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Time evolution of a rifted continental arc: Integrated ID-TIMS and LA-ICPMS study of magmatic zircons from the Eastern Srednogorie, Bulgaria

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ABSTRACT

Eastern Srednogorie in Bulgaria is the widest segment of an extensive magmatic arc that formed by convergence of Africa and Europe during Mesozoic to Tertiary times. Northward subduction of the Tethys Ocean beneath Europe in the Late Cretaceous gave rise to a broad range of basaltic to more evolved magmas with locally associated Cu–Au mineralization along this arc. We used U–Pb geochronology of single zircons to constrain the temporal evolution of the Upper Cretaceous magmatism and the age of basement rocks through which the magmas were emplaced in this arc segment. High precision isotope dilution-thermal ionization mass spectrometry (ID-TIMS) was combined with laser ablation-inductively coupled plasma mass spectrometry (LA–ICPMS) for spatial resolution within single zircon grains.

Three tectono-magmatic regions are distinguished from north to south within Eastern Srednogorie: East Balkan, Yambol–Burgas and Strandzha. Late Cretaceous magmatic activity started at ~92 Ma in the northernmost East Balkan region, based on stratigraphic evidence and limited geochronology, with the emplacement of minor shallow intrusions and volcanic rocks onto pre-Cretaceous basement. In the southernmost Strandzha region, magmatism was initiated at ~86 Ma with emplacement of gabbroic to dioritic intrusions and related dikes into metamorphic basement rocks that have previously been overprinted by Jurassic–Lower Cretaceous metamorphism. The Yambol–Burgas region is an extensional basin between the East Balkan and the Strandzha regions, which broadens and deepens toward the Black Sea further east and is filled with a thick pile of marine sediments and submarine extrusive volcanic rocks accompanied by coeval intrusions. This dominantly mafic magmatism in the intermediate Yambol–Burgas region commenced at ~81 Ma and produced large volumes of potassium-rich magma until ~78 Ma. These shoshonitic to ultrapotassic basaltic to intermediate magmas formed by differentiation of ankaramitic (high Ca) parental melts, produced from partial remelting of amphibole clinopyroxenites upon interaction with subduction-modified mantle wedge melts, according to earlier petrological studies. This peak of dominantly extrusive activity in the Yambol–Burgas region extended into the Strandzha region further south, in the form of numerous tholeiitic, calc-alkaline and high-K intrusions emplaced in the same time period between 81 and 78 Ma.

Granitic rocks from exposed basement of Eastern Srednogorie zone are dated as Permian/Carboniferous (~275–300 Ma). Zircons with similar ages occur in Upper Cretaceous rocks from the East Balkan and Strandzha regions, indicating local incorporation as xenocrysts. In contrast, magmatic rocks from the intermediate Yambol–Burgas region contain mostly Ordovician (~460 Ma) or older inherited zircons, suggesting a either a different basement history or, more likely, a different level of magma storage and crustal assimilation.

Integrating these geochronological results with a synthesis of the regional geology, we propose a two-stage geodynamic evolution for the Eastern Srednogorie segment of the Tethyan arc. The earlier stage of normal arc magmatism was driven by a southward slab retreat, which formed the ~92 Ma calc-alkaline to high-K shallow intrusions and volcanics in the north (East Balkan), 87–86 Ma old tholeiitic and calc-alkaline intrusions in the south (Strandzha), and the voluminous 81–78 Ma old gabbroic to granitic intrusions with predominantly calc-alkaline to high-K composition throughout the Strandzha region. This stage continued westward into the Central Srednogorie zone, where the southward younging of calc-alkaline magmatism correlates well with an increased input of primitive mantle melts, indicating asthenospheric incursion into a widening mantle wedge as a result of slab roll-back. The second stage proceeded in the Eastern Srednogorie zone only, where more extreme extension associated with the opening of the Black Sea back-arc basin led to the formation of an intra-arc rift in the Yambol–Burgas region, which now separates the East Balkan region from the Strandzha region. In this extensional environment, crustal thinning lead to decompression and increased heat flow,

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facilitating large-scale melting of lower crustal rocks and the formation of 81–78 Ma magmas. The unusual calcic composition of the parent magmas, their isotopic character and distinct xenocrystic population are consistent with a component of re-melting of hydrous lower-crustal cumulates, which probably formed in part during the first stage of the evolving arc.

1. Introduction

The Alpine orogeny in Europe formed from the long-term convergence between Africa and Europe and the associated consumption of Mesozoic oceanic basins through northward subduction of oceanic lithosphere beneath the European continent (Burg, 2011; Janković, 1997; Neubauer, 2002; Schmid et al., 2008). The Carpathian–Balkan segment of the Alpine orogen preserves geochemical evidence for these large-scale processes. The Apuseni–Banat–Timok–Srednogorie (ABTS) belt (Popov et al., 2002) is a more than 1000 km long belt of Upper Cretaceous calc-alkaline magmatic rocks with subduction-like geochemical signature. Presently, the ABTS belt extends from south Romania through east Serbia and across Bulgaria (Fig. 1) and hosts Europe's major Cu-porphyry deposits (Berza et al., 1998; Heinrich and Neubauer, 2002; Mitchell, 1996).

Since the first plate-tectonic interpretations, the formation of the ABTS belt and the Srednogorie zone is attributed to the northward subduction of the Vardar oceanic branch of the Tethys Ocean beneath the Serbo–Macedonian–Rhodope massif and the Moesian promontory of the European continent (Aiello et al., 1977; Boccaletti et al., 1974; Dabovski et al., 1991; Dewey et al., 1973; Hsü et al., 1977; Janković, 1997; Ricou et al., 1998; Stampfli and Borel, 2004). Other models

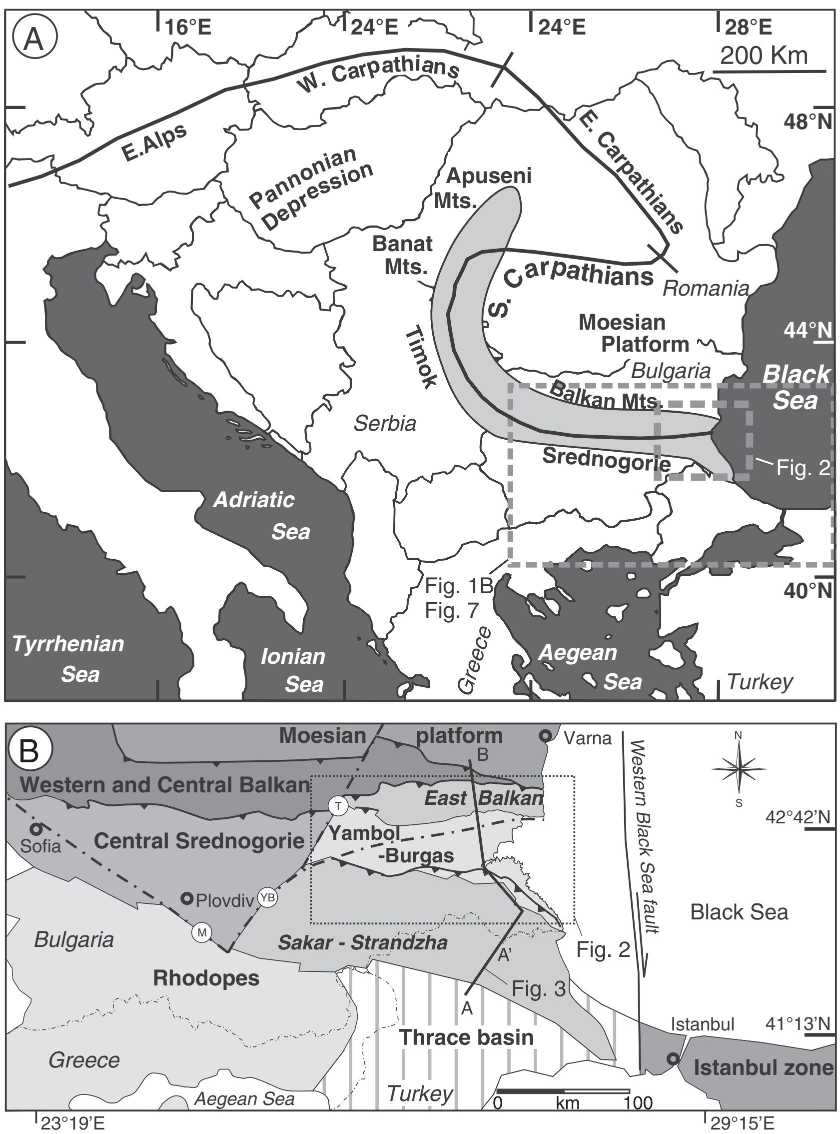

Fig. 1. A) Sketch map of south-eastern Europe showing the location of Apuseni–Banat–Timok–Srednogorie Upper Cretaceous magmatic belt (gray field). Solid black line is the main front of the Alpine–Carpathian–Balkan orogeny. Eastern Srednogorie zone occupies the easternmost parts of ABTS belt (gray dashed square). Modified after Ciobanu et al. (2002). B) Simplified tectonic map of Eastern Srednogorie zone (dotted rectangle) and adjacent units. Modified after Banks (1997), Dabovski et al. (2009a), Ivanov (1998), Kamenov et al. (2003) and Okay et al. (2001). Location of Western Black Sea fault after Okay et al. (1994). Thick dash–dot–dash lines are major deep seated faults: YB — Yambol–Burgas Fault (Dachev, 1988); M — Maritsa Fault; T — Tvarditsa Fault (Bončev, 1971). Additional details are shown in Fig. 7.

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had considered the ABTS belt as an extensional structure in an epicontinental rift environment that formed as a result of post-collisional collapse and related asthenospheric diapirism (Antonijevic et al., 1974; Popov, 1981, 1987). Neubauer (2002) suggested that some characteristics of the ABTS belt can be explained by progressive east to west tear-off of the subducted oceanic slab in a syn-collisional regime.

Intense post-emplacement tectonics and erosion during the Alpine orogeny, combined with poor outcrops due to the low relief and young sediment infills, hinder a detailed geodynamic reconstruction of this area. High-precision geochronological dating provides a key tool to decipher the sequence of magmatic events in such terranes with complex post-emplacement history and poor preservation. High-precision U–Pb ID-TIMS zircon ages were reported for Late Cretaceous rocks from the Central Srednogorie zone (von Quadt et al., 2005). In the Panagyurishte transect, a Cu–Au-mineralized trend oriented obliquely to the main strike of the ABTS belt, magmatic ages gradually decrease from ~92 Ma in the north to ~78 Ma in the south. Re–Os molybdenite ages confirm the age progression of porphyry and epithermal Cu–Au mineralization in this transect (Zimmerman et al., 2008). This trend is accompanied by changing igneous geochemistry, showing increasing mantle input from north to south (Kamenov et al., 2007; von Quadt et al., 2005). The combination of age and geochemical progressions is explained by a geodynamic model involving north-dipping subduction of Vardar oceanic lithosphere that experienced a progressive southward roll back of the subducting slab (von Quadt et al., 2005). In this model, steepening of the slab during roll-back leads to an increased corner flow of upper lithospheric mantle and asthenospheric material, combined with extension of the upper plate.

