Lithology and Mineral Resources, Vol. 39, No. 5, 2004, pp. 412–424. Translated from Litologiya i Poleznye Iskopaemye, No. 5, 2004, pp. 476–490.

The South Ushkoty Eluvial Kaolin Deposit in the Southeastern Orenburg Region

B. F. Gorbachev[1], A. F. Sharapov[2], P. V. Lyadskii[3], and N. T. Shmel'kov[3]

[1]Central Research Institute of Geology of Nonmetalliferous Mineral Resources, ul. Zinina 4, Kazan, 420097 Tatarstan, Russia
e-mail: root@geolnerud.mi.ru
[2]Main Administration for Natural Resources and Environment Protection in the Orenburg District, Parkovyi pr. 6, Orenburg, 460000 Russia
[3]Orenburggeoresurs Federal Geological Unitary Enterprise, Shkol'naya ul., Nezhinka, Orenburg oblast, 461320 Russia
Received September 23, 2003

Abstract—The South Ushkoty eluvial kaolin deposit discovered and explored by the authors is situated 20 km away from the railway in the Dombarov district of the Orenburg region. The deposit is localized in the axial zone of the East Ural Uplift. Leucogranites of the Upper Ushkoty Pluton serve as bedrocks. The deposit comprises five lodes, among which the largest deposit has a reserve of ~40 Mt. The lodes are erosion remnants of the well-developed linear-areal weathering zone related to the fragments of Mesozoic peneplain at the hypsometric level not lower than 360 m. Variation of the kaolin zone thickness, the entire weathering zone, and the deposit morphology is largely governed by the nearly meridional and northeastern faults. Two productive zones—the normal kaolin (kaolinite + quartz) zone and the alkaline kaolin (kaolinite + quartz + potassium feldspar and/or muscovite) zones—are recognized in the weathering profile of leucogranites of the Upper Ushkoty Pluton. The alkaline kaolin is of commercial significance as a complex raw material if the potassium oxide content is above 3.5%. The composition and properties of the concentrated kaolin meet the requirements of its traditional consumers (fine ceramic works, paper mills, and others). The discovery of the South Ushkoty deposit confirmed the previous forecast on considerable prospects of the Orsk Transural region for kaolin. We hope that this discovery will stimulate the further investigation and assessment of resources in the Mugodzhary kaolin-bearing subprovince.

INTRODUCTION

Many researchers have pointed out that the southern Transural region can include economic deposits of high-quality kaolin (Belov, 1969; Blokhintseva and Ivanov, 1990; Gorbachev and Vasyanov, 1983; Petrov, 1968; Stepanov and Gerasimneko, 1974). Gorbachev and Vasyanov (1974) scrutinized regularities of the localization of eluvial kaolin deposits in the Mugodzhary area. Weathering crusts of granites of the Upper Ushkoty, Middle Ushkoty, and Koshensai plutons were selected as the most prospective ones. Nonetheless, the purposeful geological exploration of the Chelyabinsk and Orsk areas of the Transural region was only sporadically conducted before the 1990s. The exploration was characterized by methodical errors and, therefore, could not yield positive results.

The lack of interest for studying kaolin deposits in the Transural region was caused by the domination of stereotypic notions that the entire demand of Russian enterprises for kaolin products will be always and fully supplied by deposits in the Ukraine.

After 1992, the necessity in an efficient source of kaolin raw materials in Russia became evident and stimulated the search for kaolin lodes in the southern Transural region, where remnants of the Mesozoic Transural peneplain are locally retained from erosion. In recent years, prospecting works were carried out in the Transural areas characterized by the development of kaolin weathering crust in granitic rocks. The obtained results fit the commonly accepted concepts related to the formation and localization constraints of eluvial kaolin deposits (*Metodicheskie…*, 1984; *Prognoznaya…*, 1998).

Results of the prospecting provided additional information concerning specific features of the occurrence and preservation of the Mesozoic weathering crust in the Transural region. For example, the complete weathering crust is only locally developed in granitic plutons and mainly confined to their linear fragments, the orientation and morphology of which are controlled by faults or configuration of blocks produced by neotectonic deformations of the Mesozoic peneplain. In addition to specific features of the weathering, petrochemistry of the weathered substrate plays a crucial role in the formation of high-quality (light-colored, low-Fe, and low-Ti) kaolin. The most favorable effect is achieved during the weathering of the hydrothermally altered leucogranites and the formation of products

0024-4902/04/3905-0412 © 2004 MAIK "Nauka/Interperiodica"

marked by the absence or minimal content of dark-colored minerals.

