period from just prior to and during the late Eocene–Oligocene is the transition from convergent to extensional tectonism, consistent with the changing source for magmatic activity evolving from a progressive thinning of the lithosphere. The processes operating during the transitional period of tectonism eventually lead to regional extension caused by trench rollback that dominated the Aegean area to the south beginning in Miocene time.

Continuation of the South Balkan Extensional System into Northwestern Turkey

Paleogene geology in the South Balkan extensional system is similar to the geology of northwestern Turkey, and while it is not the focus of this study, the correlation is important for at least two reasons. (1) There is a suggestion that tectonic events in western and northwestern Turkey may be somewhat younger than in Bulgaria. (2) The two areas are separated by the Thrace basin, a region showing significant subsidence, that does not permit the direct connection between Rhodope and Turkish geology. Western Turkey has extensive regional extension and core complex development in the Menderes Massif (Cemen et al., 2006) extending north into the Biga Peninsula (Altunkaynak and Dilek, 2006; Figs. 3 and 4). There remains controversy about the structure of core complex formation in the Menderes massif, for example, whether there is one major north-vergent detachment across the entire Menderes (Seyitoglu et al., 2004) or more than one detachment fault (e.g., Ring et al., 2003; Bozkurt and Park, 1994; Hetzel et al., 1995; Isik et al., 2003; Isik and Tekeli, 2001; Thomson and Ring, 2005). The timing of detachment faulting is well constrained in only a few places.

Isik et al. (2004) showed that the north-vergent Simav detachment north of the Menderes massif was active between ca. 25 and ca. 19 Ma, and rapid cooling of the shallowly intruded Egrigoz pluton took place ca. 20 Ma (see Isik et al., 2004; Thomson and Ring, 2006). Ages are from $^{40}Ar/^{39}Ar$ and fission track analyses and are thus cooling ages, so the initiation of detachment faulting could be a little older, but initiation was probably late Oligocene and displacement extended into early Miocene time. Thomson and Ring (2006) showed from fission track data that cooling of the northern part of the Menderes massif was isochronous, and suggested that a north-south width of >100 km of the massif was part of the footwall for a single north-vergent detachment system that was active from ca. 25 to ca. 19 Ma, the Simav detachment forming the northernmost exposure of the detachment system. In the southern part of the Menderes massif, ages of 43–37 Ma and 36 Ma have been reported for the Kayabuku and Buyuk shear zones, respectively (Hetzel and Reischmann, l966; Lips et al., 2001). The relation of these ages to detachment faulting is controversial and still debated (see Isik et al., 2004; Seyitoglu et al., 2004).

Within the Biga Peninsula area there are several north-northeast–trending uplifts of metamorphic rock associated with shallowly intruded plutons. One of these, the Kazdag uplift, has been described as a core complex (Okay and Satir, 2000), and others may have a similar extensional origin. Plutons that intrude into three of these uplifts, including the Kazdag, yield ages of 20–25 Ma (see Yilmaz et al., 2001) and are a part of several plutons that extend eastward across the peninsula into the area of the detachment faulted area considered as the northern extent of the Menderes massif. The plutons are generally regarded to have intruded during late Oligocene–early Miocene time and are related to a sequence of largely acidic and intermediate volcanic rocks that extend across the same area and range from Oligocene to early and middle Miocene in age. The volcanic rocks show an evolution similar to that of the eastern Rhodope area, and have been interpreted in a similar way, to progressive lithospheric thinning and elevation of asthenosphere (Aldanmaz et al., 2000; Altunkaynak and Dilek, 2006). In contrast, Yilmaz et al. (2001; Aldanmaz et el., 2000; Altunkaynak and Dilek, 2006) related these volcanic rocks to a compressional regime that lasted until the end of middle Miocene time followed by regional extension beginning in late Miocene time. The oldest volcanic rocks of this succession yield ages of ca. 31 Ma, similar to those in Rhodope, but most of them are dated as Oligocene–middle Miocene in age, an upper range that is younger than the volcanic rocks in Rhodope. Unfortunately most of the radiometric ages for the magmatic rocks are K/Ar analyses and more modern work needs to be done to determine ages more precisely.

Available data suggest, but are not conclusive, that even though the geology of the southern South Balkan extensional system and western and northwestern Turkey have great similarity, they may be of slightly different ages, suggesting diachroneity of their tectonic evolution. The termination of Vardar subduction, initiation of regional extension, formation of core complexes, and evolution of magmatism appear to have been older in the west and younger in the east. Whether this is the case, the direct connection between these two regions from surface geology is not continuous with the Thrace basin being between the two areas. Thus, during the formation of the extensional core complexes and exposure of upper to middle crustal rocks in Rhodope, the Thrace basin was undergoing continued subsidence. To the west of the Thrace basin, Paleogene strata contemporaneous with those in the basin lie both unconformably and in faulted basins above Rhodopian rocks. The present southeast side of the basin is marked by strands of the North Anatolian fault system, and some small areas of Paleogene sedimentary and broader areas of volcanic rocks are preserved on the Biga Peninsula to the south, where they are interspersed with exposures of metamorphic and plutonic rocks in possible extensionally uplifted areas. Even if ~100 km of dextral slip is removed along the North Anatolian fault system, the Thrace basin remains an area of major subsidence between Rhodope and northwestern Turkey. Whether geology similar to Rhodope and northwestern Turkey underlies the Thrace basin, it remains an area of significantly greater subsidence between the two areas. The tectonic explanation for the origin and position of the Thrace basin remains unclear.

Although these two areas on either side of the Thrace basin have similar geology, the exposure of core complexes is across a much greater width in Turkey, ~300 km north-south, than in the southern South Balkan extensional system, ~100 km after removal of younger extension on the Strymon detachment (see following). This difference is probably due to the greater width of continental fragments accreted to Europe in the Eocene, Sakaria and Menderes-Taurides in Turkey and the Pelagonian in Greece, and the greater shift in the position of the post-Eocene subduction zone away from Europe in Turkey than in Greece. These differences in the tectonic development of western Turkey and Greece are only a few of the many that exist, not only in this time period, but in younger time periods, and need extensive future study.

LATE OLIGOCENE TO MIDDLE MIOCENE SHORTENING

During late Oligocene–middle Miocene time one or more short-lived, local (?) events of shortening occurred, marking a change in the tectonic setting within the South Balkan extensional system that suggests a complex pattern of structural development and a probably equally complex development of the dynamic environment. During this time period there was a major break in sedimentation; deposits of this age are largely missing, particularly those of early Miocene age (Nakov et al., 2001b; Boyanov and Goranov, 2001; Dumurdzanov et al., 2004). Within the Tikves-Ovche (Dumurdzanov et al., 2005), Bobov dol-Persink, and Pernik basins (Zagorchev, 1998), folds and thrust faults formed. Folds and normal and thrust faults developed within the Thrace basin (Perincek, l991), and thrust faults occurred along the easternmost end of the Fore-Balkan thrust belt that continued into the Black Sea, where they are well dated in offshore Bulgaria (Dachev et al., l988; Betzov and Dikova, l969; Fig. 5). It is not clear whether all these events are related to a single dynamic system, but we suggest that they were caused by more local processes.

