

U-Pb monazite and zircon ages of a granite xenolith and its host alkaline basalt from the Byala Reka Dome

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Abstract. The Oligocene Krumovgrad alkaline basalts and lamprophyre (KABL) intruded into the Kesebir-Kardamos and Byala Reka metamorphic domes carry various mantle and crustal xenoliths. This study presents the results from petrological and geochronological investigations of one granitic xenolith entrained in an alkaline (camptonite) dyke intruded into the Byala Reka dome, close to the village of Gorni Yurutsi (SE Bulgaria). The studied xenolith is granite formed at an estimated depth of 6–9 km. During the transport to the surface, it records some host-melt interaction with the penetrating melt, reflected mainly in the reaction with the biotite. In-situ U/Pb dating of four zircons and one monazite from the xenolith yield different and slightly discordant to nearly concordant ages. One zircon reveals Ediacaran (606 ± 19 Ma) $^{206}\text{Pb}/^{238}\text{U}$ age of the core and Permian (277 ± 16 Ma) of the rim (all error uncertainties are 2σ). Two zircons at three analytical points overlap in their error uncertainties at 198 ± 10 Ma and 207 ± 8 Ma, and one zircon rim yields a concordant Jurassic age of 157 ± 10 Ma. The age of this zircon should reflect the age of the crystallization of the granitic xenolith, whereas the older zircons are inherited and are typical for the metamorphic and magmatic rocks in the Rhodope Massif. The monazite crystal yields two almost concordant Chattian ages of 28.8 ± 1.3 Ma and 27.6 ± 1.8 Ma. They coincide with previous K/Ar dating of the alkaline basalts, thus confirming their Oligocene (Chattian) age.

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INTRODUCTION

The major result from the fast transport of intraplate alkaline basalts from the place of their origin to the Earth surface is their ability to bring large amount of xenoliths from the underlying upper mantle and crust, serving as very deep no-cost drill holes. All these xenoliths are the subject of justifiable scientific interest, because they provide us with valuable information about the composition and the processes in the upper mantle and mantle-crustal transition. Alkaline basalts of Miocene and Oligocene age are widely distributed in Bulgaria, forming an almost

N–S strip crossing major tectonic zones (Mavroudiev, 1964). The prevailing amount of entrained xenoliths in these alkaline basalts are spinel lherzolites from the uppermost mantle, often accompanied by cumulitic rocks of upper mantle and lower crustal origin (Marchev *et al.*, 1992, 1997, 2006, 2017; Marchev, 1993). Upper crustal xenoliths entrained in these magmas are of no less importance. Combined study of their composition and datable minerals, such as zircon and monazite, may serve as a powerful tool to constrain the composition and age of the deeper parts of the local crust and understand its contribution to magma compositions.

Some of the Oligocene KABL export large amounts of cumulitic lower crustal xenoliths and crystal clast, small spinel lherzolite xenoliths and crustal granitic and metamorphic xenoliths (Marchev *et al.*, 2006, 2008). Marchev *et al.* (2006, 2008) suggested that the formation of cumulitic xenoliths is related to the intrusions of mafic magma that produced a layered complex which played a fundamental role in the latest extension and formation of the metamorphic core complexes.

This short communication focuses on a small granitic xenolith entrained into one of the lamprophyre dykes located close to the village of Gorni Yurutsi (SE Bulgaria). Our goal is to date the monazite and zircon crystals in the xenolith and to study the mineral composition of the latter in order to obtain some information about the age of the xenolith and the host alkaline basalt and the crystallization conditions of the granite.

GEOLOGICAL BACKGROUND

The regional-scale tectonic setting of the Eastern Rhodopes is dominated by two late Alpine metamorphic core complexes, namely the Kesebir-Kardamos and the Byala Reka-Kechros domes (Burg *et al.*, 1996; Bonev *et al.*, 2006; Fig. 1a). The rocks comprising the domes are divided into four tectonostratigraphic units bounded by extensional tectonic contacts of Early Eocene low-angle detachments (Bonev *et al.*, 2006). From base to top, they are: (i) a lower high-grade unit; (ii) an upper high-grade unit, both constituting the high-grade metamorphic basement; (iii) an overlying low-grade Mesozoic unit; and (iv) a Maastrichtian–Paleocene to Pliocene sedimentary and volcanic unit of cover sequences, including voluminous Late Eocene–Oligocene volcanics and volcano-sedimentary successions (see also Bonev *et al.*, 2023).

The metamorphic rocks of the core complexes were intruded by numerous dykes, which can be divided into two groups (Marchev *et al.*, 2004). The older one (~32 Ma) is represented by bimodal acid (rhyolite-rhyodacite) and intermediate (basaltic-andesite-latite) compositions. The younger dykes in the Kesebir and Byala Reka domes are of Middle Oligocene age (28–26 Ma; Marchev *et al.*, 1997). The dykes are located 20–30 km SE of the town of Krumovgrad (Fig. 1b). They crop out over an E–W-oriented area of 100 km² in the Byala Reka and Kesebir domes. The emplacement of the dykes is controlled by a major NW–SE fault system, although some of them strike E–W and N–S. Most of the dykes