The southern Transural region is the major region of Russia in terms of the hypothetical resources, identified reserves, and number of deposits and occurrences of eluvial kaolin genetically related to the Mesozoic weathering crust of older igneous and metamorphic rocks.

Geological prospecting and appraisal of flanks of the Zhuravlinyi Log deposit near the town of Plast in the Chelyabinsk region (South Ural kaolin subprovince) resulted in the discovery of possible crude kaolin reserves estimated at 60 Mt (category C_2 in the Russian classification), locally including high-quality ores (up to 50%).

The prospecting for kaolin lodes in the Orsk region (Mugodzhary kaolin subprovince) initiated in 1996 resulted in the discovery of several eluvial kaolin occurrences. The South Ushkoty deposit was accepted as the most promising one and, therefore, explored in 1999–2001.

The deposit is situated in the Domarov district of the Orenburg region at the upper reaches of the Sully–Karagandy ravine near the Kazakhstan border.

In terms of mineragenic subdivision of the territory, the South Ushkoty deposit is a part of the Ushkoty kaolin-bearing district related to the central (axial) zone of the East Ural Uplift with abundant granitic rocks. This district was characterized by continental conditions after the weathering crust formation. However, the complete weathering crust profile has been only locally preserved due to the subsequent erosion and abrasion.

The deposit was drilled down to a depth of 30 m along a grid of 200×400 m. Areas with white kaolin were explored in more detail and the layer-by-layer sampling of sections was conducted. Separate and composite samples were transferred to laboratories of the Central Research Institute of Geology of Nonmetalliferous Mineral Resources, where a comprehensive study of kaolin and its dressing products was undertaken with the fulfillment of normative requirements (Gorbachev *et al.,* 2000).

GEOLOGIC SETTING AND MORPHOLOGY OF LODES

The South Ushkoty deposit is a set of kaolin bodies (lodes) in the upper zone of the weathering profile in granitoids of the Upper Ushkoty Pluton. The kaolin lodes are traceable within a zone, up to 6 km long and 2.5 km wide, oriented along the main Ural trend. The upper kaolin zone is scoured along the Sully–Karagandy ravine where the northern (better explored) and southern sectors of the deposit are localized.

The complete weathering crust is mainly preserved in the least eroded relicts of the Mesozoic peneplain. The wellheads of boreholes, which penetrated the whole profile of weathered granitoids, are located at hypsometric levels not lower than 360 m (Fig. 1). In the present-day relief, these levels are displayed as flat (poorly expressed) isolated rises divided by small flattened ravines occasionally passing into narrow incisions with rocky slopes or thresholds (e.g., the Sully-Karagandy ravine). This relief gives way to the Oligocene–Miocene hillocky topography in the northern and western areas. Consequently, the eluvial cover is almost completely scoured and the granitic bedrock is exposed in these areas. The denudation plain with Pliocene variegated clays extends to the east of the deposit.

Thus, the South Ushkoty deposit is a relict of Mesozoic peneplain with the locally retained complete weathering crust (including kaolin zone) of linear and areal types. The presence of linear fragments is indicated by the abrupt thickening of both the weathered crust and the kaolin zone (Fig. 2). The morphology of kaolin bodies inherits heterogeneities in the geological structure and is governed by at least five specific features:

(1) compositional variability of granitic rocks largely depending on postmagmatic processes of alkaline and acid metasomatism;

(2) compositional variability of weathering products as a result of mineralogical and geochemical zoning of the weathering crust;

(3) variable depth of kaolinization mainly controlled by ancient (older than the weathering crust) faults, along which the kaolin zone development is maximal;

(4) variable preservation degree of the weathered crust, particularly its upper (kaolin) zone, in response to the differentiated vertical block displacements in combination with denudation from the Pliocene to the present time; and

(5) variable thickness of Pliocene sediments affecting the underlying kaolin composition (its replacement by limonite and calcite and contamination with alien clayey materials).

The summary influence of the aforementioned factors controls the morphology of kaolin lodes both in plan view and section. The fields of weathered rocks and eluvial materials pertaining to the specific zones of the weathering profile are shown in the schematic lithogeological map (Fig. 3). The contours on this map are mainly controlled by faults that are older or younger than the weathering crust. Maximums of the kaolin zone thickness are mainly confined to two (submeridional and northeastern) older faults (Fig. 4). The light-colored or white kaolin is concentrated in the central part of the weathered crust, while the periphery primarily accommodates the variegated kaolin and rocks that underwent the incipient kaolinization and disintegration. Thus, the interaction of neotectonic movements and denudation disintegrated the formerly continuous kaolin lode into discrete fragments separated by subeconomic eluvial materials.

