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## The Paleoproterozoic and Mesoproterozoic TTGs of the western Azov area, the Ukrainian Shield

*Presented by Academician of the NAS of Ukraine O.M. Ponomarenko*

*A large anticline structure occurs in the western part of the Azov Domain of the Ukrainian Shield. It is composed of rocks of the Mesoproterozoic (3.2-3.0 Ga) granite-greenstone association and relics of an older basement. The anticline is divided into two parts by the Bilotserkiivka structure of sub-latitudinal strike. The northern part includes the Huliaipole and Remivka blocks, and the southern part comprises the Saltycha anticline. The U-Pb age of plagiogneisses of the Lantsevo anticline of the Bilotserkiivka structure is  $3299 \pm 11$  Ma. In terms of geochemical characteristics, they correspond to TTGs. In the western part of the Bilotserkiivka structure, we previously identified quartz diorites having an age of  $3297 \pm 22$  Ma. These data show that the Bilotserkiivka structure represents an ancient basement. Dislocated trondhjemites were studied in the Ivaniivka area at the eastern part of the Saltycha anticline. They contain numerous relics of heavily altered amphibolites. The U-Pb age of zircons from trondhjemite is  $3013 \pm 15$  Ma. These rocks are of the same age as TTGs of the Shevchenko Complex cutting through the sedimentary-volcanogenic rocks of the greenstone structures of the Azov Domain. They share age and geochemical characteristics with biotite and amphibole-biotite gneisses of the "Kainkulak beds" in the Zrazkove village located at the Mokra Konka river (3.1-3.0 Ga) and with biotite gneisses in the lower reaches of the Kainkulak river (2.92 Ga). Thus, gneisses of the "Kainkulak beds" actually represent the Mesoproterozoic TTGs of the Shevchenko Complex, transformed in the Paleoproterozoic time due to the dislocation metamorphism. The late Paleoproterozoic (3.3 Ga) tonalites are known in the West Azov and KMA domains; they probably also occur in the basement of the Middle Dnieper domains, where detrital zircons of this age have been reported. These data allow us to assume the existence of a large Late Paleoproterozoic (3.3 Ga) protocraton, in which the Mesoproterozoic (3.2-3.0 Ga) greenstone belts and TTGs of the eastern part of the Ukrainian Shield and the KMA Domain were formed.*

**Keywords:** West Azov, Bilotserkiivka structure, Paleoproterozoic protocraton, Mesoproterozoic craton, TTG, Ukrainian Shield, zircon, U-Pb age.

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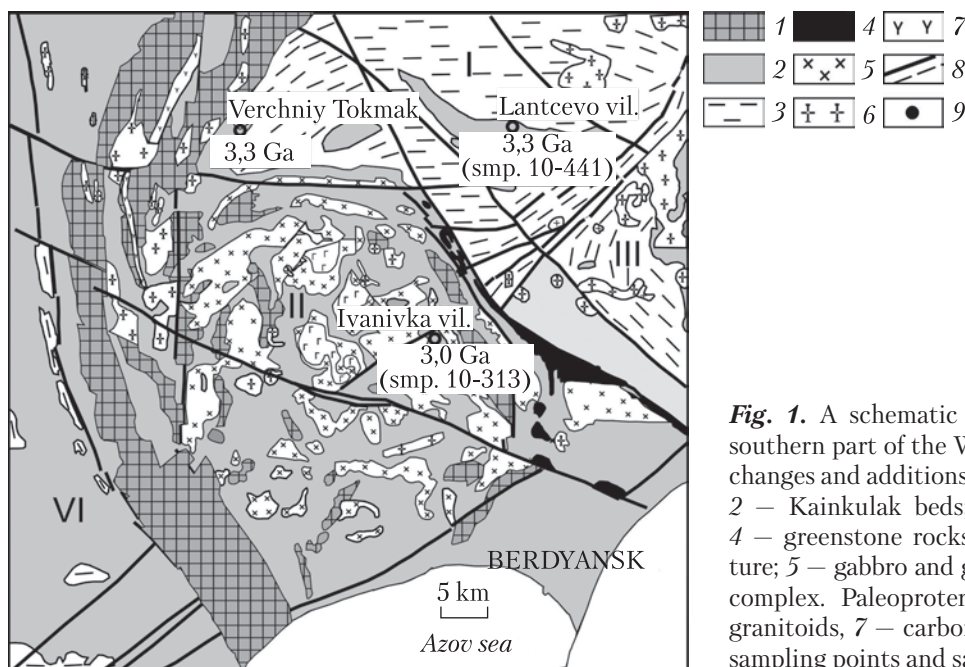
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**Introduction.** A large anticline structure that comprises the West Azov and Remivka blocks occurs in the western part of the Azov Domain of the Ukrainian Shield. These blocks are composed of rocks of the Mesoarchean (3.2-3.0 Ga) granite-greenstone association and relics of an older basement. The anticline is divided into two parts by the Bilotserkivka structure of sub-latitudinal strike; the northern part includes the Huliaipole and Remivka blocks, and the southern part is comprised of the Saltycha anticline (Fig. 1). The Archean plagiogranitoids of the West Azov underwent the intense dislocation metamorphism during the Paleoproterozoic. In many areas, they were transformed into plagioclase gneisses that were attributed to the Paleoproterozoic “Kainkulak beds” of the West Azov Series [1]. Alternating thin “layers” of biotite-, amphibole-, and biotite-amphibole gneisses crop out locally in the upper reaches of the Konka and Kainkulak rivers. A high degree of dislocation metamorphism is observed in plagiogranitoids of the peripheral parts of the Saltycha anticline. Archean rocks are strongly deformed in the Bilotserkivka structure, where plagiogneisses with a thin-stripe structure can be observed. For this reason, detailed geological-structural and geochronological studies are required for the chronostratigraphic subdivision of these gneisses. We have chosen two areas for our studies: the Lantsevo anticline within the Bilotserkivka structure and the Ivanivka area in the eastern part of the Saltycha anticline (see Fig. 1).

**Geological structure of the studied areas. The Bilotserkivka structure** (up to  $20 \times 45$  km in size) of a sub-latitudinal strike is located between the Haichur block and Saltycha anticline (see Fig. 1). In the east, it borders the Central Azov syncline, and its western boundary is drawn along the Chernihivka fault [3]. The inclination of the rocks of the Bilotserkivka structure along the contacts in the west, north, and south is very steep, ranging from  $70-80^\circ$  to  $90^\circ$ . Several anticline and syncline folds are found within its borders. The synclines are composed of rocks of the Dragunove beds (formerly known as the Temryuk Suite of the Central Azov Series),



**Fig. 1.** A schematic geological map of the southern part of the West Azov area [2] with changes and additions. 1 – West Azov Series; 2 – Kainkulak beds; 3 – Dragunka beds; 4 – greenstone rocks of Greenstone Structure; 5 – gabbro and granitoids of Obitochno complex. Paleoproterozoic intrusions: 6 – granitoids, 7 – carbonatites. 8 – faults, 9 – sampling points and sample numbers

whereas anticlines (Oleksiivo, Lantsevo, etc.) are composed of plagiogneisses of the “Kainkulak beds” with relics of two-pyroxene crystalline schists, amphibolites, and ferruginous-siliceous rocks [2, 4]. Metamorphic rocks compose lenses and slices from a few centimeters to hundreds of meters thick.