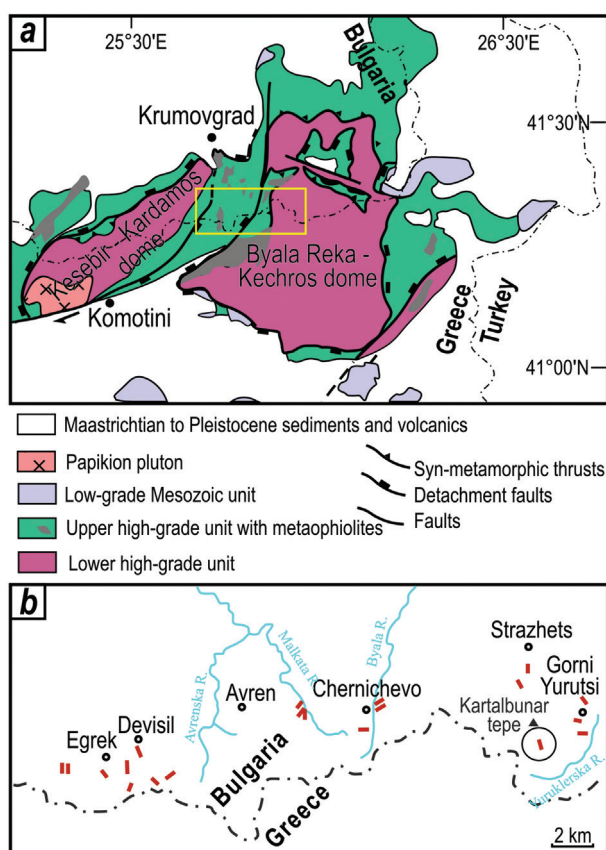


Fig. 1. a) Schematic geologic map of the eastern Rhodopes compiled from Ricou *et al.* (1998) and Bonev *et al.* (2015). Outlined is the distribution of the alkaline basaltic dykes; b) Map showing the location of the KABL dykes (after Marchev *et al.*, 1997). Circled dyke is the host of the xenolith.

are 0.5–2 m thick, except the Parzhenaka northwest–southeast-striking dyke, which is up to 40 m thick. The rocks were first described by Mavroudchiev (1964) as transitional between lamprophyres and alkaline rocks and classified as lamprobasalts. Based on their mineral and chemical composition and the presence of kaersutite megacrysts, Marchev *et al.* (1997, 1998) classified them as basanites, alkaline basalts, trachybasalts and alkaline lamprophyres (camptonites). Entrained xenoliths are of three dominant types: (i) mantle peridotites; (ii) ultramafic and mafic cumulates; and (iii) metamorphic rocks from the Rhodopean metamorphic basement (Marchev *et al.*, 2006, 2008). Marchev *et al.* (*ibid.*) described in details the ultramafic and mafic cumulates and provided information about their chemical, mineral and isotopic compositions, along with description of the entrained cumulitic rocks. Metamorphic xenoliths and xenocrysts consist of a large

variety of lithologies, which include gneisses, granites, micaschists, marbles, similar in composition to those observed in the local metamorphic basement. Plagioclase, biotite and quartz xenocrysts are also present.

GORNI YURUTSI DYKE

The Gorni Yurutsi dyke, which hosts the granitic xenolith, is in the group of the easternmost dykes of the KABL complex. The dyke is located close to the village of Gorni Yurutsi, 1.5 km south of Kartal Bunar Peak (1254.7 m; Fig.1b). The dyke is ~2 m thick, composed of olivine, clinopyroxene and amphibole. Five major-element analyses from the dyke (Marchev *et al.*, 1998) give a comparatively narrow range of composition: SiO₂ (45.50–47.90 wt.%); TiO₂ (2.08–2.23 wt.%); Mg# (59.7–61.3 wt.%). Compatible elements are moderate: Ni (69–78 ppm) and Cr (71–83 ppm), whereas HFSE Zr (262–266 ppm) and Nb (93–94 ppm) are high. According to Rock's (1987) classification, the rock is an alkaline lamprophyre (camptonite).

ANALYTICAL METHODS

Minerals of the granite xenolith were studied by optical microscopy and analyzed for major elements on an automatic wavelength dispersive JEOL Superprobe 8800R at Kanazawa University (Japan) and an energy-dispersive Oxford X-Max Large Area Analytical Silicon Drifted spectrometer coupled with a SEM JSM-259 6610 LV at the University of Belgrade (Serbia). Natural and synthetic minerals were used as external standards.

Trace element composition of one melt inclusion was analyzed at the Department of Physics and Geology, Perugia University (Italy) on a New Wave UP213 (ESI - New Wave, UK) LA system coupled with a Thermo X Series (Thermo Fisher Scientific, Bremen, DE) ICP-MS.

Cathodoluminescence (CL) and backscatter images (BSE) on individual zircon and monazite grains were obtained, using a JEOL JSM-6610 LV SEM-EDS at the University of Belgrade directly on the thin sections. *In-situ* U/Pb zircon and monazite geochronology was carried out on the same grains at the Geological Institute of the Bulgarian Academy of Sciences, using a New Wave Research Excimer 193 nm laser-ablation system UP-193FX attached to a Perkin-Elmer ELAN DRC-e inductively coupled plasma mass spectrometer. A laser-crater of 25 µm diameter, repetition rate 7 and laser flu-

ence of ~7 J/cm² were applied, using the GJ1 as primary (Jackson *et al.*, 2004), and Plešovice (Sláma *et al.*, 2008) as secondary standard reference material (SRM). During the daily session, the Plešovice SRM was dated at 335±5 Ma. The results of *in-situ* U-Pb geochronology were calculated, using the Iolite data reduction program (Paton *et al.*, 2011) combined with VisualAge to obtain ages and ratios corrected for instrumental drift and down-hole fractionation.

