Ofioliti, 2016, 41 (2), 75-84 - doi: 10.4454/ofioliti.v41i2.443

TIMING OF LOWER CRUST GENERATION IN THE VOYKAR OPHIOLITE MASSIF, POLAR URALS, RUSSIA: U-Pb (LA-ICP-MS) DATA FROM PLAGIOGRANITE ZIRCONS

Gláucia Queiroga*,✉, Maximiliano Martins*, Nikolay Kuznetsov, Farid Chemale Jr. ***, Ivo Dussin°, Antônio Carlos Pedrosa-Soares°, Ksenia Kulikova°°** and **Marco Paulo de Castro***

* *DEGEO/EM, Federal University of Ouro Preto, Brazil.*
** *Geological Institute, Russian Academy of Science, Moscow, Russia.*
*** *Vale do Rio dos Sinos University, São Leopoldo, Brazil.*
° *CPMTC/IGC, Federal University of Minas Gerais, Belo Horizonte, Brazil.*
°° *Institute of Geology, Komi Scientific Center, Russian Academy of Science, Syktvykar, Russia.*
✉ *Corresponding author, e-mail: glauciaqueiroga@yahoo.com.br*

Keywords: *U-Pb geochronology, ophiolite, Voykar Massif, Polar Urals.*

ABSTRACT

The Uralide Orogen is one of the main Paleozoic belts formed during the assembly of Pangea. The present-day Urals (Uralian Mountains, N-S-trending through northern Eurasia) expose the relicts of this Paleozoic orogen. The Voykar Massif, located at the Polar Urals, is an ophiolite assemblage composed mainly of mantle tectonite, gabbroic to ultramafic plutonic sequence and sheeted dikes with a MORB-type source. Geochronological data for this region show a wide range of ages and are mainly based on U-Pb zircon data, although some Rb-Sr and Sm-Nd are available. We present high-resolution U-Pb (LA-ICP-MS) analyses performed on zircon crystals extracted from a plagiogranite vein associated with a porphyritic dolerite dike. Magmatic zircon grains yielded a U-Pb age of 428.1±7.4 Ma, corresponding to the Wenlock Period (middle Silurian). This age suggests a late stage of oceanic crust generation in the Voykar basin. Different ages from plagiogranite and gabbroic bodies suggest that oceanic spreading lasted from ca. 490 to 425 Ma, i.e., at least 65 Ma or even longer, in the Voykar basin.

INTRODUCTION

The northern part of Wegener's Pangea was formed as a result of several large Precambrian and early Paleozoic paleocontinents assembly: Baltica, Laurentia, Siberia, Arctida, Kazakh-Kyrgyz and smaller terranes of different origins (e.g., micro-continents, oceanic arcs, fragments of oceanic basins) (see review in Kuznetsov et al., 2007; 2010 and references therein). These smaller terranes are involved in Phanerozoic orogenic belts that lie between the more ancient cratonic shields and along their edges (see the first plate tectonic reconstructions for the Uralian region in Zonenshain et al., 1984; 1990; Sengör et al., 1993, and the most recent ones in Stampfli and Borel, 2002 and Lawver et al., 2002). The late Paleozoic Uralide Orogen is part of a Paleozoic fold-thrust belt that was formed during the final stage of assembly of N-Pangea when the Arct-Laurussia (Arctida + Baltica + Laurentia), Siberia and Kazakh-Kyrgyz paleocontinents were sutured.

The present-day Ural Mountains, the Urals, took the form of a north-south-trending mountain range in the late Paleozoic Uralide Orogen. The Urals expose late Cambrian to late Paleozoic rocks that collectively form the Uralides. Older complexes that crop out in and west of the Urals are collectively defined as the Pre-Uralides. The Pre-Uralides are separated from the Uralides by a tectonic contact. This subdivision was firstly proposed by Kheraskov (1948).

The Main Uralian Fault (MUF) or Uralian Suture subdivides the Urals into the Eastern-Uralian and Western-Uralian megazones (Fig. 1). The eastern Uralides mostly consist of Paleozoic ophiolites and volcanic island-arc complexes and are generally thought to be allochthonous with respect to the East European Craton (Baltica). The Western-Uralian megazone contains both the Uralides and the Pre-Uralides. Across the strike, the Urals are subdivided into the Southern, Northern and Polar segments (Kuznetsov et al., 2010) (Fig. 1B).

Many geological aspects of the Southern and Northern segments of the Urals (e.g., relations of individual sequences at different scales and their biostratigraphic and isotopic-geochronological characteristics) are presently well understood, allowing many stages and events in the geodynamical history of those segments to be reconstrained (see the review articles by Puchkov, 1993; 1997; 2000; 2003; Brown et al., 1996, 2006; 2011; Ivanov, 1998; Alvarez-Marron, 2002; Chaplygina et al., 2002; Savelieva et al., 2002; Ruzhentsev and Samygin, 2004; Desyatnichenko et al., 2005; Fershtater et al., 2007; 2010; Ryazantsev et al., 2008). In contrast, the geology of the Polar segment of the Urals (Polar Urals) is poorly known (Voinovsky-Kriger, 1945; 1966; 1967; Puchkov, 1979; Savelieva, 1987; Dembovsky et al., 1990; Dushin, 1997; Aristov and Ruzhentsev, 1998; Scarrow et al., 2002; Shishkin et al., 2004) mainly due to their poor accessibility. As a result, many key problems of the geology, stratigraphy and geochronology of the Polar Urals remain unresolved.

Although the Uralides have been extensively overprinted by post-orogenic processes (see a review in Puchkov, 2000 and references therein) and by the flood basalts of the Siberian superplume (Permo-Triassic boundary, Reichow et al., 2009), many petrotectonic assemblages are well preserved, including the Voykar Massif, which is one of the main tectonic units of the Polar Urals (Fig. 1). The Voykar is an ophiolite assemblage mainly composed of mantle tectonite, gabbro-ultramafic plutonic rocks and a sheeted dike complex. In this paper, in situ U-Pb measurements (LA-MC-ICPMS) for

