

## Rapid Communication

**Cite this article:** Bonev N, Filipov P, Raicheva R, Chiaradia M, and Moritz R (2019) Detrital zircon age and Sr isotopic constraints for a Late Palaeozoic carbonate platform in the lower Rhodope thrust system, Pirin, SW Bulgaria. *Geological Magazine* **156**: 2117–2124. <https://doi.org/10.1017/S0016756819001183>

Received: 24 June 2019

Revised: 20 August 2019

Accepted: 27 August 2019

First published online: 29 October 2019


**Keywords:**

U–Pb geochronology; strontium isotopes; carbonate platform; Rhodope; Bulgaria

**Author for correspondence:**

Nikolay Bonev, Email: [niki@gea.uni-sofia.bg](mailto:niki@gea.uni-sofia.bg)

# Detrital zircon age and Sr isotopic constraints for a Late Palaeozoic carbonate platform in the lower Rhodope thrust system, Pirin, SW Bulgaria

Nikolay Bonev<sup>1</sup> , Petyo Filipov<sup>2</sup>, Raya Raicheva<sup>2</sup>, Massimo Chiaradia<sup>3</sup> and Robert Moritz<sup>3</sup>

<sup>1</sup>Department of Geology, Paleontology and Fossil Fuels, Sofia University 'St. Kliment Ohridski', 1504 Sofia, Bulgaria;

<sup>2</sup>Department of Geochemistry and Petrology, Geological Institute, Bulgarian Academy of Sciences, 1113 Sofia, Bulgaria and <sup>3</sup>Department of Earth Sciences, University of Geneva, CH-1205 Geneva, Switzerland

**Abstract**

We focused on the Pirin–Pangeon–Thasos carbonate sequence of the Rhodope thrust system, combining Sr isotopes from marble with U–Pb dating of detrital zircons from interlayered schists with outcrop near the villages of Ilindentsi and Petrovo in Bulgaria. The youngest zircon age at Ilindentsi is 266 Ma, i.e. Middle Permian, while the youngest zircon at Petrovo yielded an age of 290 Ma, i.e. Early Permian. Strontium isotopes range from 0.707420 to 0.707653, and are consistent with a Middle Permian maximum depositional age. Middle Permian sedimentation of this carbonate platform most likely occurred along the Eurasian margin rather than the Gondwana margin.

**1. Introduction**

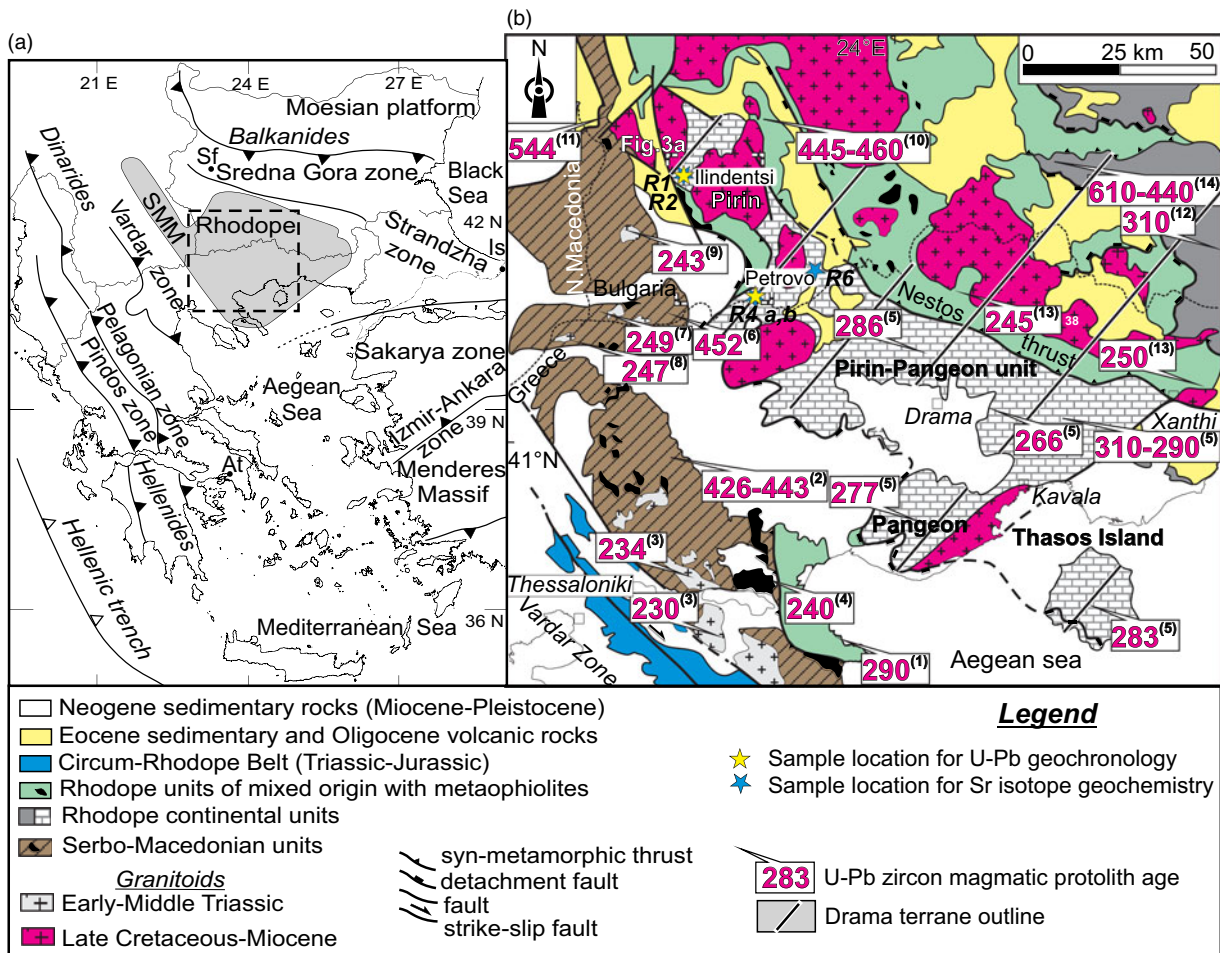
The Rhodope Massif is a major tectonic zone of the Alpine orogen in the northern Aegean region of the eastern Mediterranean (Fig. 1a). A thick marble-dominated succession is interpreted as representing a carbonate platform involved in the lower Rhodope thrust system of Bulgaria and Greece (Burg *et al.* 1996; Fig. 1b). It is known as the Pangeon (Pangaion, Boz Dağ) unit (Jordan, 1969; Kronberg, 1969; Papanikolaou & Panagopoulos, 1981; Papanikolaou, 1984; Dimadis & Zachos, 1989) or Pirin–Pangaion zone, which includes the Bulgarian Pirin unit and the Greek Pangaion and Thasos Island units (Zagorčev, 1994). This regional Pirin–Pangeon–Thasos (PPT) composite unit is considered as a separate crustal terrane in the tectonic framework of the Hellenides (Burg, 2012; Papanikolaou, 2013). It is of critical importance for understanding the organization of the terranes involved in the Mesozoic tectonic evolution of the region.