The Eastern Srednogorie zone is the easternmost part of the ABTS belt, situated between the Central Srednogorie zone and the Black Sea (Figs. 1 and 2). It is characterized by a presently thinner crust (28–30 km) compared to the rest of the Balkan Peninsula (e.g. crustal thickness in the adjacent Central Srednogorie zone is ~40 km; Dachev, 1988). Compared to the remaining ABTS belt, this zone hosts voluminous, mostly extrusive magmatism with unusually mafic and alkaline composition and a clear across-arc geochemical zonation (Georgiev et al., 2009 and references therein). The large volume and geochemical diversity of Eastern Srednogorie magmatism provides an excellent opportunity for detailed geochronological and geochemical studies to aid deciphering the evolution of the whole ABTS belt and the Balkan region. The position of Eastern Srednogorie zone next to the Central Srednogorie zone allows direct age and geochemical correlations within the Upper Cretaceous belt. Eastern Srednogorie zone is also the potential link of the ABTS belt with the Upper Cretaceous Pontide belt in Turkey to the southeast (Janković, 1997), and with the Black Sea basin to the east. The Black Sea is an extensional back-arc basin (Zonenshain and Le Pichon, 1986) that formed during an Aptian–Albian (~125 Ma to 100 Ma) main rifting phase, followed by intensive oceanic crust formation in spreading centers (Görür, 1988; Kaz'min and Tikhonova, 2006; Nikishin et al., 2001; Starostenko et al., 2004).

In this paper we aim to constrain the time evolution of the Late Cretaceous magmatism in the Eastern Srednogorie zone. We address the following main questions: 1) What is the precise age of magmatic rocks? 2) Is there any along- or across strike age zonation within Eastern Srednogorie zone or correlations between ages and geochemistry of the magmatic rocks? 3) What is the age of the exposed basement intrusive rocks and is there any evidence for assimilation of basement rocks by the Upper Cretaceous magmas? 4) What is the geodynamic significance of the age data? To address these issues, we present and discuss an extensive dataset of U–Pb zircon ages from Eastern Srednogorie zone.

2. Regional geology

2.1. Geology of Eastern Srednogorie zone

The basement of Eastern Srednogorie zone begins with Precambrian (?) high-grade metamorphic rocks, Paleozoic granites and greenschist facies rocks, followed by Permian clastics, Triassic carbonates and Lower–Middle Jurassic marine clastics and shales exposed in the present-day Strandzha Mountains (Figs. 2 and 3) (Chatalov, 1990; Dabovski et al., 2002; Gerdjikov, 2005). In the southeastern part of Strandzha these rocks are tectonically overlain by allochthonous Paleozoic and Triassic metasediments. In the East Balkan region, basement rocks are exposed in a narrow strip of Triassic carbonates and flysch-like sediments, and Jurassic shales (e.g. Dabovski et al., 2002). The Upper Cretaceous succession begins with Cenomanian continental and shallow marine clastic sediments preserved along the border between the Strandzha Mountains and the Yambol–Burgas depression, and also in the East Balkan Mountains. During the Turonian, deeper marine shales and argillaceous carbonates were deposited in a deepening basin. In the Coniacian–Campanian the Yambol–Burgas depression was filled with a 5–6 km thick volcano–sedimentary succession (Nachev and Dimitrova, 1995a,b). The East Balkan basin also records a thick Coniacian–Campanian deep marine sequence but lacks voluminous volcanic products. The Upper Cretaceous volcano–sedimentary sequence is unconformably overlain by shallow-marine Maastrichtian carbonates in the Yambol–Burgas depression and by Paleogene and Neogene continental to shallow marine clastics and carbonate rocks in the East Balkan. Additional description of the geology of Eastern Srednogorie zone is given in Dabovski et al. (1991, 2002), Georgiev et al. (2001) and Georgiev (2008).

2.2. Magmatism

More than 90 intrusions and volcanic centers are described in the Eastern Srednogorie zone (Nachev and Nachev, 2001; Popov, 1981), comprising more than 60 area percent of the exposed magmatic rocks of Cretaceous age in the whole Srednogorie zone (Stanisheva-Vassileva, 1989). In contrast to most of the ABTS magmatic belt, where calc-alkaline rocks of intermediate composition prevail, the Eastern Srednogorie zone is characterized by a large geochemical variability and a predominance of mafic to intermediate over felsic magmas. Primitive nepheline-normative ankaramites have been reported among the mafic lavas (Georgiev et al., 2009; Marchev et al., 2009). Abundant major element geochemical data show that the mafic and intermediate magmatism in Eastern Srednogorie zone covers the entire spectrum of chemical series observed in volcanic arcs: from tholeiitic through calc-alkaline to alkaline (shoshonitic) compositions (Georgiev et al., 2009; Popov, 1981; Stanisheva-Vassileva, 1980, 1989). An increase of the K_2O content of the rocks from south to north has been interpreted as evidence for the progressive deepening of the melt-generation regions, consistent with a northward subduction of the Vardar Ocean plate below the European platform (Dabovski et al., 1991; Stanisheva-Vassileva, 1980, 1989). However, new geochemical data from the northernmost magmatic products in Eastern Srednogorie zone reveals a complex zonation with more evolved calc-alkaline magmas to the south and north and more mafic shoshonitic to ultra-potassic magmas in the center (Georgiev, 2008; Georgiev et al., 2006, 2009). Four magmatic regions are traditionally distinguished within Eastern Srednogorie zone: Strandzha, Yambol–Burgas, North Burgas and East Balkan from south to north. The North Burgas region, which has been considered a back-arc rift (Dabovski et al., 1991; Georgiev et al., 2001), shows similar major and trace element characteristics and isotopic fingerprints as the Yambol–Burgas region (Georgiev et al., 2009; Marchev et al., 2009). Based on these similarities, Georgiev et al. (2009) proposed a common origin for the magmatic rocks from the Yambol–Burgas and the North Burgas regions. Here, we adopt this view and merge the two regions into one extended region named Yambol–Burgas region (Figs. 2 and 3).

The Yambol–Burgas and Strandzha regions host most of the Upper Cretaceous magmatic products in the Eastern Srednogorie zone, whereas only few small outcrops are known in the East Balkan region (Georgiev et al., 2009). Magmatic rocks from the Strandzha and East

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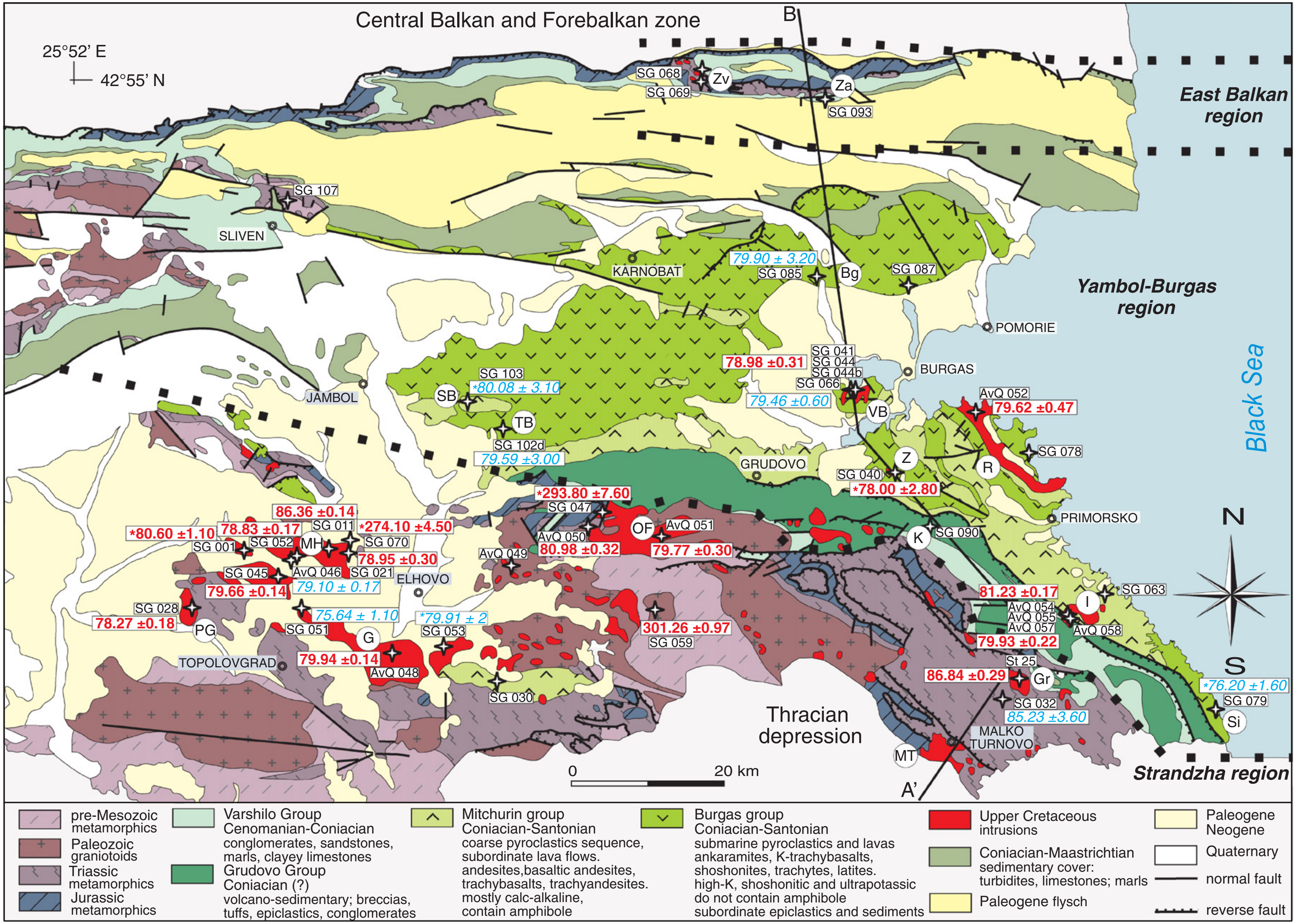

Fig. 2. Geological map of Eastern Srednogorie zone, modified after Cheshitev and Kanchev (1989), showing sample location (white stars, SG-, AvQ- and St- numbered samples) and U–Pb zircon ages of magmatic rocks obtained in this study. Bold red numbers indicate confidently determined ages and italic cyan numbers are for tentative ages. Ages preceded with * are obtained by LA-ICPMS. The A′–B line marks the approximate location of a summary cross-section, presented in Fig. 3. Thick dotted lines mark the three magmatic regions within Eastern Srednogorie. White labeled circles are major magmatic centers as follows: in Strandzha region — PG — Polski Gradetz; MH — Monastery Heights; G — Granitovo; OF — Oman-Fakya; MT — Malko Turnovo; Gr — Gramatikovo; in Yambol–Burgas region — Si — Silistar; I — Izgrev; K — Krushevetz; R — Rossen; Z — Zidarovo; VB — Vurli Brjag; TB — Tamarino Bakadzhik; SB — Sveti Spaski Bakadzhik; Bg — Bulgarovo; in East Balkan region — Za — Zaimchevo; Zv — Zvezda.