In western Bulgaria and eastern Macedonia there is a short lived and well-dated period of shortening during latest Oligocene–early Miocene time in the Pernik, Bobov dol-Persink (Zagorchev, l996), and Tikvis-Ovche basins (Dumurdzanov et al., 2005; Fig. 5). We interpret this shortening event to be related to short-lived collision with the Kruja continental fragment at the north Hellenic trench in Albania (Dumurdzanov et al., 2005; Fig. 5), causing a temporary change in the stress regime east of the trench before normal subduction rollback was reestablished. This may be a local event, as the Kruja fragment may not have continued very far south of Albania. As we view the subduction process, the subducted lithospheric slab remained intact during accretion, and the accretion process stripped off the upper part of the continental crust, forming the Kruja fragment; the lower part of the crust remained attached to the downgoing lithospheric slab. Accretion of the upper crust caused a slowing of the subduction rate and changed the stress regime in the overriding plate sufficiently to cause local shortening, a process described by Royden (1999), and Royden and Husson (2006).

A period of shortening occurred within the Thrace basin in northwest Turkey, but its age is poorly established (Figs. 4 and 5). Perincek (1991) studied this deformation and considered it to be late-middle Miocene; however, uncertainty remains because its age is bracketed by an unconformity between the Danisment Formation of late Oligocene–early-early Miocene age and the unconformably overlying Ergene Group, dated as late Miocene (?)–Pliocene. However, it appears that this deformation, while possibly the same age as that in western Bulgaria and eastern Macedonia, may be younger. Perincek (1991) interpreted the deformation to be related to restraining bends along right-lateral strike-slip faults that strike west-northwest through the northern part of the Thrace basin. The projection of these faults into Bulgaria would continue them along the Maritza fault zone (MFZ in Fig. 5) that flanks the Rhodope Mountains on the north. North of Haskovo, Bulgaria, late Eocene–Oligocene (perhaps earliest Miocene) strata are folded (Nakov et al., 2001b). These folds could be the northwestern continuation of the folds from the Thrace basin. There is, however, a broad area from Haskovo to the folded rocks in western Bulgaria where there are no rocks of the correct age to show if this deformation is present between the two areas: how these two areas might be related remains unknown. However, if the deformation in western Bulgaria and eastern Macedonia is related to activity at the northern Hellenic trench, it seems unlikely that the deformation in the Thrace basin would be directly related. It is more likely related to strike-slip faulting that began as broad zone of distributed shear in late Miocene time (Şengör et al., 2004; see following), preceding or in the early part of North Anatolian fault zone formation. The shortening at the eastern end of the Fore-Balkan thrust belt in the Black Sea area is probably related to the westernmost extent of Miocene shortening within the Pontide belt in northern Turkey (Yilmaz et al., 1997). The deformations recorded in the Black Sea and in the Thrace basin are probably related to the tectonic regime in northwestern Turkey and farther east, and may represent its westernmost extent.

These shortening events and the lack of sedimentary basin development, with a possible lack of, or rare, evidence for extension, makes a convenient division between late Paleogene extension and younger extension of early-middle Miocene age (Badenian) that is associated with deposition in several extensional basins (Dumurdzanov et al., 2004, 2005; Nakov et al., 2001b).

TECTONIC SETTING OF MIDDLE MIOCENE TO PRESENT: THE DIACHRONOUS DEVELOPMENT OF EXTENSION AND FORMATION OF SEDIMENTARY BASINS

Extensional faulting and associated basin formation was well developed by middle Miocene time (Fig. 6), and it was at this time that extension began that progressed to the present day within the South Balkan extensional system and the Aegean realm. In the western part of the Balkans extension may have continued from Paleogene time, but with the short interruption by a brief period of local upper crustal shortening (see above), whereas in the eastern part of the Balkans the beginning of extension appears to be younger, starting in early-late Miocene time (Fig. 7).

In the western part of the Balkan region the geometry of the extensional faults suggests that the dynamics of extension may have been similar before and after the local shortening

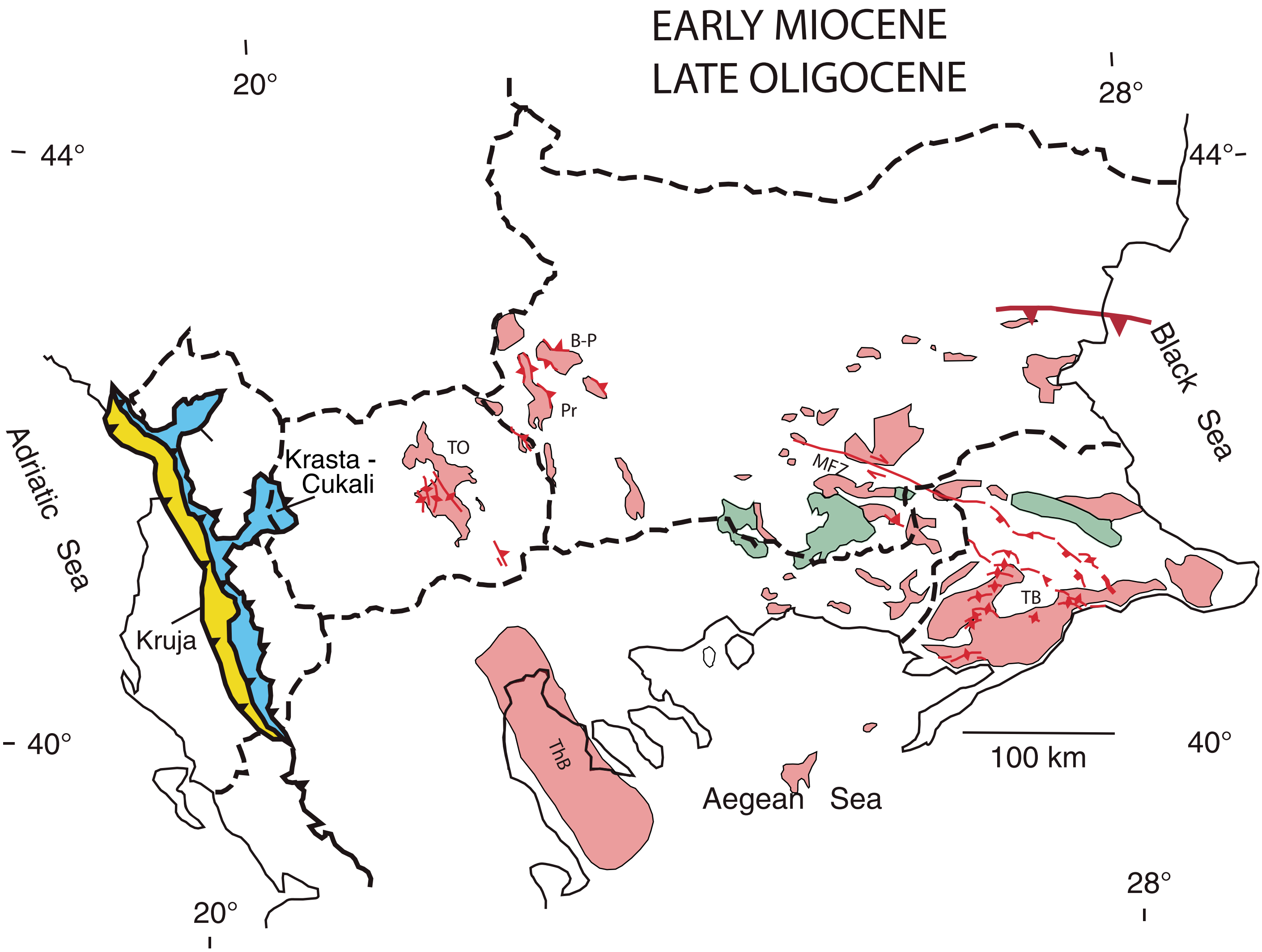

Figure 5. Location of thrust faults (red barbed lines), normal faults (red lines with squares), and folds (red lines with diamonds) of latest Oligocene and early Miocene age. Background shows location of sedimentary basins (orange) and basins with mixed volcanic and sedimentary rocks (green). Accreted deep-water strata along the north Hellenic trench (blue) and the accreted Kruja continental fragment (yellow) are shown in Albania. The age of the structures in the Thrace basin (TB) and southeastern Bulgaria are poorly known, and their age is bracketed only between late Oligocene–early Miocene and late Miocene (?)–Pliocene time, but they are shown in this time interval, as suggested by Perincek (1991). B-P—Bobov dol-Persink basin, MFZ—Maritza fault zone, Pr—Pernik basin, ThB—Thermikos basin, TO—Tikvis-Ovche basin.

