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Specific Features of the Mineral Composition of Titanium–Zirconium Placers in Russia

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Abstract—Specific features of the mineral composition of economically promising titanium–zirconium placers in Russia are analyzed. Generalization of the data made it possible to classify titanium–zirconium deposits with respect to different parameters of mineral composition, which can govern technological properties, and to identify specific characteristics with insignificant differences. Ore sands of titanium–zirconium placers are characterized by the following qualitative characteristics: TiO_2 content; mineral form of this dioxide (zircon); mineral-carriers of elements that degrade the quality of sands (primarily, Cr and P); physical properties of minerals; grain size composition of sands; and mass and composition of clayey fraction in the sands. Characteristics of the currently exploited Malyshev deposit are given.

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In other countries, complex coastal-marine placers (CMP) are virtually the single source of whole rutile, more than 95% of zircon, and more than 70% of ilmenite that accounts for 55.2% of the reserve. Among all titanium deposits currently exploited in the world, only three deposits belong to the native type, while the majority of deposits belong to the complex CMP type. Grades in the exploited CMPs are as follows: 50–100 kg/m^3 (occasionally, more) for ilmenite, 5–10 kg/m^3 for rutile, and 3–30 kg/m^3 for zircon. In the former Soviet Union (FSU), the CMPs also yielded more than 90% of the whole zirconium raw material, including as much as 10% obtained from baddeleyite concentrates of the Kovdor deposit and nearly 50% of ilmenite concentrates (the remaining part was extracted from monomineral ilmenite placers of the Irshin group). In total, the FSU territory incorporates approximately 20 CMP deposits of various scales and exploration degrees, including 4 deposits in the Ukraine, 4 deposits in Kazakhstan, and 12 deposits in Russia. As compared to deposits in other countries, CMP deposits in Russia are characterized by lower concentrations of ilmenite, rutile, zircon, and other minerals; worse geographic–economic and mining–technological conditions (thick overburden); and worse mineralogical–technological properties of sands (high clay content and fine-grained structure). In the CIS states, the sole exploited deposit of this type is represented by the Malyshev (Samotkan) deposit (Dnepropetrovsk district, southern Ukraine) that was discovered in 1954 and put into operation in 1961 by the Verkhne-Dneprovsk mining-metallurgical plant. The Malyshev deposit is provided with adequate reserves for not more than 15 yr. At the same time, contents of the major useful components and, consequently, the output of commercial concentrates are significantly decreasing. Perspectives of the growth of placer reserves are unfavorable in the Ukraine. In Russia, we have a number of well-explored placer deposits (with demonstrated reserves) that can satisfy the internal consumption for some tens of years, such as the Lukoyanov (Nizhegorod district), Central (Tambov district), Tugan (Tomsk district), Tarsk (Omsk district), and Ordyn (Novosibirsk district) deposits. The Beshpagir deposit (Stavropol region) represents the best studied and largest object among the titanium–zirconium placer deposits with inferred reserves (Fig. 1, Table 1).

ANALYSIS OF THE MINERAL COMPOSITION OF TITANIUM–ZIRCONIUM PLACERS

Based on the rational complex of mineralogical–analytical methods (Izoitko, 1999; Sidorenko *et al.*, 1997), we analyzed specific features of the mineral composition of the Beshpagir, Central, Lukoyanov, Ordyn, and Tarsk deposits; the mineral composition and grain size distribution of sands therein; physical, chemical, and morphostructural properties of minerals; and other parameters.

Chemical composition of ore sands. We did not observe any significant differences in the chemical composition of ore sands in the studied deposits. The most important conclusions obtained from the chemical analysis are related to the contents of useful components (titanium and zirconium oxides) and hazardous admixtures (P and Cr). Contents of the major oxides vary within a relatively narrow range (Fig. 2). The highest contents of titanium and zirconium oxides are observed in the Beshpagir and Lukoyanov deposits.

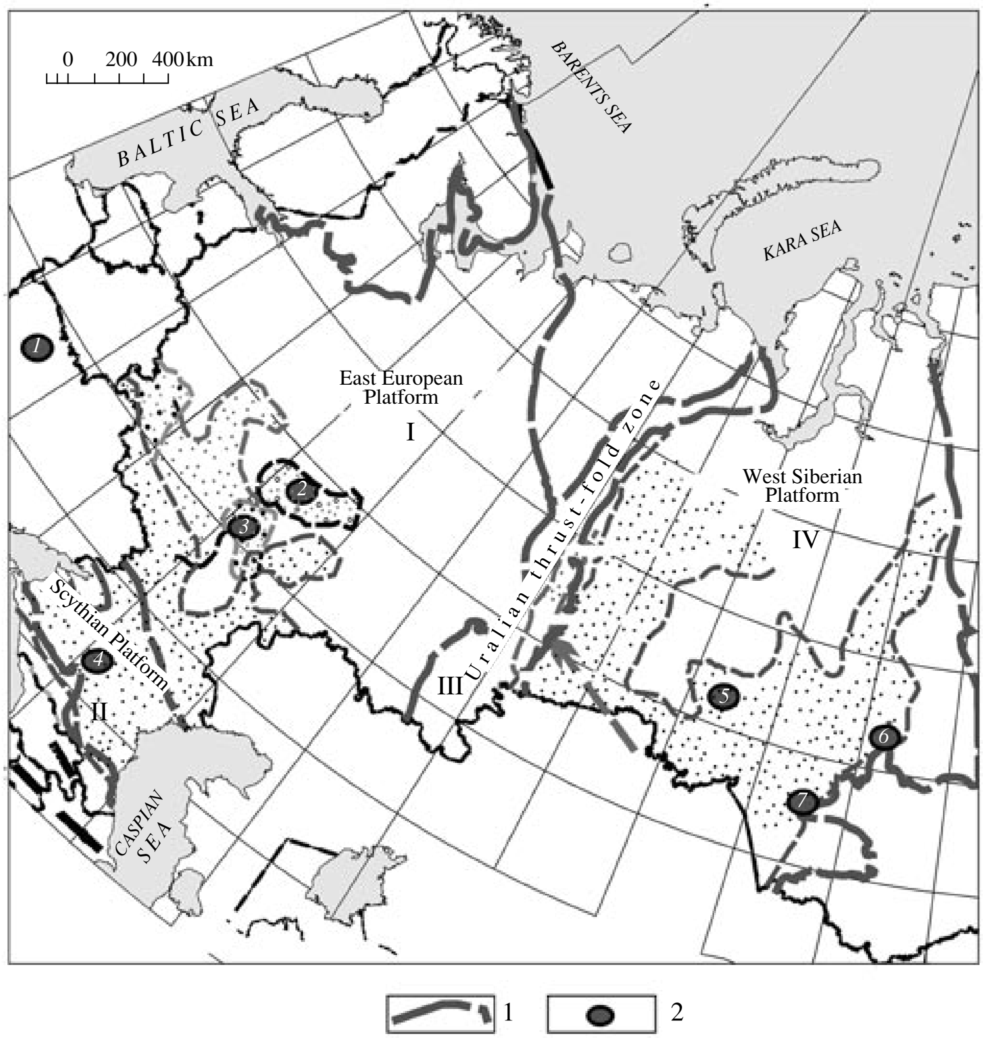

Fig. 1. Sketch map of titanium–zirconium placers in Russia. (1) Boundaries of titanium–zirconium placer provinces: (I) East European, (II) North Caucasian; (III) Uralian, (IV) West Siberian; (2) titanium–zirconium placer deposits: (*1*) Malyshev, (*2*) Central, (*3*) Lukoyanov, (*4*) Beshpagir, (*5*) Tarsk, (*6*) Tugan, (*7*) Ordyn.

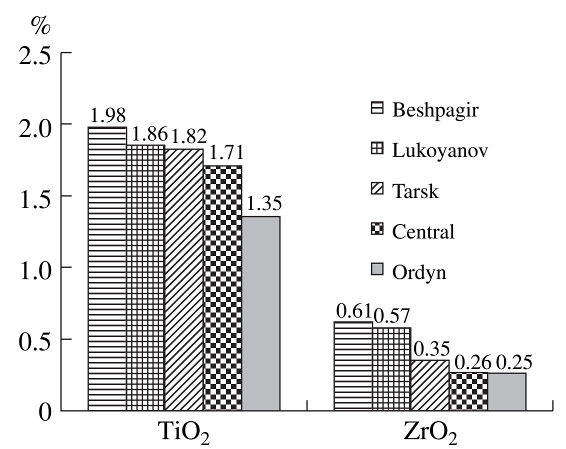

Fig. 2. Contents of titanium and zirconium oxides in ore sands of titanium–zirconium deposits.

However, rocks of the Lukoyanov deposit contain the highest amount of hazardous admixture (Cr), while rocks of the Central deposit contain abundant P (Table 2). The Central and Lukoyanov deposits are marked by the highest Fe content. We did not observe other noticeable differences in the chemical composition of samples from different deposits. Contents of the major oxides are generally consistent with the mineral compositions, the characteristics of which usually serve as a key to solution of the problem of dressability of sands.

Grain size composition of sands. Data on the grain size composition of sands in titanium–zirconium placer deposits of Russia show that the Beshpagir and Central deposits are the closest analogues of the Malyshev deposit in terms of grain size distribution. Among deposits in western Siberia, the Tugan deposit is the closest counterpart, although the content of fine-grained material in this deposit is as much as 18% (Table 3). Like the

Table 1. Characteristics of economic placer deposits in Russia and Ukraine

Placer province, country	Deposit	Average content of ore minerals,* kg/m^3		
		Ilmenite	Rutile + leucoxene	Zircon
East European	Central	36.42	8.3	7.28
	Lukoyanov	90.54**	6.93	24.32
West Siberian	Ordyn	25.91	5.41	6.82
	Tarsk	27.9	4.9	4.7
	Tugan	30.4	4.6	10.7
North Caucasian	Beshpagir	23.65	9.44	9.91
Ukraine	Malyshev	41.6	15.2	9.8

Note: *In top-priority development sectors; **ilmenite + chromite + hematite.

