MONAZITES OF THE LATE GRANITIC PEGMATITES FROM ILMENY MOUNTAINS: AN AGE CHEMICAL DATING OF ZONAL AND SECTORIAL CRYSTALS

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Crystals of monazite-(Ce) from granitic amazonite pegmatite of the Blyumovskaya mine (N 50) and amazoniteless granitic pegmatite of the mine N 244 from the Ilmeny mountains of the Southern Urals are investigated. Heterovalent isomorphism according to the scheme $[(Th^{4+},U^{4+},Pb^{2+})_{1-x}Ca_x^{2+}] + Si^{4+} \leftrightarrow (REE^{3+},Y^{3+}) + P^{5+}$ is revealed in composition of the investigated monazites. Monazite-(Ce) from the granitic amazonite pegmatite of the Blyumovskaya mine with a semi-specious stones mineralization is enriched in Th and Pb and it is characterized by sharp sectoriality of composition with higher concentrations of ThO_2 (32 – 33 wt.%), UO_2 and PbO in pyramids of growth <110> and <32$\bar{2}$>, and with the lowest concentrations of these components in <101> pyramids. According to chemical dating, age of monazite from the Blyumovskaya mine accounts for 240 ± 11 – 12 million years. Monazite-(Ce) from granitic amazoniteless pegmatite of the mine N 244 is zonal with smaller concentrations of Th, U and Pb in the central zones of crystal. According to the ratio La_2O_3-Nd_2O_3 in monazite of the mine N 244, this vein is attributed to the late granitic pegmatites (formed before amazonite ones). Radiological age of the monazite from this vein is a little bit more ancient than from the Blyumovskaya (247 ± 16 million years) that corresponds with the data on sequence of formation of different pegmatites in the Ilmeny mountains.
4 tables, 6 figures, 11 references.
Keywords: monazite-(Ce), chemical dating of radiological age, granitic pegmatites of the Ilmeny mountains.

Structure of pegmatites and localization of monazite-(Ce)

Blyumovskaya mine was founded in 1835 by the fifth "gem stone" party under the direction of mining engineer F.F. Blum on a place of P.A. Versilov`s prospecting shaft on the latidunally directed hill situated in 2.5 km from the confluence of Cheremshanka river into the Ilmenskoe lake. The mine strips a vein of amazonite pegmatites with a length of about 150 m and thickness reaching up to 4 – 8 m (Minerals., 1949) in gneisses with amphibolite interbeds of the Ilmenogorsky stratum (PR1*il*). This vein has got its historical popularity not only because of the largest in the Ilmeny mountains (for that time) transparent crystals of topaz, but also due to the first findings of samarskite that was used during researches of radioactivity and gave to the world a new chemical element – samarium. In 1897 Blyumovskaya mine was examined by the participants of the VII International mineralogical congress. Pegmatite of this mine was one of the objects for A.E. Fersman during the development of pegmatite formation model and substantiation of the crystallographic induction law during cocrystallization of minerals.

In the vein, from selvage to the center occur coarse- and finegraphic zones with yellowish and pinkish microcline, fine- and coarsegraphic zones with greenish amazonite and albite, block zone with bluish-green amazonite, albite, topaz, and beryl. In eastern wall of the Academichesky passage, block zone is intersected by quartz-albite blastomylonite with accessory samarskite-(Y) (Melnikov, 1882; Popov, Popova, 2006). Crystals of monazite-(Ce) tabular along (100) and varying from 1 – 2 mm up to 1 – 2.5 sm in size have sites of induction surfaces (Fig. 1) with associating minerals: biotite (siderophyillite), almandine, ilmenorutile, ferrocolumbite, samarskite-(Y), and zircon (Fersman, 1940). Crystals of monazite – (Ce) generally have tabular shape with predominance of habitus form {100}, also crystals reveal areas of facets of the following different simple forms (in relative abundance): {110}, {120}, {101}, {$\bar{1}$01}, and {102}, other are rare. The idealized form of crystals is shown at Fig. 2.

Mine N 244 was founded in 1977 by E.P. Makagonov on submeridianal ridge of bedrock outcrops of gneisses and amphibolites in the extent of about 250 m of presumably Selyankinsky strata (A-PR*sl*) in a middle part of the Ilmeny reserve, in 3 km to the west from the lake Tatkul`. On the southern end of this ridge rocks are intersected by a vein of granitic graphic pegmatite (1 m thick) with almandine, biotite, zircon, ilmenite, gahnite, and monazite-(Ce). Small crystals of monazite-(Ce) up to 1 mm in size have elongated-tabular shape with prevalence of facets of the following forms: {100}, {110}, {102}, $\{\bar{3}22\}$; other are lesser developed.

Amazonite pegmatites are the latest in the Ilmeny mountains. Radiological age of different minerals according to 40 definitions by various methods accounts for about 240 million years (generalization, see. Popova *et al.*, 1982). Age of minerals belonging to pegmatite of the mine N 244 was not determined earlier.