**The Saltycha anticline** is a dome-shaped structure having an area of about 2000 km<sup>2</sup>. Its prevalent area is composed of plagiogranitoids (TTGs) of the Shevchenko Complex and gneisses of the West Azov Series. Among them, relics of amphibolites and meta-ultrabasic rocks having a thickness of up to 400 m, are found. More than half of the area of the Saltycha anticline is occupied by small (up to 85 km<sup>2</sup>) intrusions of gabbro, diorites, and granodiorites of the Obitochne complex having an age of 2.91-2.92 Ga. Their geochemical characteristics correspond to intra-plate magmatic rocks [5]. Paleoproterozoic potassium-sodium granitoids of the Saltycha and Anadol complexes are spread in a part of the Saltycha anticline. They compose small stocks having an area of up to 2.5 km<sup>2</sup>, as well as smaller bodies confined mainly to tectonic zones.

**Analytical methods.** Zircon has been extracted from the rock using a shaking table, heavy liquids, and a magnetic separator to produce a heavy non-magnetic fraction. Zircons were hand-picked under a binocular microscope. Zircon morphology has been studied under an optical microscope, whereas the internal structure was documented using cathodoluminescence. U-Pb isotopic data were collected using the laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) in the GeoHistory Facility, John de Laeter Centre, Curtin University. Zircon was ablated using a Resonetics RESOLUTION M-50A-LR system, incorporating a COMPex 102-193 nm excimer UV laser that was coupled to an Agilent 8900 QQQ mass spectrometer. Zircon standard OG1 (3465 ± 0.6 Ma [6]; all uncertainties at 2σ) was utilized as the primary reference material and analyzed in blocks with secondary standards GJ-1 (601.2 ± 0.4 Ma [7]), and Plešovice (337.13 ± 0.37 Ma [8]). The secondary standards yielded weighted mean <sup>207</sup>Pb/<sup>206</sup>Pb ages and <sup>238</sup>U/<sup>206</sup>Pb ages within an uncertainty of the recommended values. The time-resolved mass spectra were reduced using Iolite 3.7™ ([9] and references therein) with final ages calculated using Isoplot. Silicate rock analyses were carried out at IGMOF of the NAS of Ukraine, Kyiv.

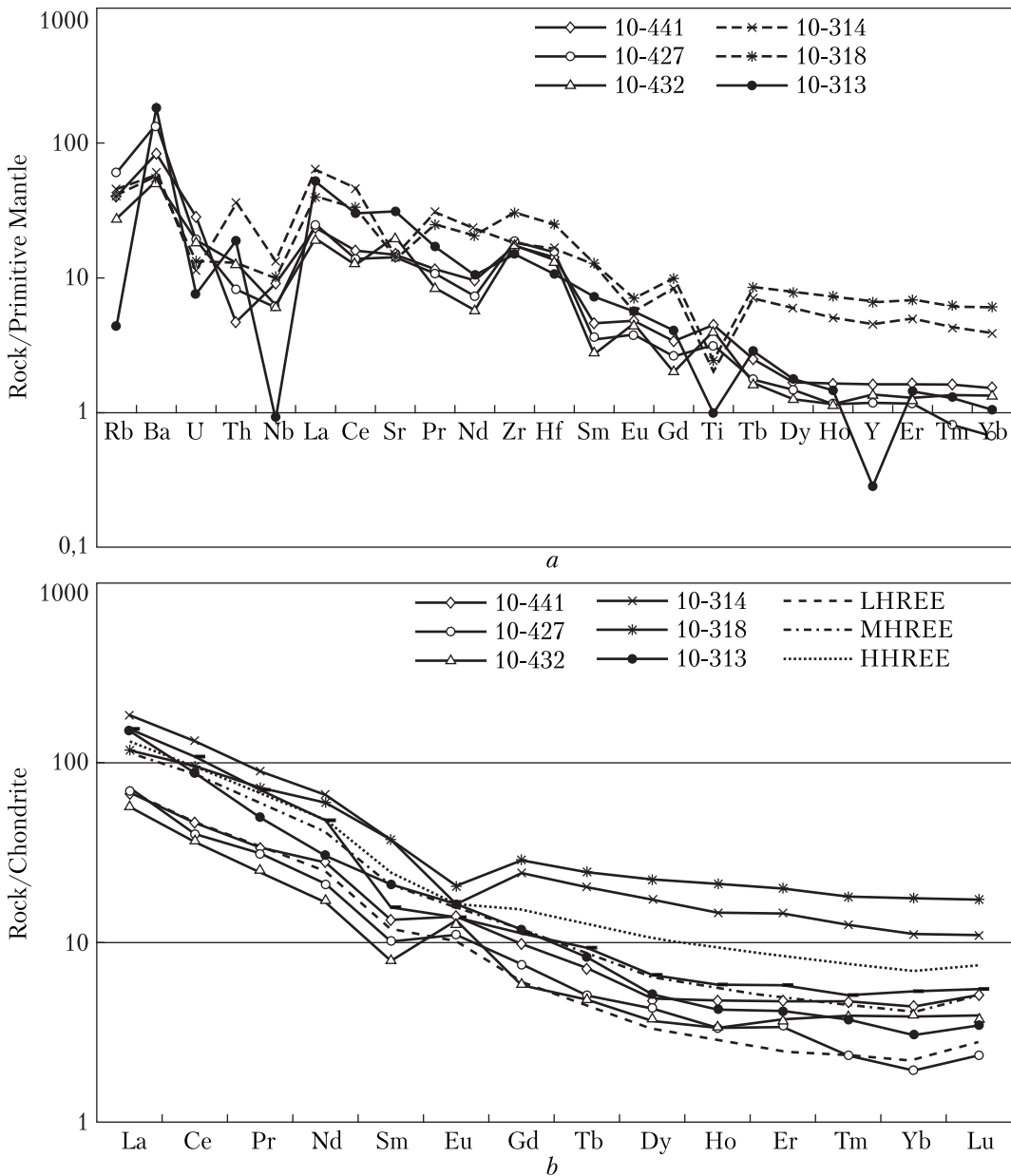
**Research results. The Bilotserkiivka structure** (area of the Lantsevo village). We have dated plagiogneisses of the Lantsevo anticline that were considered to belong to the Kainkulak beds [2]. They often host large xenoliths of metamorphic rocks, i.e., two-pyroxene and pyroxene schists and pyroxene-magnetite quartzites. A sample of biotite gneisses was taken in the upper reaches of the Berda river right tributary (ravine), at the north-eastern outskirts of the Lantsevo village. Bedding elements of gneisses: strike NW 275°, dip NE 5°, inclination 65°.