There are two contrasting Late Permian palaeogeographic interpretations for the PPT unit. One interpretation links it as the Drama terrane to the Pelagonia microcontinent derived from the northern passive margin of Gondwana (Ricou, 1994; Fig. 2a). A second interpretation considers it as a Rhodope unit next to Pelagonia along the Eurasian active margin and associated north-directed subduction of the Palaeotethys (Ziegler & Stampfli, 2001; Fig. 2b). Both interpretations commonly account for the Neotethys rifting episode along Gondwana's northern margin following the Late Palaeozoic Variscan orogeny in Europe. The age of the PPT carbonate platform is interpreted as Silurian to Carboniferous based on a single coral find (reefal *Rugosa* determined by R. Wolfart in Jordan, 1969), or Ordovician to Carboniferous as inferred from brachiopod (*Atrypida?*) remains (Ancirev *et al.* 1980). Therefore, constraining the protracted Palaeozoic depositional age of the PPT carbonate platform is critical for a better understanding of the Rhodope palaeogeography. Furthermore, this carbonate platform, which records the geodynamic evolution of the Tethyan margins in the Aegean region, allows constraining the Gondwana–Eurasia crustal organization and interaction at the Palaeozoic–Mesozoic transition.

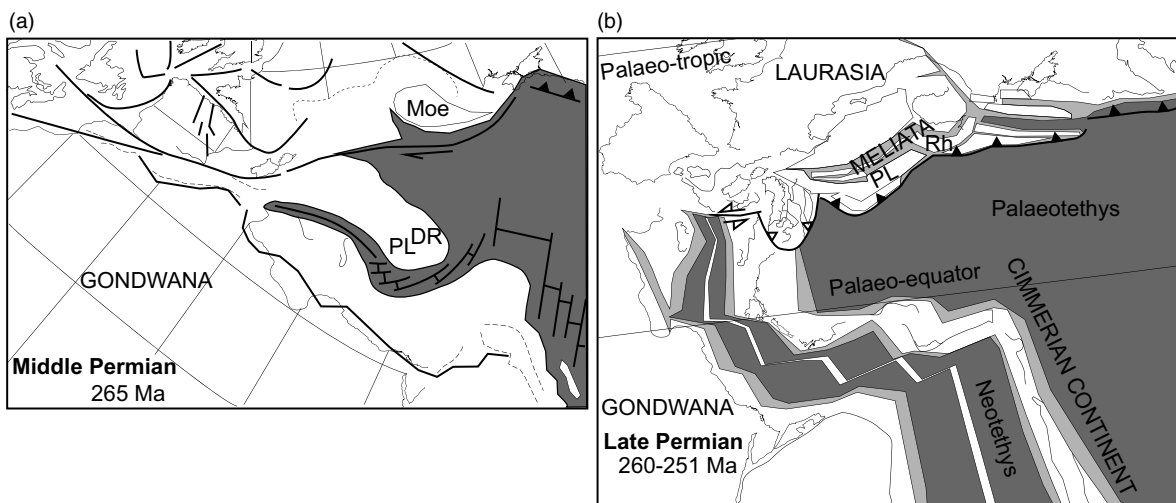
In this paper, we combine U–Pb laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) dating of detrital zircons from schist layers interstratified with marble and Sr isotopic compositions of marble from the Pirin unit in Bulgaria. The aim is to constrain the deposition of the regional PPT carbonate platform, having in mind its critical position and its role during the Mesozoic evolution of the Alpine orogen in the Aegean region.

**2. Geological background**

The Pangeon unit belongs to the metamorphic basement of the Rhodope Massif (Fig. 1b). It consists of a lower gneiss sequence underlying a marble–gneiss sequence, which is overlain by a thick marble sequence, and an upper sequence of interlayered two-mica schist, calc-schist



**Fig. 1.** (Colour online) (a) Tectonic framework of the Alpine orogen in the northern Aegean region of the eastern Mediterranean. Abbreviations: SMM, Serbo-Macedonian Massif; Sf, Sofia; At, Athens; Is, Istanbul. (b) Synthetic map of the Rhodope and Serbo-Macedonian massifs in southern Bulgaria and northern Greece (compiled after Ricou et al. 1998; Bonev et al. 2013). U-Pb zircon geochronology: 1, Himmerkus et al. (2012); 2, Himmerkus et al. (2009a); 3, Himmerkus et al. (2009b); 4, Bonev et al. (2019c); 5, Turpaud & Reischmann (2010); 6, Macheva et al. (2006); 7, Peytcheva et al. (2005); 8, Christofides et al. (2007); 9, Peytcheva et al. (2009a); 10, Peytcheva et al. (2009b); 11, Kounov et al. (2012); 12, Peytcheva et al. (2004); 13, Liati et al. (2011); 14, Arkadaskiy et al. (2003).



**Fig. 2.** Gondwana–Eurasia palaeotectonic reconstructions for the Late Permian: (a) according to Ricou (1994) (DR, Drama; Moe, Moesia; PL, Pelagonian), (b) according to Ziegler & Stampfli (2001) (PL, Pelagonian; Rh, Rhodope).

and marble (Dimadis & Zachos, 1989). The thickness of the marble sequence in the Greek Rhodope varies between 700 and 2800 m and generally becomes thinner to the east (e.g. Dimadis & Kosmas, 1989). In Bulgaria, the Pirin unit exposes the Pangeon-type marble sequence, which is *c.* 1000 m thick in the north, and *c.* 1600 m thick in the south (Zagorčev, 1994). On Thasos Island, the Pangeon-type metamorphic section contains two schist sequences alternating with two marble sequences, which altogether reach a thickness of *c.* 2000 m (Dimitriadis, 1989).

To the northeast, along the late Alpine SW-directed Nestos syn-metamorphic ductile thrust, the Pirin–Pangeon unit is overlain by the intermediate unit of the Rhodope thrust stack called the Sideronero unit (Papanikolaou & Panagopoulos, 1981) or Mesta–Sideronero unit (Burg *et al.* 1996; Fig. 1). Multiple-phased isoclinal folding of the Pirin–Pangeon metamorphic section is associated with inverted metamorphic zones ranging from upper greenschist facies to the south, to sillimanite-bearing amphibolite facies to the north, against the Nestos thrust (Kronberg & Raith, 1977; Zachos & Dimadis, 1983; Mposkos & Liati, 1993). Similar sillimanite-bearing schists have been described in Thasos Island (Dimitriadis, 1989). The thickness of 7000 m initially proposed by Kronberg (1969) for the Pangeon unit marble was subsequently questioned, and attributed to an overestimated section due to folding and thrusting (Papanikolaou & Panagopoulos, 1981; Zachos & Dimadis, 1983; Dimadis & Kosmas, 1989). To the SW, the Pirin–Pangeon unit is bounded by the Strymon thrust (Kockel & Walther, 1965) reworked by the Cenozoic Strymon extensional detachment (Dinter, 1998) from the Kerdilion unit of the Serbo-Macedonian Massif (Kockel *et al.* 1977). The Strymon detachment was recently put under question (Brun & Sokoutis, 2018). The Kerdilion unit is considered as a gneissic complex similar to the Rhodope Massif and representing its integral crustal component (Burg *et al.* 1995; Kydonakis *et al.* 2015).