Methodics of investigation

Chemical dating of radiological age of accessory monazites with the help of electron-sound microanalyzers is applied rather widely (Suzuki *et al.*, 1991; Montel *et al.*, 1996; Williams *et al.*, 1999; Suzuki, Kato, 2008; etc.). The method is based on an assumption that there was no loss of lead during evolution of monazites, and the initial concentration of lead during the formation of radioactive mineral is low and frequently equals to zero; thus simultaneous measurement of U, Th and Pb allows to receive the value of age from electron-sound microanalysis in individual grain (for ages more than 100 million years; probably, a little bit younger).

Images of monazite grains in secondary electrons are made at low force of current (3 nA) due to the fact that grains of the mineral have been mounted in epoxy resin. The analysis was carried out on electron-sound microanalyzer SX 100 of the Cameca firm with five wave spectrometers (Sp1-5). Pressure in the chamber of samples accounted for $8 \cdot 10^{-5}$ Pa, pressure in the field of electron gun accounted for $2.3 \cdot 10^{-6}$ Pa. In order to achieve the high resolution during the analysis of monazites with non-uniform distribution of elements accelerating voltage of 15 kV and force of a current of 250 nA was used. A corner of selection of X-ray radiation by wave spectrometers accounts for 40°, diameter of electron beam focused on a sample accounts for 2 micron. An operating mode of the detector is differential. Measured lines: Th M_α, U M_β, Pb M_α, P K_α, La L_α, Ce L_α, Pr L_β, Nd L_α, Sm L_β, Eu L_α, Gd L_β, Dy L_α, Ho L_β, Y L_α, Si K_α, Ca K_α. For analysis of Th, U, and Pb in monazite *M*-lines were more preferable than *L*-

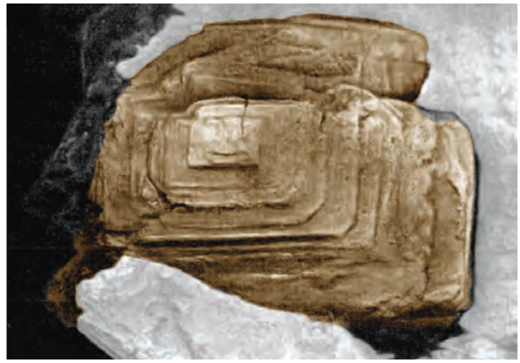

Fig. 1. Crystal of monazite-(Ce) 1.5 sm in size with induction surfaces with biotite (black) and microcline (light grey). Blyumovskaya mine. A.G. Zhabin`s photo (1960).

lines as energy of excitation for *L*-shells of thorium and uranium exceeds 15 keV. For the full quantitative analysis of monazites concentrations of uranium, thorium, lead, yttrium (numerous overlapping of lines of rare earth and other elements are taken into account), silicon, calcium, phosphorus and rare earth elements (for the account of numerous imposings of lines and matrix corrections) are determined. For acceleration of carrying out of the analysis determination of elements was produced on different spectrometers: Y and Si – on spectrometer Sp1 with crystal-analyzer TAP; U and Ca – on Sp2 with increased crystal LPET; Pb – on Sp3 with LPET; Th and P – on Sp4 with PET; lanthanides – on Sp5 with crystal-analyzer LIF. Measurements of intensities of peaks of U, Th and Pb were carried out during 300 seconds, other elements – during 10 seconds. For definition of the minimal error of monazites` age, the analysis was carried out during 600 seconds for peaks of U, Th and Pb. The following standard samples are used: for calculation of Th metal thorium and ThO_2 are used; for calculation of Si pyrope is used; for Ca – $Ca_2P_2O_7$; Y – YPO_4; for U – UO_2; for Pb – $Pb_2P_2O_7$; for Ce and P – $CePO_4$; for other rare earth elements monophosphatic glasses are also used.

In this article it is used the earlier suggested formula of dating of mineral age based on the

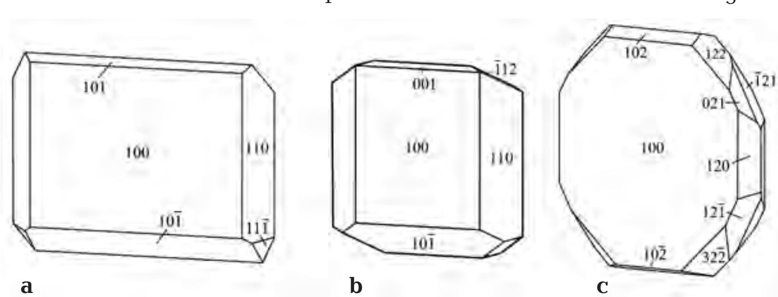

Fig. 2. The idealized form of monazite-(Ce) crystals from the Blyumovskaya mine. Crystals are measured by the authors and drawn according to the program Shape 7.1.

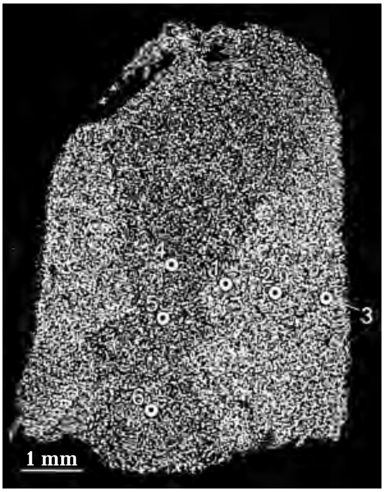

Fig. 3. Sectorial structure of monazite-(Ce) from the Blyumovskaya mine in X-ray characteristic radiation of Th M_α. Figures correspond to numbers of analyses in Table 1.