Biotite gneiss (sample 10-441) has a lepidogranoblastic texture and the following mineral composition (vol. %): feldspar (albite) – 75; quartz – 15; biotite – 5-7; clinopyroxene – 1-2; apatite, zircon – single grains. In terms of the chemical composition [7], biotite gneiss belongs to the family of granodiorite-tonalites of the potassium-sodium series (SiO<sub>2</sub> = 65.05 %; Al<sub>2</sub>O<sub>3</sub> = 14.79 %; Na<sub>2</sub>O = 4.40 %; K<sub>2</sub>O = 1.16 %) (Table 1). These rocks have low Mg# = 33.9. In the O’Connor-Barker classification diagram Ab-An-Or, they plot in the tonalite field. They are poor in Rb (25.7 ppm) and rich in Sr (313 ppm) (Table 2). Average concentrations of HFS elements are as follows: Y (7.4 ppm), Nb (6.5 ppm), Yb (0.75 ppm); an average concentration of Ni (the only transition element found) is 19.7 ppm. The multielement diagram shows

Table 1. Silicate chemical composition of rocks of the Belotserkivka structure and the Salytcha anticline, wt. %

Sample #	10-441	10-427	10-430	10-432	10-314	10-318	10-312	10-313	10-440	10-378	10-397	10-276	13	14	15
SiO <sub>2</sub>	65.05	69.49	69.55	64.69	63.51	62.93	71.67	70.90	51.93	50.54	46.07	49.57	71.12	68.29	68.81
TiO <sub>2</sub>	1.04	0.74	0.74	0.94	0.47	0.57	0.09	0.23	1.71	1.71	0.03	0.74	0.25	0.40	0.42
Al <sub>2</sub> O <sub>3</sub>	14.79	14.88	12.99	15.92	15.76	16.01	15.61	14.69	15.89	10.05	0.61	14.08	15.55	15.65	15.21
Fe <sub>2</sub> O <sub>3</sub>	2.48	1.02	2.59	1.05	1.16	1.16	<0.01	0.66	2.72	1.45	18.95	0.44	-	-	-
FeO	3.23	2.51	2.37	3.88	4.67	4.81	2.01	2.44	7.33	9.36	25.98	9.69	1.83*	3.02*	3.31*
MnO	0.05	0.04	0.04	0.07	0.08	0.08	<0.02	<0.02	0.07	0.22	0.31	0.21	0.04	0.05	0.06
MgO	1.57	0.94	1.65	1.57	1.97	1.89	0.39	0.55	4.52	10.05	3.23	7.31	0.79	1.33	1.29
CaO	4.83	3.22	4.95	5.17	5.06	5.70	3.42	3.31	8.61	11.26	2.82	10.69	2.63	3.44	3.24
Na <sub>2</sub> O	4.40	4.18	3.83	4.40	4.62	4.30	5.24	5.26	4.20	2.00	0.10	3.3	5.24	4.70	4.47
K <sub>2</sub> O	1.16	1.66	0.58	0.66	1.24	1.00	0.46	0.46	1.08	1.70	0.05	0.50	1.71	1.64	1.76
Stot.	-	-	-	-	-	<0.02	<0.02	<0.02	-	0.03	<0.02	<0.02	-	-	-
P <sub>2</sub> O <sub>5</sub>	0.27	0.27	0.21	0.27	0.23	0.11	0.05	0.08	0.40	0.12	0.64	0.08	0.09	0.14	0.13
H <sub>2</sub> O <sup>-</sup>	0.19	0.18	0.16	0.22	0.48	0.39	0.38	0.43	0.21	0.26	0.11	0.26	-	-	-
LOI	0.60	0.37	0.31	0.80	0.66	0.69	0.54	0.59	1.15	1.26	0.67	1.83	-	-	-
Total	99.66	99.50	100.02	99.61	99.91	99.66	99.86	99.60	99.82	100.01	99.51	98.72	-	-	-
Mg#	33.9	32.8	38.5	36.7	38.1	36.5	25.7	24.4	45.2	62.7	-	56.4	43.5	44	41

Note. 10-441 – tonalite, outcrop in the upper reaches of the gully flowing into the river Berda in the eastern part of the Lantsevo village; 10-427 – tonalite, outcrop in the Vodyane village; 10-430 and 10-432 – tonalite, the same place; 10-314 – tonalite, outcrop in the dam drain on the river Tokmak, in the northern part of the Verkhniy Tokmak village; 10-318 – tonalite, outcrop on the right bank of the river Tokmak, in the middle part of the Verkhniy Tokmak village; 10-312 – trondhjemite, outcrop on the right bank of the river Kiltychcha in the southern part of the Ivanivka village; 10-313 – trondhjemite, in the same place; 10-440 – amphibolized two-pyroxene schist, upper reaches of the gully flowing into Berda river in the eastern part of the Lantsevo village; 10/378 – amphibolized two-pyroxene schist, left side of Ocheretyna stream; 10/397 – pyroxene-magnetite ferruginous quartzite, the same place; 10/276 – amphibolite, outcrop on the right bank of the river Kiltychcha in the Ivanivka village. Composition of various TTG types according to (Martin, 1994): 13 – Low REE TTG; 14 – Medium REE TTG; 15 – high REE TTG. Mg# = 100\*Mg/(Mg+Fe<sub>total</sub>) in cation mole percent. Silicate chemical analyzes were performed at the IGMOF NAS of Ukraine.



**Fig. 2. a:** Multi-element diagrams for tonalites of the Bilotserkivka structure and trondhjemites of the Saltycha anticline. Normalized to the primitive mantle [10].

**b:** REE distribution for tonalites of the Bilotserkivka structure and trondhjemites of the Saltycha anticline. Normalized to the composition of chondrite [10]

positive Ti, Eu, and Sr anomalies, and negative Nb anomaly (Fig. 2, a). The REE pattern is differentiated:  $(La/Yb)_N = 15.5$  at  $Yb_N = 4.4$  (Fig. 2, b). A positive europium anomaly is found:  $Eu/Eu^* = 1.2$ .