U–Pb zircon geochronological studies of the gneissic units of the Serbo-Macedonian Massif have identified Late Neoproterozoic meta-granitoids (Himmerkus *et al.* 2006). They are coeval with the meta-granitoids of the Carpathian–Balkan units located to the north (Kounov *et al.* 2012). They probably also have their age counterparts in the Rhodope (Arkadaskiy *et al.* 2003; Fig. 1). Ordovician–Silurian meta-granitoids (Macheva *et al.* 2006; Himmerkus *et al.* 2009a; Kounov *et al.* 2012; Bonev *et al.* 2013) and voluminous Late Carboniferous – Permian meta-granitoids (Peytcheva & von Quadt, 1995; Peytcheva *et al.* 2004; Cornelius, 2008; Turpaud & Reischmann, 2010; Himmerkus *et al.* 2012) are common in the Serbo-Macedonian and Rhodope massifs. They provide the age of the igneous components involved in the continental build-up of both massifs (Fig. 1b). Early–Middle Triassic meta-granitoids and gabbroids (Christofides *et al.* 2007; Himmerkus *et al.* 2009b; Peytcheva *et al.* 2009a; Drakoulis *et al.* 2013; Bonev *et al.* 2019c) in the Serbo-Macedonian and Rhodope massifs record Triassic rifting during opening of the Neotethys (Fig. 1b). Jurassic – Early Cretaceous meta-granitoids and granitoids in the Serbo-Macedonian and Rhodope massifs (*c.* 163–134 Ma) are attributed to an arc/back-arc system (not shown in Fig. 1), which subsequently developed in the Neotethys during its Mesozoic evolution (Turpaud & Reischmann, 2010; Himmerkus *et al.* 2012; Bonev *et al.* 2015a, b).

Further geological components adjacent to the Pirin–Pangeon unit are Late Cretaceous to Oligocene granitoids (e.g. Marchev *et al.* 2013, and references therein) and Eocene to Quaternary sedimentary rocks (e.g. Zagorchev, 1998, and references therein), which represent a syn- and post-tectonic Cenozoic cover and magmatic units related to the extensional evolution of the Rhodope

Massif in Bulgaria and Greece (e.g. Burg *et al.* 1996; Bonev *et al.* 2006; Bonev & Beccaletto, 2007; Burchfiel *et al.* 2008; Brun & Sokoutis, 2018 and references therein).

### 3. Field data, samples and their composition

Thin schist layers are interstratified with marble of the Pirin unit near the villages of Ilindentsi and Petrovo (Fig. 3; Supplementary Table S1 available online at <https://doi.org/10.1017/S0016756819001183>). Their structures were characterized during mapping at a scale of 1:1000 conducted for marble quarry exploration (Dabovski *et al.* 1980).

At Ilindentsi, a 30 m thick, weathered biotite schist layer is overlain by grey massive marble and underlain by impure white mica-rich marble that passes down-section into a white crystalline marble. In thin-section, the biotite schist consists of modally decreasing quartz, biotite, plagioclase and garnet. Grain size of quartz and plagioclase is variable and is attributed to its detrital origin. Biotite is strongly chloritized, and epidote replaces the plagioclase. Both minerals indicate retrogression. Garnet occurs as small unaltered porphyroblasts. Zircon and apatite are accessory minerals. A layer of biotite schist (sample R2) was sampled for U–Pb dating of detrital zircons (see Fig. 4), and the underlying white fine-grained crystalline marble (sample R1) was collected to determine its Sr isotopic composition. The whole-rock chemical composition of sample R1 indicates that it is a dolomitic marble (Supplementary Table S1, available online at <https://doi.org/10.1017/S0016756819001183>).

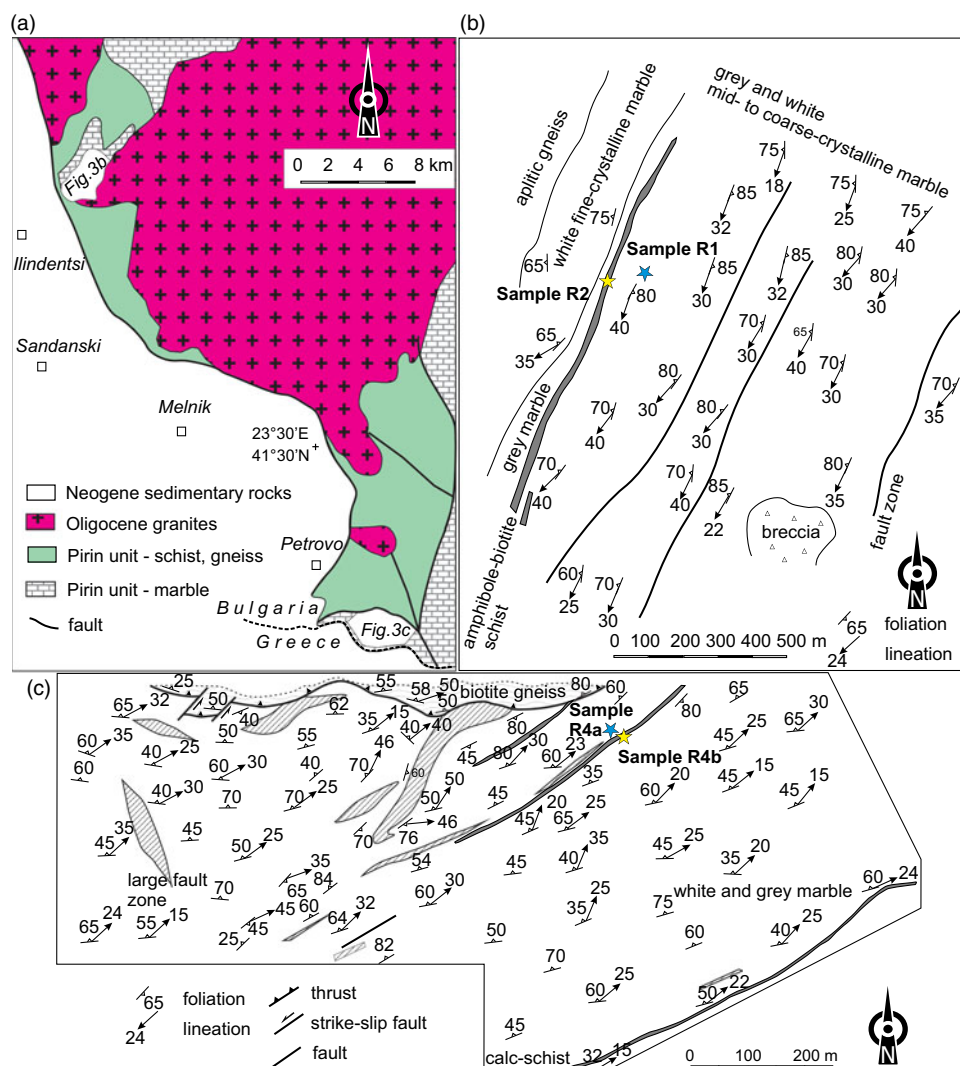
At Petrovo, a 10 m thick layer of Fe-rich calc-schist is underlain by a 10 m thick layer of biotite schist. Both lithologies are interbedded within marble. The schist succession is overlain by white marble, which contains fine-grained shale laminae. A medium-grained white massive marble underlies the schist succession. In thin-section, the Fe-rich calc-schist consists of modally decreasing quartz, chlorite, hematite, calcite and feldspar. Quartz forms mono- and polycrystalline grains, while red-brown chlorite defines discontinuous aggregates and nests together with hematite. Rare magnetite and quartz–feldspar lithic fragments also occur. Accessory minerals include zircon, apatite and rare white mica flakes. The foliation of calc-schist is parallel to the primary lamination of the host marble. We sampled Fe-rich calc-schist (sample R4b) for U–Pb geochronology of detrital zircons, and the white overlying marble containing fine shale laminae (sample R4a) for Sr isotope geochemistry. The whole-rock chemical composition classifies sample R4b as calcareous Fe-rich shale (e.g. Herron, 1988), while sample R4a is a calcitic marble (Supplementary Table S1, available online at <https://doi.org/10.1017/S0016756819001183>). In addition, sample R6, consisting of gray calcitic marble, was used for Sr isotope geochemistry (Fig. 1b for location). The studied marble samples are characterized by low contents of trace and rare-earth elements (Supplementary Table S1, available online at <https://doi.org/10.1017/S0016756819001183>).