Table 2. Average content of hazardous admixtures in ore sands of deposits, %

Oxide	Beshpagir	Central	Ordyn	Tarsk	Lukoyanov
Cr_2O_3	0.08	0.012	0.053	0.07	0.49
P_2O_5	0.05	0.789	0.05	<0.02	0.12

Table 3. Classification of deposits based on grain size composition of sands

<table>
<tr><th>Class, mm</th><th colspan="7">Yield of dominant grain size from the initial sand, %</th></tr>
<tr><td colspan="8">With respect to grain size in productive classes</td></tr>
<tr><td></td><td>Malyshev</td><td>Central</td><td>Tugan</td><td>Lukoyanov</td><td>Beshpagir</td><td>Ordyn</td><td>Tarsk</td></tr>
<tr><td>−0.25 + 0.14</td><td rowspan="3">85.2</td><td rowspan="3">83.8</td><td rowspan="3">49.8</td><td rowspan="3">45.6</td><td></td><td></td><td></td></tr>
<tr><td>−0.14 + 0.1</td><td rowspan="3">89.4</td><td></td><td></td></tr>
<tr><td>−0.1 + 0.074</td><td rowspan="2">69.9</td><td rowspan="2">78.8</td></tr>
<tr><td>−0.074 + 0.044</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="8">With respect to the slime content</td></tr>
<tr><td></td><td>Beshpagir</td><td>Malyshev</td><td>Central</td><td>Tarsk</td><td>Ordyn</td><td>Tugan</td><td>Lukoyanov</td></tr>
<tr><td>−0.044 + 0</td><td>0.81</td><td>2.1</td><td>4.1</td><td>15.9</td><td>17.6</td><td>18.0</td><td>36.3</td></tr>
</table>

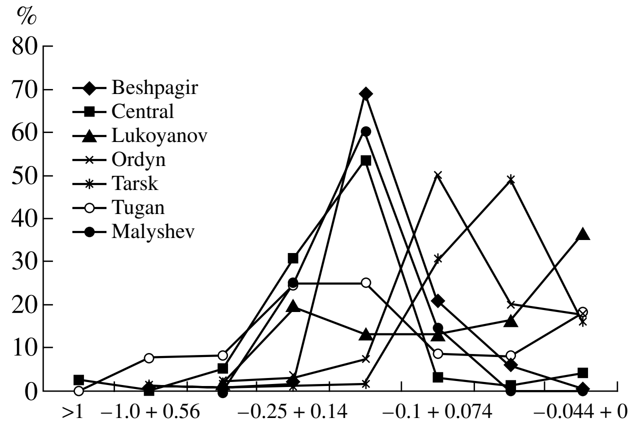

Fig. 3. Gain size distribution of ore sands.

Lukoyanov deposit, other deposits in western Siberia contain a significant amount of fine-grained particles. They constitute the major mass of sands in the Ordyn and Tarsk deposits. However, their grain size distribution is more homogeneous in the Lukoyanov deposit. The finest sand is typical of the Tarsk and Ordyn deposits (Table 3, Fig. 3).The highest content of class –0.044 mm is observed in the Lukoyanov deposit, where the sand is least sorted and relatively uniformly distributed in different size classes. A similar distribution is observed in the Tugan deposit.

The grain size distribution of useful components is not always consistent with the distribution in the initial sand. However, this parameter is most essential for results of technological tests. In the Beshpagir and Ordyn deposits, the maximal content of useful components is recorded in the finer-grained classes, relative to the initial sand (Table 4, Fig. 4). Grain class –0.044 mm of the Beshpagir deposit contains only 0.5% of TiO_2 and 2.6% of ZrO_2, relative to the initial sand. In the Ordyn deposit, the contents are 25 and 44%, respectively, suggesting the removal of a large amount of useful components together with the slime, as in the Tarsk deposit.

The grain size distribution of useful components is of primary importance for the prognosis of ore dressability, because the distribution may not coincide with the pattern in the initial sand. Comparison of data in Table 4 and Fig. 4 shows that TiO_2 and ZrO_2 are mainly concentrated in grain class –0.14+0.1 mm, as in the initial sand. In the Tarsk deposit, they are confined to class –0.074+0.044 mm. In the Beshpagir and Ordyn deposits, the useful components are concentrated in the finer classes, relative to the initial sand.

Comparison of data on the distribution of Ti and Zr suggests that they are usually concentrated in a similar grain size class. The grain size distribution of hazardous admixtures (Cr and P) is very important for the assessment of the mineral composition of sands. Table 5 shows that productive classes of the Central deposit accounts for only about 28% of P in the initial sand, while the major mass of this element is concentrated in the coarse class (51%) and slime (18%). Thus, approx-

Table 4. Grain size distribution of useful components in various deposits, %

<table>
<tr><th>Class, mm</th><th>Central</th><th>Beshpagir</th><th>Tarsk</th><th>Ordyn</th><th>Lukoyanov</th></tr>
<tr><td colspan="6">TiO_2</td></tr>
<tr><td>–0.25 + 0.14</td><td rowspan="2">76.1</td><td></td><td></td><td></td><td></td></tr>
<tr><td>–0.14 + 0.1</td><td></td><td></td><td></td><td></td></tr>
<tr><td>–0.1 + 0.074</td><td></td><td rowspan="2">88.3</td><td rowspan="2">81.9</td><td></td><td></td></tr>
<tr><td>–0.074 + 0.044</td><td></td><td rowspan="2">79.3</td><td rowspan="2">86.2</td></tr>
<tr><td>–0.044 + 0</td><td></td><td></td><td></td></tr>
<tr><td>–0.044 + 0</td><td>1.6</td><td>0.5</td><td>17.6</td><td>including 25.2</td><td>including 37.56</td></tr>
<tr><td colspan="6">ZrO_2</td></tr>
<tr><td>–0.25 + 0.14</td><td rowspan="2">75.0</td><td></td><td></td><td></td><td></td></tr>
<tr><td>–0.14 + 0.1</td><td></td><td></td><td></td><td></td></tr>
<tr><td>–0.1 + 0.074</td><td></td><td rowspan="2">92.7</td><td rowspan="2">87.3</td><td></td><td></td></tr>
<tr><td>–0.074 + 0.044</td><td></td><td rowspan="2">79.3</td><td rowspan="2">98.54</td></tr>
<tr><td>–0.044 + 0</td><td></td><td></td><td></td></tr>
<tr><td>–0.044 + 0</td><td>1.5</td><td>2.6</td><td>12.2</td><td>including 44.4</td><td>including 55.52</td></tr>
</table>

Note: Distribution of components in the slime is italicized.

imately 70% of P is removed together with the waste in the course of ore dressing. The distribution of Cr in the Tarsk sand is different. The maximal Cr content is confined to grain classes with the highest contents of Ti and Zr, while the slime contains only 22% of chromium oxide.

Mineral composition of ore sands. All titanium–zirconium placers are rather similar in terms of mineral composition (Table 6). In total, they include approximately 50 minerals. The majority of these minerals are present in all placers studied.

Many researchers of placers admit that the constancy of mineral composition is related to the regional (areal) scale of provenances, multiple redepositions of sediments, and the similarity of facies and hydrodynamic environments (Bykhovskii *et al.*, 1998; Patyk-Kara *et al.*, 1997; Tsymbal and Polkanov, 1975).

Nevertheless, the placers display some differences in mineral composition. As was demonstrated in earlier works, sands of the Central deposit are enriched in glauconite and phosphates; sands of the Lukoyanov deposit contain abundant chromite and ilmenohematite; sands of the Lukoyanov, Ordyn, and Tarsk deposits are enriched in clay minerals and organic matter; and sands of the Central and Beshpagir deposits contain the fine-grained gold.

In general, the content of clay minerals matches the distribution of slime. The highest content of clay minerals (15–21%) is typical of the Lukoyanov, Tugan, and Tarsk deposits. Their content does not exceed 1% in the Central deposit and is 7% in the Ordyn deposit.

Like Cr in the initial sand, the highest content of chrome spinels is typical of the Lukoyanov (0.58% in the mineral composition) and Central (0.31%) deposits. The content of these minerals decreases to 0.0*n*–0.00*n*% in placers of the Stavropol and West Siberian regions. High contents of phosphates and phosphorites are typical of the Central deposit.

Other specific features of the mineral composition include the abundance of glauconite in sands of the Central deposit and the maximal content of organic matter in clays of the Lukoyanov deposit.

TYPOMORPHIC FEATURES OF THE MAJOR INDUSTRIAL MINERALS

Results of detailed investigation show that heavy minerals of various placers and even different sectors of a single placer can be represented by varieties with different physicochemical properties and other specific features. These differences are most essential for the ore minerals.

Ilmenite is the major industrial mineral of titanium. The majority of titanium–zirconium placers is characterized by the presence of significantly altered ilmenite with properties strongly differing from those of the unaltered variety. Signs of alteration of mineral grains are diverse and interrelated (color, luster, surface, density, size, hardness, crushing strength at static loading, surface electric resistance, and so on). The degree of ilmenite alteration can qualitatively be estimated on the basis of its chemical composition, in which the TiO_2

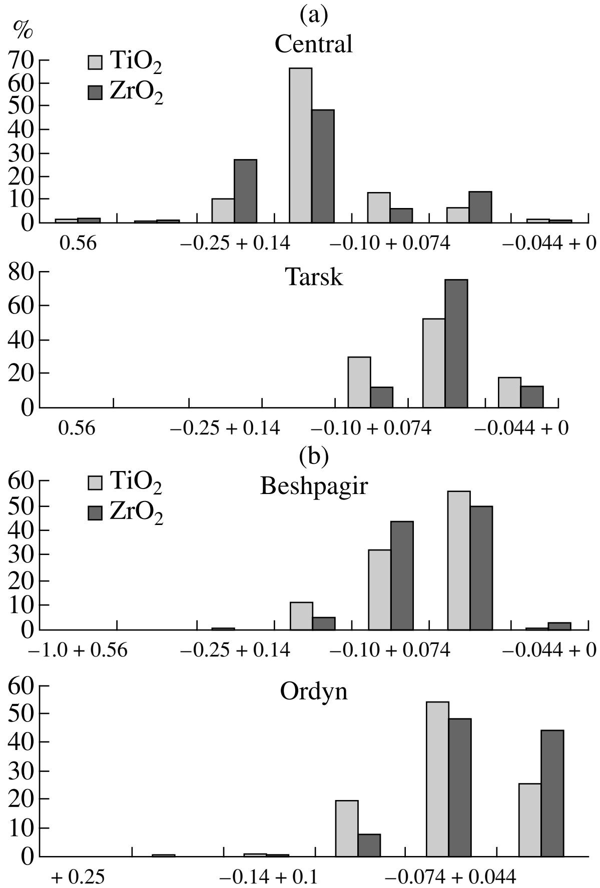

Fig. 4. Distribution of TiO_2 and ZrO_2 with respect to grain size of ore sands. (a) With similar distribution in terms of grain size and useful components; (b) with dissimilar distribution with respect to grain size and useful components.