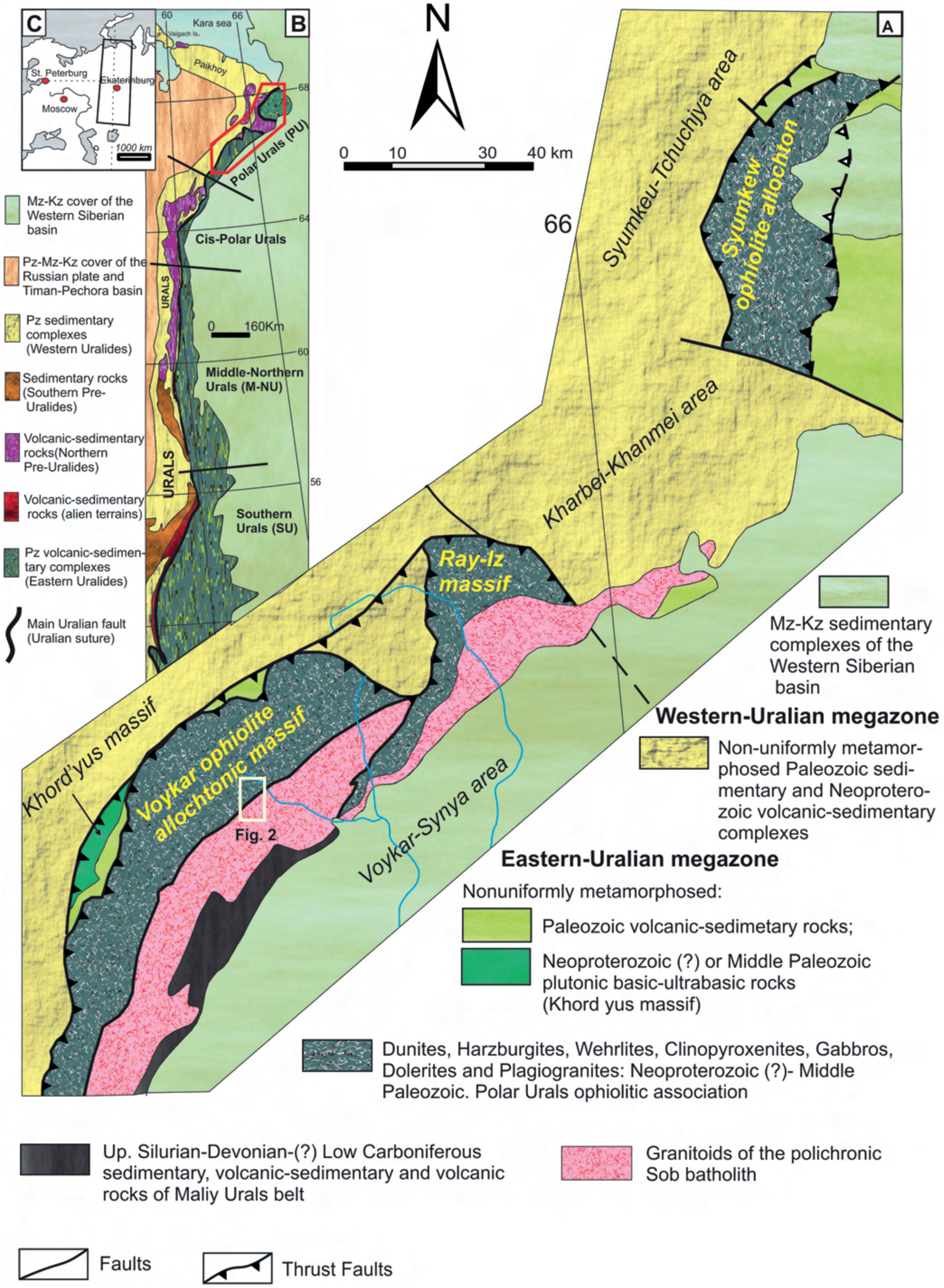

Fig. 1 - Geological scheme of the Polar Urals showing the sampling locality within the Voykar Massif (A) and index schemes (B, C) (based on Udoratina et al., 2008 and Kuznetsov et al., 2010).

a plagiogranite vein associated with dolerites were carried out in order to constrain the magmatic age of the Voykar Massif. Together with previously published data, the new results allow us to constrain the age of the generation of oceanic crust in the Voykar basin.

GEOLOGICAL SETTING

The Voykar Massif is located in the Eastern-Uralian megazone of the Polar Urals (Fig. 1) and belongs to the Uralides. The Uralides in this megazone are represented by a collage, including allochthonous mafic-ultramafic complexes (*Khord'yus, Voykar, Rai-Iz,* and *Syumkeu Massifs*) forming the largest mafic-ultramafic belt in the world (approximately 400 km long). The Eastern-Uralian megazone at the Polar Urals is divided into two main zones (from southwest to northwest): *(1)* the *Maliy Urals* volcanic-plutonic belt and *(2)* the *Voykar Massif*. The Maliy Urals are represented by a volcanic island-arc (VIA). A vast granitoid complex, the Sob' batholith, is located in the western/northwestern part of the belt. The Sob' batholith is composed of tonalites, trondhjemites and granodiorites dated at 408-390 Ma (Udoratina et al., 2005; 2008; 2014; Udoratina and Kuznetsov, 2007). The Sob' complex is intruded by a few elongated or isometric bodies of biotite granites and leucogranites of the Middle Devonian Yanaslor complex, dated at *ca*. 380 Ma (Udoratina and Kuznetsov, 2007, Fig. 2). Eastward to the Sob' batholith, the Maliy Urals volcanic-plutonic belt is composed of volcanic, volcanic-sedimentary and carbonatic rocks of the late Silurian (Ludlow and Pridoli), Devonian and early Missisippian (Tournasian, Early Carboniferous; Lupanov and Markin, 1964; Yazeva and Bochkarev, 1984; Didenko et al., 2001, and others).

The Voykar Massif, composed mainly of ophiolitic rocks, occurs within large allochthonous complexes of an oceanic and island-arc lithosphere that is up to 200 km long, approximately 20-30 km wide and more than 4 km thick. All this system, including the ophiolites and the overlying and intruding island-arc complexes, were thrust over by the continental margin of the East European Plate in the middle-late Paleozoic due to the closure of the Uralian Paleo-ocean (Puchkov, 1993; 2010; Saveliev et al., 1996; Koronovsky, 2001; Kuznetsov et al., 2010). Most of the Voykar ophiolite is composed of tectonized mantle harzburgites and dunites. Plutonic units are exposed at the Lagorta and Trubayu regions, localized in the central part of the Voykar Massif. In both regions, the base of the allochthonous massif is marked by the appearance of garnet-zoisite amphibolites and blueschists. Sharma et al. (1995) postulated that both crustal and mantle rocks of the Voykar Massif have a MORB-type source. According to Saveliev et al. (1999), Pertsev et al. (2003) and Savelieva et al. (2002; 2007), the Voykar ophiolite comprises the following sequences (Fig. 2):

Residual mantle rocks, up to 6 km in thickness, consisting of a dominant harzburgite package with subordinate dunite and small bodies of llerzolite. Chromite mineralizations can be hosted in the harzburgite and dunite at different structural levels of the residual mantle section. Dunite layers become larger toward the contact with the overlaying plutonic ultramafic unit.

Dunite-wehrlite-clinopyroxenite section, 100-700 m thick, occurs with subordinate amounts of troctolites and plagioclase-bearing ultramafic rocks.

Plutonic layered and banded gabbro, gabbronorite and olivine gabbro, up to 1 km in thickness.

Pegmatoid gabbro, amphibole-rich gabbro and gabbrodolerites closely associated with dolerite dikes, 1 km in thickness.

Plagiogranites occur as rare small-volume stock-like bodies, dikes and veins related to the gabbros and/or dolerites (see details in Chapter 4).

Pillow lavas intermixed with pelagic sediments, 50-100 m thick, occur at the top of the sheeted dikes and isotropic gabbro through tectonic contacts. According to Savelieva et al. (2007) their affinity with ophiolitic sequence is not confirmed and for Saveliev et al. (1999) pillow lava unit is missing from all the ophiolite sequence in the Voykar zone.

PREVIOUS GEOCHRONOLOGICAL INVESTIGATIONS

There were some attempts to determine the age of the Polar Urals ophiolites. In the northern part of the Voykar Massif, samples of harzburgite, dunite and websterite from the mantle section and of gabbro and diabase from the overlying crustal section yielded a Sm-Nd whole rock isochron of 387±34 Ma (Sharma et al., 1995) (Table 1). Ronkin et al. (2000) obtained a Sm-Nd isochron age from a harzburgite from the allochthonous mafic-ultramafic Rai-Iz Massif of 406±26 Ma and a Sm-Nd isochron age of a dunite-wehrlite-clinopyroxenite-gabbro complex from the eastern side of the same massif of 410±15 Ma. Glodny et al. (2003) obtained for the metasomatic veins in the Rai-Iz ophiolite a Rb/Sr mineral isochron age of 373.1±5.4 Ma. According to the authors, this result could represent the minimum age for the onset of subduction in the Polar Urals and the incipient obduction time for the ophiolites (Table 1).