PETROGRAPHY OF THE GRANITIC XENOLITHS

The granitic xenolith (GJ-12) was found into a thin section from the dyke. The xenolith is rounded, ellipsoidal, 2.0×1.5 cm in size, with equigranular texture and composed of exceptionally fresh plagioclase, K feldspar, biotite and quartz (Fig. 2). The plagioclase is oligoclase displaying slight compositional variations with An_{24.2–26.1} and Or_{5.9–11.6}. The potassium feldspar is Or_{69.5} with little Cn_{0.6} component. The biotite is Fe-rich, with Mg# 54.4–57.7. Silicate melt inclusions (MI), sized between 30 µm and 80 µm, occur in plagioclase and quartz crystals (Fig. 2a). The composition of the minerals is shown in Tables 1, 2. Contacts with the host lavas are diffuse, with some host melt penetrated between the minerals (Fig. 2b). Accessory minerals are zircon, apatite and monazite.

The penetrated host basalt melt forms some brown glass between the crystals or pools consisting of corroded biotite crystals and individualized fine-grained mass of feldspars, orthopyroxene Mg#62.9 and fine magnetite and ilmenite (Fig. 2c, d). The plagioclase microlites from the reaction zones are more Ca-rich (An₃₅) compared to those in the xenolith. The composition of the reaction minerals is given in Table 3.

MELT INCLUSION CHEMISTRY AND CONDITIONS OF CRYSTALLIZATION

Due to the small size of the xenolith, chemical analyses for major and trace elements from the two xenoliths are not made. However, based on their modal mineralogy, they can be determined as granitic. This is confirmed by the chemical composition of a trapped MI into the quartz crystals in the xenolith, which is considered to better approximate the real composition of the magma. The microprobe analyses (Table 4) of the MI gave SiO₂ content of 75.13 wt.%, and Na₂O and K₂O of 2.06 wt.% and

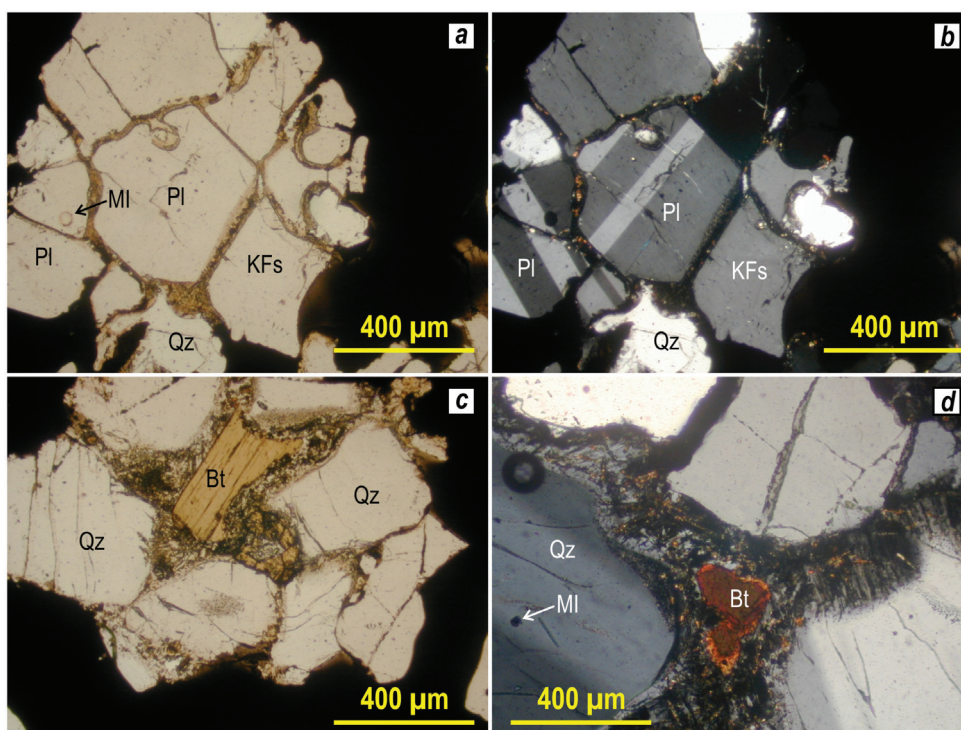


Fig. 2. Photomicrographs of the studied granitic xenoliths: a) grains surrounded by rims of brown glass (arrows) and MI in Pl (plane-polarized light); b) same as a (cross-polarized light); c) crystallized melt and reaction around Bt converted into Pl microlites, Qz and Kfs, and grains of Cpx? (plane-polarized light); d) similar situation with MI in Qz (cross-polarized light). Abbreviations: Pl – plagioclase, Kfs – potassium feldspar, Qz – quartz, Bt – biotite, MI – melt inclusion, Cpx – clinopyroxene.

Table 1
Microprobe composition of plagioclase in the granite xenolith GJ-12

	I-4	II-1	II-2	III-1	5-1	p.1	5-2
SiO ₂	62.87	62.44	61.58	62.72	60.36	62.96	65.71
TiO ₂	0.05	0.00	0.00	0.03	bdl	0.02	bdl
Al ₂ O ₃	23.22	23.30	23.04	23.00	24.17	23.68	20.05
FeO	0.14	0.17	0.21	0.21	bdl	0.30	bdl
CaO	4.98	5.01	5.31	5.06	5.24	5.22	bdl
Na ₂ O	7.89	8.03	6.99	7.78	7.73	7.29	3.26
K ₂ O	1.10	1.11	1.98	1.11	1.01	1.29	11.52
BaO							0.34
Total	100.27	100.07	99.11	99.90	98.51	100.76	100.88
Si	2.784	2.774	2.771	2.788	2.725	2.774	2.961
Ti	0.002	0.000	0.000	0.001	0.000	0.001	0.000
Al	1.212	1.220	1.222	1.205	1.286	1.230	1.065
Fe	0.005	0.006	0.008	0.008	0.000	0.011	0.000
Ca	0.236	0.239	0.256	0.241	0.253	0.246	0.000
Na	0.677	0.691	0.610	0.671	0.677	0.623	0.285
K	0.062	0.063	0.114	0.063	0.058	0.073	0.662
Ba	0.000	0.000	0.000	0.000	0.000	0.000	0.006
An	24.2	24.0	26.1	24.7	25.6	26.2	0.0
Ab	69.4	69.6	62.3	68.8	68.5	66.1	29.9
Or	6.4	6.4	11.6	6.4	5.9	7.7	69.5
Cn	0.0	0.0	0.0	0.0	0.0	0.0	0.6