**The Saltycha anticline.** Separate outcrops of trondhjemites with numerous metabasite relics are observed in a one-kilometer-long section on the right steep bank of the Kiltichia river in the Ivanivka village. Amphibolites are cut by trondhjemite veins. In the southern part of this section, ISSN 1025-6415. Донов. Нац. акад. наук Укр. 2021. № 5

Table 2. Trace elements concentrations in rocks of the Belotserkivka structure and Saltycha anticline

Ppm	10-441	10-427	10-432	10-314	10-318	10-313	10-378	10-397	10-276	Low REE	Med REE	High REE
Rb	25.7	38.3	17.5	29.0	25.9	2.8	2.9	3.3	0.5	46.4	55.0	70.6
Sr	313	30	426	315	299	657	290	153	24.9	583	483	327
Ba	583	966	367	417	390	1279	391	162	9.8	542	531	447
V	76	29	82	75	65	29	283	234	13	213	36	42
Cr	50	30	50	21.3	14.6	15.5	103	749	22.8	42.5	38.2	27.6
Co	13.6	6.3	13.7	15.9	15.1	5.5	49.10	56.61	3.32	—	—	—
Ni	19.7	13.1	18.9	29.0	31.7	12.8	138	239	13.9	86.2	21.6	15.2
Cu	31.3	12.0	37.8	36.1	45.9	37.4	47.0	29.82	6.95	—	—	—
Zn	45	44	30	83	69	27	117	107	18	—	—	—
Ga	15.7	15.4	15.8	19.5	—	16.1	16.7	16.8	1.9	—	—	—
Y	7.4	5.4	6.2	20.7	30.0	1.3	16.0	14.4	8.4	5.4	8.3	18.2
Nb	6.5	4.3	4.5	9.5	7.1	0.6	2.5	3.1	2.4	2.9	5.3	8.1
Ta	2.0	0.4	1.2	0.56	0.24	0.02	—	—	—	0.52	0.81	0.79
Zr	193	208	195	199	343	168	41	42	2.6	114	143	174
Hf	4.4	4.8	4.2	5.1	7.7	3.3	1.1	1.4	0.1	3.0	4.2	4.5
U	0.60	0.40	0.40	0.24	0.28	0.16	4.50	0.11	0.18	0.83	1.31	1.83
Th	0.40	0.70	1.10	3.10	1.10	1.60	0.66	0.63	0.27	3.86	6.16	7.16
La	16.2	17.2	13.5	43.7	27.8	35.7	4.7	9.0	3.4	16.4	26.9	31.0
Ce	28.3	24.6	22.2	80.8	58.7	53.6	12.4	20.96	8.03	28.72	52.87	57.91
Pr	3.21	2.98	2.33	8.5	6.90	4.70	1.80	2.70	1.03	—	—	—
Nd	13.0	9.9	7.8	30.9	28.0	14.2	7.7	12.1	4.8	11.6	19.3	22.5
Sm	2.05	1.55	1.21	5.70	5.70	3.22	2.20	2.94	1.19	1.82	3.18	3.76
Eu	0.81	0.64	0.77	0.95	1.20	0.95	0.67	0.97	0.60	0.59	0.91	0.95
Gd	2.02	1.56	1.19	5.00	5.90	2.43	2.40	3.37	1.46	1.24	2.43	3.15
Tb	0.27	0.19	0.18	0.76	0.92	0.31	0.41	0.54	0.24	—	—	—
Dy	1.24	1.09	0.93	4.40	5.70	1.31	2.80	3.50	1.68	0.84	1.63	2.68
Ho	0.27	0.19	0.19	0.83	1.20	0.24	0.66	0.68	0.35	—	—	—
Er	0.78	0.56	0.62	2.40	3.30	0.69	2.10	1.99	1.10	0.41	0.81	1.39
Tm	0.12	0.06	0.10	0.32	0.46	0.10	0.31	0.27	0.16	—	—	—
Yb	0.75	0.33	0.66	1.90	3.00	0.52	2.10	1.74	1.07	0.38	0.70	1.18
Lu	0.13	0.06	0.10	0.28	0.44	0.09	0.30	0.25	0.16	0.07	0.13	0.19
Mo	0.5	0.5	0.4	0.5	0.8	<1	0.3	0.5	1.3	—	—	—
Pb	1.1	1.0	1.2	9.4	10.4	7.83	5.70	2.89	0.63	—	—	—
Yb <sub>N</sub>	4.4	1.9	3.9	11.2	17.6	3.1	12.4	10.2	6.3	2.2	4.1	6.9
(La/Yb) <sub>N</sub>	15.5	37.4	14.7	16.5	6.7	49.2	3.7	2.3	1.6	28.7	26.0	17.7
Eu/Eu*	1.2	1.3	2.0	0.5	0.6	1.0	0.9	0.9	1.4	1.2	1.0	0.8
Sr/Y	42.3	55.5	68.7	15.2	10.0	80.3	18.1	10.6	3.0	107.2	58.1	18.0
Nb/Ta	3.3	10.8	3.8	17	29.6	33.6	—	—	—	5.6	6.5	10.3

Note. For the description of samples see Table 1.

amphibolites strike NW 300°, dip NE 30°, inclination 75°; at the northern edge, their strike is changed to a latitudinal one.

A sample of trondhjemites (10-313) was taken in the area located ca. 500 m away from the southern outskirts of the Ivanivka village. The rock is fine-grained, the texture is lepidogranoblastic. Mineral composition (vol. %): plagioclase (albite) – 65; quartz – 25; biotite – 5-7; K-feldspar – 2-3; single grains of apatite, zircon, and opaque minerals. Feldspar is replaced by accumulations of secondary minerals.

In terms of the chemical composition [11], trondhjemites correspond to low alkaline granites ( $\text{SiO}_2 = 70.90\text{-}71.67$ ;  $\text{Al}_2\text{O}_3 = 14.69\text{-}15.61$  %;  $\text{Na}_2\text{O} = 5.24\text{-}5.26$  %;  $\text{K}_2\text{O} = 0.46$  %) of the sodium series (see Table 1). The Mg# of the rock is low (25.7-36.2). In the O'Connor-Barker diagram, they plot in the trondhjemite field. They are poor in Rb (2.8) and rich in Sr (657 ppm) (see Table 2). They also have a very low content of such HFSE as Y (1.3 ppm), Nb (0.6 ppm), Yb (0.5 ppm), and of transitional elements, namely, Ni (12.8 ppm) and Cr (15.5 ppm). Negative anomalies of Nb and Ti and positive anomalies of Sr and Eu (see Fig. 2, a) are seen in the multi-element diagram. The REE pattern is highly differentiated:  $(\text{La}/\text{Yb})_{\text{N}} = 49.2$ ,  $\text{Yb}_{\text{N}} = 3.1$  (see Fig. 2, b). In terms of their geochemical characteristics, trondhjemites correspond to TTGs [12].