event (Figs. 4 and 6). The Paleogene extension occurred above west-dipping detachment faults; however, the two main areas where these faults are recognized, the Mesta and Osogovo areas, cannot be directly connected by known faults. The small east-tilted half-graben extensional basins in western Bulgaria and eastern Macedonia have distributions and geometries that suggest they were above a master west-dipping detachment fault, but this cannot be proved at present. These basins have strata that locally continue into the early Miocene (Dumurdzanov et al., 2004, 2005; Nakov et al., 2001b). By early-middle Miocene time (ca. 15 Ma, Badinian) extension on the west-dipping Strymon Valley detachment fault began in northern Greece and southwestern Bulgaria (Fig. 6; Dinter and Royden; 1993; Zagorchev, 1992). The Strymon Valley detachment is to the west and is parallel to the Mesta detachment. It has a geometry, kinematics, and timing that could be interpreted to be the westward younging of the active part of the Mesta detachment, a pattern of migration of faulting well known in regionally extensional terrains such as the Basin and Range province in the western United States (Lister and Davis, 1989). During its evolution the Paleogene Mesta detachment may have begun to be rotated to a more horizontal orientation with rotation of the Pirin Mountains in its hanging wall, and younger extension migrated to the west along the western flank of the Pirin Mountains, forming the Strymon Valley and Sandanski basins, leaving an inactive Mesta detachment in its footwall.

The Strymon Valley detachment continued to be active, but at an increasingly slower rate, until perhaps Pliocene time (ca. 3.5 Ma, Dinter and Royden, 1993; Figs. 6, 7, and 8). North-south extensional basins became active progressively farther west, reaching western Macedonia and eastern Albania by latest Miocene–early Pliocene time (Dumurdzanov et al., 2005; Figs. 7 and 8). This progressive formation of more western north-trending basins could have occurred in the hanging wall of a master west-dipping

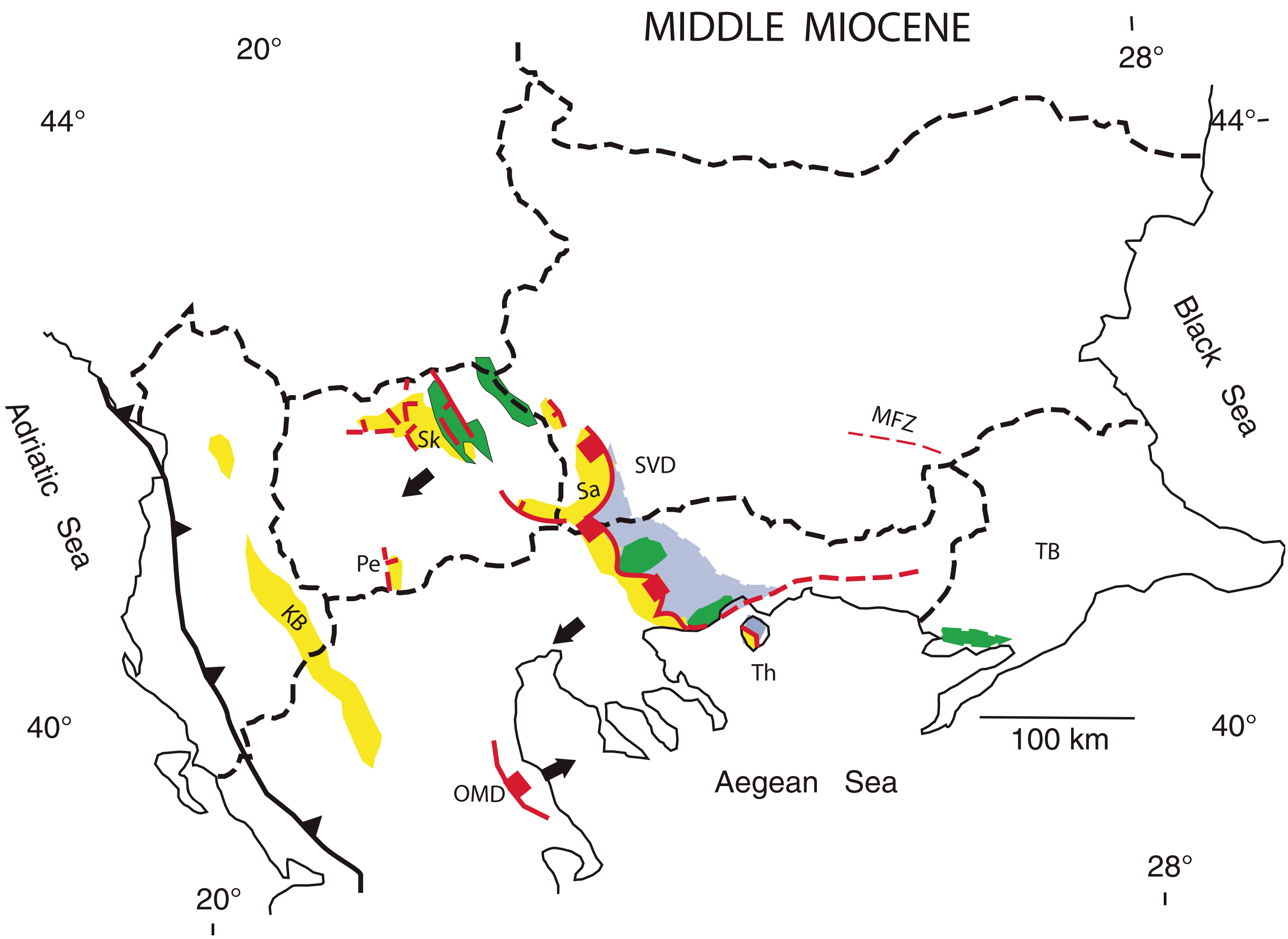

Figure 6. Tectonic setting in middle Miocene time showing the location of sedimentary basins (yellow) and magmatic rocks (green). Thick red lines are normal faults, single tick line shows direction of dip on moderate to high-angle normal faults, and red square shows dip direction for low-angle normal faults (detachment faults). Large black arrows show directions of relative motion of hanging wall of detachment faults. Position of North Hellenic trench of middle Miocene time in Albania and northwestern Greece is shown. Gray area is footwall metamorphic rocks for Strymon Valley detachment fault. KB—Korce basin, OMD—Olympus detachment fault, Pe—Pelagonian basin, Sa—Sandanski basin, Sk—Skopje basin, SVD—Strymon Valley detachment fault, Th—Thasos. Thrace basin (TB) is devoid of sediments at this time and some folding may have occurred, but its timing is poorly constrained. Maritza fault zone (MFZ) may have had activity at the time.

detachment (Strymon Valley detachment), but such geometry cannot be demonstrated. The westward progression of north-trending extensional basins continued into Albania, where these basins are active in western Macedonia and eastern Albania (Dumurdzanov et al., 2005: Figs. 8, 9, and 10).