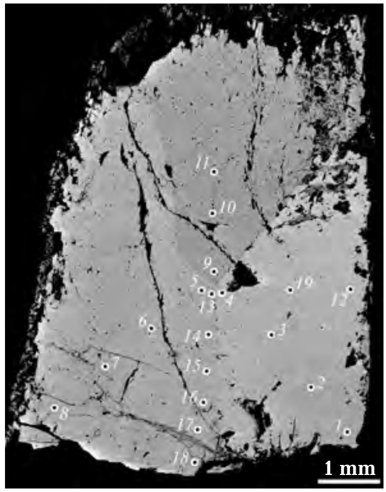

Fig. 4. Picture of sectoriality in secondary electrons in the new section (see the text) of monazite-(Ce) from the Blyumovskaya mine. Figures correspond to numbers of analyses in Table 2.

Table 1. **Chemical composition (wt.%) of monazite (Ce) from the Blyumovskaya mine**

	Prism *m* {110} zones of growth (see Fig. 3)				Pinacoid *x* {$\bar{1}$01} zones of growth			
№ an.	1 *c*	2	3 *e*	Average	4 *c*	5	6 *e*	Average
ThO_2	32.11	32.26	32.79	32.22	24.92	26.47	26.93	26.11
UO_2	*N.d.*	*N.d.*	1.13	1.13	*N.d.*	*N.d.*	1.04	1.04
P_2O_5	18.19	18.60	18.19	18.33	21.39	20.92	20.95	21.09
La_2O_3	5.72	5.70	3.04	4.82	6.26	6.17	5.87	6.10
Ce_2O_3	22.25	22.02	23.48	22.58	24.63	24.20	23.86	24.23
Pr_2O_3	2.66	2.47	2.76	2.63	3.27	3.13	2.89	3.10
Nd_2O_3	7.59	8.20	8.82	8.20	9.35	9.16	9.06	9.19
Sm_2O_3	1.58	1.56	1.52	1.55	1.93	1.55	1.91	1.80
Gd_2O_3	0.43	0.40	0.56	0.46	0.57	0.55	0.54	0.55
Dy_2O_3	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Y_2O_3	0.67	0.53	0.64	0.61	0.75	0.95	0.90	0.87
CaO	0.10	0.09	0.08	0.09	0.16	0.15	0.15	0.15
SiO_2	7.13	7.14	7.20	7.16	5.70	5.83	5.79	5.77
Total	98.43	98.97	100.21	99.78	98.93	99.08	99.87	100.0
Empirical formulas based on O = 4 (average data)								
Analyses 1 – 3: $(Ce_{0.36}Th_{0.32}Nd_{0.13}La_{0.08}Pr_{0.04}Sm_{0.02}Gd_{0.01}Y_{0.01}U_{0.01})_{0.98}(P_{0.68}Si_{0.32})_{1.00}O_4$;								
Analyses 4 – 6: $(Ce_{0.38}Th_{0.25}Nd_{0.14}La_{0.10}Pr_{0.05}Sm_{0.03}Gd_{0.01}Y_{0.02}U_{0.01}Ca_{0.01})_{1.00}(P_{0.76}Si_{0.25})_{1.01}O_4$								

Notes: Microprobe JXA-733 Superprobe with energy-dispersion spectrometer INCA, accelerating voltage 20 kV, electron beam diameter 5 micron, analyst E.I. Churin. Y_2O_3 and Eu_2O_3 (<0.3 wt. %) contents have been detected with the help of wave spectrometer. N. d. – not detected; c – center of the crystal, e – edge of the crystal.

equation of disintegration of parent isotopes of U and Th and accumulation of radiogenic lead (Montel *et al.*, 1996; Williams *et al.*, 1999). This formula has after transformations at a ratio of isotopes` abundance $^{238}U/^{235}U$ = 137.88 the following form: $Pb = Th\{\exp(\lambda^{232}t)-1\} + U[\{\exp(\lambda^{235}t) + 137.88\cdot\exp(\lambda^{238}t)\}/138.88-1]$, where Pb, U, and Th correspond to the contents of elements (in ppm); $\lambda^{232}, \lambda^{235}, \lambda^{238}$ correspond to constants of radioactive disintegration of ^{232}Th, ^{235}U, and ^{238}U; t corresponds to radiological age (in years).

The decision of the equation relatively to t with the use of the specialized software products gives the age of a mineral determined for grain in a point of the analysis.