Table 5. Distribution of hazardous admixtures in terms of grain size, %

Class, mm	Central	Tarsk
	P_2O_5	Cr_2O_3
+0.56	50.96	1.7
−0.56 + 0.25	2.08	1.6
−0.25 + 0.14	5.62	1.36
−0.14 + 0.10	20.96	3.18
−0.10 + 0.074	1.69	8.45
−0.074 + 0.044	0.53	61.38
−0.044 + 0	18.15	22.33

Table 6. Mineral composition of initial ore sands, %

Minerals	Beshpagir	Central	Lukoyanov	Ordyn	Tarsk
Minerals of heavy fraction					
Ilmenite (including ingrowths), ilmenohematite	1.95	1.86 (0.2)	1.78	1.7	2.14
Rutile + pseudorutile	0.49	0.49	0.26	0.35	0.134
Leucoxene	0.4	0.316	0.34	0.1	0.27
Zircon	0.82	0.396	0.73	0.42	0.35
Metamict zircon	0.02	0.024	0.011	0.001	0.002
Monazite	0.07	0.01	–	–	0.005
Garnet group	0.15	0.65	0.26	0.095	0.08
Epidote group	0.35	0.39	4.08	0.95	0.55
Chrome spinels	0.008	0.001	0.26	0.0013	0.08
Kyanite, andalusite, and sillimanite	0.252	0.84	0.19	0.06	0.1
Staurolite	0.06	0.105	0.05	0.0095	0.041
Tourmaline	0.11	0.17	0.09	0.07	0.07
Amphiboles and pyroxenes	0.0003	0.02	–	0.03	0.016
Magnetite and titanomagnetite	0.18	0.004	0.66	0.03	0.016
Hematite and martite	–	0.23	1.24	–	–
Iron hydroxides	0.012	0.124	2.76	–	–
Iron sulfides (including ingrowths)	–	–	–	0.052	0.0014
Gold	0.085 g/t	0.085–0.14 g/t	–	–	–
Minerals of light fraction					
Quartz + feldspar	94.3	78.23	61.87	77.825	87.79
Clay minerals Fine-dispersed clay–quartz–feldspar	0.81	3.551	21.05	16.65	7.06
Glauconite	–	2.12	–	0.003	–
Mica group	0.016	0.026	2.32	0.933	0.094
Phosphates (including phosphorites)	0.015	3.81	0.09	0.18	0.51
Organic and coaly materials	0.016	0.025	1.56	0.67	0.69

Note: (–) Not detected.

Table 7. Average chemical composition of ilmenite from titanium–zirconium placers of Russia and Ukraine (based on microprobe data, wt %)

Deposit	TiO_2	FeO	Fe_2O_3	MgO	MnO	Cr_2O_3	P_2O_5	V_2O_5	Al_2O_3
Beshpagir	55.5	41.1	n.a.	0.45	0.28	0.09	0.03	0.14	0.02
Central	61.4	6.10	25.5	0.32	1.78	0.47	0.35	0.15	0.66
Lukoyanov	47.4	17.4	29.4	0.23	2.1	1.5	0.03	0.15	0.05
Ordyn	50.2	45.7	n.a.	0.1	2.06	0.39	0.04	1.30	0.03
Tarsk	58.3	27.1	14.0	0.75	2.3	0.60	0.12	0.16	0.7
Tugan	81.0	0.34	1.12	0.11	n.a.	0.025	0.07	n.a.	2.39
Malyshev	67.1	0.12	26.6	0.9	0.14	0.14	0.19	0.21	0.8

Note: (n.a.) Not analyzed.

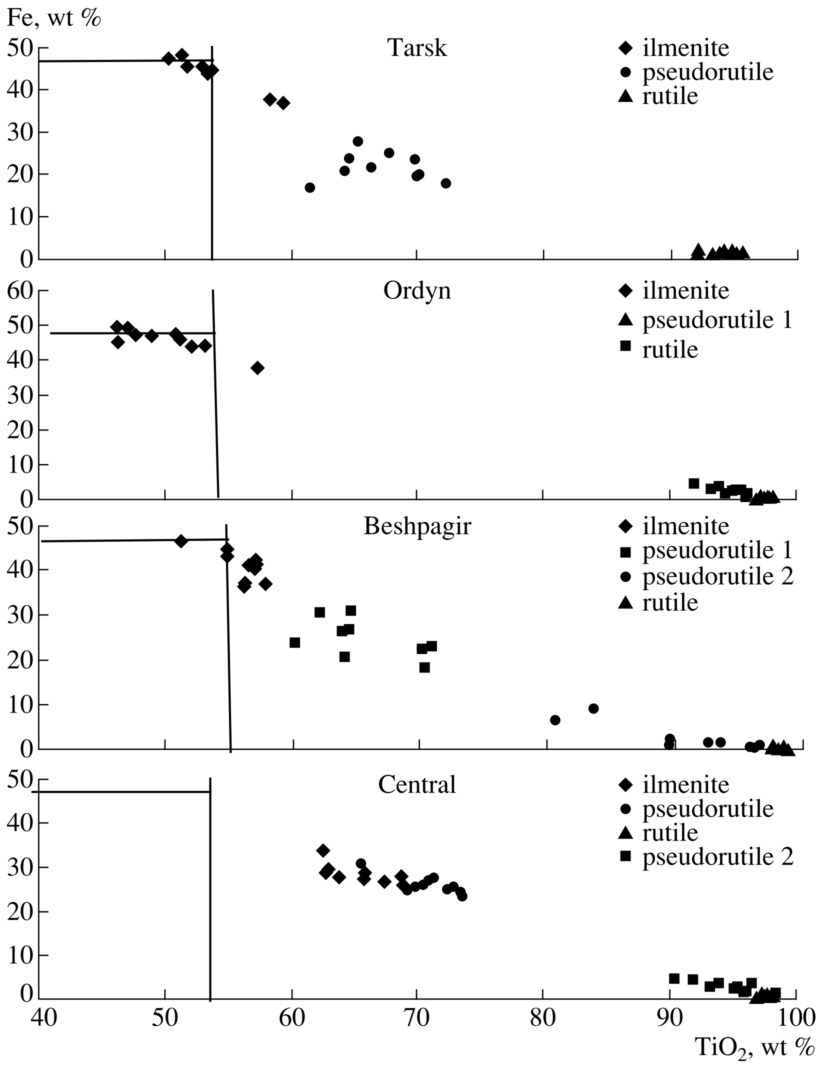

Fig. 5. Variation in Fe and TiO_2 contents in the ilmenite–pseudorutile–rutile series (based on microprobe data).

content usually exceeds the theoretical value. Supergene alteration of ilmenite is related to the oxidation and leaching of Fe. Products of its alteration include leucoxene, rutile, anatase, brookite, hematite, pseudobrookite, intermediate members of the ilmenite–hematite series, X-ray amorphous phase $Fe_2O_3 \cdot nTiO_2 \cdot mH_2O$, and pseudorutile $Fe_2TiO_2O_7$ (Yakubovskaya *et al.*, 1985). Ilmenite and products of its alteration have been discussed in numerous works (Armand *et al.*, 1985; Dyadchenko and Khatuntseva, 1961; Tsymbal and Polkanov, 1975; Zherdeva and Abulevich, 1964; Ziv, 1961). However, unified terminology for products of intermediate stages is lacking so far. The tentative scenario of ilmenite transformation includes the following stages: fresh ilmenite ⟶ altered (leucoxenized) ilmenite ⟶ leucoxene ⟶ pseudorutile.

Many researchers have noted the multistage nature of ilmenite transformation. The majority of researchers admit that the first stage of transformation includes the oxidation and partial leaching of Fe. Destruction of the crystal lattice of ilmenite promotes the formation of new phases (free TiO_2 and Fe_2O_3). The first stage terminates with the nearly complete disappearance of the ilmenite phase. Products of this stage are commonly known as altered (leucoxenized) ilmenites. At the next stage, ilmenite is mainly decomposed owing to the leaching of Fe and simultaneous crystallization of titanium hydroxides. Alteration products without the ilmenite phase are usually referred to as leucoxenes. The nearly complete leaching of Fe produces pseudorutile (secondary rutile). It is rather difficult to discriminate clearly products of ilmenite alteration. Therefore, each sample contains a blend of differently altered ilmenite grains. The chemical composition of ilmenite depends on the degree of its alteration (Table 7). The TiO_2 content (47–81%) is commonly higher than the theoretical content. The highest variations are typical of

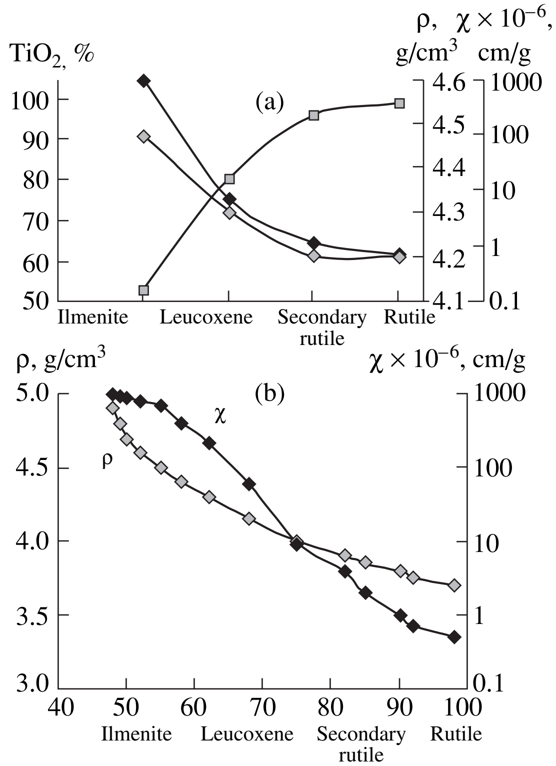

Fig. 6. Dependence of the TiO_2 content and physical properties (χ, ρ) of ilmenite on the degree of its alteration (with the Central deposit as an example). (a) Model; (b) factual.