Numerous amphibolite xenoliths of a uniform composition, a few meters in size, are found in trondhjemites in the Ivanivka area. In terms of the chemical composition, these are mafic rocks of the normal sodium series ( $\text{SiO}_2 = 49.57$  %;  $\text{TiO}_2 = 0.74$  %;  $\text{MgO} = 7.31$  %;  $\text{Na}_2\text{O} = 3.3$  %;  $\text{K}_2\text{O} = 0.50$  %) (see Table 1). They are low in Ti and have a low Mg# = 42. In terms of geochemical characteristics, they are similar to THI tholeiitic basalts.

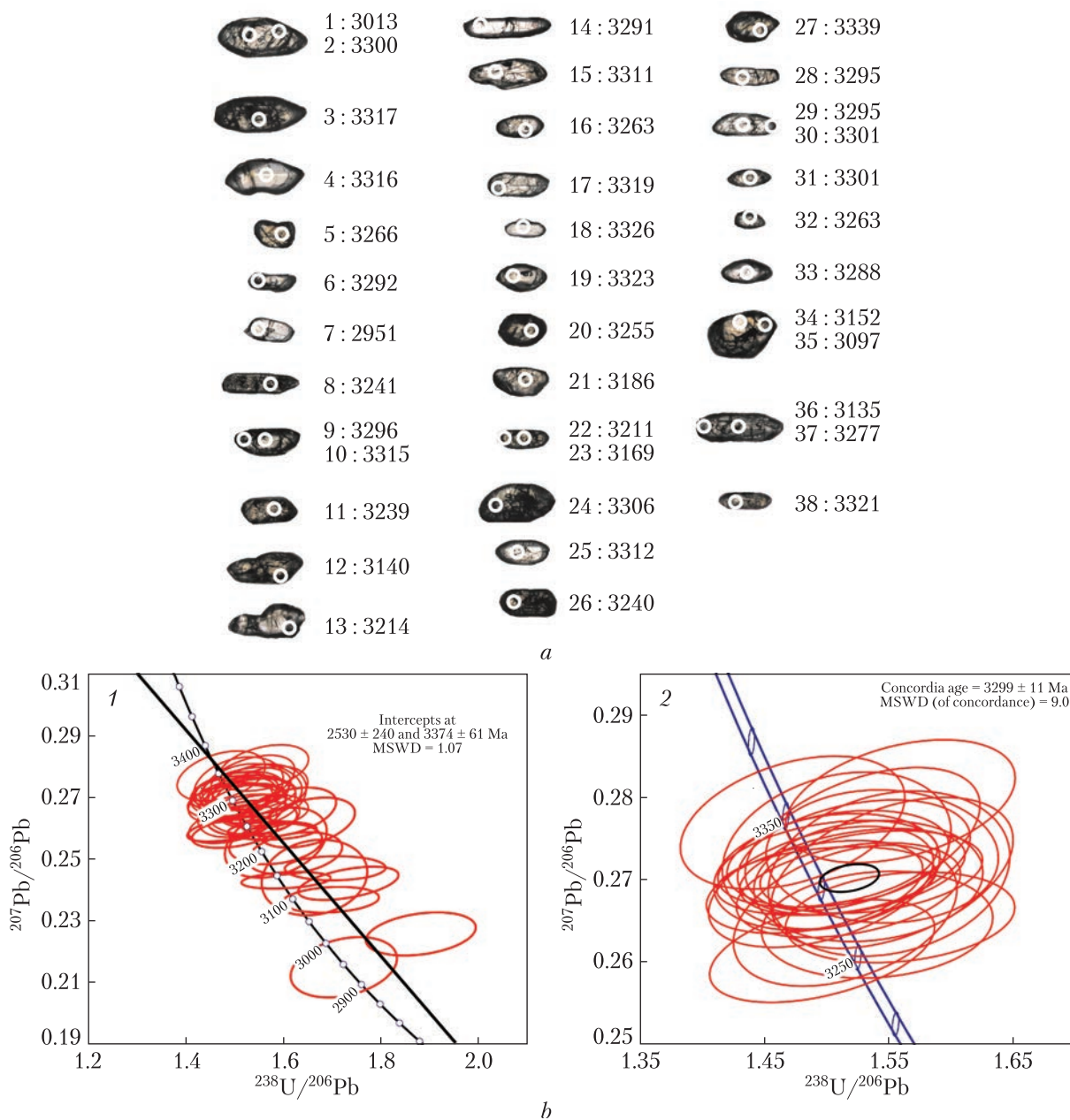
**Results of the U-Pb zircon dating.** We have analyzed 32 zircon grains in sample 10-441. In six grains, two analyses were performed, one in the core part of the crystal, and another one in the marginal part (Fig. 3, a). Altogether, 38 analyses were carried out in this sample. The results of these analyses are reported in Table 3.

In general, the obtained results spread along the discordia line that intercepts the concordia at  $3374 \pm 61$  and  $2530 \pm 240$  Ma (see Fig. 3, b). However, most of the results (22 spots) cluster near the upper intercept; the concordia age calculated for this cluster is  $3299 \pm 11$  Ma (see Fig. 3, c). We accept that age as the time of the primary tonalite crystallization. The lower intercept age may indicate a metamorphic event during which primary igneous tonalite was transformed into biotite gneiss. In the cases where zircon grains were analyzed in two spots, the core portions have yielded lower ages than the margins. This may be explained by variable Pb-loss during the metamorphic event rather than by the presence of younger zircon populations in the sample.

**Sample 10-313.** In total, 52 analyses have been performed in 42 grains separated from trondhjemite of the Saltycha anticline (Ivanivka village). Ten grains were analyzed both in the core and marginal parts of the crystals (Fig. 4, a). Results of the analyses are reported in Table 3.

Around 65 % of the analyses yielded concordant results, while the rest demonstrate a significant spread toward younger ages. The upper intercept age calculated for all results is  $3027 \pm 30$  Ma (the low intercept is at ca. 500 Ma, MSWD = 12) (see Fig. 4, b). The weighted average  $^{207}\text{Pb}/^{206}\text{Pb}$  age calculated for the concordant results is  $3013 \pm 15$  Ma (MSWD = 3.9). We assume that this age corresponds to the time of the initial trondhjemite crystallization.