Results of investigation and their discussion

Monazite-(Ce) of amazonite pegmatite of the Blyumovskaya mine of the Ilmeny mountains. The first data about contrast sectoriality of monazite-(Ce) composition from pegmatite of this mine have been received during investigation of monazites of different veins of the Urals according to the Task program of interdisciplinary projects between the UrO of the Russian Academy of Sciences and Siberian Branch of the Russian Academy of Sciences (Popova, Churin, 2009). With the help of X-ray spectral energy dispersive analysis in the section along (100) of monazite grains in zones of growth of a prism *m* {110} it is determined about 32 wt.% of ThO_2, and in the zones of pinacoid *x* $\{\bar{1}01\}$ it is determined 25 – 27 wt.% of ThO_2 (Fig. 3; tab. 1). Respectively, pyramids of growth $\langle 110\rangle$ contain higher concentrations of SiO_2 and smaller concentrations of P, La, Ce, and Y oxides. Such sharp differences in composition of the monazite-(Ce) growth pyramids of different simple forms have caused more detailed investigation of this grain.

After additional grinding and polishing of the asymmetric grain it was obtained the new section a little bit distinguishing from the early one. In secondary electrons and in X-ray characteristic radiation of Si, P, Ce and Th it was revealed more complex picture of the grain structure with additional sectors of growth of crystal facets differing in composition (Figs. 4, 5). According to facets occurring on crystals of monazite and pictures of distribution of elements, it is possible to assume display in the analyzed section not only sectors of growth $\langle 110\rangle$ and $\langle\bar{1}01\rangle$, but also $\langle 101\rangle$, $\langle 100\rangle$, $\langle\bar{1}\bar{2}\bar{2}\rangle$, $\langle 32\bar{2}\rangle$ and $\langle 1\bar{2}\bar{1}\rangle$ (Table 2). In sectors of growth of different simple forms the greatest contents of ThO_2 are characteristic for $\langle 110\rangle$ (from 33.8 wt.% in the central part of grain up to 31.6 % – on the periphery), and the least – for $\langle 101\rangle$ (22.7 – 22 wt.%); the analysis in $\langle 32\bar{2}\rangle$ is similar to average analyses in sector $\langle 110\rangle$. Concentration of ThO_2 in other sectors – $\langle 100\rangle$, $\langle\bar{1}\bar{2}\bar{2}\rangle$, $\langle 1\bar{2}\bar{1}\rangle$ accounts for 25.5 – 27 wt.% and are close to the data resulted for $\langle\bar{1}01\rangle$ (Table 1).

Directly proportional connection between the concentrations of ThO_2 with UO_2, PbO, SiO_2 and inversely proportional – between P_2O_5, rare earth elements, Y_2O_3, and CaO (Table 2) is distinctly shown. Concentrations of UO_2 and PbO within the limits of each sector of growth are relatively sustained. The sum of rare earths in different analyses accounts for 39 – 47 wt.% with absolute prevalence of Ce and Nd above La. According to the distribution of elements, it is possible to expect in monazite microinclusion of thorianite, cheralite, huttonite, apatite, and quartz (see Fig. 5, the right top corner) not influencing on the general laws of composition in sec-

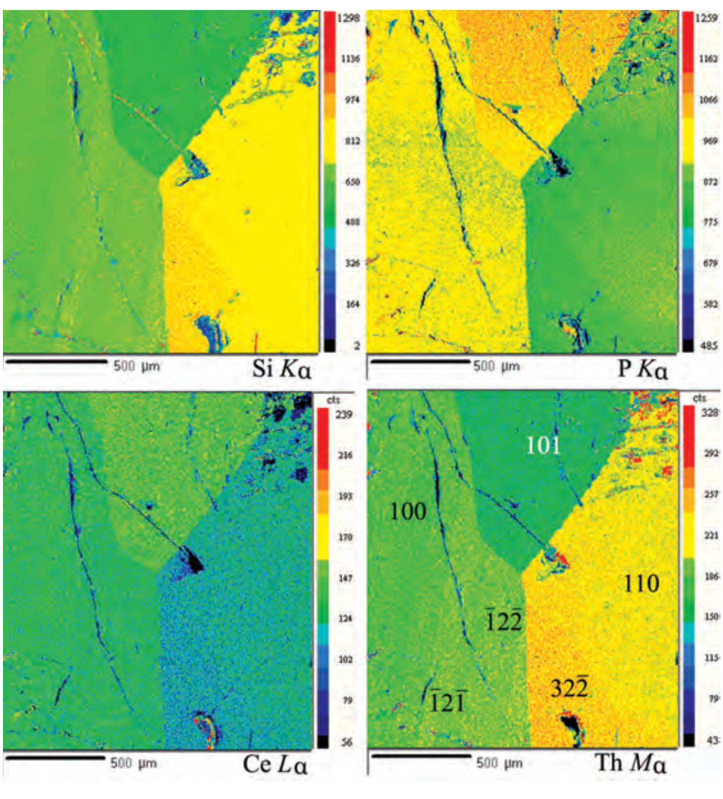

Fig. 5. Sectoriality of monazite-(Ce) composition in the central part of the grain (see Fig. 4) in X-ray characteristic radiation of elements.