Major east-dipping normal faults are also well known. The oldest, middle Miocene, is at Mount Olympus in Greece (Schermer, 1990, 1993) and farther east, east-dipping faults, some of which are active, occur along the west side of the Thermikos basin (Fig. 6). How these east-dipping faults would interact with a master west-dipping detachment fault along the Strymon Valley detachment fault has not been investigated and is unknown (see Dinter, 1998).

By early Pliocene time the north-trending basins in eastern Macedonia began to be disrupted by east-west–trending basins (Dumurdzanov et al., 2005; Fig. 8). These younger basins appear be the result of north-south extension and westward migration of the east-west–trending basins that developed first in the eastern part of the South Balkan extensional system in early-late Miocene time (Nakov et al., 2001b; Fig. 7; see following). It would suggest that even though movement on the Strymon Valley detachment continued into the middle Pliocene, its activity as a master detachment may have ceased and the eastern limit of north-trending normal faults migrated into central Macedonia then to its present position in western Macedonia and eastern Albania (Figs. 8, 9, and 10). The temporal and spatial pattern of extensional faults is becoming well established; however, the existence and nature of major crustal detachments are mostly speculation. The westward migration of both east-west and the north-south extensional faults in tandem appears to be real, and it indicates that the two systems of faults are related to two different dynamic systems at best only loosely connected (see following).

The eastern part of the South Balkan extensional system in Bulgaria is characterized by

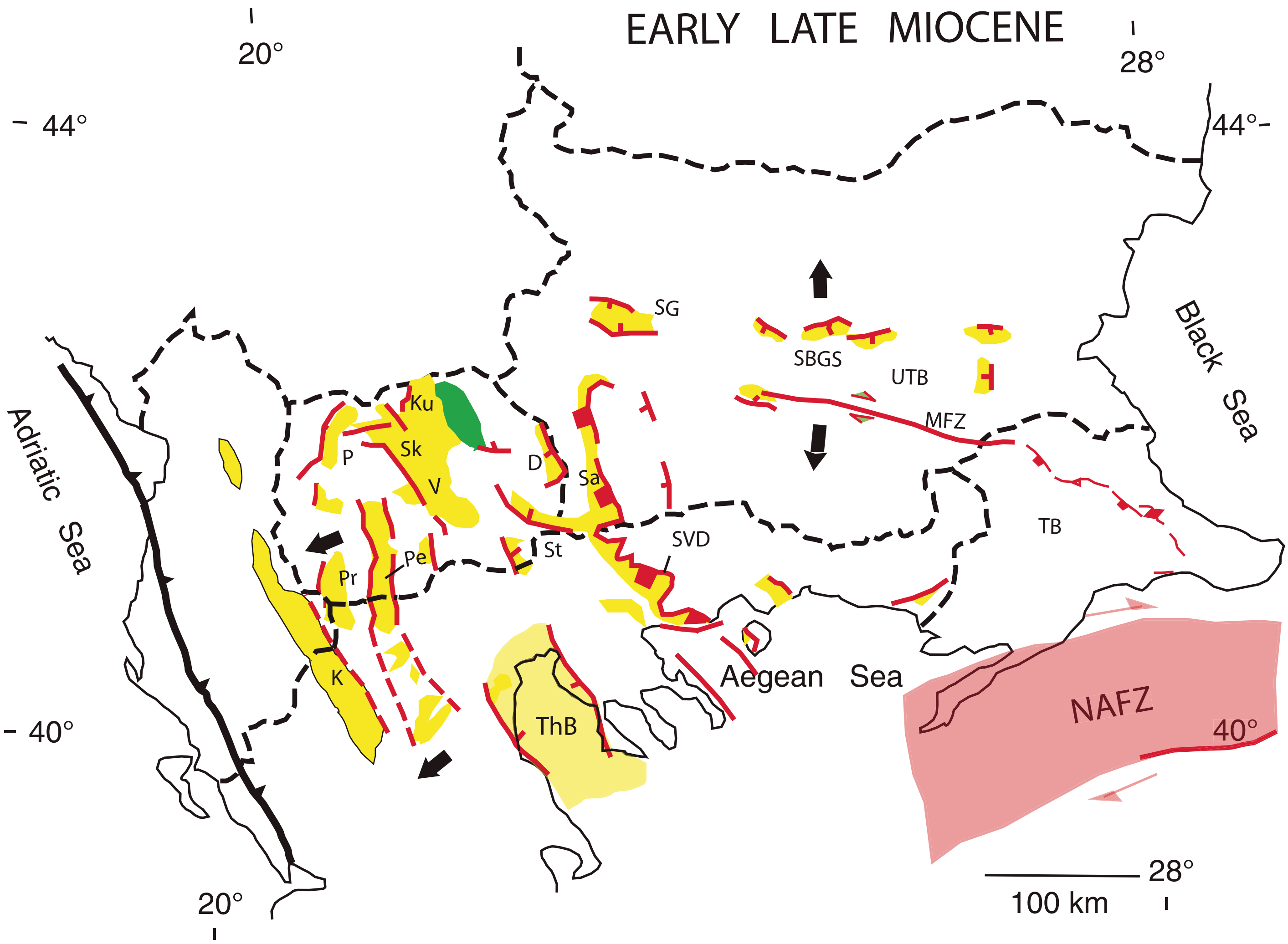

Figure 7. Tectonic setting in early late Miocene time showing the early development of the North Anatolian fault zone (NAFZ) as a broad zone of shear that has not differentiated into discrete faults in western Turkey, except possibly for its southern branch (Şengör et al., 2004). Basin development related to north-south extension begins in the Upper Thracian basin (UTB), South Balkan graben system (SBGS), Sofia graben (SG), and movement on the Strymon Valley detachment fault (SVD) continues. East-west extension migrates west into western Macedonia, northwestern Greece, and eastern Albania. Position of the subduction zone in western Albania is shown. D—Delcevo-Pehcevo basin, K—Korce basin, Ku—Kumanovo basin, MFZ—Maritza fault zone, P—Polog basin, Pe—Pelagonian basin, Pr—Prespa basin, Sa—Sandanski basin, Sk—Skopje basin, St—Strumica basin, TB—Thrace basin (no sediments at this time), ThB—Thermikos basin.

north-south extension that began by late Miocene time (Nakov et al., 2001b; Fig. 7). Middle Miocene strata that could be related to extensional faulting are rare in this region (Nakov et al., 2001b). By late Miocene time (late Sarmatian–early Meotian, 11–8 Ma) strata related to east-west–trending normal faults are present along the north and south sides of the Upper Thracian basin, the South Balkan graben system, and along the Sofia graben (Fig. 7). East-west–trending extensional faults and related basinal strata became more widespread in latest Miocene–early Pliocene time (Fig. 8; 7–3.5 Ma) and east-west–trending faults and related sediments began to extend westward into eastern Macedonia as the north-south–striking faults progressively migrated westward into western Macedonia and eastern Albania (Figs. 7 and 8). This pattern of faults and fault migration continued into the Pleistocene, when all of Bulgaria and easternmost Macedonia was characterized by north-south extension (Fig. 9). In northern and parts of southeastern Macedonia and north-central Greece the two fault patterns appear to overlap (Fig. 8; see Pavlides and Mountrakis, 1987).