5.04 wt.%, respectively. Analyses show a total of 94.99, suggesting ~5 % water, which can be interpreted to represent dissolved H₂O content of the melt at the time of quenching (see Sisson and Layne, 1993). This quantity of water would be saturated at lithostatic pressures of 1.8–2.7 kbar (6–9 km) (program of Holloway and Blank, 1994). Trace elements of the glass are low, with only slightly higher contents of Rb (130 ppm), Ba (24.5 ppm), Zr (33.6 ppm) and Pb (6 ppm).

ZIRCON AND MONAZITE INTERNAL STRUCTURE AND AGES

Studied zircon and monazite grains are small, 30 µm to 65 µm in size. CL images of three of all

Table 2
Microprobe composition of biotite in the granite xenolith GJ-12

	center	center	rim	
SiO ₂	38.01	37.91	38.62	37.31
TiO ₂	4.48	4.20	4.09	4.33
Al ₂ O ₃	13.67	13.45	13.26	13.59
Cr ₂ O ₃	0.02	0.00	0.00	0.04
FeO	17.85	17.66	17.74	18.89
MnO	0.51	0.52	0.50	0.49
MgO	12.78	12.85	13.55	12.66
CaO	0.01	0.01	0.12	0.06
Na ₂ O	0.54	0.63	0.70	0.57
K ₂ O	9.26	9.28	8.64	9.96
SrO				0.08
F				0.08
Cl				0.12
Total	97.13	96.51	97.22	99.02
O=F,Cl	0.00	0.00	0.00	0.06
Si	5.659	5.680	5.717	5.572
Al IV	2.341	2.320	2.283	2.392
Al VI	0.056	0.056	0.031	0.000
Ti	0.501	0.474	0.455	0.486
Cr	0.003	0.000	0.000	0.005
Fe	2.222	2.213	2.196	2.359
Mn	0.064	0.066	0.062	0.062
Mg	2.835	2.871	2.991	2.818
Ca	0.001	0.001	0.020	0.010
Na	0.156	0.182	0.200	0.165
K	1.759	1.774	1.631	1.897
Sr	0.000	0.000	0.000	0.007
F	0.000	0.000	0.000	0.038
Cl	0.000	0.000	0.000	0.030
Mg#	56.1	56.5	57.7	54.4

four studied zircons are shown in Fig. 3. The zircons show a core–rim structure. Two of the zircons are characterized by oscillatory or irregular white and dark domains with white outer rim (Fig. 3a, b). One zircon has an irregular dark inner core surrounded by white outer rim (Fig. 3c). The dark core zones (position 4-2 and 4-4) differ in having about 1.5 wt.% U (Table 5). Monazite shows almost imperceptible variations in the color of BSE image (Fig. 3d), which is reflected in its almost constant composition (Table 5).

The four zircon grains from the xenolith were analyzed by six points (Table 6). Three nearly concordant to slightly discordant spots from grains 1, 2 and 3 yielded Late Triassic–Early Jurassic ²⁰⁶Pb/²³⁸U ages between 198±10 Ma and 207±8 Ma (all error uncertainties reported as 2σ). A second spot of grain 2 was dated at 157±10 Ma. The core and rim spots of grain 3 gave Ediacaran (606 ±19 Ma) and Permian ²⁰⁶Pb/²³⁸U ages (277±16 Ma), respectively. The monazite crystal yielded two concordant to slightly discordant Chattian ages of 28.8±1.3 Ma and 27.6±1.8 Ma.

DISCUSSION

Based on the data obtained in this study, we will discuss several issues: (i) the reaction of the zircon and the monazite on the temperature of the host alkaline magma; (ii) the age of the alkaline basalts obtained from monazite; and (iii) possible significance of the granitic xenolith for the granitoid magmatism in the Eastern Rhodopes.

Inferences from the closing temperatures and resetting of the monazite and the zircon

Based on the obtained ages from the monazite and zircons in the xenolith, we can draw some conclusions about the behavior of the two minerals in the host alkaline magma and the conditions of their crystallization. Monazite and zircon are two minerals that are commonly employed in geochronology to study geological history (Ayers *et al.*, 2002). Both minerals have high closing temperature (>900 °C). However, the different ages of monazite and zircon in the xenolith suggest different reactions to the host alkaline melt. The temperature of the host magma is calculated at ~1000 °C. Apparently, the zircon behaved stable at these conditions, whereas the monazite was completely reset. This cannot be due to the size of the crystals because they have approximately the same size (~30–60 µm). Some low-temperature