Table 2. **Chemical composition wt.%) and radiological age (*t*, million years) of the monazite-(Ce) from the Blyumovskaya mine, new section**

	Composition in spots of analysis (see Fig. 4)																		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
ThO_2	32.75	31.84	33.41	33.78	26.87	26.99	25.52	26.16	22.71	22.25	22.04	31.57	27.03	27.09	27.19	27.59	28.64	26.15	32.38
UO_2	0.64	0.63	0.66	0.66	0.58	0.57	0.56	0.54	0.48	0.49	0.48	0.62	0.61	0.62	0.60	0.60	0.65	0.59	0.63
PbO	0.36	0.34	0.37	0.36	0.29	0.30	0.28	0.29	0.25	0.24	0.24	0.34	0.29	0.29	0.30	0.31	0.32	0.28	0.34
P_2O_5	17.59	17.59	17.28	16.98	19.99	19.93	20.69	20.74	21.64	21.94	21.99	18.32	19.39	19.17	19.15	19.11	19.11	19.63	17.15
La_2O_3	7.31	7.50	7.44	7.25	7.80	7.81	8.01	7.94	8.59	8.81	8.91	7.63	7.99	8.20	8.15	7.98	8.10	8.12	7.82
Ce_2O_3	20.92	21.43	21.38	20.81	23.16	22.93	23.61	23.24	24.66	24.85	24.85	21.65	23.20	23.04	23.19	22.55	22.62	23.26	21.20
Pr_2O_3	2.65	2.53	2.51	2.47	2.92	2.83	2.89	2.81	2.95	2.93	2.89	2.48	2.73	2.96	2.87	2.98	2.85	3.04	2.76
Nd_2O_3	7.80	8.02	7.94	7.72	9.13	8.89	9.18	8.87	9.34	9.58	9.63	8.04	8.88	8.81	8.73	8.85	8.45	8.78	7.73
Sm_2O_3	0.40	0.32	0.47	0.37	0.54	0.67	0.61	0.44	0.59	0.57	0.65	0.40	1.22	1.13	0.97	1.01	1.12	0.98	0.87
Eu_2O_3	–	–	0.10	–	–	–	–	–	–	0.01	–	–	–	0.04	–	0.07	–	–	–
Gd_2O_3	0.02	0.10	0.10	0.06	0.10	0.12	0.15	0.16	0.17	0.09	0.13	0.06	0.39	0.33	0.44	0.30	0.41	0.47	0.41
Dy_2O_3	0.03	0.07	0.08	0.08	0.08	0.09	0.07	0.05	0.07	0.05	0.10	0.07	–	0.09	–	–	0.06	0.09	–
Ho_2O_3	0.08	0.05	–	0.05	–	–	–	–	0.03	0.06	–	–	–	–	–	–	–	–	–
Y_2O_3	0.51	0.51	0.53	0.52	0.75	0.73	0.78	0.67	0.74	0.77	0.76	0.57	0.74	0.73	0.74	0.70	0.67	0.71	0.51
CaO	0.15	0.15	0.14	0.14	0.24	0.23	0.25	0.24	0.25	0.26	0.25	0.15	0.22	0.23	0.23	0.21	0.20	0.30	0.14
SiO_2	7.37	7.16	7.54	7.61	5.87	5.93	5.62	5.73	4.88	4.78	4.72	7.08	5.86	5.86	5.90	6.02	6.13	5.83	7.16
Total	98.59	98.26	99.95	98.88	98.32	98.01	98.21	97.88	97.34	97.68	97.66	98.99	98.57	98.58	98.48	98.28	99.31	98.23	99.11
t	**242**	**241**	**245**	**240**	**242**	**245**	**241**	**243**	**239**	**237**	**244**	**238**	**236**	**233**	**240**	**245**	**244**	**237**	**237**
$\pm\Delta t$	11	11	11	11	11	11	11	11	11	11	11	11	12	12	12	12	12	12	12

Empirical formulas for average analyses from different sectors of growth (O = 4)

<110> – an. 2–4, 12, 19 (average of 5 analyses.): $(Ce_{0.35}Th_{0.33}Nd_{0.12}La_{0.12}Pr_{0.04}Sm_{0.01}Y_{0.01}U_{0.01}Ca_{0.01})_{1.00}(P_{0.66}Si_{0.33})_{0.99}O_4$;

<$\bar{1}\bar{2}\bar{2}$> – an. 5, 13–18 (average of 7 analyses): $(Ce_{0.37}Th_{0.27}Nd_{0.14}La_{0.13}Pr_{0.05}Sm_{0.02}Gd_{0.01}Y_{0.02}U_{0.01}Ca_{0.01})_{1.03}(P_{0.72}Si_{0.26})_{0.98}O_4$;

<101> – an. 9–11 (average of 3 analyses): $(Ce_{0.39}Th_{0.22}Nd_{0.15}La_{0.14}Pr_{0.05}Sm_{0.01}Y_{0.02}Ca_{0.01})_{0.99}(P_{0.80}Si_{0.21})_{1.01}O_4$

Note. Analyses in sectors of growth: 1 – <$32\bar{2}$>; 2–4, 12, 19 – <110>; 9–11– <101>; 7–8 – <100>; 5, 13–18 – <$\bar{1}\bar{2}\bar{2}$>; 6 – <$1\bar{2}\bar{1}$>. Microprobe SX 100 Cameca, analyst V.V. Hiller. Dash – not detected (less than detection limit).

tors of crystal growth. Calculated values of radiological age *t* in different points of the analysis make from 233 up to 245 million years (average of 19 definitions accounts for 240 ± 11–12 million years) that is comparable to the available average data obtained by other methods of analysis of minerals from this vein.