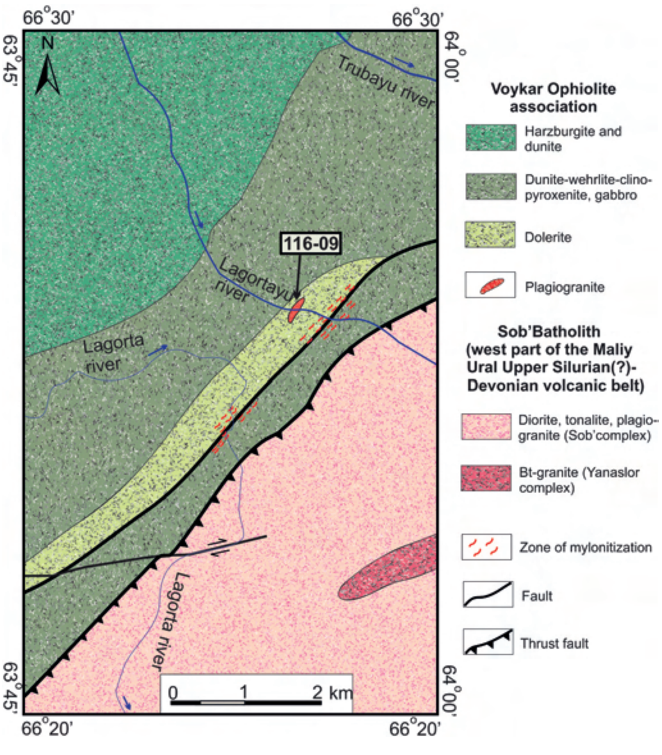

Fig. 2 - Geological sketch map showing the sampled plagiogranite (number 116-09) associated with dolerites (based on Remizov et al., 2012).

Savelieva et al. (2007) dated zircon grains in a chromitite from the northern part of the Voykar Massif. Their U-Pb SHRIMP study yielded the following results: a concordant cluster of seven grains centered at 585.3±6 Ma (Mean Square Weighted Deviation, MSWD = 0.036 and the probability of concordance is 0.85), a concordant age of the eighth grain at 622±11 Ma and a concordant age of the ninth grain at 2552±25 Ma (Table 1). The age of 585.3±6 Ma was interpreted as a Vendian (Ediacaran) tectonomagmatic event that occurred in the upper mantle of a transitional ocean-continent domain. Neither the 622 Ma nor 2552 Ma ages were explained. Note that the Vendian (Ediacaran) age does not agree with the common assumed age for the Polar Urals ophiolites, which is estimated as middle (or, rarely, early) Paleozoic (see summary on the Table 1). For this reason, the age of 585 Ma was connected with a Pre-Uralian event (e.g., Kuznetsov et al., 2007).

Khain et al. (2008) have performed U-Pb isotopic study in plagiogranite zircon crystals from the Voykar Massif. This U-Pb study was conducted using three zircon samples collected from size fractions ranging from -100+60 μm, > 100 μm, and > 60 μm. The zircons showed insignificant discordance and their data points yielded a Discordia with the upper intercept at 489±20 Ma (the lower intersection being almost zero, MSWD = 0.4). The average age value calculated using the $^{207}Pb/^{206}Pb$ ratio for the examined zircons was 490±7 Ma (MSWD = 0.21) and coincide with that obtained using the upper intersection of the Discordia. Taking into account that the morphological features of the studied zircons suggested their magmatic origin, 490±7 Ma was proposed as the best estimate for the plagiogranite crystallization in the Voykar Massif (Table 1).

Remizov et al. (2010) reported the results of a U-Pb SHRIMP study in zircon grains of milonized amphibolized gabbro (sample 5052/3) and amphibolized and sossuritized gabbro (samples 2004/5 and 11081/1) from the southeastern edge of the Voykar Massif. One rock sample (5052/3) was collected in the left bank of the Bolshaya Lagorta River, which is only 2 km southwestward from the location of our study (see Fig. 2). Two other samples were collected in the north (Khoila River - 2004/5) and south (Igyadeiegart Creek - 11081/1). Ten zircon grains for each sample yielded concordant ages at 446±2 Ma (sample 5052/3, MSWD = 0.47), 446.8±4.3 Ma (sample 2004/5, MSWD = 0.094) and 454±7 Ma (sample 11081/1, MSWD = 0.049) thereby constraining the generation of the Voykar's gabbroic rocks as Late Ordovician (Table 1).

More recently, Remizov et al. (2012) and Estrada et al.

Table 1 - Summary of the main features and isotopic ages of the Polar Urals ophiolites.

No	Locations of sampling	Rocks type	Ages (Ma)	Method	References
1	Northern part of the Voykar Massif	Harzburgite, dunite, websterite, gabbro and diabase	387 ± 34	Sm-Nd	Sharma et al. (1995)
2	Rai-Iz Massif	Harzburgite	406 ± 26	Sm-Nd	Rokin et al. (2000)
3	Rai-Iz Massif	Wehrlite, clinopyroxenite, gabbro	410 ± 15	Sm-Nd	Rokin et al. (2000)
4	Rai-Iz Massif	Cm- to m-wide albite + amphibole + chromite + phlogopite + ruby ± apatite veins	373.1 ± 5.4	Rb-Sr	Glodny et al. (2003)
5	Northern part of the Voykar Massif	Chromitite	585.3 ± 6	U-Pb	Savelieva et al. (2007)
6	Voykar Massif at Lagortai River	Plagiogranite	490 ± 7	U-Pb	Khain et al. (2008)
7	Southeastern edge of the Voykar Massif at Bolshaya Lagorta River	Milonized amphibolized gabbro	446 ± 2	U-Pb	Remizov et al. (2010)
8	Left bank of the Koila River	Amphibolized and sossuritized gabbro	446.8 ± 4.3	U-Pb	Remizov et al. (2010)
9	Right bank of the Igyadeiegart Creek	Amphibolized gabbro	454 ± 7	U-Pb	Remizov et al. (2010)
10	Voykar Massif at Lagortayu River	Plagiogranite	452.7 ± 5.1	U-Pb	Remizov et al. (2012)
11	Voykar Massif at Malaya Lagorta River	Plagiogranite	444.4 ± 6.5	U-Pb	Remizov et al. (2012)
12	Voykar Massif at Malaya Lagorta River	Leucocratic band in gabbro	454.8 ± 1.1	U-Pb	Estrada et al. (2012)
13	Voykar Massif at Trubayu River	Plagiogranite	443.8 ± 1.5	U-Pb	Estrada et al. (2012)

Sm-Nd: whole rock isochron; Rb-Sr: mineral isochron; U-Pb: LA-ICP-MS or SHRIMP in zircon grains.

(2012) dated single zircons from plagiogranite and gabbroic rocks in the central part of the Voykar ophiolite. Remizov et al. (2012) analyzed, using SHRIMP method, plagiogranites from the Lagortayu River (sample 8813), very close to our study area, and from the Malaya Lagorta River (outcrop 13503). The zircons yielded concordant ages at 452.7±5.1 Ma (MSWD = 0.107, 10 grains analyzed) and 444.1±6.5 Ma (MSWD = 0.17, 10 grains for the Concordia age), respectively. Estrada et al. (2012) dated single zircons from an approx. 5 cm-thick leucocratic band in gabbro (sample RUB-145, Malaya Lagorta River) and from a plagiogranite sample from the Trubayu River (RUB-347). Three zircons from the gabbro yielded a mean $^{207}Pb/Pb^{206}$ age at 454.8±1.1 Ma (MSWD = 0.83) while one zircon grain from the plagiogranite sample showed slightly younger $^{206}Pb/U^{238}$ age of 443.8±1.5 Ma (Table 1).