## 4. Results

### 4.a. U–Pb zircon geochronology

In order to date the marble deposition in the Pirin unit, we have analysed detrital zircons of the two schist samples R2 and R4b for U–Pb geochronology (see Fig. 4). The locations of samples are given in Figures 1 and 3 and Supplementary Table S1 (available online at <https://doi.org/10.1017/S0016756819001183>). The sample preparation and analytical procedures are the same as described by Bonev *et al.* (2019a). The analytical data are presented in Supplementary Table S2 (available online at <https://doi.org/10.1017/S0016756819001183>). U–Pb *in situ* LA-ICP-MS zircon





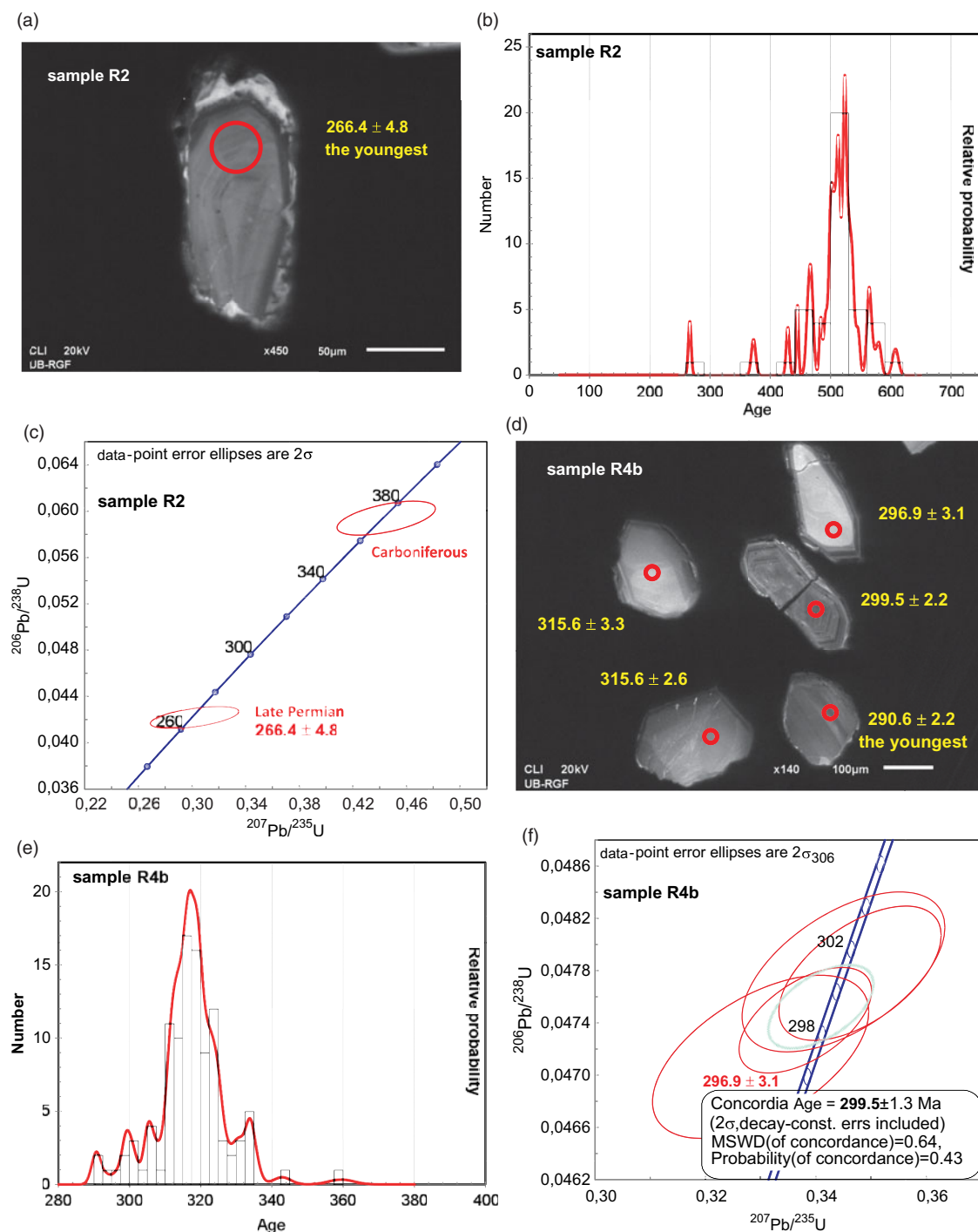
**Fig. 3.** (Colour online) Simplified geological maps for (a) Pirin unit (location in Fig. 1b), (b) Ilindentsi locality and (c) Petrovo locality (locations in (a)). Modified after Dabovski *et al.* (1980).

dating was performed at the laboratory of the Geological Institute of the Bulgarian Academy of Sciences using a New Wave UP193FX LA coupled to a Perkin Elmer ELAN DRC-e quadrupole ICP-MS.

The dated zircons in sample R2 vary in size from 50  $\mu\text{m}$  to 300  $\mu\text{m}$ , with an average aspect ratio of 1.86. They display irregular or semi-rounded shapes and rarely preserved oscillatory zoning patterns disturbed by resorption and corrosion, which are characteristic for a magmatic origin (Fig. 4a). Thirty-six concordant zircon analyses out of 92 performed in total yielded Neoproterozoic to Permian ages (Fig. 4b). Four-grains concordant ages range from 607.7 Ma to 563.5 Ma, corresponding to the Neoproterozoic (Supplementary Figure S1, available online at <https://doi.org/10.1017/S0016756819001183>). The main age cluster of 25 zircons between 545.6 and 491.2 Ma encompasses the Cambrian, with a peak around 520 Ma. A further minor age cluster includes five Ordovician zircons dated between 468.8 Ma and 429 Ma. One zircon yielded a Carboniferous age of  $372.1 \pm 7.2$  Ma. The youngest zircon yielded an age of  $266.4 \pm 4.8$  Ma, and hence defines the maximum depositional age in the latest Middle Permian (Fig. 4c). The Th/U ratios of the dated zircons vary from 0.01 to 0.79, with the majority of zircon grains having a high ratio of

0.12–0.79 (Supplementary Table S2, available online at <https://doi.org/10.1017/S0016756819001183>), which is characteristic for magmatic zircons (Rubatto, 2002; Tiepel *et al.* 2004).