FeO and Fe_2O_3. Variations in the Al_2O_3, Cr_2O_3, and P_2O_5 contents can reach an order of magnitude.

Detailed investigation of the ilmenite composition in placers of a single district (Tsymbal and Polkanov, 1975) showed that the compositional variation of this mineral depending on rock alteration degree matches the general behavior style of major components. Inverse correlation is best observed in the TiO_2–FeO and FeO–Fe_2O_3 systems. The correlation is less distinct in the TiO_2–Fe_2O_3 system. Figure 5 shows that the titanium–zirconium deposits are characterized by different degrees of ilmenite alteration. The alteration is minimal in deposits of western Siberia. In the Beshpagir and, particularly, Central deposits, the degree of ilmenite alteration reaches 42 and 80%, respectively. At the same time, these deposits are depleted in Fe and enriched in TiO_2. Variation in chemical composition in titanium minerals is accompanied by the respective variation in physical properties (Levchenko, 2004). The degree of alteration inversely correlates with the specific magnetic susceptibility (Fig. 6). Model curves in this plot are supported by factual data on the Central deposit.

Density of the altered ilmenite varies from 3.7 to 4.7 g/cm^3. The average density of ilmenite grains is approximately 4.2 g/cm^3. The density of ilmenites and their alteration products have an inverse correlation with the TiO_2 content. For example, increase in the TiO_2 content from 5–10 to 55–60% is accompanied by decrease in density from 4.7 to 4.1. The density is also correlated with the grain size owing to the natural hydraulic sorting during the formation of placers. The relationships mentioned above can be used for the choice of technological dressing regime in order to enhance the extraction of titanium minerals and separate ilmenite from rutile.

The set of characteristics discussed above shows that the most altered ilmenites are typical of the Central deposit, while the least altered variety is observed in the Tarsk and Ordyn deposits, where the ilmenite is repre-

Table 8. Grain size composition of ilmenite

Grain size class, mm	Beshpagir		Central		Tarsk		Lukoyanov		Malyshev	
	rel %	wt %	rel %	wt %	rel %	wt %	rel %	wt %	rel %	wt %
−2 + 1	–	–	–	–	–	–	–	–	–	–
−1 + 0.5	–	–	–	–	–	–	–	–	–	–
−0.5 + 0.25	–	–	–	–	–	–	–	–	0.15	1.63
−0.25 + 0.125	–	–	0.08	0.94	0.10	2.58	–	–	26.32	70.40
−0.125 + 0.074	4.86	18.82	11.26	38.36	2.34	17.24	–	–	30.23	22.77
−0.074 + 0.044	45.89	62.45	37.53	44.97	20.24	52.52	9.30	44.50	11.35	3.01
−0.044 + 0.02	46.53	18.63	43.91	15.48	31.79	24.27	33.90	47.70	27.71	2.16
−0.02 + 0	2.72	0.11	7.22	0.25	45.54	3.40	56.80	7.80	4.24	0.03

Note: (–) Grain size class is absent.

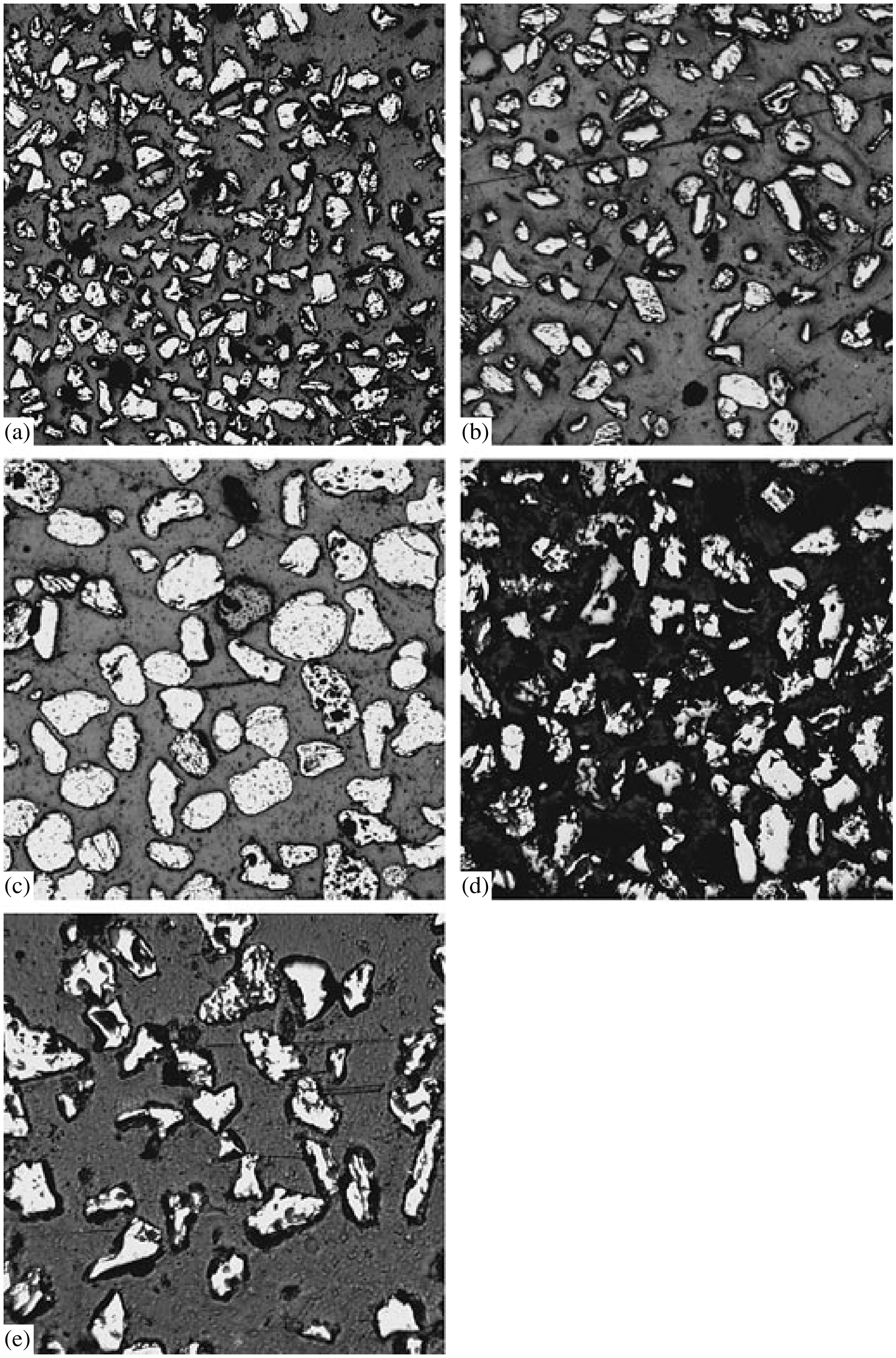

Fig. 7. Ilmenite grains in various deposits (polished sections). (a) Beshpagir, magn. 40; (b) Central, magn. 40; (c) Malyshev, magn. 40; (d) Lukoyanov, magn. 100; (e) Tarsk, magn. 100.

sented by black grains with metallic luster and partly retained crystal edges.

Using the TOMANALYSIS image system (Levchenko *et al.*, 2000, 2001), we obtained data on the grain size composition of ilmenites in concentrates from different deposits (Figs. 7, 8; Table 8). The analysis shows that ilmenite is concentrated in the coarsest (however, less coarse relative to the Malyshev deposit) fractions of the Central and Beshpagir deposits. In con-

Table 9. Structural parameters of ilmenite grains

Deposit	Number of particles	Length			Width			Dimension, µm		
		min	max	average	min	max	average	min	max	average
Beshpagir	2241	13.68	157.06	51.72	6.04	102.5	25.5	12	115	40
Central	1672	14.87	181.33	53.84	6.04	116.12	28.75	12	131	41
Tarsk	1334	5	171.57	32.31	2.89	162.72	17.39	5	167	25
Lukoyanov	1242	5.92	106.39	24.44	3	66.32	13.92	5	73	19
Malyshev	1733	14.87	582.56	95.62	7.11	245.73	59.58	13	387	78
Deposit	Number of particles	Shape factor			Elongation			Compactness		
		min	max	average	min	max	average	min	max	average
Beshpagir	2241	0.39	0.85	0.65	1	10.68	2.01	0.35	1.51	0.63
Central	1672	0.42	0.9	0.66	1	6.73	2.06	0.35	1.59	0.66
Tarsk	1334	0.37	0.88	0.65	1	7.91	2.11	0.25	1.86	0.62
Lukoyanov	1242	0.39	0.85	0.66	1	6.74	1.90	0.3	1.12	0.62
Malyshev	1733	0.35	0.92	0.70	1	8.33	1.86	0.27	1.75	0.67

Table 10. Grain size composition of rutile

Class, mm	Beshpagir		Central		Tarsk		Lukoyanov	
	rel %	wt %	rel %	wt %	rel %	wt %	rel %	wt %
–2 + 1	–	–	–	–	–	–	–	–
–1 + 0.5	–	–	–	–	–	–	–	–
–0.5 + 0.25	–	–	–	–	–	–	–	–
–0.25 + 0.125	–	–	–	–	0.11	2.09	–	–
–0.125 + 0.074	1.11	7.65	13.09	44.74	3.80	19.84	0.24	2.38
–0.074 + 0.044	22.04	53.44	31.30	37.59	21.99	40.33	12.62	44.63
–0.044 + 0.02	52.14	37.19	49.41	17.46	69.49	37.50	47.02	48.91
–0.02 + 0	24.71	1.72	6.21	0.21	4.61	0.24	40.13	4.08

Note: (–) Grain size class is absent.

trast, the ilmenite content in fraction –0.02+0 mm is 56.8% (7.8 wt %) in the Lukoyanov deposit and 45.5% (3.4 wt %) in the Tarsk deposit. In terms of geometric parameters (elongation, shape factor, and others), ilmenites from titanium–zirconium deposits in Russia are similar (Table 9), but they differ from their more equant counterparts in the Malyshev deposit (Ukraine).