FIELD AND PETROGRAPHIC FEATURES OF THE PLAGIOGRANITE BODIES

Some outcrops of oceanic plagiogranite occur within the central part of the Voykar Massif at the Lagortayu River (Figs. 2 and 3a). These leucocratic bodies have irregular vein-like shapes, ranging in size from centimetre to metre, and are associated with porphyritic dolerites containing flow-oriented plagioclase crystals (Fig. 3a). The studied plagiogranite is white to yellowish, fine- to medium-coarse grained, showing hypidiomorphic granular texture. Zoned plagioclase (0.5 to 2.0 mm) and quartz (0.5 to 1.5 mm) are the principal mineral constituents, making up 90-95 vol%, with subordinate amounts of amphibole (5-7 vol%) partially altered to chlorite (Fig. 3b and c). Zircon occurs as accessory phase. The petrochemical characteristics of this low-K oceanic plagiogranite differs essentially from the Early Devonian plagiogranitoids, tonalites and granodiorites of the Sob' batholith, which are tholeiitic to calc-alkaline, Sr-poor and compositionally related to volcanic island-arc plutons (Udoratina and Kuznetsov, 2007; Udoratina et al., 2014). Our plagiogranite can be considered the youngest element of the Polar Urals ophiolitic association, and its age could give constraints about the minimum age for the lower crust generation within the Voykar sequence.

U-Pb GEOCRONOLOGY OF THE SELECTED SAMPLE

A precise age for the ophiolites of the Ural Mountains is important to understand the tectonic evolution of this orogenic

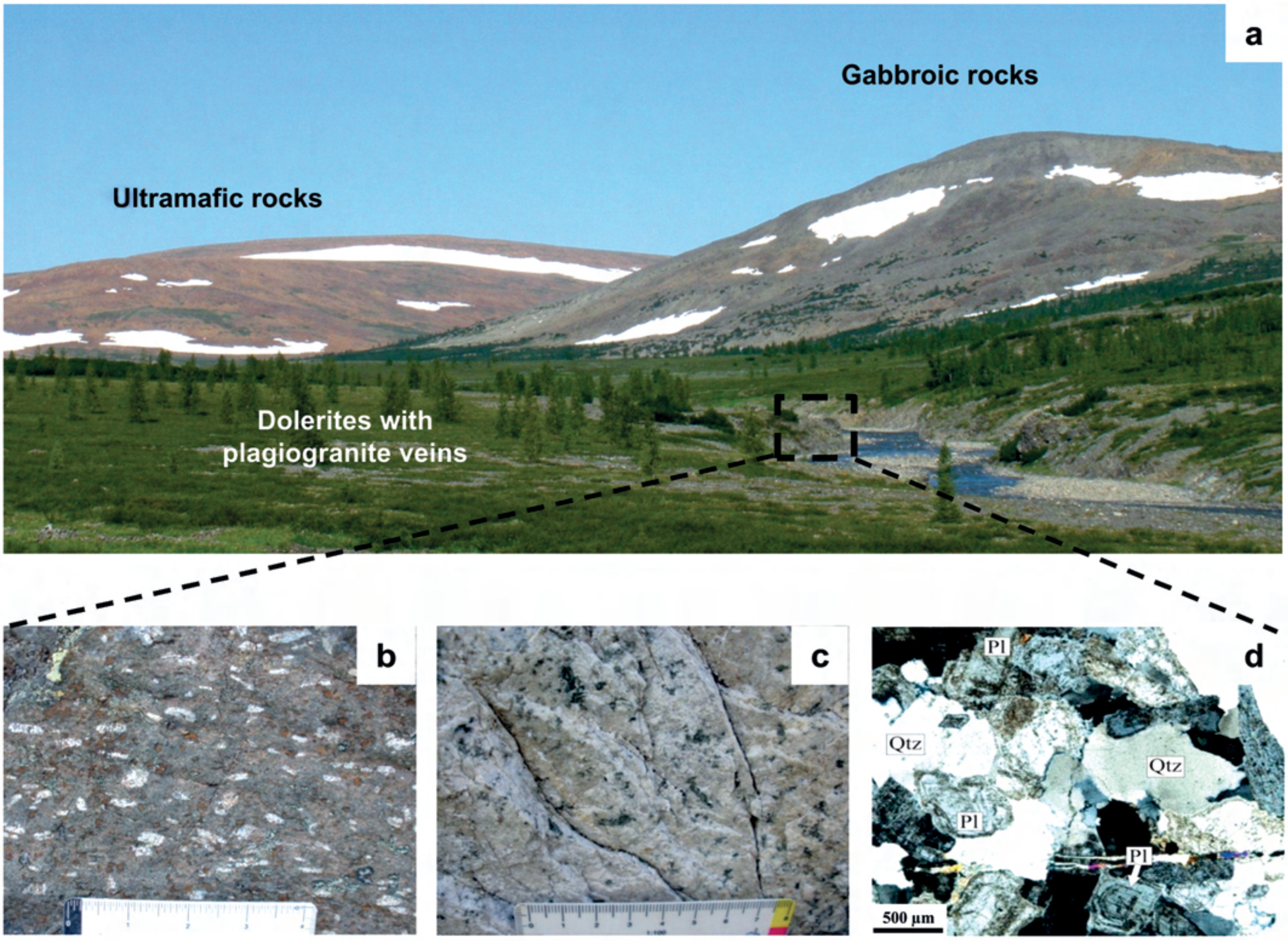

Fig. 3 - a- General view of the profile along the Lagortayu River. b- Porphyritic dolerite with flow-oriented plagioclase. c- One of the plagiogranite veins found at the Lagortayu River, showing felsic minerals (quartz + plagioclase) and amphibole. d- Photomicrograph showing plagiogranite with a hypidiomorphic granular texture and zoned plagioclase. Qtz = quartz; pl = plagioclase.

Table 2 - LA-ICP-MS U-Pb zircon data from the plagiogranite (sample 116-09).

Spot number	f206	Th/U	Th ppm	U ppm	Pb ppm	$^{207}Pb^*/^{235}U$	% err	$^{206}Pb^*/^{238}U$	% err	Rho	$^{238}U/^{206}Pb^*$	% err	$^{207}Pb^*/^{206}Pb^*$	% err	Age (Ma) $^{206}Pb/^{238}U$	error
A-I-02	0.0022	0.33	6	18	1	0.5538	9.17	0.0679	7.42	0.81	14.7347	7.42	0.0592	5.39	423	31
A-I-3	0.0018	0.33	10	30	2	0.5780	7.89	0.0669	6.00	0.76	14.9503	6.00	0.0627	5.12	417	25
A-I-5	0.0012	0.50	30	61	4	0.5399	7.19	0.0663	4.79	0.67	15.0889	4.79	0.0591	5.36	414	20
A-I-6	0.0006	0.42	38	91	6	0.5199	9.82	0.0666	5.10	0.52	15.0166	5.10	0.0566	8.40	416	21
B1	0.0005	0.34	9	27	2	0.5326	5.98	0.0661	4.37	0.73	15.1245	4.37	0.0584	4.08	413	18
B6	0.0007	0.38	22	58	5	0.5051	7.20	0.0663	3.14	0.44	15.0750	3.14	0.0552	6.48	414	13
B7	0.0011	0.32	8	26	2	0.5398	8.51	0.0669	4.27	0.50	14.9503	4.27	0.0585	7.37	417	18
C-03	0.0009	0.36	10	27	2	0.5315	6.78	0.0695	3.60	0.53	14.3986	3.60	0.0555	5.75	433	16
C-05	0.0009	0.39	7	18	1	0.5403	5.65	0.0689	3.16	0.56	14.5213	3.16	0.0569	4.68	429	14
C-06	0.0002	0.37	55	147	11	0.5353	5.75	0.0706	2.70	0.47	14.1568	2.70	0.0550	5.08	440	12
C-07	0.0010	0.24	6	24	2	0.5561	8.29	0.0691	3.16	0.38	14.4711	3.16	0.0584	7.66	431	14
C-08	0.0002	0.29	37	124	9	0.5287	5.65	0.0703	2.70	0.48	14.2232	2.70	0.0545	4.96	438	12
C-09	0.0007	0.28	11	40	3	0.5433	6.38	0.0699	2.94	0.46	14.3151	2.94	0.0564	5.66	435	13
D-02	0.0017	0.38	4	11	1	0.5487	6.92	0.0682	4.09	0.59	14.6697	4.09	0.0584	5.58	425	17
D-03	0.0002	0.34	59	172	13	0.5142	5.98	0.0679	2.72	0.45	14.7215	2.72	0.0549	5.32	424	12
D-05	0.0001	1.09	390	356	28	0.5451	4.86	0.0708	3.40	0.70	14.1179	3.40	0.0558	3.48	441	15