Zircons from the Fe-rich calc-schist sample R4b show semi-rounded to rounded shapes, as well as prismatic and pyramidal crystals varying in size from 100  $\mu\text{m}$  to 400  $\mu\text{m}$  (average aspect ratio 1.4), which have a homogeneous and a strongly obliterated magmatic oscillatory zoning pattern (Fig. 4d). The  $^{206}\text{Pb}/^{238}\text{U}$  ages obtained from 105 analyses range from 359.5 Ma to 290.2 Ma. Sixty-two concordant zircon grain analyses yielded Carboniferous–Permian ages from 334.5 Ma to 296.9 Ma. Zircon ages span across the Carboniferous, with concordant clusters at  $333.9 \pm 1.5$  Ma,  $323.98 \pm 0.92$  Ma,  $317.54 \pm 0.68$  Ma,  $311.6 \pm 1.1$  Ma and  $305.4 \pm 1.1$  Ma (Supplementary Figure S2, available online at <https://doi.org/10.1017/S0016756819001183>). The youngest zircon out of 105 grains provided an age of  $290.2 \pm 3.7$  Ma, and hence defines a maximum Early Permian depositional age. This age is consistent with four more grains, which define a concordia age of  $299.5 \pm 1.3$  Ma. The Th/U ratios of the zircons in this sample range from 0.05 to 1.29 (Supplementary Table S2, available online at <https://doi.org/10.1017/S0016756819001183>), but the majority



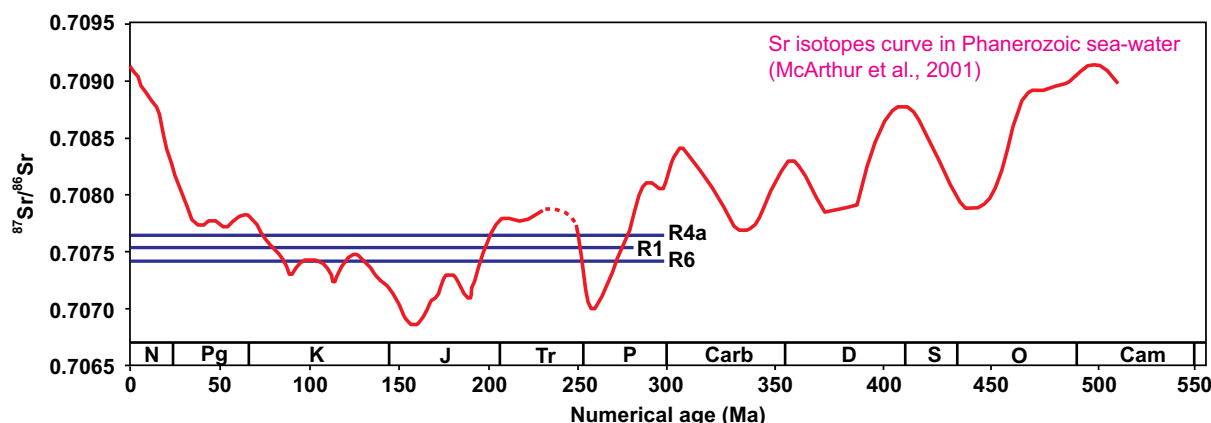
**Fig. 4.** (Colour online) Selected cathodoluminescence (CL) images of dated zircons in the schist layers interstratified with marble of the Pirin unit, and diagrams of U–Pb LA-ICP-MS zircon analyses. Circles represent the location of spot analyses with corresponding ages given with  $2\sigma$  error. (a) CL image of the youngest zircon in sample R2; (b) density distribution diagram of zircons from sample R2; (c) concordia diagram for the two youngest zircons in sample R2; (d) CL image of the zircons in sample R4b; (e) density distribution diagram of the zircons in sample R4b; (f) concordia diagram for the four youngest zircons in sample R4b.

of these ratios are in the 0.36–1.29 range, which is typical for magmatic zircons.

#### 4.b. Sr isotopes

For strontium chemical separation, whole rock samples were prepared in the clean laboratory at the University of Geneva, where Sr isotopes were also measured on a Thermo Scientific TRITON

Thermal Ionization Mass Spectrometer.  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios were corrected for internal fractionation using a  $^{88}\text{Sr}/^{86}\text{Sr}$  ratio of 8.357209 and for external fractionation using a nominal value of SRM 987, with a  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of 0.710248 (McArthur *et al.* 2001). Analytical details and procedures can be found in Chiaradia *et al.* (2011). The whole-rock Sr isotopic compositions are given in Supplementary Table S3 (available online at <https://doi.org/10.1017/S0016756819001183>).



**Fig. 5.** (Colour online) Diagram of Sr isotopic compositions of the Pirin unit marble samples vs age-constrained Sr isotopic compositions of Phanerozoic sea-water (after McArthur *et al.* 2001).

Strontium isotopic ratios of the three marble samples (R1, R4a and R6) range from 0.707420 to 0.707653 (see Supplementary Table S3, available online at <https://doi.org/10.1017/S0016756819001183>). These values are close to the previously published Sr isotopic compositions of the Pirin unit marble, with a  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio between 0.70766 and 0.70776 (Georgiev *et al.* 2012). In Figure 5, Sr isotopic compositions of the Pirin unit marble samples are plotted against the Sr isotopic compositions of Phanerozoic sea-water (McArthur *et al.* 2001). The range of the Sr isotopic compositions of the marble under study are consistent with a Middle Permian depositional age (Fig. 5).

## 5. Discussion

The U–Pb detrital zircon geochronological data obtained for the Pirin unit indicate a latest Middle Permian maximum depositional age as young as 262.4 Ma (within error) for the biotite schist layer within marble. The Fe-rich calc-schist layer within the marble has a Lower Permian maximum depositional age of 287.5 Ma (within error) (Fig. 4). The number of dated zircons from the R2 biotite schist nearly meets the required amount for statistical criteria, which is met for the Fe-rich calc-schist (Vermeesch, 2004). Taken collectively, the number of dated zircons from both schist samples satisfies and exceeds the statistical confidence at the 95 % level. Thus, the Lower–Middle Permian detrital zircon record obtained in this study provides an unequivocal depositional age constraint for the Pirin–Pangeon marble hosting the schist layers.