Monazite-(Ce) of the granitic pegmatite from the mine N 244 of the Ilmeny mountains is investigated also in section along (100) of elongated-tabular crystal (Fig. 6). In secondary electrons distinct zones of facet growth of simple forms {$\bar{1}$10}, {$\bar{1}$22}, {$\bar{3}$22}, {$\bar{3}$02}, {102} were revealed; zones are characterized by different thickness at rather same alternation of dark (more "light ") and light-coloured zones; the central part of a crystal, probably, is a zone {100}. Profile of microprobe analysis is passed only through the parts of sectors of forms <$\bar{1}$22>, <100>, <$\bar{1}0\bar{2}$> and <$32\bar{2}$> (Table 3). Dark zones of the central part of the crystal contain about 14 wt.% of ThO_2, and light peripheral – up to 19–23%. Comparison of compositions of peripheral zones of growth sectors <$\bar{1}$22> (Table 3, analyses 3, 4, 6) and zones corresponding to them in sector <$\bar{1}0\bar{2}$> (Table 3, analyses 11, 12, 13) shows their significant distinction: in <$\bar{1}$22> in analyses 3 and 4 concentration of ThO_2 is lower than in respective zones <$\bar{1}0\bar{2}$> (analyses 11, 12), but in analyses 6 and 13 the relationship is reverse; distinctions and contents of P, Si, Ce, and Y oxides are shown that reflects sectoriality of composition of monazite-(Ce) crystal. Coefficients of correlation of oxides in the monazites` composition show (Table 4) strong positive connections between the contents of ThO_2-UO_2-PbO-SiO_2; P_2O_5-La_2O_3-Ce_2O_3-CaO; Y_2O_3-Dy_2O_3 and accordingly inverse relationship between these groups. According to the monazite from the mine N 244 analyses, average value of radiological age accounted for 247 ± 16 million years (on 16 analyses).

Conclusions

Heterovalent isomorphism is revealed in composition of the investigated monazites-(Ce) according to the scheme $[(Th^{4+},U^{4+},Pb^{2+})_{1-x}Ca_x^{2+}] + Si^{4+} \leftrightarrow (REE^{3+},Y^{3+}) + P^{5+}$. Monazite-(Ce) from granitic amazonite pegmatite of the Blyumovskaya mine with a gem stone mineralization is enriched in Th and Pb and is charac-

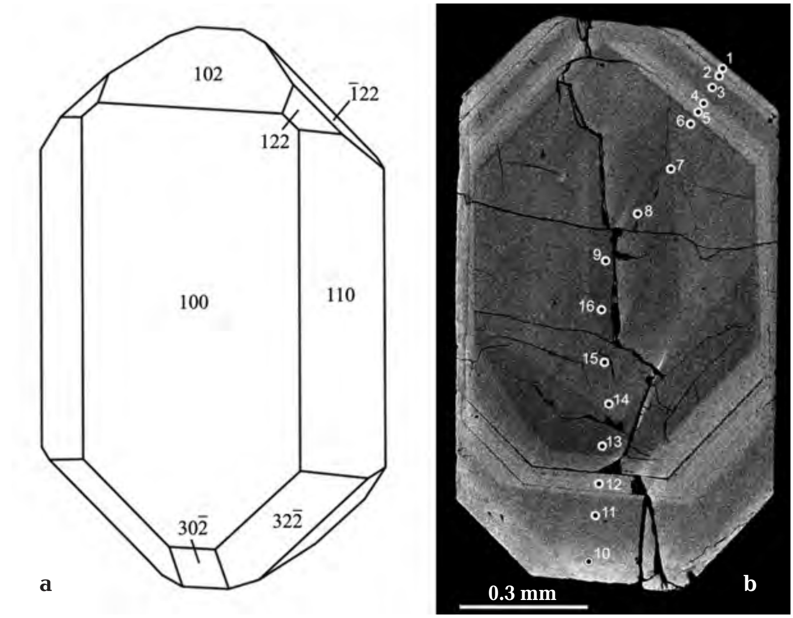

Fig. 6. The ideal form (the crystal is measured by the authors and it is drawn according to the program Shape 7.1): a — zonality in secondary electrons; b — sections of monazite-(Ce) crystal from pegmatite N 244 of the Ilmen mountains. Figures correspond to the numbers of analyses in the Table 3.