1. Sample and standard are corrected after Pb and Hg blanks

2. $^{207}Pb/^{206}Pb$ and $^{206}Pb/^{238}U$ are corrected after common Pb presence. Common Pb assuming $^{206}Pb/^{238}U$ $^{207}Pb/^{235}U$ concordant age

3. ^{235}U = 1/137.88*Utotal

4. Standard GJ-1

5. All errors in the table are calculated 1 sigma (% for isotope ratios, absolute for ages)

system. Until now, few reliable ages for the Voykar ophiolitic sequence in the Lagortayu area were available, mostly due to the difficulty of sampling this part of the Ural Mountains. In order to determine the crystallization age of this ophiolite, we collected one sample of a plagiogranite at the Lagortayu River (number 116-09). The sample was crushed and milled using a jaw crusher and the zircons were separated using a manual pan, conventional heavy liquids and magnetic procedures. All zircon grains were mounted in epoxy in 2.5-cm-diameter circular grain mounts and polished until the zircon grains were revealed. The internal features of the crystals were characterized by cathodoluminescence (CL) imaging, using a CL detector (Oxford Instruments - X-Max) coupled to a scanning electron microscope (Jeol JSM 6510) at the Microanalysis Laboratory of the Universidade Federal de Ouro Preto, Brazil. The zircon grains were dated with a laser ablation microprobe (New Wave UP213) coupled to an MC-ICP-MS (Neptune) at the Laboratory of Geochronology of the Universidade de Brasília, Brazil. Isotope data were acquired in static mode with spot sizes of 30 µm. Laser-induced elemental fractional and instrumental mass discrimination were corrected using the reference zircon GJ-1 (Jackson et al. 2004). Two GJ-1 analyses were measured after every five zircon samples. The external error was calculated after the propagation error of the GJ-1 mean and the individual sample zircon (or spot). The collector configuration was mixed, with faraday cups for ^{208}Pb, ^{232}Th, and ^{238}U and multiplier ion counting channels for ^{202}Hg, ^{204}Hg + ^{204}Pb, ^{206}Pb and ^{207}Pb. Detailed analytical methods and data treatment can be found elsewhere (Guadagnin et al., 2010).

The zircon grains are euhedral, prismatic and well crystallized, displaying an oscillatory zoning with no inherited cores and sizes varying from 100 to 200 µm (Fig. 4). The U-Pb in situ zircon data for the plagiogranite sample are presented in Table 2. We dated 16 inclusion-free single-phase zircon grains. Fifteen zircons have U contents from 18 to 172 ppm, Th from 6 to 59 ppm, a very low amount of Pb (1-13 ppm) and Th/U ratios between 0.24-0.50. One zircon grain (D-05) presented higher U, Th, and Pb values (366, 390 and 28 ppm, respectively) and a Th/U ratio of 1.09. The $^{238}U/^{206}Pb^*$ ratios of all dated zircons (where * corresponds to radiogenic Pb) ranged between 14.118 and 15.124. The 16 analyzed zircons yielded a Concordia with a mean $^{206}Pb/U^{238}$ age at 428.1±7.4 Ma (95% conf., MSWD = 0.43 and a probability = 0.97) (Fig. 5). We interpreted the age of 428 Ma as the crystallization age of the Voykar plagiogranite.

DISCUSSIONS AND CONCLUSIONS

According to the global geodynamic reconstructions, the Polar Urals ophiolites are large fragments of oceanic lithosphere formed in the middle Paleozoic back-arc and inter-arc basins, including fragments related to a suprasubduction setting (see details in Kuznetsov et al., 2007; 2010). An initial episode of seafloor spreading in the Voykar ocean basin may be constrained by the crystallization age of the plagiogranite veins at 490±7 Ma (Khain et al., 2008) (Fig. 6). A continuing spreading into the Voykar basin has been marked by the generation of gabbro and plagiogranite dated at 454.8±1.1 Ma (Estrada et al., 2012) and 452.7±5.1 (Remizov et al., 2012), respectively, and by the production of younger gabbroic rocks and plagiogranitoids ranging from 440 to 446 Ma (for details see Table 1) (Fershtater et al., 1998; Remizov et al., 2010; Estrada et al., 2012; Remizov et al., 2012). Spreading in this basin lasted at least up to the middle Silurian, as

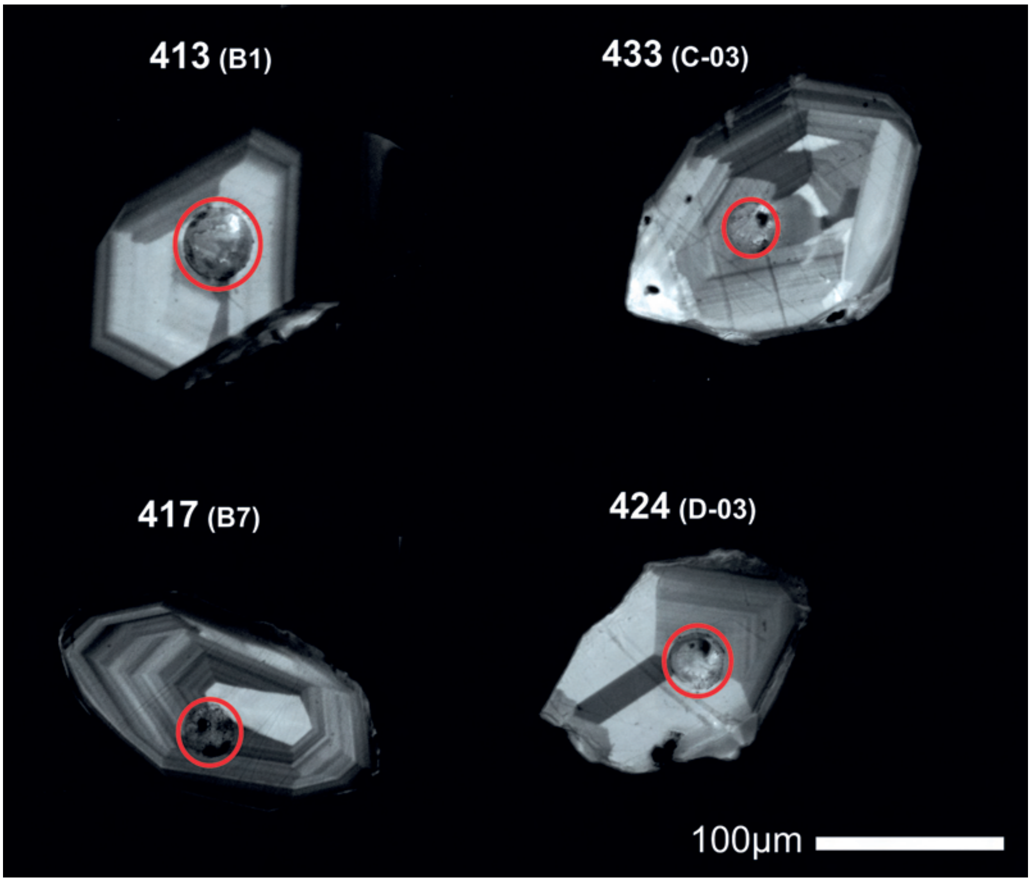

Fig. 4 - Cathodoluminescence images showing the external characteristics and internal structures of the zircons from the sample 116-09.