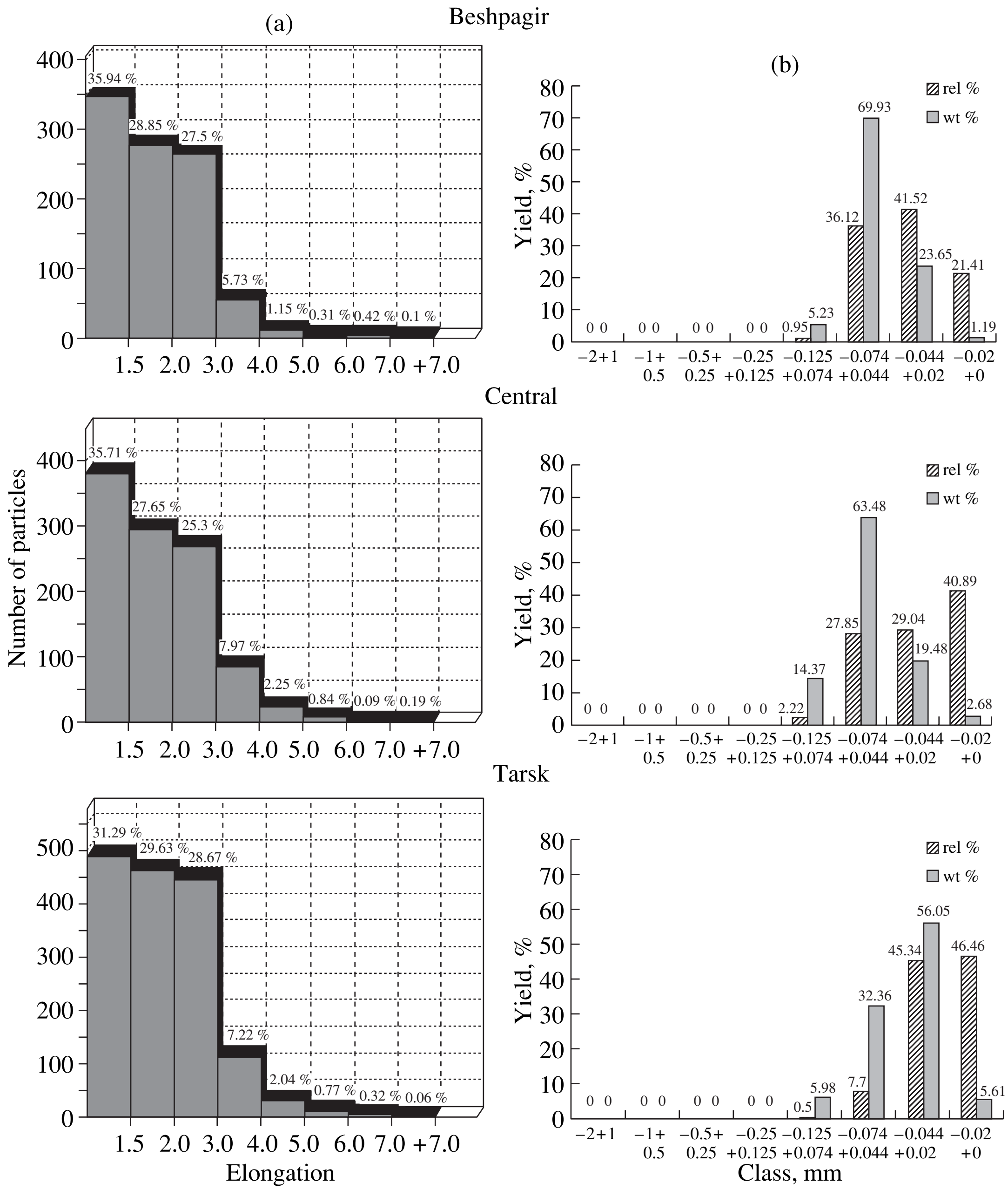

Fig. 8. Bar charts of ilmenite grain distribution in titanium–zirconium deposits in terms of (a) elongation and (b) grain size.

Rutile, as compared to ilmenite, is characterized by a lesser variation in properties. This mineral is present as primary and secondary (authigenic) varieties related to leucoxenization of ilmenite. The share of authigenic rutile in placers is usually small. The primary rutile is distinguished from the authigenic variety by elongated shape, black color, brighter luster, and higher density. The black denser variety is enriched in TiO_2 relative to the red and reddish brown varieties. The optical-geometrical analysis of rutile grain images with the TOMANALYSIS system demonstrated that the grain size distribution of rutile concentrates is most contrasting for fraction –0.02+0 mm (Table 10; Figs. 9, 10). For example, the rutile content in this fraction is 40.1% (4.1 wt %) in the Lukoyanov deposit and 24.7% (1.7 wt %) in the Beshpagir deposit. Geometric parameters of rutile grains show a greater similarity. The average elongation of rutile grains in all deposits varies from 2.02 to 2.23; the shape factor, from 0.62 to 0.66 (Table 11). Some rutile grains are characterized by a stronger magnetism owing to the presence of ilmenite and magnetite inclusions and iron hydroxide coating on the surface. Rutile of the Central deposit is enriched in Fe_2O_3 (1.2%), SiO_2 (2.6%), Al_2O_3 (0.7%), V_2O_5 (0.2%), and P_2O_5 (0.18%)

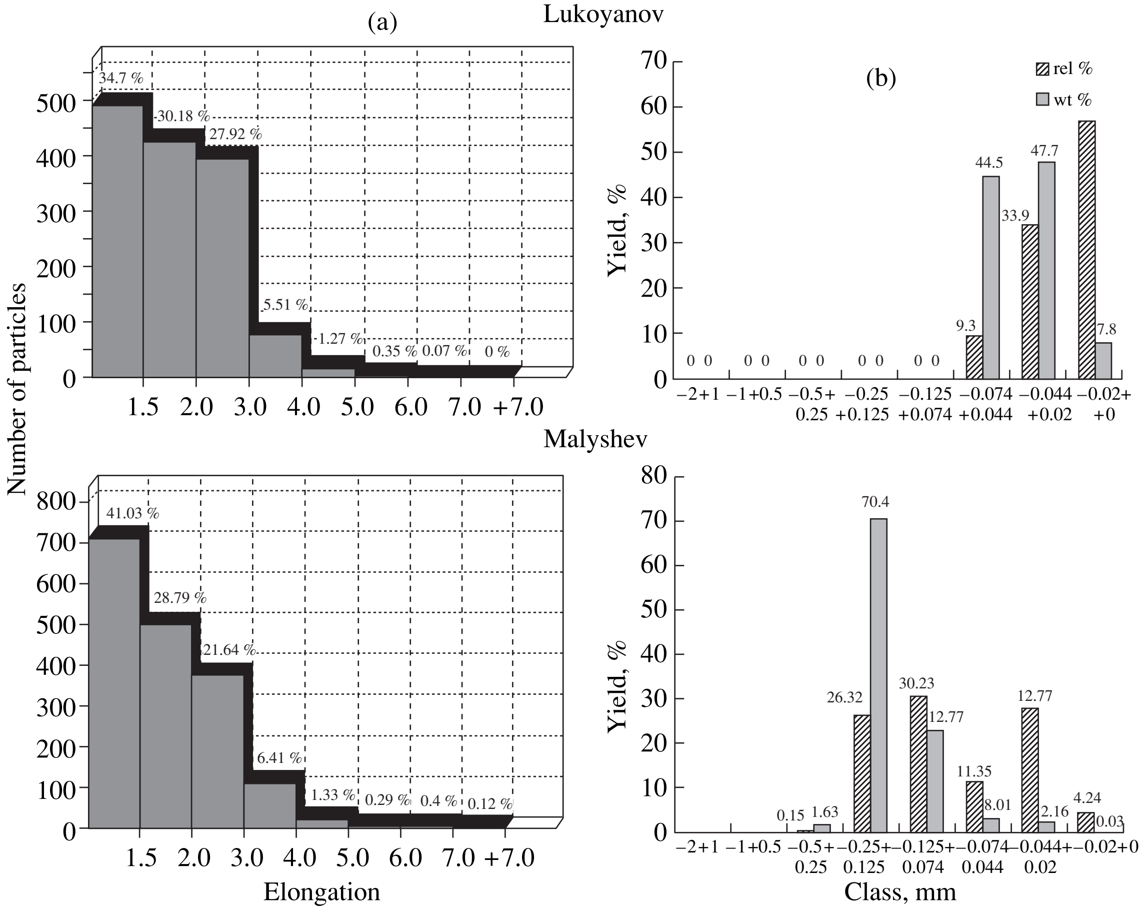

Fig. 8. (Contd.)

due to the presence of a coating of phosphorite, quartz, kyanite, and other minerals. Some rutile grains from the Lukoyanov deposit include an isomorphous admixture of ZrO_2 (0.1–0.56%).