Table 3. **Chemical composition (wt.%) and calculated age (*t*, million years) of monazite-(Ce) from pegmatite of the mine N 244**

	Composition in spots of analysis (see Fig. 6)															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
ThO_2	22.07	20.99	15.38	19.39	20.41	15.74	13.90	13.92	14.21	18.12	16.32	23.06	12.15	15.57	15.20	14.12
UO_2	1.08	1.09	0.86	1.08	1.09	0.64	0.63	0.62	0.63	0.94	0.90	1.17	0.50	0.64	0.66	0.61
PbO	0.25	0.24	0.19	0.24	0.25	0.19	0.18	0.17	0.17	0.22	0.20	0.28	0.15	0.18	0.18	0.17
P_2O_5	21.38	21.93	24.60	22.15	21.84	24.64	26.41	25.74	25.37	24.17	23.84	20.85	26.09	25.04	25.03	25.57
La_2O_3	10.25	11.44	12.40	11.55	11.30	12.63	13.03	12.84	12.83	11.92	12.24	10.85	13.23	12.42	12.35	13.09
Ce_2O_3	21.90	22.47	25.23	23.74	23.34	24.54	25.26	25.17	25.04	23.68	24.28	22.03	25.80	24.60	24.31	25.08
Pr_2O_3	2.45	2.38	2.78	2.56	2.44	2.57	2.50	2.53	2.78	2.37	2.57	2.42	2.94	2.54	2.64	2.55
Nd_2O_3	9.00	8.25	9.08	9.13	8.93	9.14	8.93	9.06	8.87	8.65	8.94	8.46	9.82	9.34	9.14	8.91
Sm_2O_3	1.39	1.18	1.22	1.14	1.22	1.18	1.28	1.34	1.30	1.16	1.31	1.03	1.34	1.46	1.39	1.34
Eu_2O_3	0.02	0.04	–	0.05	0.03	0.03	0.02	0.13	–	–	0.07	0.05	0.02	0.03	0.05	0.03
Gd_2O_3	1.01	0.97	1.04	0.91	0.89	0.97	0.93	1.10	0.96	0.97	1.06	0.70	1.04	1.07	1.31	1.01
Dy_2O_3	0.21	0.25	0.21	0.17	0.18	0.22	0.27	0.31	0.24	0.35	0.26	0.20	0.24	0.26	0.29	0.25
Y_2O_3	0.65	0.88	0.78	0.56	0.73	0.76	0.84	0.84	0.81	1.02	0.83	0.76	0.78	0.77	0.86	0.82
CaO	0.31	0.55	0.42	0.25	0.27	0.91	1.03	0.99	1.00	0.68	0.46	0.26	0.83	0.87	1.04	0.99
SiO_2	4.75	4.38	3.24	4.35	4.53	2.69	2.19	2.17	2.30	3.32	3.29	5.04	1.94	2.65	2.47	2.25
Total	96.71	97.06	97.43	97.27	97.47	96.85	97.40	96.95	96.50	97.58	96.58	97.16	96.86	97.45	96.94	96.78
***t*±16**	**228**	**234**	**243**	**252**	**246**	**256**	**263**	**250**	**247**	**247**	**247**	**247**	**250**	**247**	**247**	**244**

Empirical formulas of selected analyses (O = 4)

Center <100> – analyses 7–9, 16 (average of 4 analyses): $(Ce_{0.39}La_{0.21}Nd_{0.13}Th_{0.13}Ca_{0.04}Pr_{0.04}Sm_{0.02}Gd_{0.01}Y_{0.02}U_{0.01})_{1.00}(P_{0.91}Si_{0.09})_{1.00}O_4$;

earlier zone <$\bar{1}22$> – analyses 6: $(Ce_{0.38}La_{0.20}Nd_{0.14}Th_{0.15}Ca_{0.04}Pr_{0.04}Sm_{0.02}Gd_{0.01}Y_{0.02}U_{0.01})_{1.01}(P_{0.88}Si_{0.11})_{0.99}O_4$;

the same zone <$\bar{1}0\bar{2}$> – analyses 13: $(Ce_{0.39}La_{0.20}Nd_{0.15}Th_{0.12}Ca_{0.04}Pr_{0.04}Sm_{0.02}Gd_{0.01}Y_{0.02})_{0.99}(P_{0.92}Si_{0.08})_{1.00}O_4$;

later zone <$\bar{1}22$> – analyses 4: $(Ce_{0.38}Th_{0.19}La_{0.18}Nd_{0.14}Pr_{0.04}Sm_{0.02}Gd_{0.01}Y_{0.01}Ca_{0.01}U_{0.01})_{0.99}(P_{0.81}Si_{0.19})_{1.00}O_4$;

the same zone <$\bar{1}0\bar{2}$> – analyses 12: $(Ce_{0.35}Th_{0.23}La_{0.18}Nd_{0.13}Pr_{0.04}Sm_{0.02}Gd_{0.01}Y_{0.02}Ca_{0.01}U_{0.01})_{1.00}(P_{0.77}Si_{0.22})_{0.99}O_4$

Note. Analyses in sectors of growth: 1–6 – <$\bar{1}22$>; 7–9, 16 – <100>; 10–13 – <$\bar{1}0\bar{2}$>; 14–15 – <$32\bar{2}$>. Microprobe SX 100 Cameca, analyst V.V. Hiller. Dash – not detected (less than detection limit)).