Table 3
Microprobe composition of minerals in the reaction zone

	plagioclase		magnetite	ilmenite	orthopyroxene		
SiO ₂	59.84	60.05	0.13	0.18	51.73		
TiO ₂	0.07	0.16	5.99	48.5	0.58		
Al ₂ O ₃	25.42	25.33	1.61	0.07	2.06		
Cr ₂ O ₃	0.04	0.02	0.15	0.07	0.00		
FeO	0.29	0.48	84.89	45.92	22.65		
MnO	0.01	0.00	0.27	0.84	0.74		
MgO	0.09	0.03	1.55	1.46	21.57		
CaO	7.00	7.00	0.01	0.07	1.20		
Na ₂ O	6.19	5.98			0.05		
K ₂ O	1.49	1.59			0.04		
Total	100.44	100.64	94.66	97.26	100.62		
Si	2.665	2.670	0.005	0.005	1.921		
Ti	0.002	0.005	0.169	0.934	0.016		
Al	1.334	1.328	0.071	0.002	0.090		
Fe ³⁺			1.578	0.120	0.039		
Fe ²⁺	0.011	0.018	1.078	0.862	0.665		
Mn	0.000	0.000	0.009	0.018	0.023		
Mg	0.006	0.002	0.086	0.056	1.194		
Ca	0.334	0.334	0.000	0.002	0.048		
Na	0.535	0.516	0.000	0.000	0.004		
K	0.085	0.090	0.000	0.000	0.000		
Cr	0.001	0.001	0.004	0.001	0.000		
An	35.0	35.5	Ulvöspinel	2.248	Wo	2.43	
Ab	56.1	54.9	Ilmenite		1.537	En	60.66
Or	8.9	9.6				Fs	36.92
			Fe ₂ O ₃	56.05	6.24	Mg#	62.9
			FeO	34.46	40.30		
			Total	100.22	97.74		

Table 4
Microprobe and LA-ICP-MS composition of the melt inclusion in quartz in the granite xenolith

Major elements				Trace elements			
SiO ₂	75.13	Sc	16.8	Ba	24.46	Ho	0.043
TiO ₂	0.03	V	2.94	La	1.77	Er	0.142
Al ₂ O ₃	11.78	Cu	4.38	Ce	2.75	Tm	0.037
FeO*	0.18	Ga	5.37	Pr	0.293	Yb	0.34
MnO	0.00	Rb	130	Nd	0.84	Lu	<0.049
MgO	0.00	Sr	25.87	Sm	<0.39	Hf	0.81
CaO	0.38	Y	1.50	Eu	0.105	Ta	<0.039
Na ₂ O	2.06	Zr	33.58	Gd	<0.46	Pb	5.99
K ₂ O	5.44	Nb	0.62	Tb	<0.044	Th	0.376
Total	94.99	Cs	2.23	Dy	0.26	U	0.144

processes, such as post-metamorphic recrystallisation and/or Pb-loss during fluid circulations, are able to reset monazite even at low (<450 °C) temperature (Crowley and Ghent, 1999; Vavra and Schaltegger, 1999; Townsend *et al.*, 2000). However, the studied xenolith was transported entrained in the hot alkaline basaltic magma, and we suggest a reset as a result of a combined influence of the high temperature and fluid circulation around the mona-

zite grain (Fig. 3d). Compared to monazite, zircon is less reactive and manages to preserve geological history, as suggested by Rubatto *et al.* (2013).

Comparison of monazite U-Pb ages with the bulk rock K/Ar ages

Four dykes from the Krumovgrad alkaline basalts have been dated previously by Marchev *et al.*

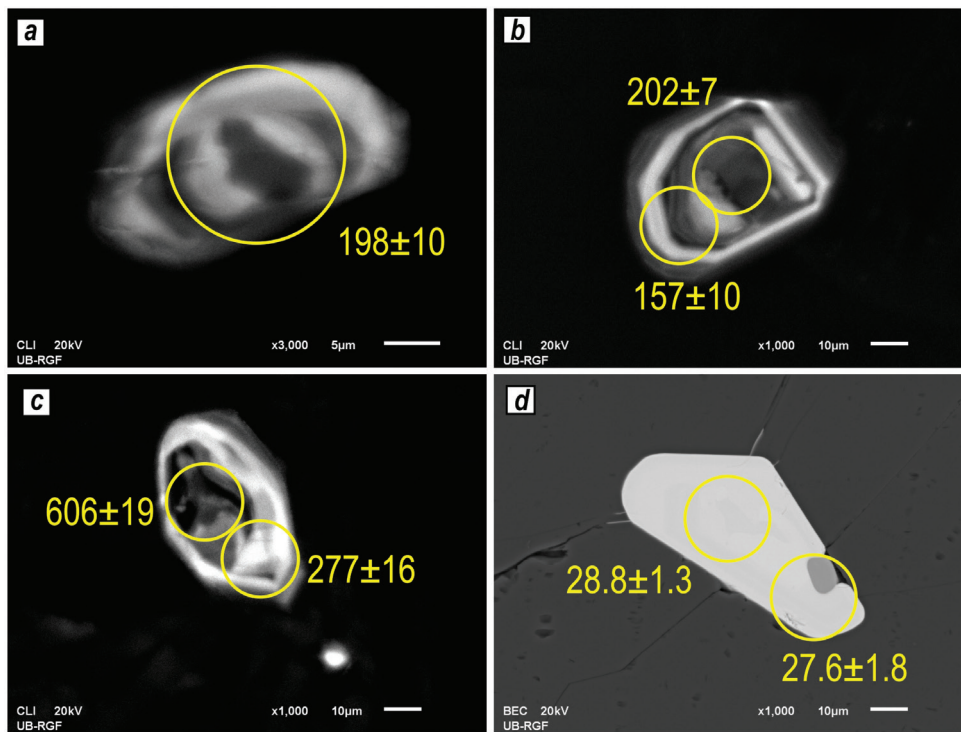


Fig. 3. a–c) CL images showing textures observed in zircons from the Gorni Yurutsi granite sample GJ-12; d) BSE image of dated monazite. Corresponding U/Pb ages are shown in Table 6.