From middle Miocene to the present the eastern limit of shortening related to subduction along the northern Hellenic trench migrated west to its present position in central Albania and northwestern Greece (Figs. 7–10). By late Pleistocene time the present distribution of normal faults had developed: north-south extension

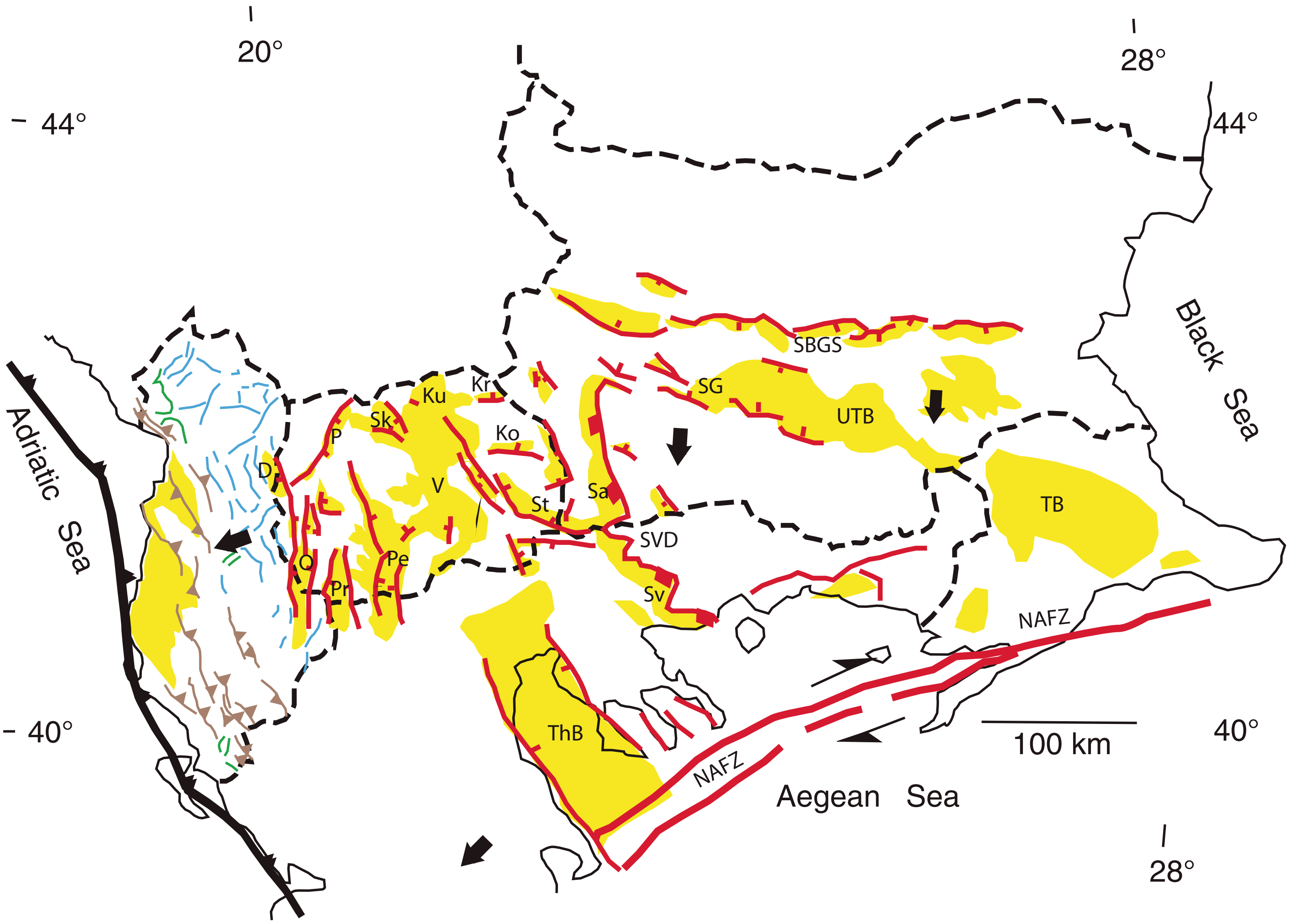

Figure 8. Tectonic setting in latest Miocene–early Pliocene time with the location of sedimentary basins (yellow). Thick red lines are normal faults, single tick line shows direction of dip on moderate to high-angle normal faults, and red square shows dip direction for low-angle normal fault (detachment fault). Blue lines are normal faults taken from unpublished Albanian maps. Brown lines are thrust faults within the zone of shortening related to the North Hellenic subduction zone of this age. Large black arrows show direction of relative extension. The northern branch of the North Anatolian fault zone (NAFZ) propagates into the north Aegean Sea. North-south extension propagates into eastern Macedonia and north-central Greece, where it overlaps with eastern part of the east-west extension. Shortening related to subduction along the North Hellenic subduction zone is shown in brown. Probable normal faults in eastern Albania are shown in blue. The Strymon Valley detachment fault (SVD) becomes progressively less active. D—Debar basin, Ko—Kocani basin, Kr—Kriva basin, Ku—Kumanovo basin, O—Ohrid basin, P—Polog basin, Pe—Pelagonian basin, Pr—Prespa basin, Sa—Sandanski basin, Sk—Skopje basin, St—Strumica basin, Sv—Strymon Valley basin, SBGS—South Balkan graben system, SG—Sofia graben, TB—Thrace basin, ThB—Thermikos basin, UTB—Upper Thrace basin, V—Veles basin. Large black arrows show direction of relative motion relative to European plate to the north.

across Bulgaria, eastern Macedonia, and northeastern and north-central Greece, and east-west extension in western Macedonia, northwestern Greece, and central and eastern Albania (Figs. 8 and 9). The boundary between these extensional fault systems is well marked in the seismicity and changes in the global positioning system (GPS) velocity field (Burchfiel et al., 2006, 2008). The two extensional fault patterns shown by location of Pleistocene and active faults are nearly at right angles to each other, indicating that the two dynamic systems causing the extension are largely independent. We relate the east-west extension to continued slab rollback along the northern Hellenic subduction zone, and the steepening of the slab caused by the arrival of thick Adriatic crust; however, the cause of the north-south extension is more complicated.