Table 4. **Correlation matrix of components in the composition of monazite-(Ce) from the mine № 244**

	ThO_2	UO_2	PbO	P_2O_5	Ce_2O_3	La_2O_3	Nd_2O_3	Pr_2O_3	Sm_2O_3	Gd_2O_3	Dy_2O_3	Eu_2O_3	SiO_2	CaO
UO_2	**0.95**													
PbO	**0.98**	**0.96**												
P_2O_5	-0.98	-0.95	-0.96											
Ce_2O_3	-0.97	-0.88	-0.93	**0.93**										
La_2O_3	-0.97	-0.91	-0.94	**0.95**	**0.96**									
Nd_2O_3	-0.62	-0.62	-0.62	0.53	0.63	0.48								
Pr_2O_3	-0.69	-0.61	-0.68	0.56	0.71	0.60	**0.72**							
Sm_2O_3	-0.54	-0.61	-0.63	0.53	0.42	0.37	0.56	0.33						
Gd_2O_3	-0.55	-0.54	-0.63	0.53	0.44	0.41	0.45	0.36	**0.75**					
Dy_2O_3	-0.42	-0.43	-0.45	0.55	0.30	0.42	-0.08	-0.13	0.31	0.49				
Eu_2O_3	-0.02	-0.02	-0.01	-0.02	-0.01	0.02	-0.02	-0.21	0.09	0.20	0.17			
SiO_2	**0.98**	**0.98**	**0.98**	-0.99	-0.91	-0.95	-0.54	-0.58	-0.56	- 0.56	- 0.54	- 0.03		
CaO	-0.81	-0.91	-0.84	**0.88**	0.69	**0.82**	0.29	0.32	0.52	0.52	0.62	0.05	- 0.91	
Y_2O_3	-0.30	-0.28	-0.31	0.42	0.21	0.37	-0.33	-0.14	0.03	0.26	**0.86**	-0.06	-0.40	0.49

Note. Strong positive relationships are bold.

terized by sharp sectoriality of composition with higher concentrations of ThO_2, UO_2 and PbO in pyramids of growth <110> and <32$\bar{2}$> and lowerst – in <101>; average age of monazite according to chemical dating accounts for 240 ± 11 – 12 million years.

Monazite-(Ce) from granitic amazoniteless pegmatite from the mine N 244 is zonal in composition with lower concentrations of Th, U and Pb in central zones of the crystal and increased concentrations in peripheral zones alternating with less rich. Monazite from the mine N 244 contains more La than Nd. According to the relashionship in it La_2O_3 – Nd_2O_3 (in percentage from the sum of *TR*), this vein is attributed to the late granitic (preamazonite) pegmatites (Popova, etc., 1982). Average radiological age of monazite from this vein is a little bit more ancient than from the Blyumovskaya mine and accounts for 247 ± 16 million years that corresponds to the data on sequence of formation different type pegmatites in the Ilmeny mountains (Popov, Popova, 2006).

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References

Fersman A.E. Pegmatites. V. 1. Granitic pegmatites. M.-L.: Acad. Sci. USSR. **1940**. 712 p.

Melnikov M.P. Ilmen mineral mines // Gorny zhurnal. **1882**. V. 1. P. 70 – 150.

Minerals of the Ilmensky reserve // Ed. A.N. Zavaritskyy. M.-L.: Acad. Sci. USSR, **1949**. 659 p.

Montel J.-M., Foret S., Veschambre M., Nicollet C., Provost A. Electron microprobe dating of monazite // Chemical Geology. **1996**. V. 131. P. 37 – 53.

Popov V.A., Popova V.I. Mineralogy of pegmatites of the Ilmen mountains // Mineralogical almanac. M.: "Ekost". **2006**. V. 9. 151 p.

Popova V.I., Churin E.I. Zonality and sectoriality of monazite-(Ce) composition of granitic pegmatites of Middle and Southern Urals // Zapiski RMO. **2009**. N. 5. P. 77 – 90.

Popova V.I., Popov V.A., Polyakov V.O., Shcherbakova E.P. Pegmatites of the Ilmen mountains. Sverdlovsk: UNTz Rus. Acad. Sci. USSR. **1982**. 49 p.

Suzuki K., Adachi M., Tanaka T. Middle Precambrian provenance of Jurassic sandstone in the Mino Terrane, central Japan: Th-U-total Pb evidence from an electron microprobe monazite study // Sedimentary Geology. **1991**. V. 75. P. 141 – 147.

Suzuki K., Kato T. Chemical dating of monazite, xenotime, zircon and polycrase: Protocol, pitfalls and chemical criterion of possibly discordant age data // Gondwana Research. **2008**. V. 14. P. 569 – 586.

Williams M.L., Jercinovic M.J., Terry M.P. Age mapping and dating of monazite on the electron microprobe: Deconvoluting multistage tectonic histories // Geology. **1999**. V. 27. N. 11. P. 1023 – 1026.

Zhabin A.G. About the time of formation of minerals of niobium, zirconium and rare earths in granitic pegmatite of the Blyumovskaya mine // Questions of mineralogy, geochemistry and genesis of deposits of rare elements. Proc. IMGRE. **1960**. V. 4. P. 74 – 84.