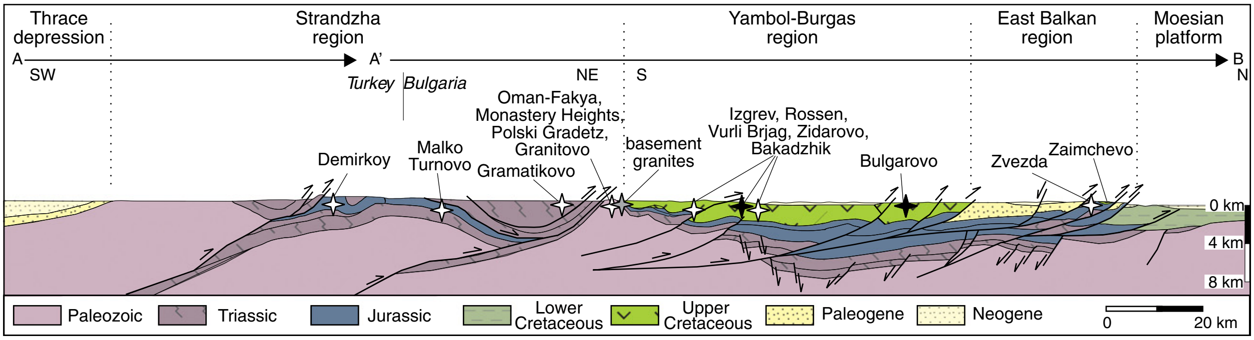

Fig. 3. Schematic cross-section of Eastern Srednogorie zone along the A′–A–B line shown in Figs. 1B and 2, with approximate north–south location of dated Upper Cretaceous intrusions (white stars), Late Cretaceous lavas (black stars), and basement granitoids (gray stars). Cross-section is based on tectonic interpretations and geophysical data from Georgiev et al. (2001) and Banks (1997).

Balkan regions are mostly calc-alkaline to high-K intrusions containing hydrous phases, whereas in the central Yambol–Burgas region they are dominantly basic to intermediate submarine shoshonitic volcanic rocks that rarely contain hydrous minerals (Georgiev et al., 2009). Stratigraphic relations constrain the magmatism in Eastern Srednogorie zone as broadly Turonian–Campanian (from ~94 to ~70 Ma) and the peak of the magmatic activity is considered as Coniacian–Campanian, from ~90 to ~70 Ma (e.g. Dabovski et al., 1991; Georgiev et al., 2001). Prior to this study, available radiometric data consisted exclusively of K–Ar ages of whole-rocks or mineral separates varying between 130 and 50 Ma (summarized in von Quadt et al., 2005). The exposed basement rocks in this zone were not dated radiometrically.

2.3. Metallogeny

The ABTS belt is the most important metallogenic belt in the Alpine–Balkanide–Carpathian–Dinaride region (Heinrich and Neubauer, 2002), hosting major porphyry style and high-sulfidation Cu ± Au polymetallic and carbonate-replacement deposits. In contrast to the Central Srednogorie and Timok parts of the ABTS belt that host the economically most important deposits, magmatism and associated hydrothermal activity in the Eastern Srednogorie zone produced mostly Fe ± Cu skarn deposits and mesothermal- to epithermal Cu–Au polymetallic vein deposits with smaller size. The different chemical composition and depth of magma emplacement predetermined the contrasting mineralization style between the Strandzha and Yambol–Burgas regions of Eastern Srednogorie zone. In the Strandzha region, emplacement of tholeiitic to calc-alkaline gabbro–dioritic intrusions in Triassic carbonates formed the Fe-skarn magnetite-rich deposit of Krumovo in the Monastery Heights and the Cu-skarn deposits near Malko Turnovo (Fig. 2), as well as numerous smaller occurrences and showings, including orthomagmatic Fe–Ti mineralizations. In the Yambol–Burgas region, ore deposits of mesothermal to epithermal Cu–polymetallic vein type are related to volcano–plutonic systems with shoshonitic and high-K magmatism (Popov, 1996), including the Zidarovo, Vurli Brjag, Rossen and Tamarino Bakadzhik ore fields (Fig. 2) that formed at shallower crustal depth compared to the skarn deposits in the Strandzha region.

3. Sample selection and analytical techniques

We sampled fresh- to minimally-altered intrusive and extrusive rocks, selecting samples where field relations indicated clear temporal succession of emplacement. Samples were crushed and ground, and mineral concentrates were purified by magnetic and density separation (Wilfley table and heavy liquids) techniques. Individual zircons were further selected using a binocular microscope.

3.1. Conventional high-precision TIMS single-grain dating

Prior to analyses, most single zircon crystals were pre-treated to remove zircon domains prone to post-crystallization Pb loss. The majority of the analyzed zircons (~60%) were air-abraded for several hours in the presence of pyrite grains following the method of Krogh (1982). The chemical abrasion technique of Mattinson (2005) was tested on ~20% of the grains, and the remaining 20% of zircon grains were analyzed without any pre-treatment (unabraded). All zircon grains were separately cleaned, spiked with a ^{205}Pb–^{235}U tracer and digested following procedures in Krogh (1973). After anion exchange column chemistry, both Pb and U were loaded on an outgassed Re filament. Isotope ratios were determined in ETH-Zurich on a Finnigan MAT 262 mass-spectrometer, using electron multiplier for most samples. Further details are given by Georgiev (2008) and von Quadt et al. (2011). The Pb MacDat Excel spreadsheet (Coleman, unpublished), which incorporates error propagation equations of Ludwig (1980), was used for data reduction. We used a mass fractionation of 0.11 ± 4.6%/AMU for Pb measured with Faraday cups, and 0.13 ± 4.0%/AMU for Pb measured with the electron multiplier, determined from multiple analyses of the NBS982 Pb standard. Total procedural blank was on average 0.8 pg Pb and 0.01 pg U with a Pb isotopic composition of ^{206}Pb/^{204}Pb = 17.8 ± 0.29, ^{207}Pb/^{204}Pb = 15.47 ± 0.30, ^{208}Pb/^{204}Pb = 37.35 ± 0.80. Concordia plots, weighted averages, and probability density plots were constructed with the Isoplot 3.00 software (Ludwig, 1991, 2003).

3.2. Zircon imaging and LA-ICPMS single grain dating

The largest and inclusion free grains were handpicked, mounted in epoxy resin and polished to expose grain cores. Chips were then carbon-coated for electron-microscope imaging. Backscattered electron (BSE) and cathode-luminescence (CL) images were acquired at ETH Zurich using a CamScan CS44LB scanning electron microscope. After imaging, chips were re-polished to remove coating and cleaned. Laser dating was performed at ETH Zurich using a 193 nm ArF excimer laser (Lambda Physik) coupled to an Elan 6100 DRC ICP-MS instrument (Perkin Elmer). More detailed description of the instrumentation is given in Günther et al. (1998) and Heinrich et al. (2003). Ablation spots were chosen based on CL and BSE images and transmitted-light petrography. Energy densities of 20 to 25 J/cm^2 and laser pulse frequency of 10 Hz were used. A typical analytical block consisted of 20 measurements (3 NIST 610 standards at the beginning, 14 zircons, and 3 standards at the end). Additional details are given in Georgiev (2008).

The reported ages and errors were calculated using an in-house Excel-based spreadsheet (Georgiev, 2008). Data were corrected for laser-induced elemental fractionation using the intercept of the linear regression through the raw ratios as described in Chang et al. (2006).

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Mass discrimination was controlled and corrected by applying an external correction method. First, we measured NIST 610 as an unknown, corrected the raw data for laser induced fractionation, and used numerous point analyses of the zircon standards Plesovice (Slama et al., 2008) and 91500 (Wiedenbeck et al., 1995) for external mass-bias correction. The resulting NIST 610 values of $^{206}Pb/^{238}U=0.21938$, $^{207}Pb/^{235}U=89.53417$ and $^{208}Pb/^{232}Th=0.44836$ were reproducible and independent of crater diameters between 20 and 70μm, provided that crater depth stayed smaller than the crater radius. These calculated NIST 610 values thus include a correction for any matrix dependence between zircon and silicate glass, and were subsequently used for external calibration of unknown zircon samples. This calibration procedure has the advantage of better counting-statistical reproducibility of the comparatively Pb-rich (426ppm Pb) NIST 610. The calculated U–Th–Pb isotope ratios differ from published TIMS values for NIST 610 (Stern and Amelin, 2003), but are close to the U–Th–Pb isotope ratios derived from concentrations and isotope abundances in NIST 610 (data from Rocholl et al., 2000).

The amount of common Pb was calculated from ^{204}Hg-corrected ^{204}Pb intensities. ^{201}Hg or ^{202}Hg masses were monitored and used to calculate ^{204}Hg counts, which were subtracted from the ^{204}Pb counts. Following Hg-correction, the $^{206}Pb/^{238}U$ age calculated from background and mass-bias corrected $^{206}Pb/^{238}U$ ratio was used to estimate the initial common Pb composition from the Stacey and Kramers (1975) model for Pb isotopic evolution through time. Using this composition, the fraction of ^{206}Pb, ^{207}Pb, ^{208}Pb proportional to the measured Hg-corrected ^{204}Pb was subtracted from the calculated $^{206}Pb/^{238}U$, $^{207}Pb/^{235}U$ and $^{208}Pb/^{232}Th$ ratios.

3.2.1. Error propagation, precision and accuracy

The reported error of individual laser dates includes two components. In addition to the counting error on the intercept regression, we included the 2σ errors from the first three and the last three standard measurements by standard error propagation. The accuracy of our LA-ICPMS U–Pb method was estimated continually by analyzing zircon standards Plesovice and 91500 as unknowns, bracketed by NIST 610 silicate glass standard and using the calibrated NIST values for mass bias correction. The long-term average for Plesovice zircon over several sessions gives an age of 338.3±2.5Ma (weighted average $^{206}Pb/^{238}U$, n=13, MSWD=2.9), which is in agreement with the ID-TIMS age of 337.13±0.37 (Slama et al., 2008). Our $^{206}Pb/^{238}U$ LA-ICPMS age for the 91500 standard is 1058.4±9.4Ma (n=15, MSWD=2.5), which overlaps within errors the 91500 ID-TIMS age of 1065±0.4Ma (Wiedenbeck et al., 1995).

4. Results

Zircon grains from 43 samples were analyzed in this study, 39 from Cretaceous magmatic rocks and 4 from the exposed pre-Cretaceous basement. Results from single-grain U–Pb ID-TIMS dating are presented in Appendix 1; LA-ICPMS U–Pb data are given in Appendix 2. The North-Burgas area is presented as a separate region in the electronic supplement for easier comparison with some published literature. However, this area is considered as part of the Yambol–Burgas region in the discussion, as noted earlier. To better constrain the crystallization age of a rock and minimize subjectivity, we followed several criteria for age calculations. We gave preference to ID-TIMS ages over LA-ICPMS data, where sufficient numbers of zircon grains were analyzed by both methods. Depending on sample population and number of studied grains, concordia ages were preferred rather than upper- or lower intercept ages or weighted averages of $^{206}Pb/^{238}U$ ages. Intercept ages and weighted $^{206}Pb/^{238}U$ ages were filtered based on the number of grains and MSWD values that indicate the overlap and scatter of data points. Although these general rules were taken into account, every sample has its own specifics. The dated samples are subdivided into two categories based on our confidence in the calculated crystallization age: a) samples with high-confidence crystallization ages; b) samples with tentative ages. The tentative ages reflect either the small number of analyzed grains or the large uncertainty, but these are geologically meaningful ages; additional analyses are likely to better constrain the age. In some rocks, however, the number of studied grains and/or the complex U–Pb systematic did not allow calculations of reliable U–Pb crystallization ages. Discussion of U–Pb zircon age data for individual rock samples is given in Appendix 3 and summarized below. BSE and CL zircon images are given together with the location of the LA-ICPMS dating in Appendix 4.