The predominantly high Th/U ratios of the detrital zircons reflect mostly a magmatic provenance and a subsidiary provenance from metamorphic basement rocks. In this sense, the Th/U ratios and the documented age clusters of detrital zircons correspond to the same age as the magmatic protoliths of the metamorphic basement of the Rhodope and Serbo-Macedonian massifs (Fig. 1b). The detrital zircons age clusters of the studied samples differ spatially in function of the immediate sedimentary source area, but the clusters precisely reflect the age of the basement rocks of each source area location. In particular, biotite schist sample R2 reveals a major cluster of Neoproterozoic–Cambrian zircons, which corresponds to the age of the abundant Neoproterozoic–Cambrian orthogneisses in the nearby Carpatho-Balkan units (Kounov *et al.* 2012). The same applies to the minor cluster of Ordovician zircons, with ages overlapping with those of the exposed Ordovician meta-magmatic rocks in the Rhodope and Serbo-Macedonian units (Macheva *et al.* 2006; Peytcheva *et al.* 2009b; Kounov *et al.*

2012; see Fig. 1) adjacent to sample R2, suggesting that the biotite schist contains sedimentary material coming from a nearby source area. The Fe-rich calc-schist sample R4b contains a major detrital component from Carboniferous–Permian magmatic rocks, which are exposed at the base of the Pirin–Pangeon–Thasos carbonate unit (Turpaud & Reischmann, 2010; see Fig. 1). As the major detrital zircon age cluster of the Fe-rich calc-schist overlaps with the ages of the underlying Carboniferous–Permian meta-magmatic rocks, it suggests that the source area was not far from the depositional area.

Collectively, the detrital zircon record in both schist samples is evidence for a provenance of the sedimentary material from the continental Rhodope–Serbo-Macedonian high-grade basement. The studied schist samples are devoid of any zircon input from Triassic magmatic bodies (e.g. Bonev *et al.* 2019c, and references therein). This supports a pre-Triassic deposition of the PPT carbonate platform. Our interpretation is consistent with the Sr isotopic compositions of the Pirin unit marble, pointing to carbonate platform sedimentation during the Middle Permian (Figs 4, 5).

There is evidence of Permian carbonate sedimentation (de Bono *et al.* 2001; Ferriere *et al.* 2016 and this study) on top of the Rhodope–Serbo-Macedonian and the Pelagonian Proterozoic and Palaeozoic igneous and metamorphic basements (e.g. Anders *et al.* 2006, 2007; Himmerkus *et al.* 2006, 2009a; Schenker *et al.* 2014). Furthermore, Permian limestone clasts and blocks were documented in the Rhodope uppermost metamorphic unit (Bonev, 2005), and Permian sedimentation was also established in the Sakar–Strandzha Zone (Bonev *et al.* 2019b) c. 60 km to the NE of the Rhodope (see Fig. 1a). The Rhodope–Serbo-Macedonian and the Pelagonian massifs are interpreted as a part of the Eurasian continental margin, which is supported by biostratigraphic and geochronological evidence for the Permian. However, the Rhodope–Serbo-Macedonian massifs and the Pelagonian Massif were separated from each other during Triassic rifting in the Neotethys in the Aegean region (e.g. Ferriere *et al.* 2016 and references therein). Thus, from a palaeogeographic viewpoint, there is more evidence for the deposition of the PPT carbonate platform at the Eurasian margin than for the deposition along the northern passive margin of Gondwana.

## 6. Conclusions

Our study shows that the Pirin–Pangeon–Thasos carbonate platform includes schist layers in which detrital zircon ages constrain

sedimentation during the Permian. Because the sedimentation source areas were the Rhodope igneous and metamorphic basement and adjacent basement units, this implies platform deposition along the Rhodope continental margin of Eurasia, but an affinity with the northern passive Gondwana margin cannot be ruled out.

**Supplementary material.** To view supplementary material for this article, please visit <https://doi.org/10.1017/S0016756819001183>

**Acknowledgements.** The study was supported by the Bulgarian National Science Fund project no. DN 04/6. We thank Jean-Pierre Burg and Dimitrios Papanikolaou for their helpful comments on the manuscript.