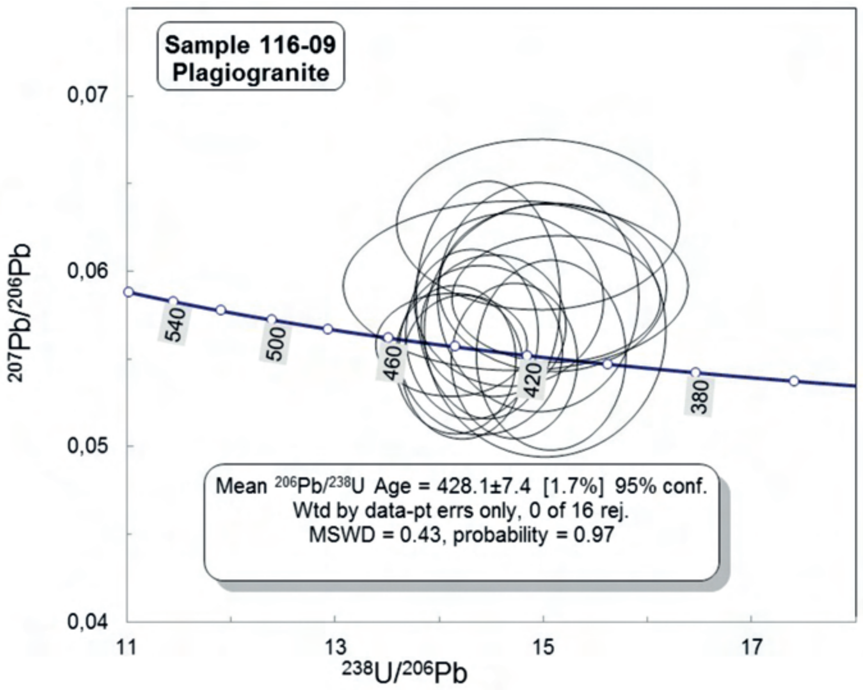

Fig. 5 - Concordia diagram for the plagiogranite of the Voykar Ophiolite Massif in the Lagortayu area.

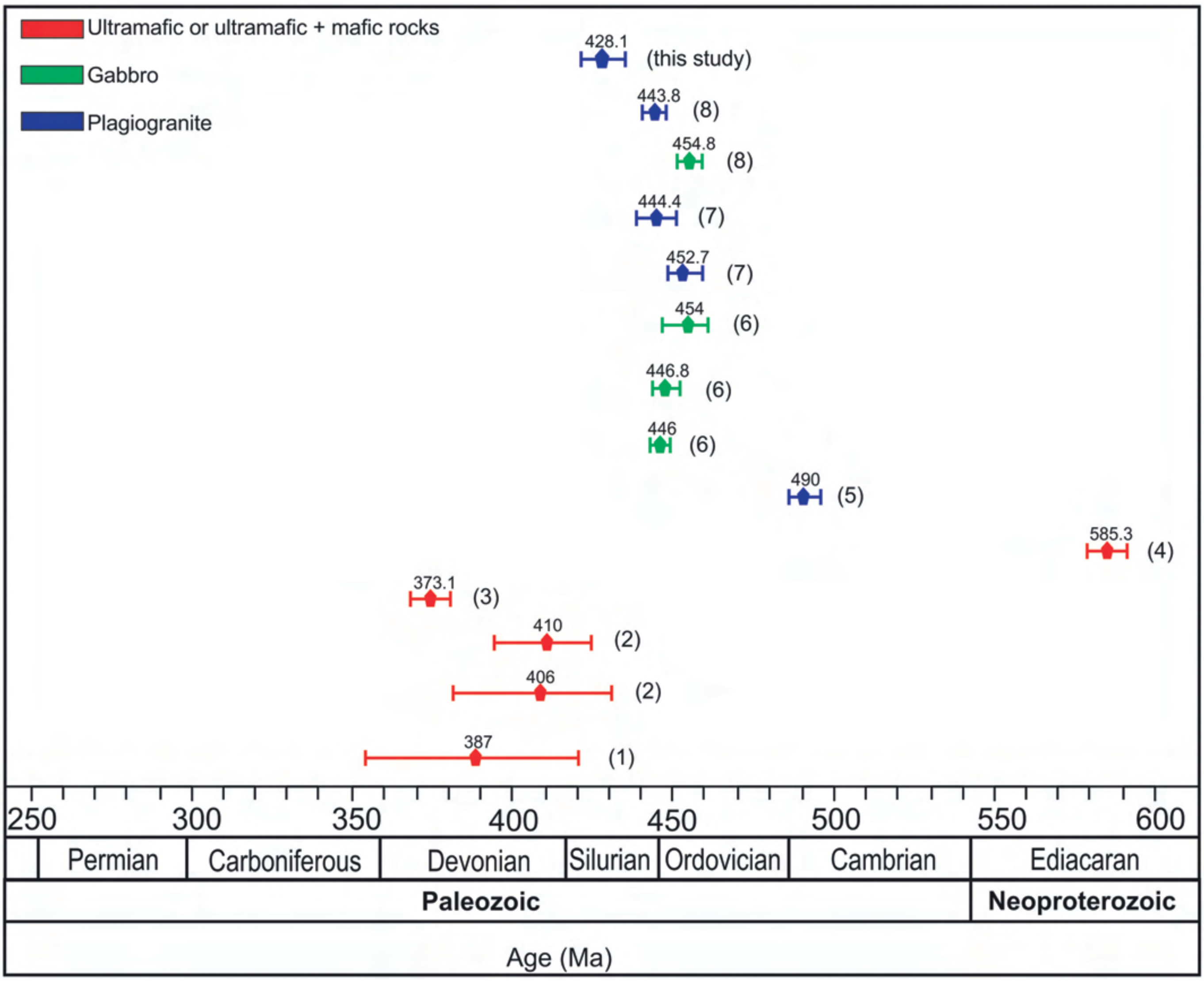

Fig. 6 - Synoptic plot of available isotopic data for the Polar Urals ophiolites. References: (1) Sharma et al. (1995), (2) Ronkin et al. (2000), (3) Glodny et al. (2003), (4) Savelieva et al. (2007), (5) Khain et al. (2008), (6) Remizov et al. (2010), (7) Remizov et al. (2012), (8) Estrada et al. (2012).

supported by our dating of plagiogranite veins associated with porphyritic dolerites at 428.1±7.4 Ma (Figs. 5 and 6). In the Voykar Massif, the dunite, wehrlite and clinopyroxenite present an isochron Sm-Nd age of 387±34 Ma (Sharma et al., 1995). This estimate could be interpreted as the result of metamorphic/metasomatic events related to the subduction process in the Voykar sector of the Polar Urals rather than the time of the spreading stage (Fig. 6), in agreement with the interpretation of Glodny et al. (2003).

The reported island-arc sequences - Maliy Urals volcanic-plutonic belt - were dated at 408-390 Ma (Udoratina and Kuznetsov, 2007; Udoratina et al., 2014), whereas the first subduction-related magmatism of Andean-I-type granites was dated at 370 to 350 Ma (Late Devonian to Early Carboniferous) (Bea et al., 2002; Udoratina et al., 2005; 2008), suggesting a relatively short time between the generation of the Voykar ophiolite and the beginning of the subduction process in the Urals Mountains.

Thus, our new data (U-Pb-dating of single zircons from plagiogranites) add new constraints for the geochronology of the Voykar Massif. The value of 428.1±7.4 Ma provided in this work is the youngest of previously obtained ages for the plagiogranitoids of the Voykar ophiolitic association. It represents an upper constraint for the timing of oceanic crust generation in the Voykar basin. Different ages of plagiogranitoids and gabbroic rocks from the Voykar Massif suggest that the generation of lower oceanic crust in this basin lasted at least 65 Ma (from ~ 425 to 490 Ma) (Fig. 6).