Zircon, like rutile, is often represented by two varieties, but many deposits contain zircon grains with similar properties (Levchenko, 2004). The second (subordinate) variety is observed as metamict zircon with a

Table 11. Structural parameters of rutile grains

Deposit	Number of particles	Length			Width			Dimension, μm		
		min	max	average	min	max	average	min	max	average
Beshpagir	1638	9.57	152.76	38.92	4.27	72.42	19.07	9	99	29
Central	1358	12.5	180.89	53.45	6.57	102.69	28.36	12	117	41
Tarsk	1139	12.5	200.18	43.89	5	87.79	23.12	12	133	34
Lukoyanov	1099	5	114.47	30.01	3	67.47	16.15	5	75	23
Deposit	**Number of particles**	**Shape factor**			**Elongation**			**Compactness**		
		min	max	average	min	max	average	min	max	average
Beshpagir	1638	0.39	0.8	0.62	1	7.92	2.23	0.24	1.17	0.6
Central	1358	0.38	0.84	0.64	1	7.61	2.02	0.29	1.27	0.6
Tarsk	1139	0.4	0.8	0.63	1	8.19	2.06	0.27	1.03	0.59
Lukoyanov	1099	0.4	0.83	0.66	1	8	2.05	0.34	1.16	0.67

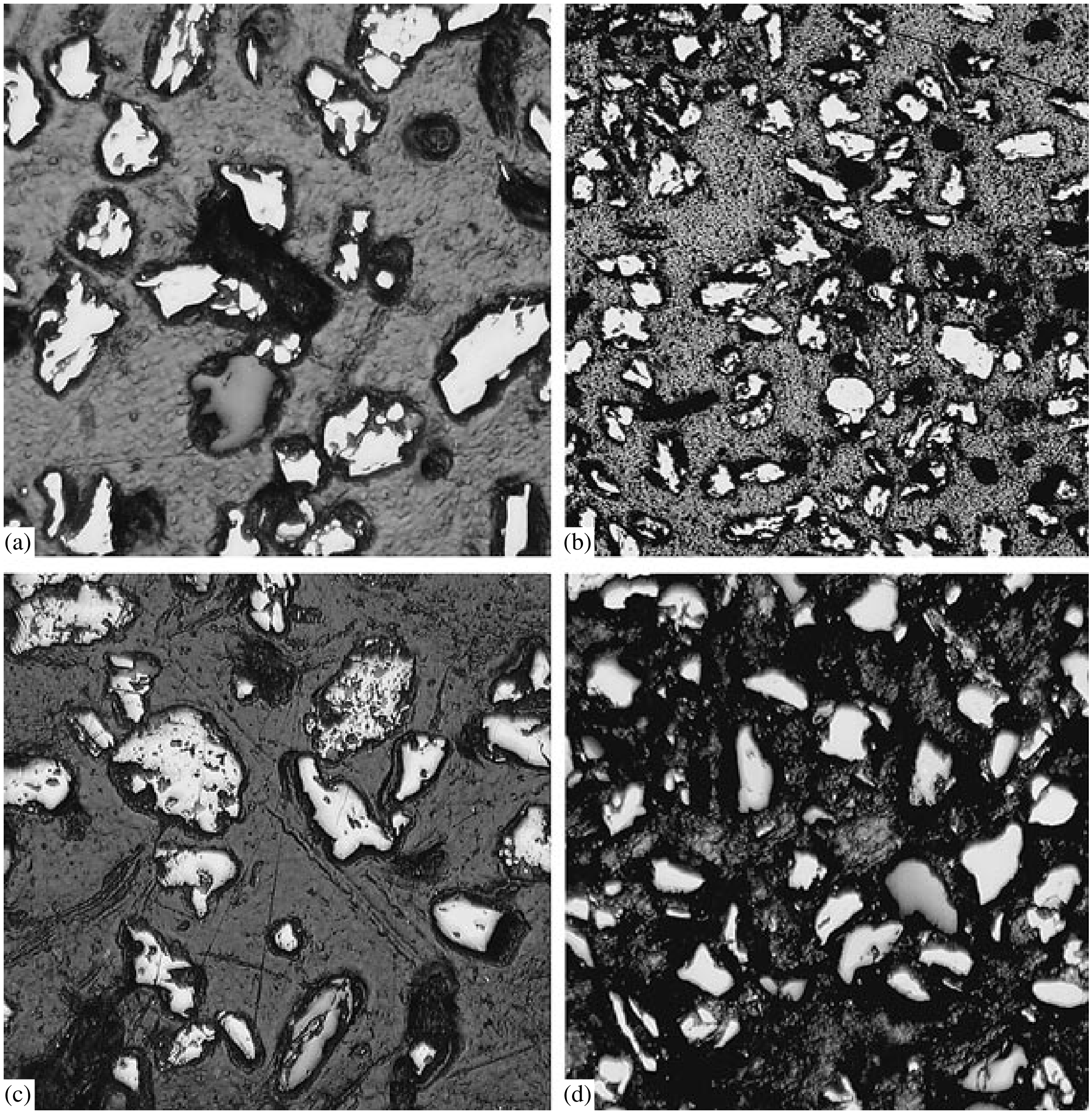

Fig. 9. Rutile grains from various deposits (polished sections, magn. 100). (a) Beshpagir, (b) Central, (c) Tarsk, (d) Lukoyanov.

high Th content. Metamictization of zircon provokes decrease in the ZrO_2 content and increase in the (U + Th) content recalculated to the Th content. Consequently, the density decreases and the specific magnetic susceptibility increases (Fig. 11). As in the case of titanium minerals, this trend can be used to choose optimal technological regimes for the removal of radioactive zircon and upgrade the zircon concentrate.

Zircon grains usually contain microinclusions and occasional coatings of other minerals, such as ilmenite, magnetite, apatite, rutile, quartz and ferrithorite. The share of microinclusion-bearing zircon grains can be as high as 30–40 wt %. The microinclusions are typical of zircon grains from the Central, Tugan, and Malyshev deposits. Zircon grains with even a minor content of ilmenite and magnetite microinclusions are weakly magnetic. Therefore, this property can affect the dressabilty index. In the Malyshev deposit, ferromanganese coatings are removed by the mechanical method. The TOMANALYSIS data on zircon concentrate show that the highest zircon concentration in the relatively coarse grain classes is typical of the Central and Beshpagir deposits. However, these deposits are similar to other deposits in terms of the abundance of zircon in grain class –0.02 mm (Table 12; Figs. 12, 13). The fine-grained zircon (class 0.02 mm) is typical of placer deposits in western Siberia (49.9% in the

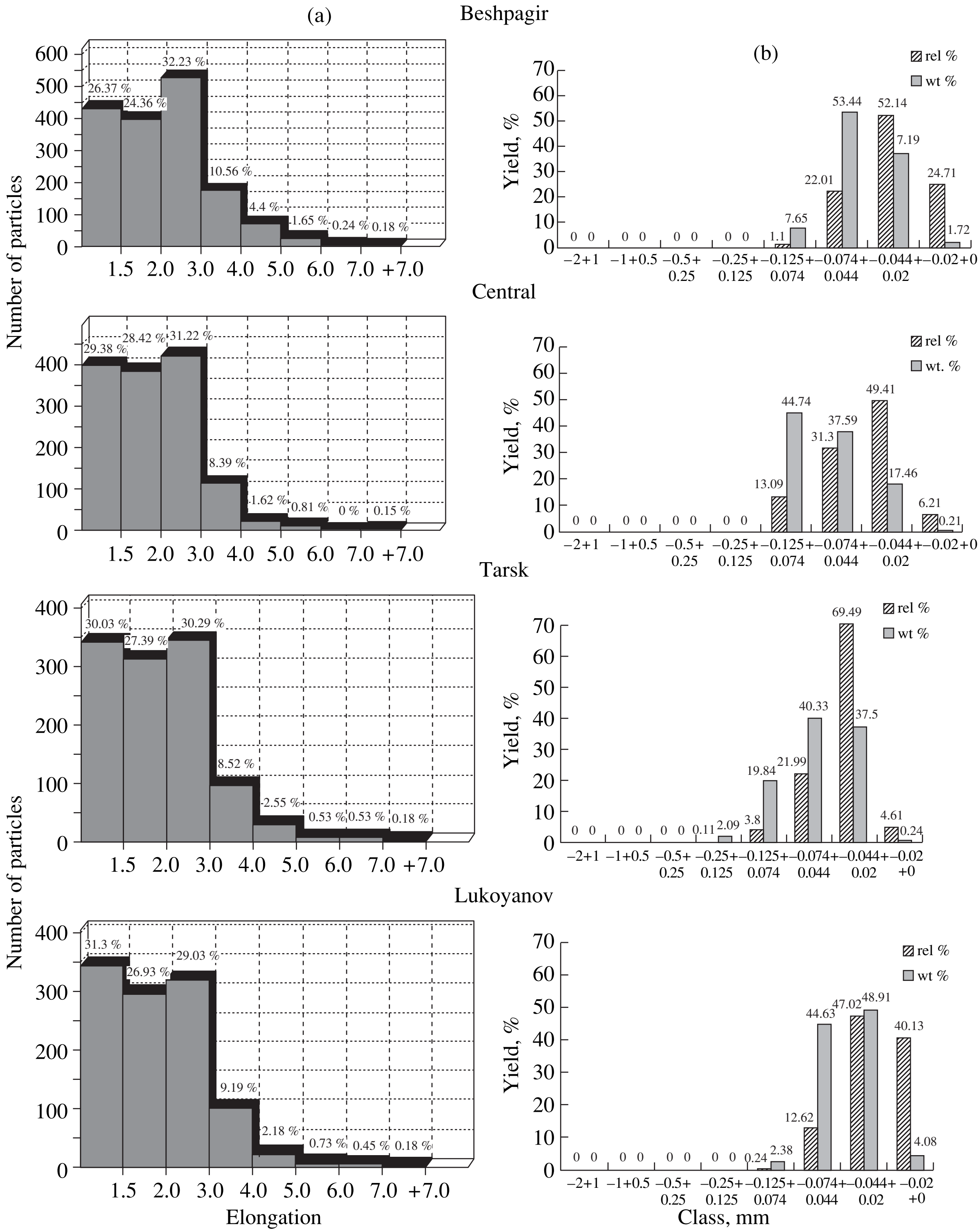

Fig. 10. Bar charts of rutile grain distribution in titanium–zirconium deposits in terms of (a) elongation and (b) grain size.