Table 5
Microprobe composition of the dated zircons and monazite

mineral		zircon										monazite				
position	1-4	2-1	2-2	2-3	3-1	3-2	4-1	4-2	4-3	4-4		1-1	1-2	1-3	5-3	
SiO ₂	33.21	33.12	33.37	33.95	32.81	33.80	33.34	32.66	33.90	33.04	SiO ₂	1.24	2.19	1.73		
ZrO ₂	66.00	62.70	65.17	66.21	66.09	65.41	65.20	62.50	65.23	63.17	P ₂ O ₅	29.87	27.61	28.46	28.32	
HfO ₂	1.46	2.46	2.81	2.15		1.96	2.47	1.88	2.11	2.55	CaO	1.10	0.61	0.87	0.92	
Fe ₂ O ₃										0.48	La ₂ O ₃	12.30	12.27	14.85	15.54	
UO ₂		0.70						1.46		1.41	Ce ₂ O ₃	27.33	28.39	30.00	28.66	
ThO ₂		0.74									Nd ₂ O ₃	10.91	12.07	9.47	10.21	
											ThO ₂	9.72	11.74	10.58	3.27	
Total	100.67	99.72	101.35	102.31	98.90	101.17	101.01	98.50	101.24	100.65	Total	92.47	94.88	95.96	86.92	

Table 6

LA-ICP-MS isotopic ratios ($^{206}\text{Pb}/^{238}\text{U}$, $^{207}\text{Pb}/^{235}\text{U}$, $^{207}\text{Pb}/^{206}\text{Pb}$, $^{208}\text{Pb}/^{232}\text{Th}$), $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{235}\text{U}$ ages of zircons and monazites, and estimated uranium and thorium content of studied zircons

#	analyzed grain	Isotopic ratio									Age [Ma]				Composition [ppm]		Ratio
		$^{207}\text{Pb}/^{235}\text{U}$	2σ	$^{206}\text{Pb}/^{238}\text{U}$	2σ	Error Corr	$^{207}\text{Pb}/^{206}\text{Pb}$	2σ	$^{208}\text{Pb}/^{232}\text{Th}$	2σ	$^{207}\text{Pb}/^{235}\text{U}$	2σ	$^{206}\text{Pb}/^{238}\text{U}$	2σ	$\approx\text{U}$	$\approx\text{Th}$	
1	zr_gr.1	0.238	0.055	0.0313	0.0016	0.113	0.063	0.017	0.0157	0.0058	197	45	198	10	472	35	0.07
2	zr_gr.2-1	0.228	0.027	0.0318	0.0012	0.219	0.054	0.006	0.0390	0.0160	204	22	202	7	1770	120	0.07
3	zr_gr.2-2	0.172	0.031	0.0247	0.0015	0.222	0.055	0.010	0.0440	0.0120	156	27	157	10	819	94	0.11
4	zr_gr.3core	0.874	0.080	0.0988	0.0033	0.179	0.064	0.006	0.0610	0.0110	602	42	606	19	582	519	0.89
5	zr_gr.3rim/mix	0.354	0.046	0.0440	0.0026	0.307	0.061	0.008	0.1720	0.0540	297	34	277	16	1009	229	0.23
6	zr_gr.4	0.272	0.025	0.0326	0.0013	0.135	0.060	0.006	0.0076	0.0008	239	20	207	8	1151	226	0.20
7	mz_gr.1-1	0.032	0.005	0.0045	0.0002	0.114	0.058	0.010	0.0017	0.00210	31.9	4.9	28.8	1.3			
8	mz_gr.1-2	0.041	0.009	0.0043	0.0003	0.308	0.065	0.014	0.0008	0.00003	39.3	8.4	27.6	1.8			

(1997), using K/Ar method on bulk rocks samples. The ages obtained (26.1 ± 1.7 Ma, 26.4 ± 2.2 Ma, 27.3 ± 1.3 Ma and 27.9 ± 0.8 Ma) show that the dykes are intruded in the age interval of 26–28 Ma. The Gorni Yurutsi dyke was not dated in the latter study; however, the monazite $\text{Pb}^{206}/\text{U}^{238}$ ages (27.6 ± 1.8 Ma and 28.8 ± 1.3 Ma) from the granite xenolith perfectly coincide with the previous K/Ar ages. Thus, the old and newly obtained ages, falling in the range of 26–28.8 Ma, confirm the latest Rupelian–earliest Chattian age of the Rhodope alkaline volcanism.

Comparison with the Eastern Rhodope basement rocks and granites

Obtained Ediacaran (606 ± 19 Ma) and Permian (277 ± 16 Ma) core and rim spot ages of one of the zircons coincide with the published ages for the basement metagranitic rocks from the Lower high-grade unit of the Kesebir and Byala Reka domes (Cornelius, 2008; Bonev *et al.*, 2013). The slightly discordant ages of ~ 200 Ma zircons fall outside of the range of published 251.4 ± 6.8 Ma and 236 ± 8 Ma Triassic ages from the deformed felsic gneisses from the nearby Kesebir–Kardamos (Drakoulis *et al.*, 2013; Marchev *et al.*, 2019) dome, which raises the question if this is a real age or the result of Pb-loss and mixed ages. The youngest measured age among the zircons is the 157 ± 10 Ma Jurassic age of the outer zircon 3 zone. The age is concordant, and it seems the most possible age of the granite xenolith.

Jurassic ages of orthogneisses were reported in the Central Rhodopes by Ovtcharova *et al.* (2004) and Turpaud and Reischmann (2010). Several Jurassic orthogneisses have also been dated in the Upper high-grade unit, not far from the Gorthi Yurutsi alkaline dyke. The age of these orthogneisses fall in the interval 150–160 Ma (Cornelius, 2008; Bonev *et al.*, 2015). However, unlike the studied xenolith, most of them are strongly deformed and contain muscovite. Less deformed and with age similar to the xenolith's are some orthogneisses from the Central Rhodopes, described by Turpaud and Reischmann (2010). Similarly to the zircons from the xenolith, these zircons usually have older inherited cores. Limited isotopic data of these rocks (Cornelius, 2008) show crustal affinity in a volcanic-arc geological setting. The genesis of the studied granite xenolith is out of the scope of this study mostly because of its small size, which does not allow extended studies. Nevertheless, based on their age similarity with the metagranites, we assume a similar genesis.