Table 1
Calculated crystallization ages for Late Cretaceous rocks from Eastern Srednogorie zone.

Sample	Region	Center	Type	Method	N	N*	Age, Ma	Error, Ma	Age type	MSWD	Type of error	Category
SG 085	Yambol–Burgas	Bulgarovo	v	ID-TIMS	3	1	79.90	3.20	C		95% conf.	Tentative
SG 103	Yambol–Burgas	Bakadzhik	v	ID-TIMS	1	1	80.08	3.10	C		95% conf.	Tentative
SG 102d	Yambol–Burgas	Bakadzhik	v	ID-TIMS	3	1	79.59	3.00	C		95% conf.	Tentative
SG 044	Yambol–Burgas	Vurli Brjag	i	ID-TIMS	7	4	78.98	0.31	LI	1.5	95% conf.	Confident
SG 044b	Yambol–Burgas	Vurli Brjag	v	ID-TIMS	4	1	79.46	0.60	C		2 sigma	tentative
SG 040	Yambol–Burgas	Zidarovo	i	LA–ICPMS	9	4	78.00	2.80	WTD	1.3	95% conf.	Tentative
AvQ 052	Yambol-Burgas	Rossen	i	ID-TIMS	2	2	79.62	0.47	C		95% conf.	Confident
AvQ 057	Yambol–Burgas	Izgrev	i	ID-TIMS	13	2	79.93	0.22	C		2 sigma	Confident
AvQ 054	Yambol–Burgas	Izgrev	i	ID-TIMS	5	4	81.23	0.17	C		2 sigma	Confident
SG 079	Yambol–Burgas	Silistar	i	LA-ICPMS	5	4	76.20	1.60	WTD	0.71	95% conf.	Tentative
SG 028	Strandzha	Polski Gradetz	i	ID-TIMS	7	1	78.27	0.18	C		2 sigma	Confident
SG 001	Strandzha	Monastery Heights	i	LA-ICPMS	5	3	80.60	1.10	C		2 sigma	Confident
AvQ 046	Strandzha	Monastery Heights	i	ID-TIMS	4	1	79.10	0.17	C		2 sigma	Tentative
SG 052	Strandzha	Monastery Heights	d	ID-TIMS	5	2	78.83	0.17	C		2 sigma	Confident
SG 011	Strandzha	Monastery Heights	i	ID-TIMS	5	3	86.36	0.14	C		2 sigma	Confident
SG 021	Strandzha	Monastery Heights	d	ID-TIMS	4	3	78.95	0.30	C		95% conf.	Confident
SG 053	Strandzha	Chernozem–Razdel	i	LA-ICPMS	8	3	79.91	2.00	Tuffzirc		75% conf.	Tentative
SG 045	Strandzha	Granitovo	i	ID-TIMS	4	1	79.66	0.14	C		2 sigma	Confident
AvQ 048	Strandzha	Granitovo	i	ID-TIMS	15	6	79.94	0.14	WTD	2.2	95% conf.	Confident
AvQ 050	Strandzha	Oman-Fakya	i	ID-TIMS	3	3	80.98	0.32	C		95% conf.	Confident
AvQ 051	Strandzha	Oman-Fakya	i	ID-TIMS	6	3	79.77	0.30	C		95% conf.	Confident
SG 032	Strandzha	Gramatikovo?	d	ID-TIMS	3	1	85.23	3.60	C		95% conf.	Tentative
ST 25	Strandzha	Gramatikovo	i	ID-TIMS	4	4	86.84	0.29	C		95% conf.	Confident

Abbreviations: v — volcanic; d — dike; I — intrusive; N — number of grains analyzed from the sample with the reported method; N* — the number of grains, used for the calculation of the crystallization age; C — concordia; WTD — weighted average $^{206}Pb/^{238}U$ age; LI — lower intercept; tuffzirc — age, calculated with the zircon age extraction algorithm of ISOPLOT.

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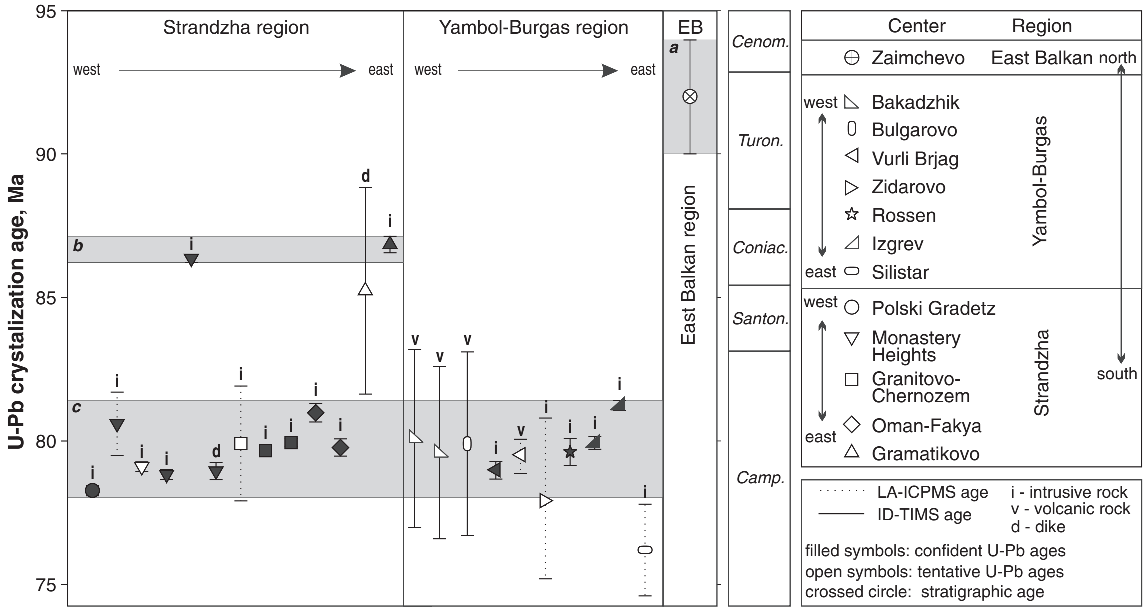

Fig. 4. High-confidence and tentative U–Pb crystallization ages of Upper Cretaceous magmatic rocks from Eastern Srednogorie zone and corresponding 2 sigma errors. Stratigraphic constraints for a Late Cenomanian–Early Turonian age (Dabovski et al., 2009b; Kunchev, 1966) are used to plot the East Balkan magmatism at 92±2 Ma. Ages for the Upper Cretaceous stage boundaries taken from Ogg et al. (2008). Gray fields delineate the three major magmatic events discussed: (a) the ~92 Ma event observed only in the East Balkan, ages are based on biostratigraphy; (b) the 87.1–86.2 Ma event based on high-confidence U-Pb ID-TIMS zircon ages, observed only in the Strandzha region; and (c) the 81.4–78.0 Ma event based on high-confidence U–Pb ID-TIMS zircon ages, observed in the Strandzha and Yambol–Burgas regions.

4.1. Age of Upper Cretaceous magmatic rocks

4.1.1. U–Pb crystallization ages

High-confidence crystallization ages were obtained for 14 Upper Cretaceous rocks (Table 1). From these, ten are from the Strandzha region and four from the Yambol–Burgas region. Most high-confidence ages are for intrusive rocks, with the exception of samples SG 021 (dike) and SG 103 (lava flow). For nine samples the calculated crystallization ages are tentative. The U–Pb ages range from ~87 Ma to ~78 Ma (Figs. 2 and 4). Most rocks from all regions crystallized between 81.23 and 78.00 Ma. A second, clearly visible age group comprises intrusive and dike rocks from Strandzha region (from Monastery Heights and Gramatikovo plutons) with ages ranging from 87.1 to 86.2 Ma. Additionally, a dioritic intrusion from Silistar has a slightly younger age near 76 Ma, but the age errors are large and overlap the 78 Ma event.

The ages within a given magmatic center vary within a narrow range and generally overlap within their errors (e.g. Izgrev pluton; Granitovo pluton). The only notable exception is the Monastery Heights pluton in the Strandzha region, where two distinct magmatic events with high-confidence ages of 86 (diorite) and 81–79 Ma (gabbro, basalt and granite) are detected. This age spread is too large to be explained with the presence of a long-lived magma chamber and indicate that the Monastery Heights intrusion was generated in at least two separate magmatic pulses. The two pulses, however, have similar Sr and Pb whole-rock isotopes (Georgiev et al., 2009).

4.1.2. Distribution of U–Pb single zircon ages

Histograms of individual $^{206}Pb/^{238}U$ ID-TIMS zircon ages show a prominent peak at 80–79 Ma (Fig. 5A). This 80–79 Ma peak is particularly pronounced in the Strandzha region, where the number of dated grains is largest. Even though LA-ICPMS ages in Strandzha are generally more dispersed, their distribution matches ID-TIMS ages with a peak between 82 and 77 Ma. A second notable age peak at 87–85 Ma is defined by both ID-TIMS and LA-ICPMS data.

Similar to the Strandzha region, the most prominent peak in the Yambol–Burgas region is also at 80–79 Ma, with most of the zircons ranging from 82 to 77 Ma. However, the 87–85 Ma peak is not observed in the Yambol–Burgas region. Additionally, there is an indication of a 71 Ma event in the Yambol–Burgas region, defined by LA-ICPMS data, but this peak is not confirmed by ID-TIMS data. These younger ages may reflect Pb loss from zircons, undetected with the lower precision of LA data (larger error ellipses do not allow unambiguous distinction between concordant and slightly discordant grains). Few even younger LA-ICPMS zircon ages in the Strandzha and Yambol–Burgas regions are also attributed to Pb loss. The few grains showing ages older than 86 Ma from both Strandzha and Yambol–Burgas regions are not sufficient indication for an older magmatic event and probably reflect the presence of minor inherited components.

The number of studied rocks and/or analyzed zircons from the East Balkan region is insufficient for a detailed interpretation. Three rocks have zircons with $^{206}Pb/^{238}U$ ages ranging from 45 to 98 Ma, with no overlap within single samples.

In summary, zircon U–Pb age data unequivocally shows that the peak of the Late Cretaceous magmatic activity in the Eastern Srednogorie zone was from 82 until 77 Ma. Abundant magmatism within this time interval is observed in the southernmost Strandzha and the intermediate Yambol–Burgas regions. Few rocks from the Strandzha region are older (87–85 Ma). The radiometric age of the magmatism in East Balkan region remains undetermined. However, stratigraphic relations constrain the age of East Balkan magmatism to ca. 90 Ma (see below).