**Discussion and conclusions.** The Paleoproterozoic (ca. 3.3 Ga) age of tonalites of the Lantsevo anticline in the Bilotserkivka structure has been established. A similar age was earlier obtained

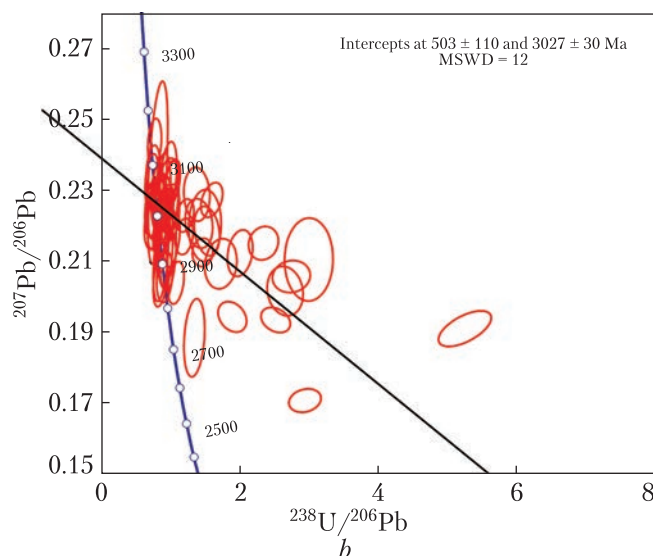
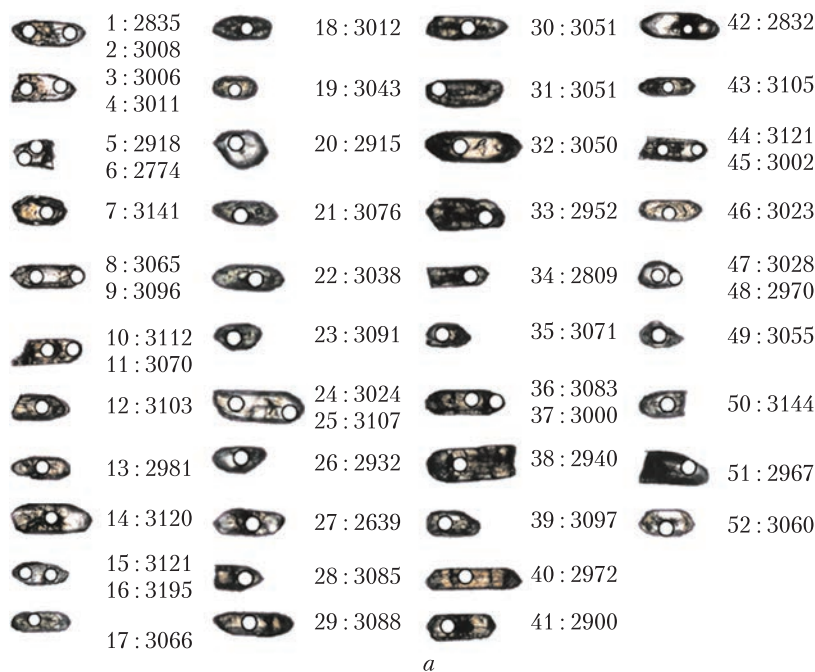


**Fig. 3. a:** Optical images of the studied zircon crystals from biotite gneisses of the Lantsevo anticline of the Bilotserkivka structure (sample 10-441). Numbers of the analyses and their  $^{207}\text{Pb}/^{206}\text{Pb}$  ages as in Table 3.

**b:** U-Pb diagram for zircons from biotite gneisses of the Lantsevo anticline of the Bilotserkivka structure (sample 10-441). 1 – diagram showing all results and corresponding concordia intercepts; 2 – the concordia age for the ca. 3000 Ma cluster

for tonalites located at 30 km in the western part of the Bilotserkivka structure (Verkhniy Tokmak area) [13]. Tonalites of the Lantsevo anticline have been formed under a medium pressure according to [12]. They have low concentrations of heavy REE and a positive anomaly  $\text{Eu}/\text{Eu}^* = 1.2$ . Rare earth elements are highly differentiated  $(\text{La}/\text{Yb})_N = 14.7\text{--}37.4$ ; Nb/Ta ratio varies





**Fig. 4.** *a*: Optical images of the studied zircon crystals from trondhjemite of the Saltycha anticline (sample 10-313). Numbers of the analyses and  $^{207}\text{Pb}/^{206}\text{Pb}$  ages as in Table 3.

*b*: U-Pb diagram with concordia for zircon from trondhjemite (Saltycha anticline, Ivanivka village, sample 10-313)

from 3.3 to 10.8. In contrast, tonalites of the Verhniy Tokmak area belong to the low-pressure TTG according to [12]. They have high concentrations of heavy REE and the negative anomaly  $\text{Eu}/\text{Eu}^* = 0.54\text{--}0.63$ . Rare earth elements are highly differentiated –  $(\text{La}/\text{Yb})_{\text{N}} = 6.65\text{--}16.50$ ;  $\text{Nb}/\text{Ta}$  ratio varies from 17 to 29.6.

Paleoproterozoic tonalites of the Lantsevo anticline contain remnants of supracrustal rocks metamorphosed in the granulite facies (two-pyroxene schists, pyroxene-magnetite quartzites, and gar-

Table 3. Results of U-Pb isotope dating of zircons from tonalite (sample 10-441) and trondhjemite (sample 10-313)

Analysis #	Isotope ratios				Isotope ages, Ma			Concentrations, ppm			
	$^{238}\text{U}/^{206}\text{Pb}$	$2\sigma$	$^{207}\text{Pb}/^{206}\text{Pb}$	$2\sigma$	Err Corr	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{238}\text{U}/^{206}\text{Pb}$	$2\sigma$	U	Pb	
Sample 10-441											
1	1.88218	0.09211	0.2257	0.0057	0.30	3300	2746	30	3013	206.8	67.7
2	1.49566	0.07382	0.2691	0.0060	0.43	64000	3303	36	3300	187.2	91
3	1.52207	0.07645	0.2727	0.0057	0.35	11700	3252	45	3317	132	73.8
4	1.50830	0.07507	0.2735	0.0078	0.25	18000	3273	49	3316	97.1	105.3
5	1.54083	0.07597	0.2645	0.0053	0.13	8200	3226	43	3266	267	127
6	1.51768	0.07371	0.2687	0.0047	0.35	200	3262	30	3292	256.9	146.5
7	1.72414	0.08918	0.2149	0.0080	0.30	2000	2951	55	2951	78.2	82.9
8	1.49009	0.07105	0.2598	0.0034	0.53	28000	3309	30	3241	832	1860
9	1.53374	0.07528	0.2698	0.0060	0.14	42000	3235	42	3296	201	108
10	1.50105	0.07210	0.2719	0.0043	0.34	10000	3290	31	3315	327	180.1
11	1.57779	0.07468	0.2592	0.0024	0.17	243000	3164	22	3239	1169	368
12	1.60565	0.07477	0.2431	0.0022	0.29	4000	3121	17	3140	952	68.8
13	1.58479	0.08539	0.2553	0.0093	0.33	10000	3145	64	3214	63.2	36.3
14	1.61031	0.08039	0.2652	0.0065	0.40	10000	3116	43	3291	157.4	63.1
15	1.50038	0.07429	0.2709	0.0058	0.25	30000	3290	38	3311	230	408
16	1.64745	0.08142	0.2618	0.0066	0.39	8300	3055	38	3263	181.6	74.9
17	1.54488	0.07637	0.2728	0.0066	0.03	8100	3215	38	3319	193	141
18	1.52905	0.07715	0.2749	0.0071	0.47	6000	3242	46	3326	121.1	104.9
19	1.55039	0.07932	0.2707	0.0082	0.21	3100	3219	47	3323	90.2	60.3
20	1.49656	0.07391	0.2613	0.0051	0.46	4000	3297	37	3255	238.7	207
21	1.62417	0.07914	0.2518	0.0056	0.30	15400	3095	31	3186	207	250
22	1.58454	0.07783	0.2549	0.0054	0.23	800	3152	31	3211	204	198.1
23	1.70649	0.08445	0.2470	0.0032	0.05	350000	2980	34	3169	754	98.4
24	1.53610	0.07315	0.2709	0.0041	0.29	22000	3231	28	3306	388	562
25	1.52091	0.07402	0.2709	0.0043	0.39	7600	3256	33	3312	418	520
26	1.50060	0.07206	0.2586	0.0041	0.39	40000	3294	29	3240	379	367.5
27	1.47275	0.07375	0.2769	0.0066	0.38	67000	3348	42	3339	155.2	258.8
28	1.49054	0.07109	0.2691	0.0046	0.40	55000	3312	32	3295	360	219.7