CONCLUSIONS

1. U/Pb ages obtained from the zircons in the studied xenolith show a range of ages, which coincide with the published ages for the basement metagranitic rocks from the high-grade units of the Kesebir and Byala Reka domes.
2. The most probable age of the granite xenolith inferred from the youngest zircon is Jurassic. The

Ediacaran and Early Permian ages of the inherited zircon in the xenolith indicate the involvement of the older crustal rocks in their genesis.

3. The finds of nondeformed xenoliths in the KABL show that such Jurassic granites may exist at depth beneath the Byala Reka metamorphic dome.
4. The new ages obtained from the monazite in the xenoliths of the Gorni Yurutsi alkaline basalt dyke fall in the range of the K/Ar ages of the earlier dated alkaline basalts (26–28 Ma) and

confirm the approximately contemporaneous intrusion of all Krumovgrad alkaline basalts in latest Rupelian–earliest Chattian times.

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REFERENCES

- Ayers, J.C., Dunkle, S., Gao, S., Miller, C.F. 2002. Constraints on timing of peak and retrograde metamorphism in the Dabie Shan ultrahigh-pressure metamorphic belt, east-central China, using U–Th–Pb dating of zircon and monazite. *Chemical Geology* 186 (3–4), 315–331, [https://doi.org/10.1016/S0009-2541\(02\)00008-6](https://doi.org/10.1016/S0009-2541(02)00008-6).
- Bonev, N., Burg, J.-P., 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, 318–340, <https://doi.org/10.1007/s00531-005-0025-y>.
- Bonev, N., Dotseva, Z., Filipov, P. 2023. Geochemistry and tectonic significance of metamorphosed mafic ophiolitic rocks in the upper high-grade basement unit of the eastern Rhodope Massif (Bulgaria–Greece). *Geologica Carpathica* 74 (1), 23–39, <https://doi.org/10.31577/GeolCarp.2023.05>.
- Bonev, N., Marchev, P., Moritz, R., Collings, D. 2015. Jurassic subduction zone tectonics of the Rhodope Massif in the Thrace region (NE Greece) as revealed by new U–Pb and $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology of the Evros ophiolite and high-grade basement rocks. *Gondwana Research* 27 (2), 760–775, <https://doi.org/10.1016/j.gr.2014.08.008>.
- Bonev, N., Ovtcharova-Schaltegger, M., Moritz, R., Marchev, P., 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 (3–4), 207–229, <https://doi.org/10.1080/09853111.2013.858942>.
- Burg, J.-P., Ricou, L.-E., Ivanov, Z., Godfriaux, I., Dimov, D., Klain, L. 1996. Syn-metamorphic nappe complex in the Rhodope Massif. Structure and kinematics. *Terra Nova* 8 (1), 6–15, <https://doi.org/10.1111/j.1365-3121.1996.tb00720.x>.
- Cornelius, N.K. 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, 173 pp.
- Crowley, J.L., Ghent, E.D. 1999. An electron microprobe study of the U–Th–Pb systematics of metamorphosed monazite: the role of Pb diffusion versus overgrowth and recrystallization. *Chemical Geology* 157 (3–4), 285–302, [https://doi.org/10.1016/S0009-2541\(99\)00009-1](https://doi.org/10.1016/S0009-2541(99)00009-1).
- Drakoulis, A., Koroneos, A., Poli, G., Soldatos, T., Papadopoulos, L., Murata, M., Eliwa, H. 2013. U–Pb zircon dating of the Mt. Papikion pluton (Central Rhodope, Greece): New constraints on the evolution of Kesebir-Kardamos Dome. *Acta Vulcanologica* 25 (1–2), 83–98.
- Jackson, S.E., Pearson, N.J., Griffin, W.L., Belousova, E.A. 2004. The application of laser ablation-inductively coupled plasma-mass spectrometry to in situ U–Pb zircon geochronology. *Chemical Geology* 211 (1–2), 47–69, <https://doi.org/10.1016/j.chemgeo.2004.06.017>.
- Holloway, J., Blank, J. 1994. Application of experimental results to C–O–H species in natural melts. In: Carroll, M.R., Holloway, J.R. (Eds), *Volatiles in Magmas. Reviews in Mineralogy and Geochemistry* 30, 187–230, <https://doi.org/10.1515/9781501509674-012>.
- Marchev, P. 1993. Metamorphic granulitic xenolith and xenocrysts from Voneshta Voda, Stara Planina. *Geologica Balcanica* 23 (3), 44, <https://doi.org/10.52321/Geol-Balc.23.3.44>.
- Marchev, P., Arai, S., Ishida, Y., Shirasaka, M., Downes, H. 2008. Trace element and isotopic composition of mafic and ultramafic cumulate xenoliths in alkaline basalts from the Eastern Rhodopes, Bulgaria: Inferences on deep processes under the metamorphic core complexes. *IOP Conference Series: Earth and Environmental Science* 2, 012015, <https://doi.org/10.1088/1755-1307/2/1/012015>.
- Marchev, P., Arai, S., Vaselli, O. 2006. Cumulate xenoliths in Oligocene alkaline basaltic and lamprophyric dykes from the eastern Rhodopes, Bulgaria: Evidence for the existence of layered plutons under the metamorphic core-complexes. In: Dilek, Y., Pavlides, S. (Eds), *Post-Collisional Tectonics & Magmatism in the Eastern Mediterranean Region*. Geological Society of America Special Paper 409, 237–258, [https://doi.org/10.1130/2006.2409\(13\)](https://doi.org/10.1130/2006.2409(13)).
- Marchev, P., Arai, S., Vaselli, O., Costa, F., Zanetti, A., Downes, H. 2017. Metasomatic Reaction Phenomena from Entrainment to Surface Cooling: Evidence from Mantle Peridotite Xenoliths from Bulgaria. *Journal of Petrology* 58 (3), 599–640, <https://doi.org/10.1093/petrology/egx028>.
- Marchev, P., Georgiev, S., Raicheva, R., Ichev, M. 2019. 250 Ma metagranitoid from Drangovo Village: a new discovery of Permo-Triassic magmatism in the Eastern Rhodopes,