4.2. Age of basement rocks

U–Pb crystallization ages of three basement rocks from the Eastern Srednogorie zone range from 301 to 274 Ma (Table 2). Basement granitoids from the Turkish part of Strandzha have similar zircon evaporation Pb ages of 271±2 Ma for the Kirklareli metagranite, 271±11 Ma for the Kula metagranite and 309±24 Ma for the Uskup metagranite (Okay et al., 2001).

4.3. Age of inherited zircons

The studied rocks contain variable amounts of inherited older zircons in the form of xenocrysts and/or xenocrystic cores overgrown by Late Cretaceous rims (Appendix 3, Appendix 4). The distribution of single-grain $^{206}Pb/^{238}U$ ages of inherited zircons is shown on Fig. 5B.

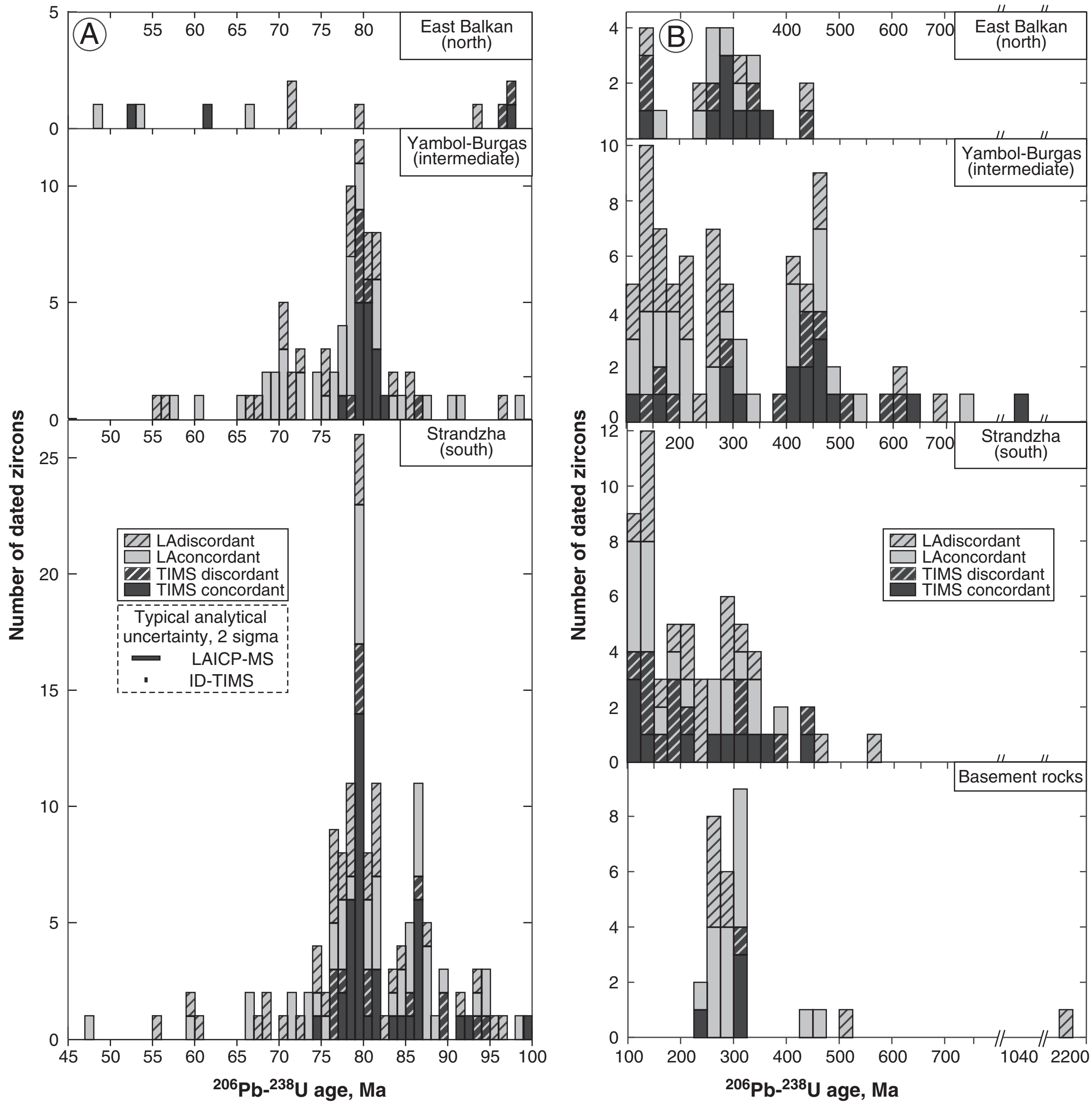

Fig. 5. Histograms of single grain $^{206}Pb/^{238}U$ ages of all studied zircons. A) zircons younger than 100 Ma. Bin width is 1 Ma; B) zircons older than 100 Ma. Bin width is 25 Ma. For plotting purposes, analyses that overlap the Concordia curve are classified and plotted as concordant. This approach avoids subjective decisions on the concordance of the grains, but it does not take into account the size of the error ellipse, or sometimes the unproportionally large error of the $^{207}Pb/^{235}U$ age compared to the $^{206}Pb/^{238}U$ age.

Zircons with 120–170 Ma ages are detected in all regions. All regions also contain a peak at ~300 Ma, but only the central Yambol–Burgas region has a prominent peak at ~460 Ma. Rare older zircon ages (550–1050 Ma) are detected only in this central region, whereas concordant Upper Cretaceous inherited zircons (80–92 Ma and discernibly older than the host rock) are found only in Granitovo and Monastery Height intrusions in the Strandzha region. Geographically, most samples with inherited zircons are from the western and central parts of the Strandzha region and from the southeastern part of the Yambol–Burgas region (Fig. 6). This could represent local variations in the basement, but may also result from the unevenly distributed sampling and the different number of studied grains from different samples.

Calculated ages from ID-TIMS analyzed inherited grains are presented in Table 3. As with the single-grain $^{206}Pb/^{238}U$ ages, in the southernmost and northernmost regions (Strandzha and East Balkan) most inherited ages are 270–350 Ma old, whereas in the central regions the 404–450 Ma inherited ages dominate. Three significantly older ages at 1, 1.4 and 2 Ga are recorded in inherited zircons from the Yambol–Burgas

Table 2
Calculated crystallization ages of exposed basement rocks from Eastern Srednogorie zone.

Sample	Region	Center	Type	Method	N	N*	Age, Ma	Error, Ma	Age type	Type of error	category
SG 047	Strandzha	Oman-Fakya	i	LA-ICPMS	10	5	293.80	7.60	C	95% conf.	Confident
SG 059	Strandzha	Zheljazkovo	i	ID-TIMS	4	3	301.26	0.97	C	2 sigma	Confident
SG 070	Strandzha	Monastery Heights	i	LA-ICPMS	11	5	274.10	4.50	C	2 sigma	Confident

Abbreviations: i — intrusive; N — number of grains analyzed from the sample with the reported method; N* — the number of grains, used for the calculation of the crystallization age; C — concordia.

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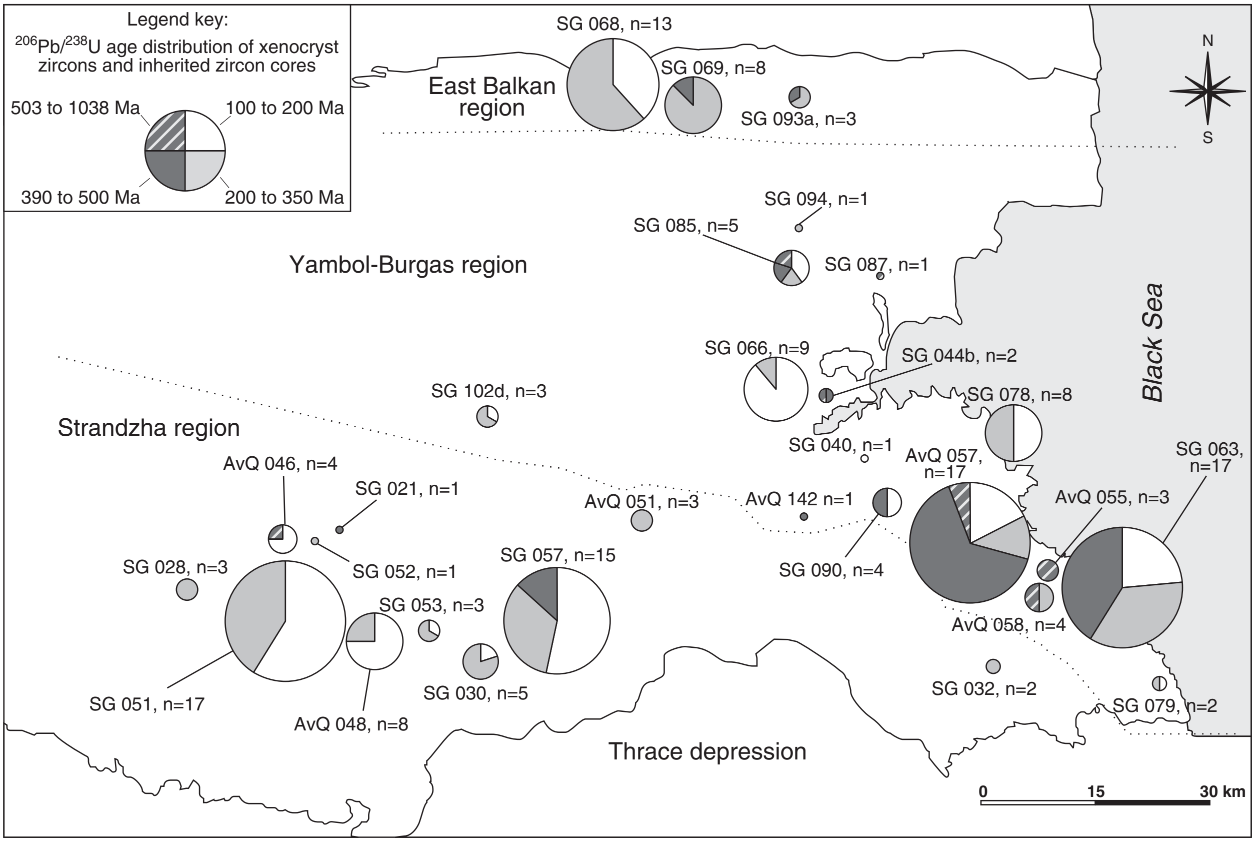

Fig. 6. Sketch map showing the $^{206}Pb/^{238}U$ age distribution of inherited zircon cores and xenocryst zircons detected in Upper Cretaceous magmatic rocks (ID–TIMS and LA-ICPMS data). Some ID-TIMS $^{206}Pb/^{238}U$ zircon ages may represent mixtures of inherited cores and younger, Late Cretaceous rims. Sample location is approximate. The size of each circle is proportional to the number (n) of inherited cores and xenocryst zircons detected in the sample.

region; such older ages were not found in Upper Cretaceous igneous rocks from the East Balkan and Strandzha region (Fig. 5B, Table 3). An inherited core in a Variscan basement rock (sample SG 047) also has a similar concordant 2 Ga LA-ICPMS age.