29	1.55958	0.07540	0.2795	0.0061	0.38	6500	3192	35	3355	35	239	276
30	1.5528	0.07957	0.2708	0.0075	0.43	3100	3202	52	3301	44	135.2	101.6
31	1.49993	0.07199	0.2698	0.0034	0.26	360000	3292	23	3301	20	800	766
32	1.53610	0.07551	0.2632	0.0047	0.19	84000	3234	33	3263	27	274	290
33	1.51515	0.07346	0.2656	0.0070	0.38	16000	3265	40	3288	40	142.3	116
34	1.66389	0.08859	0.2440	0.0100	0.15	11300	3050	59	3152	68	82.4	73.5
35	1.69751	0.08068	0.2368	0.0034	0.19	17000	2984	29	3097	23	474	252
36	1.73340	0.08413	0.2421	0.0044	0.50	1700	2934	32	3135	29	384	412
37	1.55933	0.07538	0.2654	0.0045	0.22	260000	3193	32	3277	27	373	423
38	1.50921	0.07289	0.2725	0.0048	0.29	1100	3280	35	3321	28	376	391
Sample 10-313												
1	2.77008	0.16881	0.1944	0.0035	0.28	61000	1978	66	2773	29	597	129.5
2	1.79856	0.09381	0.2160	0.0110	0.14	8400	2851	57	2947	84	46.1	47.8
3	1.89753	0.09722	0.2159	0.0062	0.44	68000	2736	51	2945	47	155	259
4	1.75747	0.08957	0.2167	0.0080	0.33	4200	2900	48	2950	60	85.4	155.2
5	1.95695	0.09574	0.2040	0.0049	0.33	23000	2659	33	2857	42	171.3	238
6	2.22222	0.12346	0.1885	0.0090	0.24	5100	2388	61	2712	85	65.4	79
7	1.62602	0.08196	0.2352	0.0061	0.23	7500	3092	45	3080	42	183	182.7
8	1.64745	0.08414	0.2224	0.0075	0.41	9100	3065	48	3004	57	126.1	94.8
9	1.76678	0.09052	0.2284	0.0049	0.16	270000	2893	52	3035	35	326	211.5
10	1.76991	0.10338	0.2292	0.0044	0.01	28000	2878	78	3051	31	333	151.8
11	1.87266	0.10521	0.2266	0.0099	0.50	102000	2760	71	3009	73	77.7	68.5
12	1.72117	0.10072	0.2260	0.0069	0.05	36000	2962	81	3043	48	213	102
13	2.34192	0.12066	0.2125	0.0032	0.07	60000	2297	46	2920	24	794	333
14	1.90114	0.09759	0.2319	0.0054	0.47	2000	2731	43	3059	37	298.6	528
15	1.60772	0.08013	0.2326	0.0062	0.30	19200	3114	43	3060	43	187.5	29.5
16	1.64881	0.08156	0.2433	0.0056	0.21	6600	3054	38	3135	37	259.1	130
17	2.08812	0.10465	0.2228	0.0038	0.27	14000	2521	34	3005	28	598	318
18	2.07426	0.10756	0.2170	0.0041	0.21	30000	2534	42	2951	31	570	123
19	1.60000	0.08192	0.2196	0.0051	0.17	33000	3131	51	2982	36	178	79.6
20	1.73611	0.08741	0.2051	0.0064	0.40	59000	2929	45	2853	52	135.9	64.7
21	1.60514	0.07987	0.2246	0.0064	0.26	1300	3120	42	3015	47	117.4	85.8
22	2.37530	0.19183	0.2201	0.0082	0.04	9600	2240	120	2977	62	231	139
23	2.47525	0.12866	0.2272	0.0040	0.37	10000	2184	46	3030	28	552	170
24	1.73130	0.08692	0.2170	0.0047	0.18	35000	2937	39	2963	35	177.7	60.7
25	1.76991	0.09085	0.2295	0.0089	0.26	800	2881	53	3046	60	66.2	1.37
26	3.62319	0.22317	0.2058	0.0037	0.08	4760	1566	57	2870	30	781	102.6
27	3.82117	0.18982	0.1708	0.0027	0.19	22000	1498	24	2575	27	1245	109.6