- Bulgaria. *Geologica Balcanica* 48 (1), 63–71, <https://doi.org/10.52321/GeolBalc.48.1.63>.
- Marchev, P., Harkovska, A., Pecskey, Z., Vaselli, O., Downes, H. 1997. Nature and age of the alkaline basaltic magmatism southeast of Krumovgrad, SE-Bulgaria. *Comptes rendus de l'Académie bulgare des Sciences* 50 (4), 77–80.
- Marchev, P., Raicheva, R., Downes, H., Vaselli, O., Chiaradia, M., Moritz, R. 2004. Compositional diversity of Eocene-Oligocene basaltic magmatism in the Eastern Rhodopes, SE Bulgaria: implications for genesis and tectonic setting. *Tectonophysics* 393 (1–4), 301–328, <https://doi.org/10.1016/j.tecto.2004.07.045>.
- Marchev, P., Saltikovski, A., Yanev, Y., Daieva, L., Genshaft, J. 1992. Petrology of the Neogene alkali basalts and included ultramafic xenoliths of the Moesian Platform, North Bulgaria. *Neues Jahrbuch für Mineralogie, Abhandlungen* 164 (2–3), 113–137.
- Marchev, P., Vaselli, O., Downes, H., Pinarelli, L., Ingram, G., Rogers, G., Raicheva, R. 1998. Petrology and geochemistry of alkaline basalts and lamprophyres: implications for the chemical composition of the upper mantle beneath the Eastern Rhodopes (Bulgaria). In: Christofides, G., Marchev, P., Serri, G. (Eds), *Tertiary Magmatism of the Rhodopian Region*. *Acta Vulcanologica* 10 (2), 233–242.
- Mavroudchiev, B. 1964. Petrology of basaltic magmatism in the Krumovgrad area. *Annuaire de l'Université de Sofia, Faculté de Géologie et Géographie* 57, 295–324.
- Ovtcharova, M., von Quadt, A., Cherneva, Z., Sarov, S., Heinrich, C., Peytcheva, I. 2004. U–Pb dating of zircon and monazite from granitoids and migmatites in the core and eastern periphery of the Central Rhodopean Dome, Bulgaria. *Geochimica et Cosmochimica Acta* 68 (11), A664.
- Paton, C., Hellstrom, J., Paul, B., Woodhead, J., Hergt, J. 2011. Iolite: Freeware for the visualisation and processing of mass spectrometric data. *Journal of Analytical Atomic Spectrometry* 26, 2508–2518, <https://doi.org/10.1039/c1ja10172b>.
- Rock, N.M.S. 1987. The nature and origin of lamprophyres: an overview. In: Fitton, J.G., Upton, B.G.J. (Eds), *Alkaline Igneous Rocks*. Geological Society, London, Special Publications 30, 191–226, <https://doi.org/10.1144/GSL.SP.1987.030.01.09>.
- Rubatto, D., Chakraborty, S., Dasgupta, S. 2013. Timescales of crustal melting in the Higher Himalayan Crystallines (Sikkim, Eastern Himalaya) inferred from trace element-constrained monazite and zircon chronology. *Contributions to Mineralogy and Petrology* 165, 349–372, <https://doi.org/10.1007/s00410-012-0812-y>.
- Sisson, T.W., Layne, G.D. 1993. H₂O in basalt and basaltic andesite glass inclusions from four subduction-related volcanoes. *Earth and Planetary Science Letters* 117 (3–4), 619–635, [https://doi.org/10.1016/0012-821X\(93\)90107-K](https://doi.org/10.1016/0012-821X(93)90107-K).
- Sláma, J., Košler, J., Condon, D.J., Crowley, J.L., Gerdes, A., Hanchar, J.M., Horstwood, M.S.A., Morris, G.A., Nasdala, L., Norberg, N., Schaltegger, U., Schoene, B., Tubrett, M.N., Whitehouse, M.J. 2008. Plešovice zircon – A new natural reference material for U–Pb and Hf isotopic microanalysis. *Chemical Geology* 249 (1–2), 1–35, <https://doi.org/10.1016/j.chemgeo.2007.11.005>.
- Townsend, K.J., Miller, C.F., D'Andrea, J.L., Ayers, J.C., Harrison, T.M., Coath, C.D. 2000. Low temperature replacement of monazite in the Ireteba granite, Southern Nevada: geochronological implications. *Chemical Geology* 172 (1–2), 95–112, [https://doi.org/10.1016/S0009-2541\(00\)00238-2](https://doi.org/10.1016/S0009-2541(00)00238-2).
- Turpaud, P., 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, 567–591, <https://doi.org/10.1007/s00531-008-0409-x>.
- Vavra, G., Schaltegger, U. 1999. Post granulite facies monazite growth and rejuvenation during Permian to Lower Jurassic thermal and fluid events in the Ivrea Zone (Southern Alps). *Contributions to Mineralogy and Petrology* 134, 405–414, <https://doi.org/10.1007/s004100050493>.