In summary, the Strandzha and East Balkan regions have similar inheritance patterns with most grains clustering at ~300 Ma, while in the Yambol–Burgas region the most prominent peak is at ~460 Ma, with several grains showing considerably older ages.

5. Discussion

5.1. Across-arc age zonation of the Late Cretaceous magmatism

Stratigraphic relations with fossil-bearing Upper Cretaceous sediments provide age constraints for the extrusive magmatism in the northernmost East Balkan region (Kunchev, 1966; summary in Dabovski et al., 2009b). These authors assign a Late Cenomanian–Early Turonian age of the magmatism based on abundant ammonite and foraminifera assemblages preserved in marly-calcareous and in flysch-like sediments intercalated with the volcanic products in the East Balkan. These stages correspond to ~95–90 Ma based on numerical ages in Ogg et al. (2008). We were unable to obtain high-confidence ages for East Balkan magmatism; the 98–93 Ma ages of four zircons old ages (Fig. 5A) are consistent with the well constrained stratigraphic age of the samples.

Further south, volcanism and sedimentation in the central Yambol–Burgas region are considered Coniacian–Santonian–Campanian (90–70 Ma) based on rare fossils in the successions (Dabovski et al., 2009b; Georgiev et al., 2001), but our data suggest a much narrower time interval between 81 and 78 Ma (Fig. 4). The Izgrev, Vurli Brjag and Rossen plutons, intruded in the volcano–sedimentary Late Cretaceous successions, yield precise and high-confidence TIMS zircon ages at ca. 80–79 Ma (Figs. 3 and 4). These ages constrain the minimum age of the intruded volcano–sedimentary sequence. Volcanic rocks have similar, but less precise U–Pb zircon ages (Fig. 4). The geochemistry and Pb and Sr isotopic composition of intrusive and volcanic rocks from a given center (e.g. Izgrev or Rossen, data from Georgiev et al., 2009) suggests that they evolved from chemically similar magmas and are therefore essentially coeval. In this region, zircons concordant within the small uncertainties of the ID-TIMS data form a single population with a clear peak at 82–79 Ma (Fig. 5A), providing additional evidence that volcanism in the Yambol–Burgas region is largely coeval with the dated intrusions. Less precise LA-ICPMS ages indicate that some of the magmatism may be younger than 78 Ma (Figs. 4 and 5A), consistent with scarce field observations for post-intrusive emplacement of volcanic rocks (Ivanov, 1979).

High-confidence crystallization ages in the southernmost Strandzha region define two distinct Late Cretaceous magmatic events at ~87–85 Ma and 81–78 Ma (Fig. 4). Concordant ID-TIMS inherited zircons at ~86 and ~90 Ma (Fig. 5A) suggest incorporation of older Upper Cretaceous rocks by the 81–78 Ma Upper Cretaceous magmas.

5.2. Comparison with Central Srednogorie zone

Detailed geochronology in the adjacent segment of the ABTS belt, the Central Srednogorie, reveals a 14 Ma age progression from north (~92 Ma) to south (~78 Ma), coupled with a southward increase of mantle input recorded by Nd, Sr and Hf isotopes (von Quadt et al., 2005). This is best explained by hinge retreat (roll back) that led to overall crustal thinning and asthenospheric incursion into an extending arc to back-arc environment (von Quadt et al., 2005). Comparison of crystallization ages of rocks from Eastern Srednogorie zone with the published age data from the Central Srednogorie zone (Fig. 7) shows important similarities.

Table 3
Calculated crystallization ages for unexposed basement rocks from Eastern Srednogorie zone, based on inherited grains entrained in Late Cretaceous igneous rocks.

Sample	Region	Center	Type	N	N*	Age, Ma	Error, Ma	Age type	MSWD	Type of error
SG 093a	East Balkan	Zaimchevo	v	3	1	271	0.7	C		2 sigma
SG 093a	East Balkan	Zaimchevo	v	3	3	577	57.0	UI	0.13	95% conf.
SG 068	East Balkan	Zvezda	i	17	4	109	6.7	LI	0.33	95% conf.
SG 068	East Balkan	Zvezda	i	17	4	139	18.0	UI	2.20	95% conf.
SG 069	East Balkan	Zvezda	d	3	1	281	0.9	C		2 sigma
SG 068	East Balkan	Zvezda	i	17	1	303	0.5	C		2 sigma
SG 068	East Balkan	Zvezda	i	17	1	350	8.8	C		95% conf.
SG 085	Yambol–Burgas	Bulgarovo	v	3	1	631	23.0	C		95% conf.
SG 044b	Yambol–Burgas	Vurli Brjag	v	4	1	442	20.0	C		95% conf.
SG 044b	Yambol–Burgas	Vurli Brjag	v	4	1	1039	4.2	C		2 sigma
AvQ 057	Yambol–Burgas	Izgrev	i	13	1	160	0.6	C		2 sigma
AvQ 057	Yambol–Burgas	Izgrev	i	13	1	280	0.7	C		2 sigma
AvQ 058	Yambol–Burgas	Izgrev	v	4	3	296	3.7	LI	0.60	95% conf.
AvQ 057	Yambol–Burgas	Izgrev	i	13	2	404	0.9	C		2 sigma
AvQ 058	Yambol–Burgas	Izgrev	v	4	1	445	1.6	C		2 sigma
AvQ 057	Yambol–Burgas	Izgrev	i	13	1	462	1.2	C		2 sigma
AvQ 057	Yambol–Burgas	Izgrev	i	13	3	1353	30.0	UI	0.46	95% conf.
AvQ 058	Yambol–Burgas	Izgrev	v	4	3	1948	3.7	UI	0.60	95% conf.
SG 063	Yambol–Burgas	Izgrev?	d	5	3	450	26.0	UI	0.56	95% conf.
SG 063	Yambol–Burgas	Izgrev?	d	5	3	507	9.2	UI	0.30	95% conf.
AvQ 046	Strandzha	Monastery Heights	i	4	1	85	0.3	C		2 sigma
AvQ 046	Strandzha	Monastery Heights	i	4	1	92	0.2	C		2 sigma
AvQ 046	Strandzha	Monastery Heights	i	4	1	104	2.0	C		2 sigma
SG 021	Strandzha	Monastery Heights	d	4	3	541	33.0	UI	0.05	95% conf.
AvQ 048	Strandzha	Granitovo	i	15	1	81	0.3	C		2 sigma
SG 051	Strandzha	Granitovo	i	6	4	268	37.0	UI	1.50	95% conf.
AvQ 048	Strandzha	Granitovo	i	15	6	281	64.0	UI	0.65	95% conf.
AvQ 051	Strandzha	Oman-Fakya	i	6	5	329	27.0	UI	6.10	95% conf.
SG 057	Strandzha	Sharkovo	i	5	3	112	5.2	LI	2.00	95% conf.
SG 057	Strandzha	Sharkovo	i	5	1	138	0.3	C		2 sigma
SG 057	Strandzha	Sharkovo	i	5	1	291	0.6	C		2 sigma
SG 057	Strandzha	Sharkovo	i	5	4	296	14.0	UI	0.28	95% conf.
SG 057	Strandzha	Sharkovo	i	5	3	442	6.1	UI	2.00	95% conf.
SG 030	Strandzha	Voden	v	5	5	162	8.1	LI	1.40	95% conf.
SG 030	Strandzha	Voden	v	5	5	285	35.0	LI	0.40	95% conf.
SG 030	Strandzha	Voden	v	5	5	397	24.0	UI	1.40	95% conf.
SG 032	Strandzha	Gramatikovo?	d	3	3	470	15.0	UI	1.90	95% conf.

Abbreviations: v — volcanic; i — intrusive; d — dike; N — number of grains analyzed from the sample with the reported method; N* — the number of grains, used for the calculation of the crystallization age; C — concordia; LI — lower intercept; UI — upper intercept.

Magmatism in the East Balkan region is initiated at ~95–90 Ma, similar to zircon ages from Elatsite and Chelopech in northernmost Central Srednogorie zone (~92 Ma, von Quadt et al., 2005). Also geochemically, the high K and calc-alkaline, shallow, and mostly intermediate subvolcanic bodies and associated volcanics from the East Balkan are similar to those from the northern part of Central Srednogorie zone (Elatsite, Chelopech, and Assarel).

Further south, the 87–85 Ma intrusions and dikes ages in the Strandzha region (Fig. 4) are similar to the 86 Ma age of Elshitsa intrusion in the central part of Central Srednogorie zone. Most intrusions in the Strandzha region crystallized between 82 and 78 Ma; such ages are reported from the southern part of Central Srednogorie zone, for Vurshilo and Capitan Dimitrievo intrusions (Peytcheva et al., 2008; von Quadt et al., 2005). In terms of geochemistry and emplacement depth, the deeply eroded middle (?)-crustal gabbroic and granodioritic intrusions with predominantly calc-alkaline affinity in the Strandzha region are similar to the deeply eroded Vurshilo and Capitan Dimitrievo intrusions in the southern Central Srednogorie zone.

Based on the overall similarities in crystallization age, geochemistry and emplacement depth of the magmatism, the East Balkan and Strandzha regions of Eastern Srednogorie zone may be considered eastwards equivalents of the northern and southern parts of Central Srednogorie zone, respectively. We conclude that the large-scale process of slab retreat that operated in Central Srednogorie zone during the Late Cretaceous was probably active also in the Eastern Srednogorie zone, with ages migrating from ca. 92 Ma in the East Balkan to 87–85 Ma and 82–78 Ma in the Strandzha region.

The voluminous mafic to intermediate alkaline magmatism in the central Yambol–Burgas region has no equivalent in Central Srednogorie. Characteristically, the 81–78 Ma old magmatism in the Yambol–Burgas region lacks evidence for the 92–86 Ma events as seen in the East Balkan and Strandzha regions, respectively. The distribution of pre-Cretaceous inherited zircons in this region also clearly differ from those in the East Balkan and Strandzha regions (Figs. 5A, B and 6), which is an indication for a possibly different origin of the Yambol–Burgas region. This, combined with the markedly elevated alkalinity of the Yambol–Burgas rocks intermingled with deep marine sediments, are all consistent with the formation of a Late Cretaceous intra-arc rift that separated a previously uniform arc (East Balkan and Strandzha regions) in two parts.

The peak of the magmatism in the Strandzha region overlaps the range of crystallization ages in the Yambol–Burgas region (81–78 Ma). The similar age, but different chemistry and emplacement depth require explanation. One possibility is that rollback caused intra-arc rifting and melting of upper mantle or lower crustal rocks; these newly formed magmas were granted a facilitated access through the thinned crust in the extensional regime of the Yambol–Burgas region. Alternatively, extension in the neighboring Black Sea might have caused rifting and related slab roll back. Regardless of the cause for rifting and slab roll back, our age data show that the thicker crust of the Strandzha region was penetrated by melts simultaneously with the rifting phase in the neighboring Yambol–Burgas region. The abundance of intrusive rocks exposed in the Strandzha region is a result of late exhumation.