Ordyn deposit and 46.5% in the Tarsk deposit). The zircon grains are more equant relative to rutile. The elongation coefficient is 1.1–1.9 in 90% of grains. With respect to structural parameters (shape factor, elongation, and compactness), zircon grains are similar in all Russian deposits (Table 13).

Quartz-containing nonore tailings of titanium–zirconium sands can be used as a raw material in the

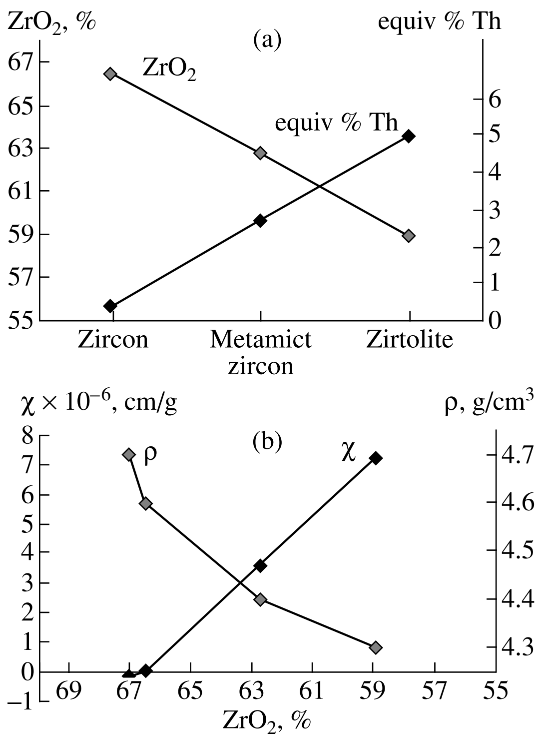

Fig. 11. Dependence of the ZrO_2 content and physical properties (χ, ρ) of zircon on the degree of its alteration (with the Tarsk deposit as an example). (a) Model, (b) factual.

glass and construction industry. Fields of their utilization are restricted by the contents of SiO_2 and admixtures (TiO_2, Fe_2O_3, and Al_2O_3) and the grain size composition. According to the Russian standard GOST-22551, the share of <0.1-mm grains in the quartz sand is limited by 77.15% for the glass industry. The content of admixtures in the Beshpagir and Central deposits is 73–75%.

With respect to the nonore constituent, placers of western Siberia are characterized by nearly monomineral composition. Quartz is the major mineral. Therefore, the SiO_2 content in the light fraction varies from 96–97 to 98%, while the Al_2O_3 content is at the GOST-22551 level (up to 2%). The major admixtures responsible for the glass color are iron and titanium oxides. In the majority of deposits (except the Ordyn and Tarsk deposits), their contents in the nonore tailings of titanium–zirconium sands exceed the GOST-22551 limitation for the production of window and technical sheet glass and other types of glass. After the additional mechanical cleaning and magnetic separation, the nonore tailings can yield the Al_2O_3-rich quartz–feldspar concentrate (grade B-100-2 in GOST-22551) that is feasible for the production of isolators, pipes, cans, semiwhite glass bottles, and fiberglass used in the construction and other fields as a binding component for heavy concrete, silicate brick, and siliceous component in the autoclave cellular concrete.

Specific features of the major industrial minerals of titanium–zirconium placers are summarized in Table 14.

CONCLUSIONS

The rational geological study of titanium–zirconium placers envisages an operative and low-cost prognosis of technological properties of new deposits discovered in the course of regional surveys with the application of methods of technical mineralogy.

Investigations of the mineral composition of placers have demonstrated that ore sands of each placer province are characterized by specific features.

Table 12. Grain size composition of zircon

Class, mm	Beshpagir		Central		Tarsk		Lukoyanov		Malyshev		Ordyn	
	rel %	wt %	rel %	wt %	rel %	wt %	rel %	wt %	rel %	wt %	rel %	wt %
−2 + 1	–	–	–	–	–	–	–	–	–	–	–	–
−1 + 0.5	–	–	–	–	–	–	–	–	–	–	–	–
−0.5 + 0.25	–	–	–	–	–	–	–	–	–	–	–	–
−0.25 + 0.125	–	–	–	–	–	–	–	–	2.51	19.93	–	–
−0.125 + 0.074	0.95	5.23	2.22	14.37	0.50	5.98	–	–	21.65	48.47	0.23	3.16
−0.074 + 0.044	36.12	69.93	27.85	63.48	7.70	32.36	13.38	42.06	26.87	21.16	5.57	26.94
−0.044 + 0.02	41.52	23.65	29.04	19.48	45.34	56.05	60.07	55.55	44.66	10.34	44.26	62.96
−0.02 + 0	21.41	1.19	40.89	2.68	46.46	5.61	26.55	2.40	4.31	0.10	49.93	6.94

Note: (–) Grain size class is absent.

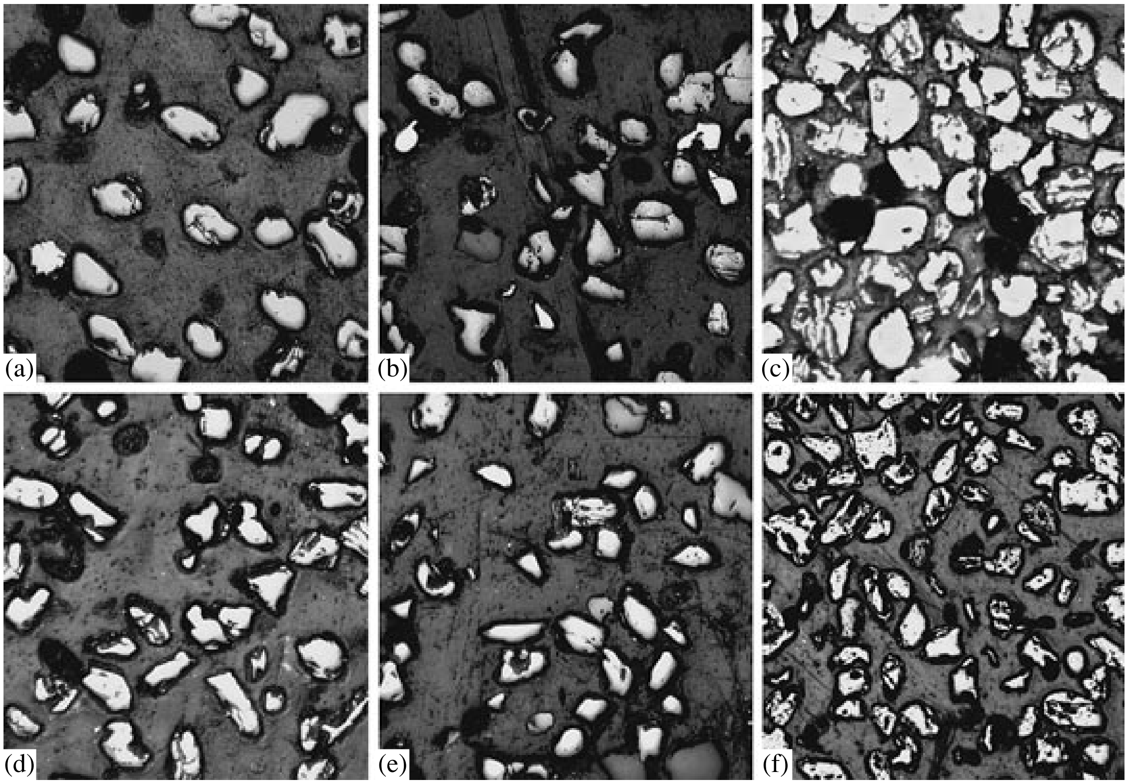

Fig. 12. Zircon grains from various deposits (polished sections, magn. 100). (a) Beshpagir; (b) Lukoyanov; (c) Central, (d) Tarsk, (e) Ordyn; (f) Malyshev (magn. 40).

Placers of the East European province are characterized by the abundance of hazardous admixtures (phosphates and chrome spinels), ingrowths of ore and nonore minerals, and microinclusions of minerals (with other physical properties) inside the ore mineral grains.

Table 13. Structural parameters of zircon grains

Deposit	Number of particles	Length			Width			Dimension, μm		
		min	max	average	min	max	average	min	max	average
Beshpagir	960	5.95	135.15	40.3	2	66.25	23.48	6	32	98
Central	1067	5	120.85	34.66	2.72	74.72	20.18	5	27	87
Tarsk	1566	5	134.75	26.98	2.89	66.91	14.77	5	21	94
Lukoyanov	947	5.92	104.8	32.29	3	59.26	18.58	5	25	75
Ordyn	1136	6	122.53	25.73	2	56.5	13.59	6	20	82
Malyshev	1557	12.5	260.56	61.84	7.35	169.31	34.36	12	48	181
Deposit	**Number of particles**	**Shape factor**			**Elongation**			**Compactness**		
		min	max	average	min	max	average	min	max	average
Beshpagir	960	0.38	0.91	0.69	1	8	1.91	0.36	1.32	0.68
Central	1067	0.33	0.92	0.67	1	11.67	1.99	0.34	1.14	0.66
Tarsk	1566	0.36	0.93	0.66	1	7.18	2.00	0.29	2.07	0.66
Lukoyanov	947	0.39	0.91	0.69	1	7.4	1.92	0.35	1.88	0.67
Ordyn	1136	0.44	0.83	0.65	1	6.08	2.02	0.29	1.06	0.66
Malyshev	1557	0.41	0.88	0.65	1	7.02	2.06	0.23	1.3	0.6