To see how the north-south extension in the eastern South Balkan extensional system evolved dynamically, several lines of evidence need to be examined. Tectonic studies indicate that crust in western Turkey has extended north-south in Cenozoic time, but the beginning of extension and the pattern of faults are controversial (e.g., see Catlos and Cemen, 2008). Paleomagnetic studies in western Turkey have not produced data as numerous or as consistent as those from the western Hellenides. They indicate that at least parts of western Turkey rotated counterclockwise by ~30° during late Cenozoic time (Kissel and Laj, 1988; Kissel et al., 1986; Duermeijer et al., 2000). At the same time crust along most of the Hellenides rotated clockwise ~50° (Van Hinsbergen et al., 2005). Thus if extension is related to slab rollback, the angle between the western and eastern parts of the subduction system would have increased from a gently convex south arc in early Cenozoic time to today, when they form an angle of from 60° to 120°, depending upon where it is measured. This increase in curvature of the

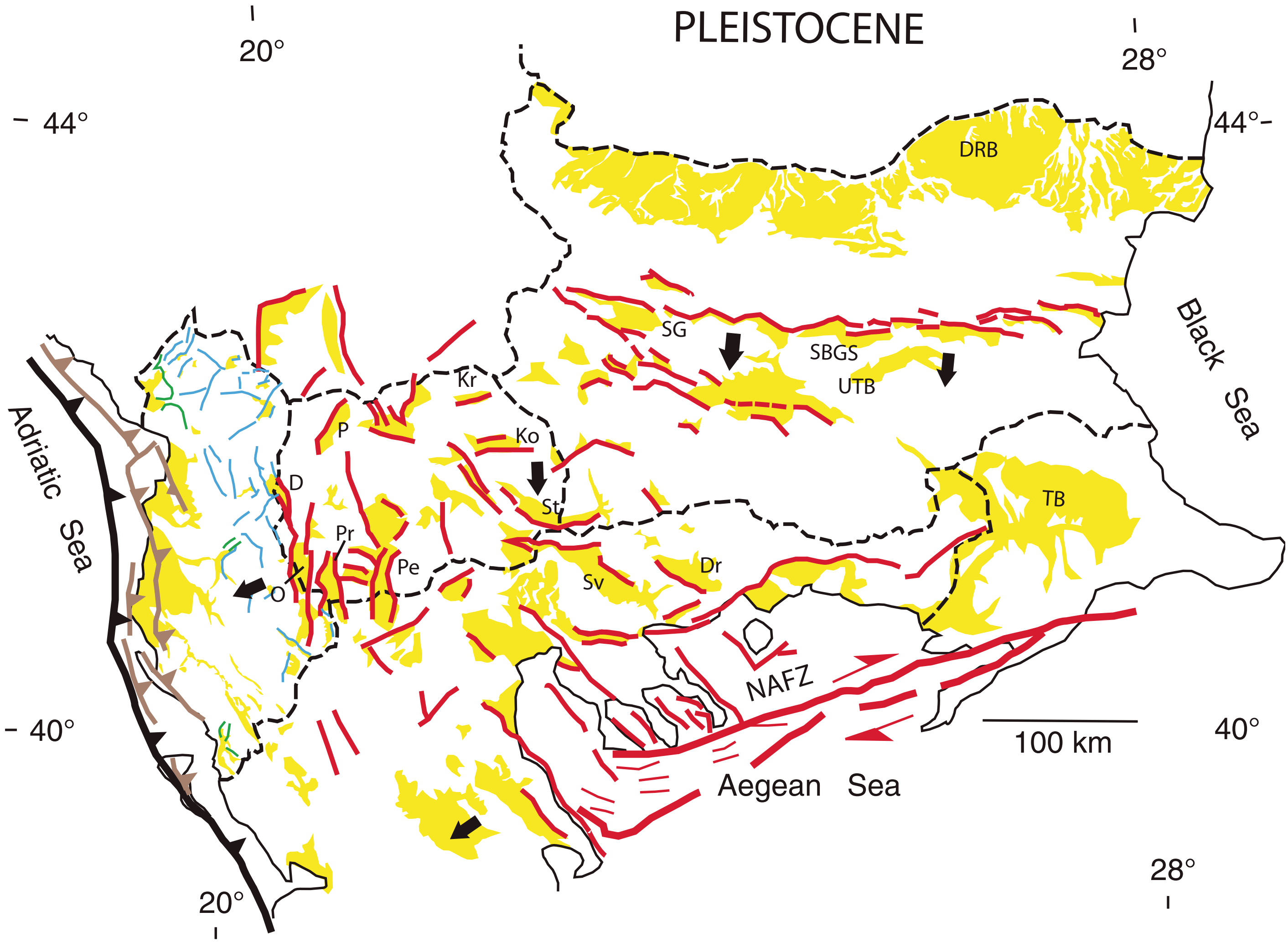

Figure 9. Tectonic setting in Pleistocene time. Thick red lines are normal faults. Blue lines are normal faults taken from unpublished Albanian maps. Brown lines are thrust faults within the zone of shortening related to the North Hellenic subduction zone. Large black arrows show direction of extension relative to European plate to the north. North-south extensional faults propagate farther west into central Macedonia and northwestern Greece, where they overlap with east-west extensional faults that dominate in western Macedonia, eastern Albania (blue), and northwestern Greece. Thrust faults related to convergence along the Northern Hellenic subduction zone are shown in brown. D—Debar basin, Dr—Drama basin, DRB—Danube River basin, NAFZ—North Anatolian fault zone, O—Ohrid basin, St—Strumica basin, Sv—Strymon Valley basin, P—Polog basin, Pe—Pelagonian basin, Pr—Prespa basin, SBGS—South Balkan graben system, SG—Sofia graben, TB—Thrace basin, UTB—upper Thrace basin.

subduction zone with time was suggested by Angelier et al. (1982), who interpreted the evolution of the Hellenic arc by slab rollback with opposite senses of rotation of the eastern and western parts of the subduction zone and a corresponding rotation of extension direction within the crust in its hanging wall. Thus as curvature of the subduction system increased, the directions of extension in the two parts of the hanging walls became more oblique, until at present they are nearly at right angles and appear to be only loosely coupled where the two normal fault systems appear to overlap in northwestern Greece and eastern Macedonia.

These postulated vertical axis rotations in the hanging walls of the subduction zones and the interpretation of rotation from the variations in the magnitude of extension for some of the structures in the western part of the South Balkan extensional system (Burchfiel et al., 2000) are consistent with paleomagnetic data. The rotation along the northern part of the Hellenic trench has been differential, as shown by the paleomagnetic results of Kissel and Laj (1988) and Van Hinsbergen et al. (2005). Their data show that the western part of the Hellenides rotated clockwise relative to central or eastern Bulgaria by ~45° to 50°. Kissel and Laj (1988) interpreted 20° of clockwise rotation from Paleogene to late Miocene time and an additional 25° of clockwise rotation from Pliocene to Holocene time, whereas Van Hinsbergen et al. (2005) interpreted that 40° of rotation occurred between 15 and 13 and 8 Ma and an additional 10° since 4 Ma. Both studies indicate that the pole of the rotation appears to be near the Pec Skutari line in northern Albania or southern Montenegro. The data can be used to estimate the magnitude of differential extension that has occurred; ~50° of rotation indicates ~250 km of extension at the latitude of Thessaloniki. Extension of this magnitude is not easily documented from present