The lack of clear along-strike age zonation in Eastern Srednogorie zone does not support the model for east-to-west slab break-off

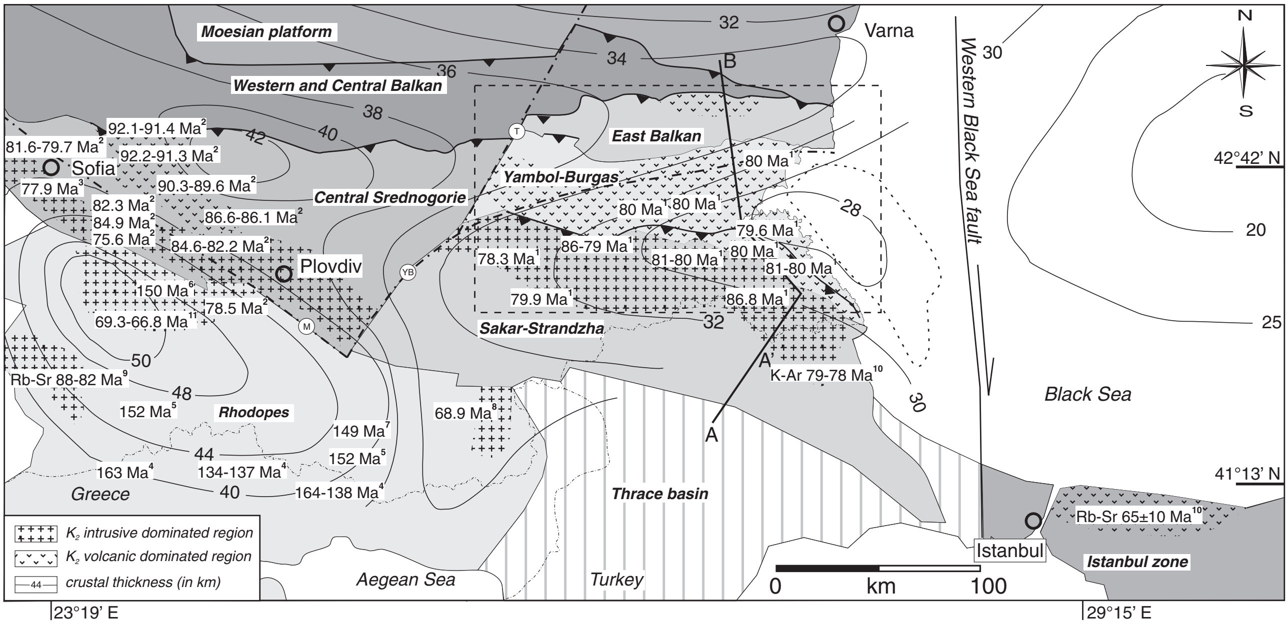

Fig. 7. Simplified tectonic map of Eastern Srednogorie zone and surrounding areas, showing crustal thickness (in km) and approximate sample location of published Late-Jurassic to Late Cretaceous magmatic ages discussed in the main text. Superscript numbers are references for radiometric ages as follows: 1 — U–Pb zircon ID-TIMS and LA-ICPMS ages, this study; 2 — U–Pb zircon ID-TIMS (von Quadt et al., 2005); 3 — U–Pb zircon ID-TIMS for Plana pluton (Lora Bidzhova, personal communication); 4 — U–Pb zircon SHRIMP and Pb–Pb evaporation (Turpaud and Reischmann, 2009); 5,6 — U–Pb zircon ID-TIMS (Ovtcharova et al., 2004; Peytcheva et al., 2004; von Quadt et al., 2009); 7 — U–Pb zircon ID-TIMS (Cherneva et al., 2006); 8 — U–Pb zircon ID-TIMS (Marchev et al., 2006); 9 — Rb–Sr whole-rock (Zagorčev and Moorbath, 1983); 10 — K–Ar on Bt and Hb (Moore et al., 1980); 11 — Rb–Sr whole-rock (Öztunali and Satir, 1975). Crustal thickness lines are from Yosifov and Pchelarov (1977); Black Sea crustal thickness is from Dachev (1988). Stippled field in the Black Sea is the area of most intense magnetic anomalies after Yosifov et al. (1986).

(Neubauer, 2002), which predicts progressively younger magmatic ages along the strike of the ABTS belt in an east–west direction. The overlapping age range of the magmatism in the Central and Eastern Srednogorie zones are also inconsistent with the slab break-off model.

5.3. Eastward continuation and relation to the Black Sea

The Srednogorie zone with its deep marine sedimentary succession (Aiello et al., 1977) is considered as a westerly continuation of the Black Sea basin (Hsü et al., 1977). However, the major subsidence and deepening of the Eastern Srednogorie basin is post-Cenomanian, about 10–30 Ma younger than the mid-Cretaceous opening of the Black Sea. A westward propagating rifting was proposed to explain the later opening of the Srednogorie basin (Görür, 1988).

In terms of volume and emplacement mechanisms, the abundant mafic magmatism in the Yambol–Burgas region could represent part of the Black Sea oceanic crust, but its subduction influenced trace element composition clearly differs from typical mid-ocean ridge magmatism (Georgiev et al., 2009). Moreover, geophysical data indicate that large Bouguer anomalies (Dachev, 1988) and positive magnetic anomalies that characterize the oxidized magmatism in the Eastern Srednogorie zone do not continue uninterrupted within the Black Sea (Dachev, 1988; Roussanov and Pchelarov, 1998). They form a zone that bends offshore at almost 90° and runs in a south-southeast direction almost parallel to the present shore (Fig. 7). These features are not consistent with the idea that the Srednogorie zone magmatism (including the Yambol–Burgas region) represents Black Sea oceanic crust.

The offshore curvature of the Yambol–Burgas region coincides with the observed orientation of the dome-like uplifts in the Strandzha region, which have an east–west orientation in its western part and a NW–SE orientation in the eastern part. This change could have resulted from syn- to post-magmatic dextral strike–slip movements along the Western Black Sea fault (Fig. 7), which is considered central for the opening of the Black Sea basin (Banks and Robinson, 1997; Nikishin et al., 2001, 2003; Okay et al., 1994). The Western Black Sea fault also separates the Srednogorie zone from the Western Pontides Mountains in the Istanbul zone, which host abundant Upper Cretaceous arc magmatism. If movements along this fault caused the separation of a formerly continuous Upper Cretaceous arc comprising the Srednogorie zone and the Western Pontides, our age results imply major movements in the order of 100–150 km along this fault occurred later than the Santonian. The south-southeast curvature of the Srednogorie zone can be explained by the tail effect of southwards syn- to post-magmatic movements of the western Black Sea plate along the Western Black Sea fault, distorting and displacing the easternmost Srednogorie zone southwards. Additionally, paleomagnetic data indicate that the Srednogorie zone drifted 200 to 400 km northwards since the Late Cretaceous (Nozharov et al., 1984) as part of stable Europe. These northward movements may have also contributed to the southward tilting of easternmost Srednogorie.

5.4. Age of basement rocks and inherited zircons

The Late Carboniferous to Early Permian (274–301 Ma) age of intrusive rocks from the Eastern Srednogorie basement (Table 2) confirm that the studied region was actively involved in the Variscan collisional orogeny, which accreted fragments of Gondwanaland (Moesian, Balkan and Thracian terranes) to each other and to Laurasia (Yanev, 2000). Similar to older U–Pb zircon ages are reported for Variscan intrusions from the Central Srednogorie (Carrigan et al., 2005; Peytcheva and von Quadt, 2004; von Quadt et al., 2005), and for metagranites from the neighboring Eastern Rhodopes (Peytcheva and von Quadt, 1995). This age similarity may indicate that the Rhodope Massif, Central Srednogorie and Eastern Srednogorie zones constituted a single terrain during the Permian.

Inherited grains provide additional age constraints for the underlying basement (Fig. 5B). Permian–Carboniferous inherited zircon ages of ~300 Ma are characteristic for the East Balkan and Strandzha regions and probably originate from assimilation of the presently exposed Permian/Carboniferous basements rocks in Strandzha and East Balkan.

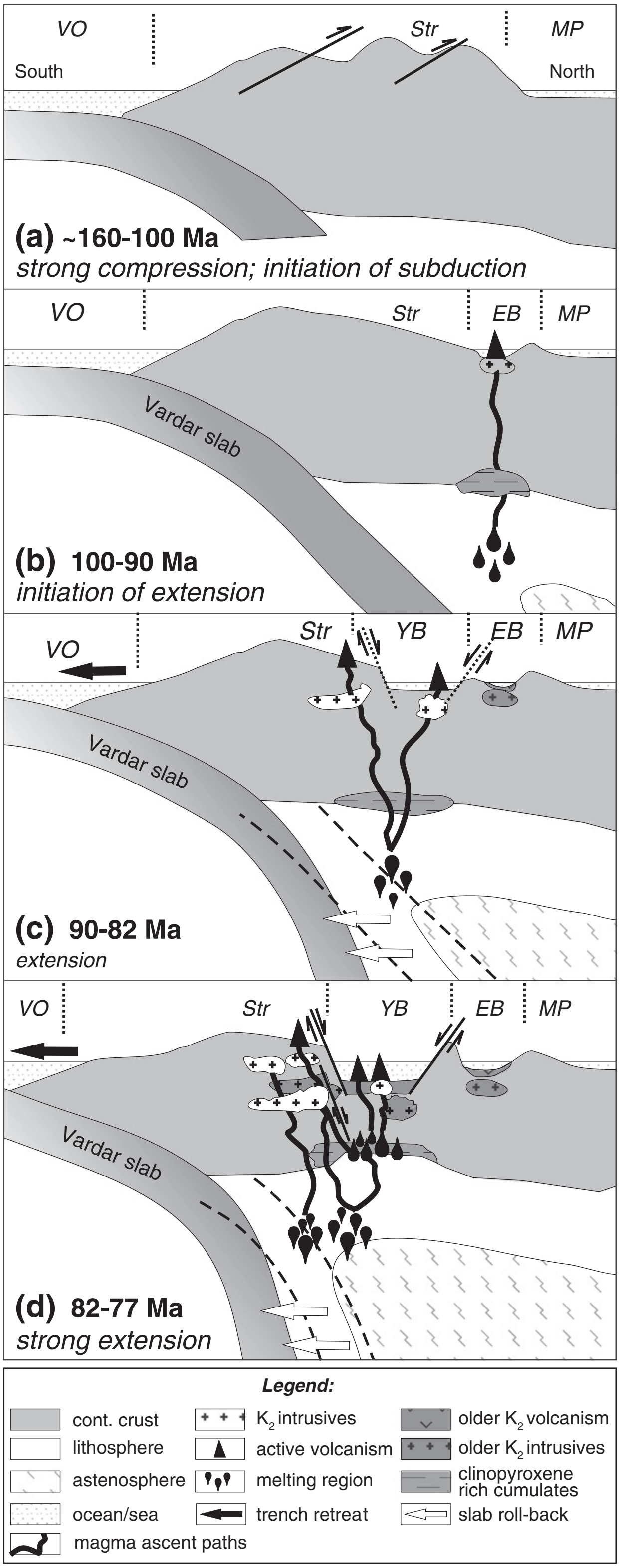

Fig. 8. Schematic cartoon, illustrating in a series of diagrams (a–d) our model for the Late Cretaceous geodynamic evolution of Eastern Srednogorie zone. VO — Vardar Ocean; Str — Strandzha region; YB — Yambol–Burgas region; EB — Eastern Balkan region; MP — Moesian platform. Note the absence of an absolute scale, due to the contrasting thickness of the upper crust, oceanic and sea depth on one side, and the subducting slab, lithosphere and asthenosphere on the other. The clinopyroxenite cumulates are drawn as products of the magmatism in (b); however, these cumulates may also have formed during an earlier stage. See text for detailed explanation.