ACKNOWLEDGMENTS

This work was partly supported by CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico). The authors would like to acknowledge academician Nikolay P. Yushkin (Russian Academy of Sciences, Syktvykar) for his interest in and logistical support of the study. Special thanks for the Microanalysis Laboratory of the Universidade Federal de Ouro Preto, a member of the Microscopy and Microanalysis Network of Minas Gerais State/Brazil/FAPEMIG. We are grateful to Tanya Romanyuk for her help and discussions. We also thank M.R. Renna and G. Garuti for their careful and constructive reviews.

REFERENCES

Alvarez-Marron J., 2002. Tectonic processes during collisional orogenesis from comparison of the Southern Urals with the Central Variscides. In: D. Brown, C. Juhlin and V. Puchkov (Eds.), Mountain building in the Uralides: Pangea to Present. Am. Geophys. Union, Geophys. Monogr., 132: 83-100.

Aristov V.A. and Ruzhentsev S.V., 1998. New data on the Polar Ural geology. In: A.I Knipper and S.A. Kurenkov (Eds.), The Ural: the basic problems of geodynamics and stratigraphy. Nauka, Moscow, 500: 25-41 (in Russian).

Bea F., Fershtater G. and Montero P., 2002. Granitoids of the Urals: implications for the evolution of the orogen. In: D. Brown, C. Juhlin and V. Puchkov (Eds.), Mountain building in the Uralides: Pangea to Present. Am. Geophys. Union, Geophys. Monogr., 132: 211-232.

Brown D., Herrington R. and Alvarez-Marron J., 2011. Processes of arc-continent collision in the Uralides. In: D. Brown and P. Ryan (Eds.), Arc-continent collision: the making of an orogen. Frontiers in earth sciences. Springer, Heidelberg, p. 311-340.

Brown D., Puchkov V., Alvarez-Marron J. and Perez-Estaun A., 1996. The structural architecture of the footwall to the Main Uralian Fault, southern Urals. Earth Sci. Rev., 40: 125-147.

Brown D., Spadea P., Puchkov V., Alvarez-Marron J., Herrington R., Willner A., Heztel R. and Gorozhanina Y., 2006. Arc-continent collision in the Southern Urals. Earth Sci. Rev., 79: 261-287.

Chaplygina N.L., Degtyarev K.E. and Savelieva G.N., 2002. Harzburgite-type ophiolites in the structured mélange of the west Magnitogorsk zone in the Southern Urals. Geotectonics, 36 (6): 25-37.

Dembovsky B.Y., Dembovskaya Z.P., Kluzhina M.L. and Nasedkina V.A., 1990. The Ordovician of the Pre-Polar Urals. Inst. Geol., Sverdlovsk, 196 pp. (in Russian).

Desyatnichenko L.I., Fadeicheva I.F. and Smirnov V.N., 2005. Late Ordovician-Silurian Volcanic Complex in Tagil Zone (Eastern Slope of the Central Urals): composition, age and refined subdivision. Litosfera, 1: 68-96 (in Russian).

Didenko A.N., Kurenkov S.A. and Ruzhentsev S.V., 2001. Tectonic History of the Polar Urals. Nauka, Moscow, 191 pp. (in Russian).

Dushin V.A., 1997. Magmatism and geodynamics of the paleocontinental sector of the Northern part of the Urals. Nedra, Moscow, 213 pp. (in Russian).

Estrada S., Henjes-Kunst F., Burgath K.-P., Roland N.W., Schäfer F., Khain E.V. and Remizov D.N., 2012. Insights into the magmatic and geotectonic history of the Voikar Massif, Polar Urals. Zeitschr. Deutsch. Gesell. Geowiss., 163 (1): 9-41.

Fershtater G.B., Bea F., Borodina N S. and Montero P., 1998. Lateral zonation, evolution, and geodynamic interpretation of magmatism of the Urals: New petrological and geochemical data. Petrology, 6: 409-433.

Fershtater G.B., Kholodnov V.V., Kremenetsky A.A., Krasnobaev A.A., Borodina N.S., Zin'kova E.A. and Pribavkin S.V., 2010. Au-bearing gabbro-tonalite-granodiorite-granite plutons of the Urals: age, geochemistry and magmatic and ore evolution. Geol. Ore Depos., 52 (1): 58-76.

Fershtater G.B., Krasnobaev A.A., Bea F., Montero P. and Borodina N.S., 2007. Geodynamic settings and history of the Paleozoic intrusive magmatism of the Central and Southern Urals: results of zircon date. Geotectonics, 41 (6): 465-486.

Glodny J., Austrheim H., Molina J.F., Rusin A.I. and Seward D., 2003. Rb/Sr record of fluid rock interaction in eclogites: the Marun-Keu complex, Polar Urals, Russia. Geochim. Cosmochim. Acta, 67 (22): 4353-4371.

Guadagnin F., Chemale Jr.F., Dussin I.A., Jelinek A.R., dos Santos M.N., Borba M.L., Justino D., Bertotti A.L. and Alessandretti L., 2010. Depositional age and provenance of the Itajaí Basin, Santa Catarina State, Brazil: Implications for SW Gondwana correlation. Precambr. Res., 180: 156-182.

Ivanov K.S., 1998. The main features of geological history (1.6-0.2 Ga) and structure of Urals. Doct. Sci. Thesis, Ekaterinburg, 253 pp. (in Russian).

Jackson S.E., Pearson N.J., Griffin W.L. and Belousova E.A., 2004. The application of laser ablation-inductively coupled plasma-mass spectrometry to in situ U-Pb zircon geochronology. Chem. Geol., 211: 47-69.

Khain E.V., Sal'nikova E.B., Kotov A.B., Burgath K.P., Fedotova A.A., Kovach V.P., Yakovleva S.Z., Remizov D.N. and Schaefer F., 2008. U-Pb age of plagiogranites from the ophiolite association in the Voykar-Synya Massif, Polar Urals. Dokl. Earth Sci., 419A (3): 392-396.

Kheraskov N.P., 1948. The principles of making of tectonic maps for the folded regions of the Southern Urals. Izv. AN SSSR. Ser. Geol., 5: 121-134 (in Russian).

Koronovsky N.V., 2001. Tectonic history of the Polar Urals. Nauka, Moscow (in Russian), p. 137-169.

Kuznetsov N.B., Natapov L.M., Belousova E.A., O'Reilly S.Y. and Griffin W.L., 2010. Geochronological, geochemical and isotopic study of detrital zircon suites from late Neoproterozoic clastic strata along the NE margin of the East European Craton: Implications for plate tectonic models. Gondw. Res., 17: 583-601.