The end of Table 3

Analysis #	Isotope ratios						Isotope ages, Ma			Concentrations, ppm		
	$^{238}\text{U}/^{206}\text{Pb}$	$2\sigma$	$^{207}\text{Pb}/^{206}\text{Pb}$	$2\sigma$	Err Corr	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{238}\text{U}/^{206}\text{Pb}$	$2\sigma$	$^{207}\text{Pb}/^{206}\text{Pb}$	$2\sigma$	U	Pb
28	1.81752	0.08919	0.2257	0.0047	0.32	90000	2824	37	3024	34	250	62.2
29	1.72414	0.08918	0.2261	0.0057	0.12	20000	2944	50	3027	41	157.2	80.6
30	1.89502	0.09337	0.2237	0.0065	0.25	13600	2730	37	2990	47	148	160
31	1.80505	0.08797	0.2207	0.0049	0.32	9200	2854	37	2989	38	179.5	169
32	2.28833	0.16233	0.2206	0.0057	0.16	7100	2320	100	2988	42	368	61.8
33	2.60417	0.18989	0.2093	0.0057	0.12	6600	2080	100	2890	48	348	125
34	6.13121	0.31201	0.1911	0.0041	0.61	2600	974	18	2747	35	1399	261
35	1.66389	0.08859	0.2269	0.0087	0.52	5300	3038	59	3010	63	68.4	53.6
36	1.72414	0.08621	0.2268	0.0057	0.28	21000	2945	47	3021	40	250	114.1
37	3.22061	0.17633	0.2151	0.0038	0.12	11100	1740	47	2938	28	580.9	93
38	1.79212	0.09314	0.2057	0.0060	0.22	8600	2854	50	2878	48	183	103.2
39	2.25734	0.15287	0.2288	0.0062	0.08	13200	2350	94	3035	43	191	143
40	2.88268	0.14958	0.2123	0.0053	0.23	23000	1917	41	2910	41	440	59.8
41	3.53357	0.21226	0.2017	0.0057	0.13	10500	1616	51	2837	45	450	80
42	3.39789	0.17319	0.1935	0.0029	0.30	5320	1665	34	2769	24	1151	100.5
43	1.71438	0.08523	0.2294	0.0044	0.27	7400	2960	37	3044	32	281	204
44	1.84843	0.09908	0.2336	0.0082	0.35	4600	2790	58	3060	56	118	59.4
45	3.87597	0.28544	0.2105	0.0095	0.02	1000	1474	72	2940	72	202	6.6
46	2.40385	0.15024	0.2185	0.0056	0.22	4600	2232	78	2961	42	329	110.9
47	1.74216	0.08802	0.2190	0.0068	0.20	14100	2925	49	2966	50	71.4	9.2
48	1.83824	0.10137	0.2140	0.0100	0.18	500	2795	64	2907	79	47.1	34.9
49	1.75747	0.09575	0.2210	0.0048	0.22	11000	2899	64	2994	34	187	79.6
50	1.84502	0.10893	0.2323	0.0055	0.29	28000	2793	82	3082	38	215	136
51	1.73913	0.09074	0.2110	0.0100	0.43	2900	2926	53	2905	82	50.8	56.5
52	1.69205	0.12025	0.2350	0.0210	0.49	330	2980	130	3000	140	12.98	4.17
26	1.50060	0.07206	0.2586	0.0041	0.39	40000	3294	29	3240	25	379	367.5
27	1.47275	0.07375	0.2769	0.0066	0.38	67000	3348	42	3339	38	155.2	258.8
28	1.49054	0.07109	0.2691	0.0046	0.40	55000	3312	32	3295	27	360	219.7

net-pyroxene-magnetite rocks) of the unknown age. In terms of the chemical composition, two-pyroxene schists correspond to tholeiitic basalts and basaltic komatiites, whereas ferruginous-siliceous rocks correspond to the Algoma type which is typical of the Archean greenstone belts.

The Mesoproterozoic (ca. 3.0 Ga) age of trondhjemites of the Ivanivka area of the Saltycha anticline was determined. In terms of geochemical characteristics, they correspond to the TTGs [12]. They are strongly depleted in HFSE: Y (1.3 ppm), Nb (0.64 ppm), Yb (0.52 ppm). Rare earth elements are highly differentiated –  $(La/Yb)_N = 49.2$ . These trondhjemites are of the same age as TTGs of the Shevchenko complex that cut through the sedimentary-volcanogenic rocks of the greenstone structures in the Azov block. These trondhjemites could have been formed due to the partial melting at depths >40 km of metabasic rocks with a restite bearing garnet and/or hornblende.

A similar age was obtained for biotite and amphibole-biotite gneisses of the “Kainkulak beds” in the area of the Zrazkove village located on the Mokra Konka river (3.1-3.0 Ga) [5] and for biotite gneisses in the lower reaches of the Kainkulak river (2.92 Ga) [14]. Correspondingly, rocks of the “Kainkulak beds” represent TTGs of the Shevchenko complex transformed into gneisses in the Paleoproterozoic due to the dislocation metamorphism.

The Late Paleoproterozoic (ca. 3.3 Ga) TTGs occur in the West Azov and the Kursk Magnetic Anomaly block of the Voronezh crystalline massif [15]. They can also be present in the basement of the Middle Dnieper Domain, where detrital zircons of this age occur in the Vysokopylyia greenstone structure [16]. These data indicate that the extensive late Paleoproterozoic (ca. 3.3 Ga) protocraton existed in the eastern part of the Ukrainian Shield and the Kursk magnetic anomaly block of the Voronezh massif. Greenstone belts and TTGs were formed on this protocraton in the Mesoproterozoic (ca. 3.2-3.0 Ga) time.

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#### ПАЛЕОАРХЕЙСЬКІ ТА МЕЗОАРХЕЙСЬКІ ТТГ ЗАХІДНОГО ПРИАЗОВ'Я (УКРАЇНСЬКИЙ ЩИТ)

У Західній частині Приазовського блока знаходиться велика антиклінорна структура, яка складена породами мезоархейської (3,2–3,0 млрд років) граніт-зеленокам'яної асоціації. Вона розділена Білоцерківською структурою субширотного простягання на дві частини – північну, що включає Гуляйпільський і Ремівський блоки, і південну – Салтичанський антиклінорій. Визначено, що U-Pb вік плагіогнейсів Ланцівської антикліналі Білоцерківської структури становить  $3299 \pm 11$  млн років. За геохімічними характеристиками біотитові гнейси відповідають ТТГ. На відстані 30 км у західній частині Білоцерківської структури раніше нами були виявлені кварцеві діорити такого ж віку –  $3297 \pm 22$  млн років. Ці дані показують, що Білоцерківська структура є блоком давнього фундаменту. На Іванівській ділянці східної частини Салтичанського антиклінорію вивчені дислоковані тронд'єміти. Визначено, що U-Pb вік тронд'ємітів  $3013 \pm 15$  млн років. Ці тронд'єміти, таким чином, є одновіковими з ТТГ шевченківського комплексу, які проривають осадово-вулканогенні породи зеленокам'яних структур Приазовського мегаблока. Пізньопалеоархейські (3,3 млрд років) тоналіти, поширені на Західному Приазов'ї, знайдено також на мегаблоці КМА Воронежського кристалічного масиву, і, ймовірно, вони є у складі гнейсового фундаменту Середньопридніпровського блока, де у Високіпільській зеленокам'яній структурі було знайдено кластогенний циркон такого віку. Ці дані вказують на вірогідне існування більш давнього протократону віком 3,3 млрд років, на якому формувалися мезоархейські (3,2–3,0 млрд років) зеленокам'яні пояси східної частини УЩ і мегаблока КМА.

**Ключові слова:** Західне Приазов'я, Білоцерківська структура, Салтичанський антиклінорій, палеоархейський прократон, мезоархейський кратон, ТТГ, Український щит, циркон, U-Pb вік.