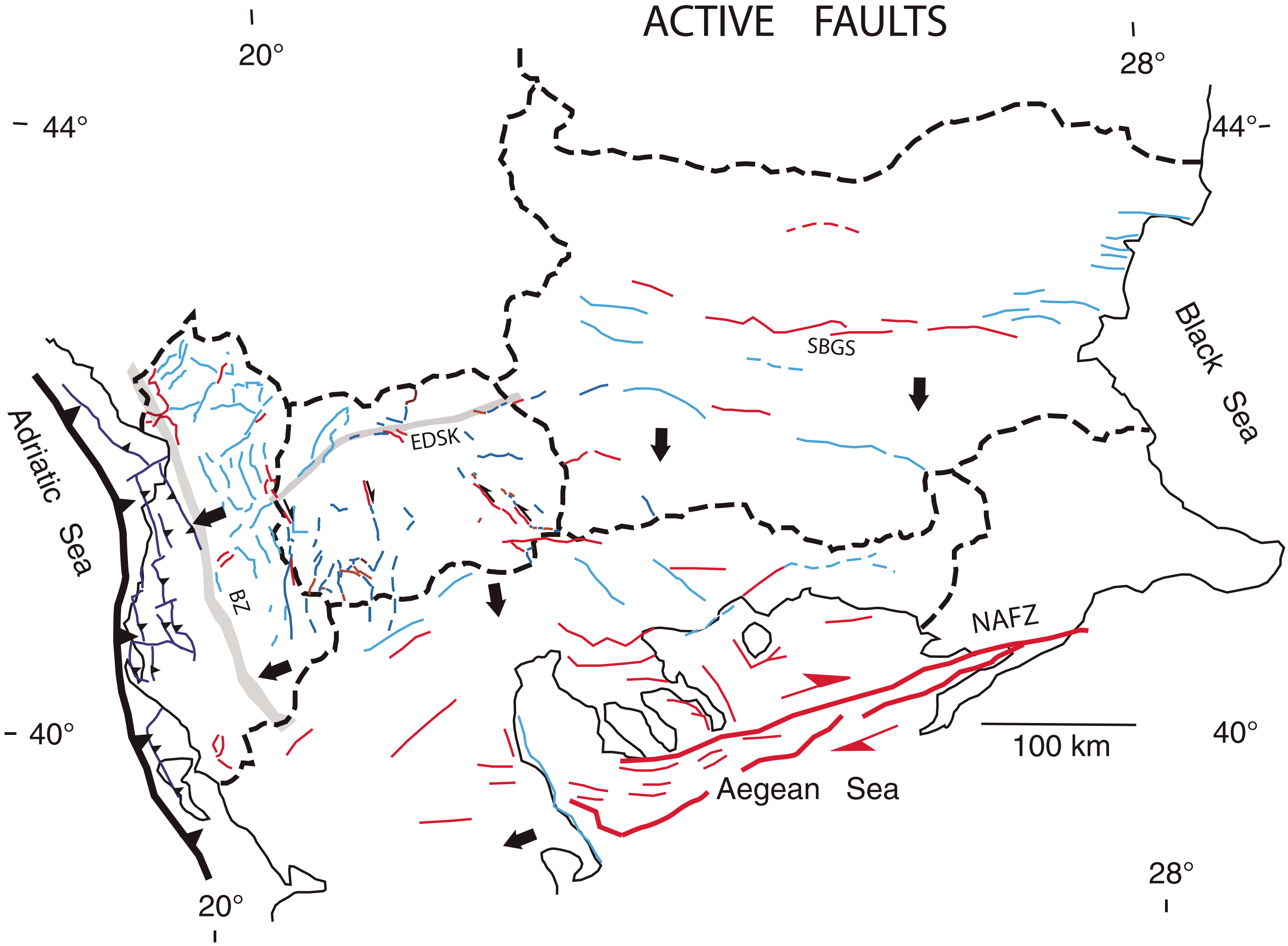

Figure 10. Active faults in the South Balkan extensional system. Red lines are faults where geological evidence shows features of active fault movement. Blue lines are faults with well-developed morphological evidence for recent activity. Dashed blue lines are faults with only weak morphological evidence for recent activity. Thick lines in northern Aegean Sea mark the trace of the North Anatolian fault zone (NAFZ). Shaded line trending north-south through central Albania marks a boundary zone (BZ) where there is an abrupt change from shortening structures to the west and north-south–trending extensional structures to the east. Purple ticked lines west of BZ are thrust faults related to shortening in the hanging wall of the North Hellenic subduction zone. EDSK—Regional Elbasan-Debar-Skopje-Kjustendil fault zone of Macedonian geologists trending north-northeast through northern Macedonia. SBGS—South Balkan graben system. Black arrows mark the sense of displacement on strike-slip faults. Large black arrows indicate direction of extension relative to European plate to the north.

knowledge of the structures in western part of the South Balkan extensional system. Approximately 100 km of extension might be accommodated on the southern part of the Strymon Valley detachment and on the large extensional faults in the Gulf of Thessaloniki and at Mount Olympus. The Strymon Valley detachment dies out northward in Bulgaria, indicating that it has a clockwise rotational component; however, the northward continuations of the other major extensional faults have not been studied, so which faults might have accommodated the rotation is unknown. Large amounts of additional extension are not obvious from our present understanding of the normal faults within the western South Balkan extensional system. In addition, the spatial and temporal distribution of displacements on extensional faults cannot be determined, and it may be complexly distributed, as shown by the paleomagnetic results of Dimitriadis et al. (1998). Calculation of the temporal and spatial distribution of the magnitudes of extension and the structures responsible for the differential extension and rotations remains an important and active area of research.

Similar problems occur for the counterclockwise rotations in western Turkey, although there are far fewer paleomagnetic and structural data. The data do not exist to make quantitative estimates for extension, identify which faults are the major structures, or identify the spatial and temporal patterns of normal faulting.

In late Miocene time, formation of the North Anatolian fault appears to have been a significant event that changed the dynamics within the South Balkan extensional system (Burchfiel et al., 2000). Right-lateral displacement along the southern branch of the Northern Anatolian fault zone and right-lateral shear across a broad zone within northwest Turkey began ca. 10 Ma (Şengör et al., 2004; Fig. 7). Since that time the North Anatolian fault zone became an increasingly more localized and active feature in the north Aegean Sea. The extension south of the North Anatolian fault zone in western Turkey and the Aegean is of much larger magnitude than the north-south extension in Bulgaria, Macedonia, and northern Greece. We postulate that the increasing activity along the North Anatolian fault zone has partially isolated the South Balkan extensional system from the Aegean extensional regime to the south, and the extension within the Aegean was directly related to rollback along the Hellenic subduction zone, whereas extension north of the North Anatolian fault zone is only indirectly related to the rollback. The relative magnitudes of the extension are unknown; however, the difference is expressed in the short-term GPS data (Burchfiel et al., 2006; Kotzev et al., 2006), which show that the Aegean area can be regarded as a single plate that moves south-southwest at 35 mm/yr relative to the South Balkan extensional system (McClusky et al., 2000). We relate the late Miocene to Holocene north-south extension in the eastern part of the South Balkan extensional system to a slow southward movement of lithosphere north of the North Anatolian fault zone to accommodate the southward movement of the Aegean Sea lithosphere. This also suggests that the North Anatolian fault zone west of the Sea of Mamara is rotating slowly counterclockwise, a rotation supported by the westward increase in the southward velocities relative to Europe in the GPS data in the area north of the fault zone (Kotzev et al., 2008). Data from the westward continuation of the North Anatolian right shear across the Corinth region in Greece suggest that the present pattern of deformation began in Pliocene time (D. Papanikolaou and L. Royden, 2007, personal commun.). Thus the complex interaction between progressive development of the western part of the North Anatolian fault zone (Şengör et al., 2004), rollback along the different segments of the Hellenic trench, and the motion of the Aegean Sea area have been responsible for the progressive temporal and spatial development of extension within the South Balkan region.