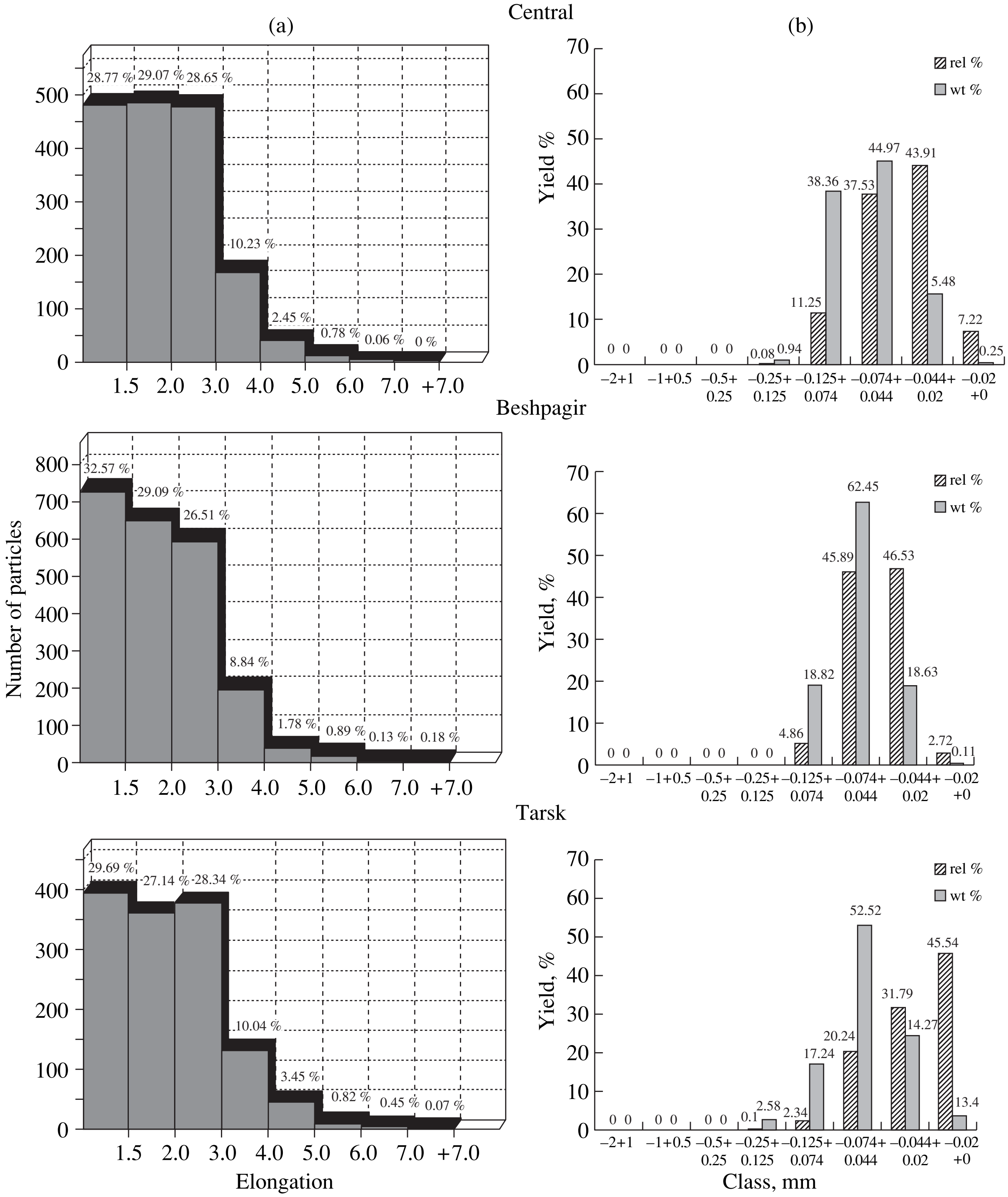

Fig. 13. Bar charts of zircon grain size distribution in titanium–zirconium deposits in terms of (a) elongation and (b) grain size.

Placers of the West Siberian province are marked by the fine-grained structure and clayey composition of sands, fine-grained structure of ore minerals, and a relatively low content of hazardous admixtures.

Placers of the North Caucasian province are characterized by a low content of the clayey fraction, relatively coarse-grained structure of sands and ore minerals, high degree of sorting, and low content of hazardous admixtures.

Based on the analysis of specific features of the mineral composition of ore sands in five placer deposits of Russia, we developed criteria for the assessment of

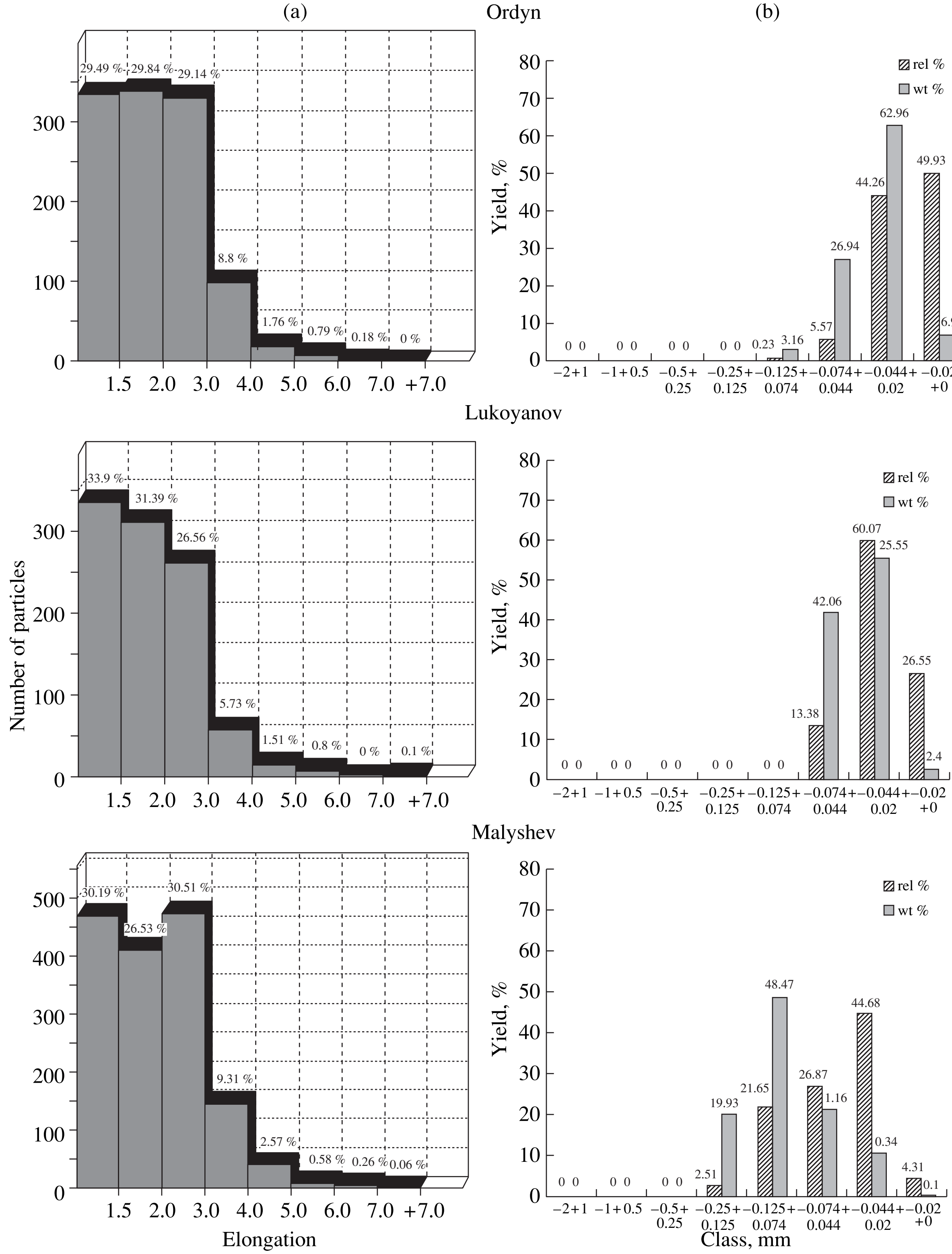

Fig. 13. (Contd.)

technological properties and dressability of titanium–zirconium placers at various stages of geological exploration.

Testing of the criteria mentioned above at prospecting and exploration sites demonstrated a high degree of their feasibility. We also classified the criteria in terms

Table 14. Specific properties of the major industrial minerals in titanium–zirconium placers

Deposit	Specific properties of minerals
Beshpagir	Relatively coarse-grained structure of ore minerals (except rutile) High degree of alteration and TiO_2 content in ilmenite Limited suitability of quartz sand for glass industry because of fine-grained structure and presence of admixtures
Central	Relatively coarse-grained structure of ore minerals High degree of alteration and TiO_2 content in ilmenite High content of P and Al in ilmenite High radioactivity of zircon and monazite Ilmenite and magnetite inclusions in rutile and presence of iron hydroxide coating on rutile grains High content of zircon (30–40 vol %) with microinclusions Phosphate coating and overgrowth on the surface of ore mineral grains Quartz sand is unsuitable for glass industry because of strong contamination
Lukoyanov	Ilmenite concentrate cannot be extracted Ore mineral concentration in the fine-grained class –0.02+0 mm Chromite inclusions in ilmenite High Zr_2O content in rutile Coating of phosphorite, quartz, kyanite, and other minerals in rutile grains
Ordyn	Fine-grained structure of ore minerals Insignificant degree of ilmenite alteration High Cr content in ilmenite Quartz is suitable for glass industry
Tarsk	Fine-grained structure of ilmenite and zircon Insignificant degree of ilmenite alteration Titanomagnetite inclusions in ilmenite Quartz is suitable for glass industry
Malyshev	Relatively coarse-grained structure of ore minerals and their equant shapes owing to high degree of roundedness Significant degree of alteration and high TiO_2 content in ilmenite Ilmenite and magnetite inclusions in rutile Microinclusions in zircon grains and their iron and manganese hydroxide coating Low radioactivity of zircon Quartz sand is suitable for glass industry

of their significance with the consideration of the possibility to negotiate negative factors with the application of refined technologies.

Therefore, we believe that the creation of scientific-methodical principles of technological mineralogy of titanium–zirconium placers (primarily, titanium–zirconium deposits in Russia that will be put into operation in the nearest future) is an urgent issue.

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