In contrast, ~460 Ma old inherited zircon grains are found mostly in the Yambol–Burgas region (Fig. 5B), where the pre-Cretaceous basement is not exposed or reached in drill cores in the Yambol–Burgas region. Similar Ordovician ages have been found in Upper Cretaceous intrusions and several Variscan granitoids from the Central Srednogorie zone (Carrigan et al., 2005; Peytcheva and von Quadt, 2004; Peytcheva et al., 2009) and in the Rhodopean metamorphic basement (Bonev et al., 2010). The different inheritance pattern in the Yambol–Burgas region suggests that either the basement here is different, or that the Late Cretaceous magma chambers were situated at a different depth, compared to those in Strandzha and East Balkan. The latter hypothesis is consistent with thermobarometric estimates for olivine and clinopyroxenes crystallization in deep magma chambers, close to the Moho discontinuity (Georgiev et al., 2009). Therefore, the Ordovician inherited ages indicate that the lower crustal rocks in the region contain abundant Ordovician igneous zircons.

5.5. Tectono-magmatic evolution of a rifted arc

This section integrates the regional geological, geochemical and age information into a model of the geodynamic evolution of the Eastern Srednogorie zone (Fig. 8).

The Late Jurassic–Early Cretaceous geodynamic evolution was characterized by successive phases of intense compression, northward thrusting, folding and uplift in the Strandzha region (Banks, 1997; Sunal et al., 2011). Ar/Ar mica ages indicate a ~140 Ma age of the deformation (Neubauer et al., 2010), whereas K–Ar ages of illites/muscovites from phyllites and diabases from the Bulgarian portion of Strandzha Mountains indicate a Jurassic (160–170 Ma) age of the low-grade greenschist facies metamorphism (Lilov et al., 2004). Rb–Sr muscovite and biotite ages from the southern part of Strandzha mountains reveal that peak metamorphic conditions occurred at around 160 Ma (Sunal et al., 2011), supporting earlier biotite whole-rock Rb–Sr Late Jurassic (155 Ma) age of the regional metamorphism (Okay et al., 2001). This compression was most likely related to the subduction/collision system in the southerly lying Rhodope Massif (e.g. Sunal et al., 2011) and resulted in the closure of the Nish–Troyan trough to the northwest of the studied area and folding of its flysch sediments at the end of the Late Jurassic (Nachev and Nachev, 2001). At this time the area of Eastern Srednogorie zone was not magmatically active and was above the sea level (Fig. 8A). The Moesian platform to the north was a shallow epicontinental sea with continuous sedimentation.

Sedimentation in Eastern Srednogorie zone commenced at the end of the Lower Cretaceous and the Cenomanian with deposition of alluvial, lake and swamp sediments, followed by initiation of marine transgression during the Cenomanian–Turonian (Nachev and Dimitrova, 1995b) when marine deposits were formed in a shallow epicontinental sea (Fig. 8B). Magmatic activity was limited to volumetrically minor shallow intrusives, dikes, and associated andesitic lava flows in the present day East Balkan. Their age is considered Late Cenomanian–Early Turonian (95–90Ma) based on characteristic fauna in associated marls and flysch sediments (Dabovski et al., 2009b; Kunchev, 1966).

The geodynamic setting changed significantly during the Coniacian with the onset of an intra-arc basin formation. The subducting slab migrated southwards, resulting in the formation of 86 Ma old intrusions and probably volcanics (which were later eroded) in the Strandzha region (Fig. 8C). In our model the slab retreat was a continuous process, similar to the slab retreat in the Central Srednogorie zone (von Quadt et al., 2005). Some 93–87 Ma magmatic products may be situated between Strandzha and East Balkan, now covered by sediments and volcanic products deposited during the intra-arc rift phase.

The 82–77 Ma time period was the most intense phase of extension and crustal thinning in the Yambol–Burgas region (Fig. 8D). A thick volcano–sedimentary succession was deposited in a deep marine basin (Nachev and Nachev, 2001). Decompression and crustal thinning combined with increased corner flow in the mantle wedge and associated rise in the temperature led to large-scale melting of lower-crustal/upper mantle clinopyroxene-rich and amphibole-bearing cumulates (Georgiev et al., 2009). The crystallization age for the cumulates is unclear: they could have formed during the previous stage of the Late Cretaceous magmatism (e.g. Fig. 8b or c), or could be significantly older. Melts from such cumulates mixed with mantle-wedge melts produced the mafic and intermediate alkaline magmatism in the Yambol–Burgas region, including the primitive nepheline-normative ankaramites (Georgiev et al., 2009; Marchev et al., 2009). During this period, mantle wedge melts penetrated the thicker crust in the Strandzha region and crystallized as lower-, middle- or upper crustal intrusions (Fig. 8D). Melt access to the crust might have been facilitated by the possible presence of normal faults, parallel to the main rift fault (Fig. 8D). The ~80 Ma old igneous rocks from the Yambol–Burgas and Strandzha regions have notably different geochemistry (e.g. Georgiev et al., 2009; Stanisheva-Vassileva, 1980). One possible explanation for these differences may be the lack of clinopyroxene-rich and amphibole containing cumulates in the lower crust of the Strandzha region. However, a more probable explanation is that the thicker crust in the Strandzha region prevented large-scale decompressional melting of clinopyroxenite cumulates. Rather, mantle-wedge-derived magmas intruded the thicker crust of Strandzha to form tholeiitic, calc-alkaline and partly high-K intrusions. The relatively similar present-day crustal thickness between the Yambol–Burgas and Strandzha regions (Fig. 7) results from post-magmatic shortening and deformation. In the Late Cretaceous the crust in the Strandzha region was probably much thicker than the crust in the Yambol–Burgas region.

Late Cretaceous magmas in the Yambol–Burgas region erupted on the seafloor or crystallized as shallow intrusives, whereas concomitant intrusions in the Strandzha region crystallized at pressures between 0.7 and 0.2 GPa (Dabovski et al., 2009a). Stronger Cenozoic erosion in the elevated Strandzha region compared to the Yambol–Burgas region may have removed Cretaceous volcanic products. The extensional Late Cretaceous environment in the intermediate Yambol–Burgas region was favorable for the formation of polymetallic vein deposits; submarine volcanogenic-hosted massive sulfide deposits may also be present. In contrast, mostly skarn deposits developed around the deeper intrusions in the Strandzha region.

During the same stage (82–77 Ma), the area of the East Balkan region developed as a separate, non-magmatic deep back-arc basin (Fig. 8D). The lack of volcanic material in the post-Turonian deep-water sediments of East Balkan and their abundance in contemporaneous Yambol–Burgas sediments suggest that both basins were physically separated during the Coniacian–Maastrichian. Nachev and Nachev (2001) proposed the existence of a second elevated arc (in addition to the frontal Rhodope arc) between the Yambol–Burgas and the East Balkan basins. In our model the elevated northern rift shoulder of the Yambol–Burgas intra-arc rift acted as a paleo-relief barrier that prevented the deposition of explosive volcanic material in the deep East Balkan basin.

Sedimentation in the Yambol–Burgas intra-arc rift continued between 77 and 73 Ma (not shown in Fig. 8), probably accompanied by volumetrically small volcanic activity. Towards the end of this period the basin was terminated by uplift, intense thrusting and folding of the sedimentary and volcanic successions, with the total shortening estimated by a factor of three to the original width (Nachev and Nachev, 2001). There is no evidence for magmatic activity in the Strandzha or East Balkan regions at that time. The slab retreat continued further to the south; some younger magmatic products in the southern Strandzha area may be present beneath the younger sediments of the Thrace depression (Fig. 7). At the beginning of Maastrichtian (~73 Ma), shallow water limestones were deposited in the Yambol–Burgas region above the folded Late Cretaceous successions. Sedimentation in the East Balkan continued in a deeper-water environment and the basin was terminated before the Late Paleocene (Nachev and Nachev, 2001). To the south, evidence for further slab retreat and subduction magmatism comes from the Eastern Rhodope and Rila Mountain area where few intrusions have 70–65 Ma ages (Fig. 7). A possible equivalent of this magmatism is a granodiorite from the Istanbul zone in Turkey, which has a Rb–Sr age of 65 ± 10 Ma (Öztunali and Satir, 1975).

The present day structure of the Eastern Srednogorie zone resulted from the multiple northward thrusting during the Early Cretaceous–Paleogene time, which superimposed Strandzha on top of the Yambol–Burgas region, and also parts of North-Burgas region on top of East Balkan (Fig. 3). The East Balkan region itself is thrusted on top of the stable Moesian platform. The surface features are dominated by northward thrusting, which is detected also in the deeper basement. Geophysical data indicate that the rift geometry is preserved only in the deep basement of the Yambol–Burgas region, and partly in the East Balkan region (Georgiev et al., 2001).

6. Conclusions

U–Pb zircon dating by ID-TIMS and LA-ICPMS methods combined with a synthesis of the regional geology shows that magmatism in the Eastern Srednogorie zone commenced at ca. 95–90 Ma with volcanism in the northernmost East Balkan region. With time, the magmatic activity migrated southwards, evidenced by several 86 Ma old plutonic bodies that intruded the basement of the present-day Strandzha region. Magmatic activity in the Eastern Srednogorie zone peaked between 81 and 78 Ma, when numerous intrusions crystallized in the Strandzha and Yambol–Burgas regions and abundant volcanics were formed in the Yambol–Burgas region. The crystallization age of basement granites and gabbros from the Strandzha region is determined as Permian to Carboniferous. Upper Cretaceous rocks from all regions contain abundant inherited zircons. Their age distribution pattern is similar in the Strandzha and East Balkan regions where ca. 300 Ma inherited zircons from the local basement prevail. In contrast, most of the inherited zircons in the Yambol–Burgas region point to an Ordovician age of ca. 450 Ma and few grains have much older ages of 1 to 2 Ga.

Integrating new geochronology results with existing geological and geochemical data, we propose a model for the temporal evolution of the magmatism in the Eastern Srednogorie zone. Our model involves a southward retreating slab and related arc magmatism similar to the one in the Central Srednogorie zone, with older calc-alkaline to high-K shallow intrusions and volcanics in the north (East Balkan) and younger large mid-crustal tholeiitic, calc-alkaline and high-K intrusions in the south (Strandzha). The southward migration of the magmatism lasted from ~92 Ma (East Balkan) to ~78 Ma (the youngest intrusions in Strandzha). Subduction roll-back, combined with processes of widening of the Black Sea basin and major dextral strike–slip movements along the western Black Sea fault led to the formation of an intra-arc rift basin (Yambol–Burgas) which separated the formerly adjacent East Balkan and Strandzha regions. The main phase of the intra-arc rift alkaline-rich magmatism was from 81 to 78 Ma. Subsequent latest Cretaceous and Cenozoic compression events led to crustal shortening, deformation and northward thrusting, forming the present-day structure of Eastern Srednogorie zone.

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