A second but unresolved important problem within the western part of the South Balkan extensional system is the role of strike-slip faulting during Cenozoic time. Little attention has been paid to large-scale lateral movements within this regime; however, regional reconstructions invariably suggest that such movements have taken place (e.g. Burchfiel, 1980; Stampfli and Borel, 2002). Plate tectonic models of the movement of crustal fragments within the eastern European area usually include the northward movement of continental fragments such as Apulia, Tizia, and Rhodopia northward into the eastern Alpine and Carpathian region during late Mesozoic and early Cenozoic time (e.g., Burchfiel, 1980; Stampfli and Borel, 2002; Fugenschuh and Schmid, 2005). However, the actual location of the north-south–striking faults that would accommodate such motion through the western Balkans is not clear. Fugenschuh and Schmid (2005) suggested that the north-striking Cerni-Timok fault in southwestern Romania accommodated right-lateral movement in middle Cenozoic time (Fig. 4). Others have suggested that faults through the Vardar zone accommodated similar displacements (e.g., Burchfiel, 1980; Picha, 2002; Stampfli and Borel, 2002); however, Paleogene deposits in eastern Macedonia cover the eastern two-thirds of the Vardar zone (Dumurdzanov et al., 2005), and such faults would have to be in a narrow zone in its western part, but little work has been done to confirm such early Cenozoic strike-slip faults. By late Miocene time all the Vardar zone was covered by sedimentary rocks that do not show major strike-slip displacements (Dumurdzanov et al., 2005). West of the Vardar zone there is little evidence from the Pelagonian zone that large faults cut through an older large antiformal structure within this tectonic unit (Fig. 3; Dumurdzanov et al., 2005), although the eastern side of this antiform has been truncated by NNW–trending faults, but the age and nature of these faults remain unknown. It is important to note that even though the GPS data strongly suggest active right-lateral strike slip through central Albania, only two short sediments of active northwest-striking strike-slip faults have been identified (Fig. 10; Dumurdzanov et al., 2005; Burchfiel et al., 2006). The existence of large-scale lateral movements of Cenozoic age, particularly of early Cenozoic age, remains a problem yet to be resolved.

CONCLUSIONS

The Southern Balkan extensional system is north of the western part of the North Anatolian fault zone and south of a poorly defined boundary that extends through northern Bulgaria west to the Adriatic coast (McKenzie, 1972; Burchfiel et al., 2006, 2008; Kotzev et al., 2006, 2008). It has been dominated from late Paleogene to Holocene time by extensional tectonism that evolved from a convergent tectonic setting in late Mesozoic–early Paleogene time. Although it is currently mostly isolated from the more active extension within the Aegean region south of the North Anatolian fault zone, its early development was more closely tied to tectonism related to the dynamics of the Vardar subduction zone in the evolving Hellenic subduction system.

The oldest extensional structures in southern and western Bulgaria and northeastern Greece are of latest Cretaceous–early Paleogene age and developed during closure of the Vardar Ocean by northward subduction. Low-angle extensional faults, mostly south vergent, formed within a regionally compressional tectonic setting that extended from the subduction zone to the Fore-Balkan thrust belt in north Bulgaria. Recent studies within the metamorphic rocks of the South Balkan extensional system where these low-angle faults are recognized show that extensional normal faults and thrust faults developed contemporaneously. Such a tectonic environment is similar to that in areas where crust has been thickened, heated, and ductile during shortening. Within such an evolving environment gravitational potential energy became sufficient to permit lateral flow of ductile lower or middle crust, permitting extension to occur at upper crustal levels while shortening continued at lower crustal levels (e.g., Burchfiel and Royden, 1984; Royden, 1996; Burchfiel et al., 1992).

Middle Eocene–Oligocene time was a transitional period when the regional convergent tectonic setting changed to a regionally extensional setting, shown by the cessation of thrusting in the Fore-Balkan thrust belt and development of detachment faults and sedimentary basins in the central and mainly southern part of the South Balkan extensional system. The dynamic processes were complex; extension in the western part of the South Balkan extensional system was apparently related to the beginning of trench rollback along the Northern Hellenic trench. However, within the eastern South Balkan extensional system, extension was related to the lowering of horizontal stress, an increase in gravitationally induced spreading of ductile crust, and the fate of the subducted slab following collision that may be marked by the beginning of trench rollback. Extension and crustal (lithospheric) thinning were accompanied by the extrusion of abundant intermediate and felsic volcanic rocks, which evolved from partial melting of a subduction-enriched subcontinental lithospheric mantle source, through fractional crystallization and crustal contamination, to decompression melting of an enriched asthenospheric source. Contemporaneously, a broad region of subsidence developed along and just north of the Vardar–Intra-Pontide suture zone extending from central Macedonia to northwestern Turkey, and formed basins where deposition of thick turbidites was followed by a shallowing upward into shallow-marine and nonmarine deposits. These basins show evidence for extension, but of a magnitude that is not commensurate with their subsidence, and their origin remains unclear.

This transitional period was terminated or slowed by a local (?) short period of shortening in latest Oligocene–early Miocene time. Folds developed within the Paleogene rocks of eastern Macedonia and western Bulgaria and within northwestern Turkey, perhaps related to strike-slip faulting, and thrusting occurred in northeast Bulgaria. In the western South Balkan extensional system, shortening may have been related to the accretion of the small Kruja continental fragment in eastern Albania. In the eastern South Balkan extensional system, shortening and faulting may be related to the end of intracontinental convergence at the Vardar–Intra-Pontide–Izmir-Ankara suture zone and/or oblique convergence in subduction zones farther south, but its cause remains unclear. Nevertheless, this period of shortening makes a convenient boundary between the complex pattern and Paleogene dynamics of extension and the middle Miocene to Holocene major extension-related trench rollback along the Hellenic subduction zone to the west and south.

Middle Miocene to Holocene north-northeast–south-southwest extension occurred in western Bulgaria and migrated westward to its present position in central Macedonia, eastern Albania, and northwestern Greece, coeval with the westward migration of the North Hellenic subduction zone. We interpret the westward migration of north-south extensional faults to be the result of progressive trench rollback. East-west normal faults in the eastern part of the South Balkan extensional system did not initiate until late Miocene time; they became more widespread and migrated to the west in tandem with westward migration of the north-south faults in western Bulgaria and eastern Macedonia. The two fault regimes currently overlap along a boundary zone in central Macedonia and northwestern Greece. The fault patterns evolved as curvature of the Hellenic trench increased by major clockwise and to a lesser extent counterclockwise rotation in the western and eastern hanging wall, respectively, of the Hellenic subduction zone.

With the formation of the western part of the North Anatolian fault zone, extension within the South Balkan extensional system became largely decoupled from the main Aegean extension south of the fault zone in late Miocene time. During late Cenozoic time, rapid south-southwest movement of the Aegean area was bounded by the North Anatolian fault zone on the north, and its rapid movement was caused by rollback at the Hellenic subduction zone that pulled the southern Balkan lithosphere more slowly to the south, causing the north-south extension and possible counterclockwise rotation of the western part of the North Anatolian fault zone. The progressive development of the Hellenic subduction zone into an increasingly more arcuate shape and formation of the North Anatolian fault zone caused the north-south extension to migrate westward in tandem with westward migration of the east-west extension in the western part of the South Balkan extensional system.

Active extension within the South Balkan extensional system consists of two parts: (1) a western part, where east-west extension in eastern Albania and western Macedonia is related to slab rollback along the northern Hellenic subduction zone marked by a narrow belt of shortening, and (2) an eastern part, consisting of north-south extension in central and southern Bulgaria, eastern Macedonia, and northern Greece related to the slow southward movement of the South Balkan extensional system lithosphere, pulled southward by rapid south-southwest movement of the Aegean Sea lithosphere, which is mostly decoupled from the South Balkan extensional system across the North Anatolian fault zone. The two regions of extension overlap within Macedonia and northwestern Greece.

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