Kuznetsov N.B., Soboleva A.A., Udoratina O.V., Gertseva O.V. and Andreichev V.L., 2007. Pre-Ordovician tectonic evolution and volcano-plutonic associations of the Timanides and northern Pre-Uralides, northeast part of the east European Braton. Gondw. Res., 12: 305-323.
Lawver L.A., Grantz A. and Gahagan I.M., 2002. Plate kinematic evolution of the present Arctic region since the Ordovician. In: E.L. Miller, A. Grantz and S.L. Klemperer (Eds.), Tectonic evolution of the Bering Shelf-Chukchi Sea-Arctic margin and adjacent landmasses. Geol. Soc. Am. Spec. Paper, 360: 333-358.
Lupanov N.P. and Markin V.V., 1964. Green-stones rock units of the Sob`-Voikar sinclinorium (Eastern slope of the PolarUrals). Nauka, Moscow-Leningrad, 175 pp. (in Russian).
Pertsev A., Savelieva G.N. and Simakin S.G., 2003. Parental melts imprited in plutonic rocks of the Voykar ophiolite, Polar Urals: evidences from clinopyroxene geochemistry. Ofioliti, 28 (1): 33-41.
Puchkov V.N., 1979. Bathyal complexes of geosyncline passive margins. Nauka Publ., Moscow (in Russian), 259 pp.
Puchkov V.N., 1993. Palaeo-oceanic structures of the Ural Mountains. Geotectonics 27 (3): 190-196.
Puchkov V.N., 1997. Structure and geodynamics of the Uralian orogen. In: J.P. Burg and M. Ford (Eds.), Orogeny through time. Geol. Soc. London Spec. Publ., 121: 201-236.
Puchkov V.N,. 2000. Paleogeodynamics of the Central and Southern Urals. Ufa, Dauria, 145 pp. (in Russian).
Puchkov V.N., 2003. Uralides and Timanides, their structural relationship and position into geological history of Uralian-Mongolian fold-thrust belt. Geol. Geophys., 44 (112): 28-39 (in Russian).
Puchkov V.N., 2010. Geology of the Urals and Cis-Urals (actual problems of stratigraphy, tectonics, geodynamics and metallogeny). Ufa, Design Poligraph Service, 280 pp. (in Russian).
Reichow M.K., Pringle M.S., Al'Mukhamedov A.I., Allen M.B., Andreichev V.L., Buslov M.M., Davies C.E., Fedoseev G.S., Fitton J.G., Inger S., Medvedev A.Ya., Mitchell C., Puchkov V.N., Safonova I.Yu., Scott R.A. and Saunders A.D., 2009. The timing and extent of the eruption of the Siberian Traps large igneous province: implications for the end-Permian environmental crisis. Earth Planet. Sci. Lett., 277: 9-20.
Remizov D.N., Grigoriev S.I., Petrov S.Yu., Kos'yanov A.O., Nosikov M.V. and Sergeev S.A., 2010. New age datings of gabbroides of the Kershor Complex (Polar Urals). Dokl. Earth Sci., 434 (1): 1235-1239.
Remizov D.N., Kulikova K.V., Sychev S.N., Nosikov M.V. and Sergeev S.A., 2012. U-Pb dating of zircons from plagiogranites of the Lagorta Yu dike Complex (Polar Urals). Dokl. Earth Sci., 447 (2): 1289-1291.
Ronkin Yu.L., Pryamonosov A.P. and Telegina T.V., 2000. Dunite-Harzburgite and Dunite-Verlite complex of Polar Urals: REE and Sr-Nd constrains. The Isotopic dating of the geological processes: New methods and results. Moscow, GEOS., p. 302-305 (in Russian).
Ruzhentsev S.V. and Samygin S.G., 2004. The structure and tectonic evolution of the East European Platform and the Southern Urals junction zone. Geotectonics, 38 (4): 255-276.
Ryazantsev A.V., Dubinina S.V., Kuznetsov N.B. and Belova A.A., 2008. Ordovician lithotectonic complexes in allochthons of the Southern Urals. Geotectonics, 42 (5): 368-395.
Saveliev A.A., Didenko A.N., Kurenkov S.A. and Lubina N.V., 1996. Paleomagnetism of the ophiolites of Voikaro-Syninsky Massif (Polar Urals). Paleomagnetism and rock magnetism. OIFZ RAN, Moscow, p. 77-79.
Saveliev, A.A., Sharaskin, A.Ja. and D'Orazio, M. 1999. Plutonic to volcanic rocks of the Voykar Ophiolite Massif (Polar Urals): structural and geochemical constraints on their origin. Ofioliti, 24 (1): 21-30.
Savelieva G.N., 1987. Gabbro-ultrabasite assemblages of the Urals ophiolites and their analogues in modern oceanic crust. Acad. Sci., Nauka Publ., Moscow, 242 pp. (in Russian).
Savelieva G.N., Sharaskin A.Y., Saveliev A.A., Spadea P., Pertsev A.N. and Barbarina I.I., 2002. Ophiolites and zoned mafic-ultramafic massifs of the Urals: a comparative analysis and some tectonic implications. In: D. Brown, C. Juhlin and Puchkov V. (Eds.), Mountain building in the Uralides: Pangea to Present. Am. Geophys. Union, Geophys. Monogr., 132: 135-154.
Savelieva G.N., Suslov P.V. and Larionov A.N., 2007. Vendian tectono-magmatic events in mantle ophiolitic complexes of the Polar Urals: U-Pb dating of zircon from chromitite. Geotectonics, 41 (2): 105-113.
Scarrow J., Ayala C. and Kimbell G.S., 2002. Insights into orogenesis: Getting to the root of the continent-ocean-continent collision in the southern Urals, Russia. J. Geol. Soc., 159: 659-672.
Sengör A.M.C., Natal'In B.A. and Burtman V.S., 1993. Evolution of the Altaid tectonic collage and Palaeozoic crustal growth in Eurasia. Nature, 364: 299-307.
Sharma M., Wasserburg G.J., Papanastassiou D.A., Quick J.E., Sharkov E.V. and Laz'ko E.E., 1995. High ^{143}Nd/^{144}Nd in extremely depleted mantle rocks. Earth Planet. Sci. Lett., 135: 101-114.
Shishkin M.A., Malykh I.M., Matukov D.I. and Sergeev S.A., 2004. Rhyolite complexes of the western slope of the Polar Urals. Geology and Mineral Resources of the European Northeast of Russia (Geoprint, Syktyvkar), Vol. 2, p. 148-150 (in Russian).
Stampfli G.M. and Borel G.D., 2002. A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrones. Earth Planet. Sci. Lett., 196: 17-33.
Udoratina O.V. and Kuznetsov N.B., 2007. The Sobsky Granitoid Complex of Polar Urals. Bull. MOIP. Dept. Geol., 82 (3): 49-59 (in Russian).
Udoratina O.V., Kuznetsov N.B., Andreichev V.L. and Savatenkov V.M., 2014. Sobsky Massif (Polar Urals): isotope-geochemical data. In: A.S. Borisenko, A.G. Vladimirov, N.N. Kruk (Eds.), Granites and Earth's evolution: granites and continental crust. Proceed. 2nd Intern. Geol. Conf., Novosibirsk, Russia, p. 211-213.
Udoratina O.V., Kuznetsov N.B. and Larionov A.N., 2008. Plagiogranites of the Sobsky Complex (Polar Ural): U-Pb data. In: Granites and Earth´s evolution: Geodynamic setting, petrogenesis and ore content of granitoid batholiths. Proceed. 1st Intern. Geol. Conf., Geol. Inst. SB RAS, Russia, p. 391-392.
Udoratina O.V., Larionov A.N., Kuznetsov N.B. and Kalinin E.P., 2005. U-Pb zircon age of the Vangyr Massif granite, Sub-Polar Urals, Russia. In: V.K. Singh and R. Chandra (Eds.), Intern. Conf. Precambrian continental growth and tectonism (PCGT-2005), Dept. Geol., Bundelkhand Univ., Jhansi, India, Abstr., p. 112-115.
Voynovsky-Kriger K.G., 1945. Two Paleozoic complexes in the western slope of the Polar Urals. Sovietic Geol., 6: 19-27.
Voynovsky-Kriger K.G., 1966. Study on tectonics of the Lemvinskaya facies-structure zone (the western slope of the Polar. Urals). Paper I., Bull. MOIP. Dept. Geol., 41 (4): 5-29.
Voynovsky-Kriger K.G., 1967. Study on tectonics of the Lemvinskaya facies-structure zone (the western slope of the Polar. Urals). Paper I.I , Bulletin of MOIP. Dept. Geol., 52 (2): 5-26.
Yazeva R.G. and Bochkarev V.V., 1984. The Voykar volcano-plutonic belt. Ural. Nauch. Centre USSR, Sverdlovsk, 156 pp. (in Russian).
Zonenshain L.P., Korinevsky V.G., Kazmin V.G., Pechersky D.M., Khain V.V. and Matveenkov V.V., 1984. Plate tectonic model of the South Urals development. Tectonophysics, 109: 95-135.
Zonenshain L.P., Kuzmin M.I. and Natapov L.M., 1990. Geology of the USSR: a plate-tectonic synthesis. Am. Geophys., Geodyn. Ser., 21: 1-242.

Received, June 21, 2016
Accepted, November 11, 2016