## References

- Ancirev A, Gorozanin O, Velichkov D and Bogoyavlenskaya O** (1980) About a find of faunistic remains in the metamorphic rocks of the Western Rhodopes. *Geologica Balcanica* **10**, 29–32.
- Anders B, Reischmann T and Kostopoulos D** (2007) Zircon geochronology of basement rocks from the Pelagonian Zone, Greece: constraints on the pre-Alpine evolution of the westernmost Internal Hellenides. *International Journal of Earth Sciences* **96**, 639–61.
- Anders B, Reischmann T, Kostopoulos D and Poller U** (2006) The oldest rocks of Greece: first evidence for a Precambrian terrane within the Pelagonian Zone. *Geological Magazine* **143**, 41–58.
- Arkadaktskiy SV, Bohm C, Heaman L, Cherneva Z, Stancheva E and Ovtcharova M** (2003) Remnants of Neoproterozoic oceanic crust in the Central Rhodope metamorphic complex. Vancouver: Geological Association of Canada – Mineralogical Association of Canada – Society of Economic Geology, 1 pp. abstract.
- Bonev N** (2005) Foraminifers from the exotic Late Permian limestone pebbles in the Mesozoic low-grade sequence of the eastern Rhodope, Bulgaria: paleogeographic and paleotectonic consequences. *Neues Jahrbuch für Geologie und Paläontologie Monatshefte* **7**, 385–403.
- Bonev N and Beccaletto L** (2007) From syn- to post-orogenic Tertiary extension in the north Aegean region: constraints on the kinematics in the eastern Rhodope-Thrace, Bulgaria-Greece and the Biga Peninsula, NW Turkey. In *The Geodynamics of Aegean and Anatolia* (eds T Taymaz, Y Yilmaz and Y Dilek), pp. 113–42. Geological Society of London, Special Publication no. 291.
- Bonev N, Burg J-P and Ivanov Z** (2006) Mesozoic-Tertiary structural evolution of an extensional gneiss dome – the Kesebir-Kardamos dome, eastern Rhodope (Bulgaria-Greece). *International Journal of Earth Sciences* **95**, 318–40.
- Bonev N, Filipov P, Raicheva R and Moritz R** (2019a) Timing and tectonic significance of Paleozoic magmatism in the Sakar unit of the Sakar-Strandzha zone, SE Bulgaria. *International Geology Review* **61**, 1957–79. doi: [10.1080/00206814.2019.1575090](https://doi.org/10.1080/00206814.2019.1575090)
- Bonev N, Filipov P, Raicheva R and Moritz R** (2019b) Detrital zircon age constraints on the deposition of the Topolovgrad Group, Sakar-Strandzha Zone, SE Bulgaria. *Geophysical Research Abstracts* **21**, EGU 2019-1921-1.
- Bonev N, Marchev P, Moritz R and Collings D** (2015a) Jurassic subduction zone tectonics of the Rhodope Massif in the Thrace region (NE Greece) as revealed by new U–Pb and <sup>40</sup>Ar/<sup>39</sup>Ar geochronology of the Evros ophiolite and high-grade basement rocks. *Gondwana Research* **27**, 760–75.
- Bonev N, Marchev P, Moritz R and Filipov P** (2015b) Timing of igneous accretion, composition, and temporal relations of the Kassandra-Sithonia rift-spreading center within the eastern Vardar suture zone, Northern Greece: insights into Jurassic arc/back-arc systems evolution at the Eurasian plate margin. *International Journal of Earth Sciences* **104**, 1837–64.
- Bonev N, Moritz R, Borisova M and Filipov P** (2019c) Therma-Volvi-Gomati complex of the Serbo-Macedonian Massif, northern Greece: a Middle Triassic continental margin ophiolite of Neotethyan origin. *Journal of the Geological Society* **176**, 931–44. doi: [10.1144/jgs2017-130](https://doi.org/10.1144/jgs2017-130)
- Bonev N, Ovtcharova-Schaltegger M, Moritz R, Marchev P and Ulianov A** (2013) Peri-Gondwanan Ordovician crustal fragments in the high-grade basement of the Eastern Rhodope Massif, Bulgaria: evidence from U–Pb LA-ICP-MS zircon geochronology and geochemistry. *Geodinamica Acta* **26**, 207–29.
- Brun J-P and Sokoutis D** (2018) Core complex segmentation in North Aegean, a dynamic view. *Tectonics* **37**, 1797–830.
- Burchfiel BC, Nakov R, Dumurdzanov M, Papanikolaou D, Tzankov T, Serafimovski T, King RW and Nurce B** (2008) Evolution and dynamics of the Cenozoic tectonics of the South Balkan extensional system. *Geosphere* **4**, 919–38.
- Burg J-P** (2012) Rhodope: from Mesozoic convergence to Cenozoic extension. Review of petro-structural data in geochronological frame. *Journal of Virtual Explorer* **42**, 1–44.
- Burg J-P, Godfriaux I and Ricou L-E** (1995) Extension of the Mesozoic Rhodope thrust units in the Vertiskos-Kerdilion Massifs (northern Greece). *Comptes Rendus de l'Académie des Sciences, Paris* **320**, 889–96.
- Burg J-P, Ricou L-E, Ivanov Z, Godfriaux I, Dimov D and Klain L** (1996) Syn-metamorphic nappe complex in the Rhodope Massif. Structure and kinematics. *Terra Nova* **8**, 6–15.
- Chiaradia M, Müntener O and Beate B** (2011) Enriched basaltic andesites from mid-crustal fractional crystallization, recharge, and assimilation (Pilavo Volcano, Western Cordillera of Ecuador). *Journal of Petrology* **52**, 1107–41.
- Christofides G, Koroneos A, Liati A and Kral J** (2007) The a-type Kerkini granitic complex in north Greece: geochronology and geodynamic implications. *Bulletin of the Geological Society of Greece* **40**, 700–11.
- Cornelius NK** (2008) *UHP metamorphic rocks of the Eastern Rhodope Massif, NE Greece: new constraints from petrology, geochemistry and zircon ages*. PhD thesis, Johannes Gutenberg University, Mainz, Germany. Published thesis.
- Dabovskii CH, Karagjuleva J, Kostadinov V, Stojanov S, Haidutov I and Tsankov TS** (1980) Deformations in marbles from the deposits Petrovo and Ilindenci, South-West Pirin. *Geotectonics, Tectonophysics and Geodynamics (Sofia)* **11**, 40–51.
- DeBono A, Martini R, Zaninetti L, Hirsch F and Stampfli GM** (2001) Permo-Triassic stratigraphy of the Pelagonian Zone in central Evia Island (Greece). *Eclogae Geologicae Helvetiae* **94**, 289–311.
- Dimadis E and Kosmas C** (1989) Geological and tectonic structure of the Lekani Mountains syncline. *Geologica Rhodopica* **1**, 145–52.
- Dimadis E and Zachos S** (1989) Geological and tectonic structure of the metamorphic basement of the Greek Rhodopes. *Geologica Rhodopica* **1**, 122–30.
- Dimitriadis S** (1989) Sillimanite grade metamorphism in Thasos Island, Rhodope Massif, Greece, and its regional significance. *Geologica Rhodopica* **1**, 190–201.
- Dinter DA** (1998) Late Cenozoic extension of the Alpine collisional orogen, northeastern Greece: origin of the north Aegean basin. *Geological Society of America Bulletin* **110**, 1208–30.
- Drakoulis A, Koroneos A, Poli G, Soldatos T, Papadopoulou L, Murata M and Eliwa H** (2013) U–Pb zircon dating of the Mt. Papikon pluton (central Rhodope, Greece): new constraints on the evolution of Kesebir-Kardamos dome. *Acta Vulcanologica* **25**, 83–98.
- Ferriere J, Baumgartner PO and Chanier F** (2016) The Maliac Ocean: the origin of Tethyan Hellenic ophiolites. *International Journal of Earth Sciences* **105**, 1941–63.
- Georgiev S, Peytcheva I, Von Quadt A, Marchev P, Grozdev V and Balkanska E** (2012) North Pirin pluton and the volcanic and subvolcanic rocks between villages of Padesh and Kresna; an example of high rate of crustal assimilation. In *Exhumation of High-Grade Metamorphic Rocks (MCC), Magmatic Arc Systems and Strike-Slip Zones, International Conference 29–30 March 2012, Sofia, Bulgaria*, pp. 37–41. Extended abstract.
- Herron MM** (1988) Geochemical classification of terrigenous sands and shales from core or log data. *Journal of Sedimentary Petrology* **58**, 820–9.
- Himmerkus F, Reischmann T and Kostopoulos D** (2006) Late Proterozoic and Silurian basement units within the Serbo-Macedonian Massif, northern Greece: the significance of terrane accretion in the Hellenides. In *Tectonic Development of the Eastern Mediterranean Region* (eds AHF Robertson and D Mountrakis), pp. 35–50. Geological Society of London, Special Publication no. 260.
- Himmerkus F, Reischmann T and Kostopoulos D** (2009a) Serbo-Macedonian revisited: a Silurian basement terrane from northern Gondwana in the Internal Hellenides, Greece. *Tectonophysics* **473**, 20–35.
- Himmerkus F, Reischmann T and Kostopoulos D** (2009b) Triassic rift-related meta-granites in the Internal Hellenides. *Geological Magazine* **146**, 252–65.



- Himmerkus F, Zachariadis P, Reischmann T and Kostopoulos D (2012) The basement of the Mount Athos peninsula, northern Greece: insights from geochemistry and zircon ages. *International Journal of Earth Sciences* **101**, 1467–85.
- Jordan H (1969) Geologie und Petrographie im Zentralteil des Bos Dağ (Drama, Griechisch-Makedonien). *Geotektonische Forschungen* **31**, 50–85.
- Kockel F and Walther HW (1965) Die Strimonlinie als Grenze zwischen Serbo-Mazedonischen und Rila-Rhodope Massiv in Ost-Mazedonien. *Geologisches Jahrbuch* **83**, 575–602.
- Kockel F, Mollat H and Walther HW (1977) *Erläuterungen zur geologischen Karte der Chalkidiki und angrenzender Gebiete 1/100.000 (Nord Griechenland)*. Hannover: Bundesanstalt für Geowissenschaften und Rohstoffe, 119 pp.
- Kounov A, Graf J, Von Quadt A, Bernoulli D, Burg J-P, Seward D, Ivanov Z and Fanning M (2012) Evidence for a “Cadomian” ophiolite and magmatic arc complex in SW Bulgaria. *Precambrian Research* **212–213**, 275–95.
- Kronberg P (1969) Gliederung, Petrographie und tectogenese des Rhodopen-Kristallins im Tsal Dağ, Simvolon und Ost-Pangäon (Griechisch-Makedonien). *Geotektonische Forschungen* **31**, 1–49.
- Kronberg P and Raith M (1977) Tectonics and metamorphism of the Rhodope crystalline complex in Eastern Greek Macedonia and parts of Western Thrace. *Neues Jahrbuch für Geologie und Paläontologie Monatshefte* **11**, 697–704.
- Kydonakis K, Moulas E, Chatzitheodoridis E, Brun J-P and Kostopoulos D (2015) First-report on Mesozoic eclogite-facies metamorphism preceding Barrovian overprint on the western Rhodope (Chalkidiki, Northern Greece). *Lithos* **220–223**, 147–63.
- Liati A, Gebauer D and Fanning CM (2011) Geochronology of the Alpine UHP Rhodope zone: a review of isotopic ages and constraints on the geodynamic evolution. In *Ultrahigh-Pressure Metamorphism 25 Years after the Discovery of Coesite and Diamond* (eds LF Dobrzhinetskaya, SW Faryad, S Wallis and S Cuthbert), pp. 295–324. Amsterdam: Elsevier.
- Macheva L, Peytcheva I, Von Quadt A, Zidarov N and Tarassova E (2006) Petrological, geochemical and isotope features of Lozen metagranite, Belasitza Mountain – evidence for widespread distribution of Ordovician metagranitoids in the Serbo-Macedonian Massif, SW Bulgaria. *Proceedings of Annual Conference of the Bulgarian Geological Society “Geosciences 2006”, Sofia, Bulgaria*, Bulgarian Geological Society, 30 November–01 December 2006, pp. 209–12.
- Marchev P, Georgiev S, Raicheva R, Peytcheva I, Von Quadt A, Ovtcharova M and Bonev N (2013) Adakitic magmatism in post-collisional setting: an example from the Early-Middle Eocene magmatic belt in South Bulgaria and North Greece. *Lithos* **180–181**, 159–80.
- McArthur JM, Howarth RJ and Bailey TR (2001) Strontium isotope stratigraphy: LOWESS version. 3: best fit for marine Sr-isotope curve for 0–509 Ma and accompanying look-up table for deriving numerical age. *Journal of Geology* **109**, 155–70.
- Mposkos E and Liati A (1993) Metamorphic evolution of metapelites in the high-pressure terrane of the Rhodope zone, northern Greece. *Canadian Mineralogist* **31**, 401–24.
- Papanikolaou D (1984) The three metamorphic belts of the Hellenides; review and kinematic interpretation. In *Tectonic Evolution of the Eastern Mediterranean* (eds AHF Robertson and JE Dixon), pp. 551–61. Geological Society of London, Special Publication no. 17.
- Papanikolaou D (2013) Tectonostratigraphic models of Alpine terranes and subduction history of the Hellenides. *Tectonophysics* **595–596**, 1–24.
- Papanikolaou D and Panagopoulos A (1981) On the structural style of Southern Rhodope, Greece. *Geologica Balcanica* **11**, 13–22.
- Peytcheva I and Von Quadt A (1995) U-Pb zircon dating of metagranites from Byala Reka region in the east Rhodopes, Bulgaria. *Geological Society of Greece Special Publications* **4**, 637–42.
- Peytcheva I, Von Quadt A, Ovtcharova M, Handler R, Neubauer F, Salnikova E, Kostitsin Y, Sarov S and Kolcheva K (2004) Metagranitoids from the eastern part of the Central Rhodopean Dome (Bulgaria): U-Pb, Rb-Sr and  $^{40}\text{Ar}/^{39}\text{Ar}$  timing of emplacement and isotopic-geochemical features. *Mineralogy and Petrology* **82**, 1–31.
- Peytcheva I, Von Quadt A, Sarov S, Voinova E and Kolcheva K (2009b) Ordovician protoliths of metamorphic rocks in eastern Pirin-Western Rhodopes: are they part of the Ograzhden Unit? *Proceedings of Annual Conference of the Bulgaria Geological Society “Geosciences 2009, Sofia, Bulgaria*, Bulgarian Geological Society, 3–4 December 2009, pp. 17–18.
- Peytcheva I, Von Quadt A, Tarassov M, Zidarov N, Tarassova E and Andreichev V (2009a) Timing of Igralishte pluton of Ograzhden Mountain, SW Bulgaria: implications for tectono-magmatic evolution of the region. *Geologica Balcanica* **38**, 5–14.
- Peytcheva I, Von Quadt A, Titorenkova R, Zidarov N and Tarassova E (2005) Skrut granitoids from Belasitza Mountain, SW Bulgaria: constraints from isotope-geochronological and geochemical zircon data. *Proceedings of Annual Conference of the Bulgarian Geological Society “Geosciences 2005”, Sofia, Bulgaria*, Bulgarian Geological Society, 17–18 November 2005, pp. 109–12.
- Ricou L-E (1994) Tethys reconstructed: plates, continental fragments and their boundaries since 260 Ma from Central America to south-eastern Asia. *Geodinamica Acta* **7**, 169–218.
- Ricou L-E, Burg J-P, Godfriaux I and Ivanov Z (1998) The Rhodope and Vardar: the metamorphic and the olistostromic paired belts related to the Cretaceous subduction under Europe. *Geodinamica Acta* **11**, 285–309.
- Rubatto D (2002) Zircon trace element geochemistry: partitioning with garnet and the link between U-Pb ages and metamorphism. *Chemical Geology* **184**, 123–38.
- Schenker FL, Burg J-P, Kostopoulos D, Moulas E, Larionov AVon Quadt A and (2014) From Mesoproterozoic magmatism to collisional Cretaceous anatexis: tectonomagmatic history of the Pelagonian Zone, Greece. *Tectonics* **33**, 1552–76.
- Tiepel U, Eichhorn R, Loth G, Rohrmülle J, Höll R and Kennedy A (2004) U-Pb SHRIMP and Nd isotopic data from the western Bohemian Massif (Bayerischer Wald, Germany): implications for Upper Vendian and Lower Ordovician magmatism. *International Journal of Earth Sciences* **93**, 782–801.
- Turpaud P and Reischmann T (2010) Characterization of igneous terranes by zircon dating: implications for UHP occurrences and suture identification in the Central Rhodope, northern Greece. *International Journal of Earth Sciences* **99**, 567–91.
- Vermeesch P (2004) How many grains are needed for provenance study? *Earth and Planetary Science Letters* **224**, 441–51.
- Zachos S and Dimadis E (1983) The geotectonic position of the Skaloti-Echinos granite and its relationships to the metamorphic formations in Greek Western and Central Rhodope. *Geologica Balcanica* **13**, 17–24.
- Zagorčev IS (1994) Structure and tectonic evolution of the Pirin-Pangaion structural zone (Rhodope Massif, southern Bulgaria and northern Greece). *Geological Journal* **29**, 241–68.
- Zagorčev IS (1998) Pre-Priabonian Palaeogene formations in southwestern Bulgaria and northern Greece: stratigraphy and tectonic implications. *Geological Magazine* **135**, 101–19.
- Ziegler PA and Stampfli GM (2001) Late Paleozoic-Early Mesozoic plate boundary reorganization: collapse of the Variscan orogen and opening of Neotethys. In *The Continental Permian of the Southern Alps and Sardinia (Italy): Regional Reports and General Correlations* (ed. R Cassins), pp. 17–34. Brescia: Anali Museo Civico Science Naturali no. 25.