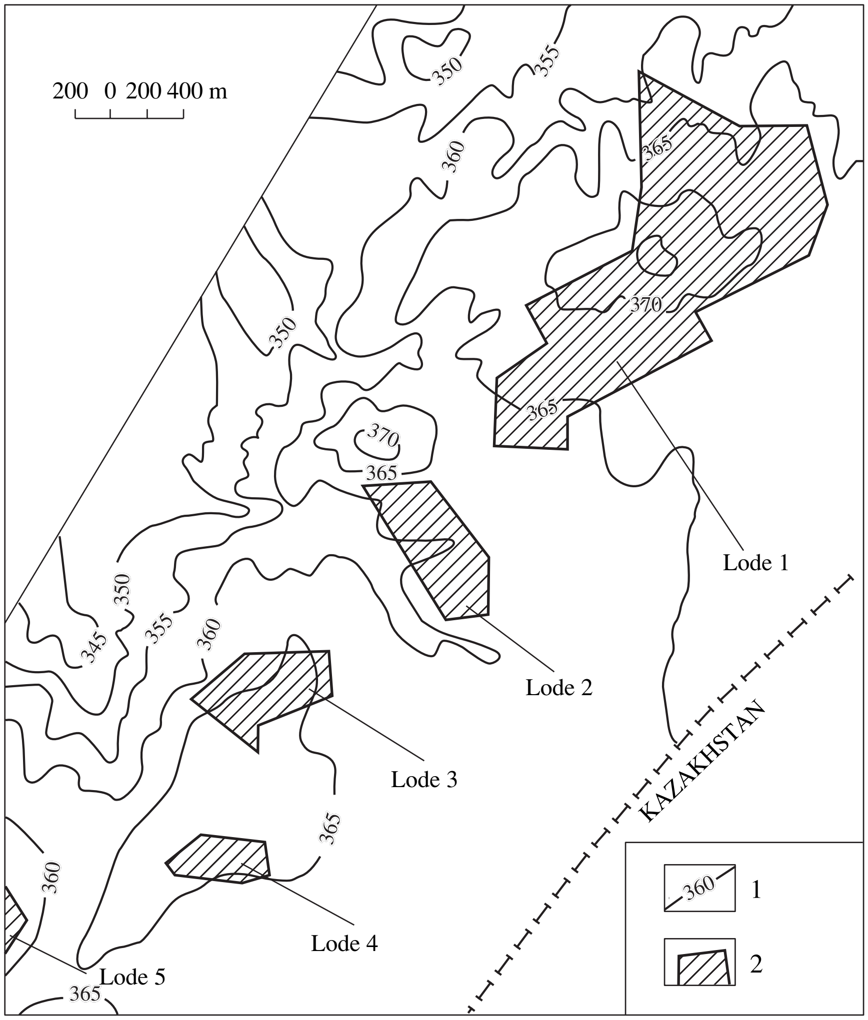

Fig. 1. Location of kaolin lodes in the present-day topography. (1) Contour lines; (2) eluvial kaolin lodes.

Results of geological exploration made it possible to outline five kaolin lodes and their parameters are listed in Table 1.

Table 1. Parameters of kaolin lodes in the South Ushkoty deposit

Lode no.	Parameters, m			Reserves, kt
	Length	Width	Thickness	
1	2800	300–1600	12.7	$C_1 + C_2$ 38494*
2	1300	300–450	9.8	C_2 4339
3	1100	400	13.7	C_2 6732
4	600	500	7.5	P_1 1130
5	500	200–250	7.4	P_1 1666

* Approved by the State Commission for Reserves of the Russian Federation (November 16, 2001).

The largest and best explored kaolin body (Lode 1) is located at the northern flank of the deposit. The kaolin bodies south of this lode are much smaller and less explored. The contours of kaolin bodies have been drawn in the plan view and sections along the lower boundary of the alkaline kaolin zone with the Fe_2O_3 content not exceeding 2%. The kaolin bodies are commonly characterized by wedge-shaped cross sections, suggesting the essential role of compaction zones in the substrate. The shape and dimensions of the kaolin bodies may be refined during further exploration.

THE WEATHERING CRUST

Among the 169 boreholes drilled at the prospecting and appraisal stages of geological exploration, 139 boreholes penetrated the weathering crust at the South Ushkoty deposit. The weathering crust consists of three—lower (disintegration), middle (incipient kaolinization), and upper (complete kaolinization)—

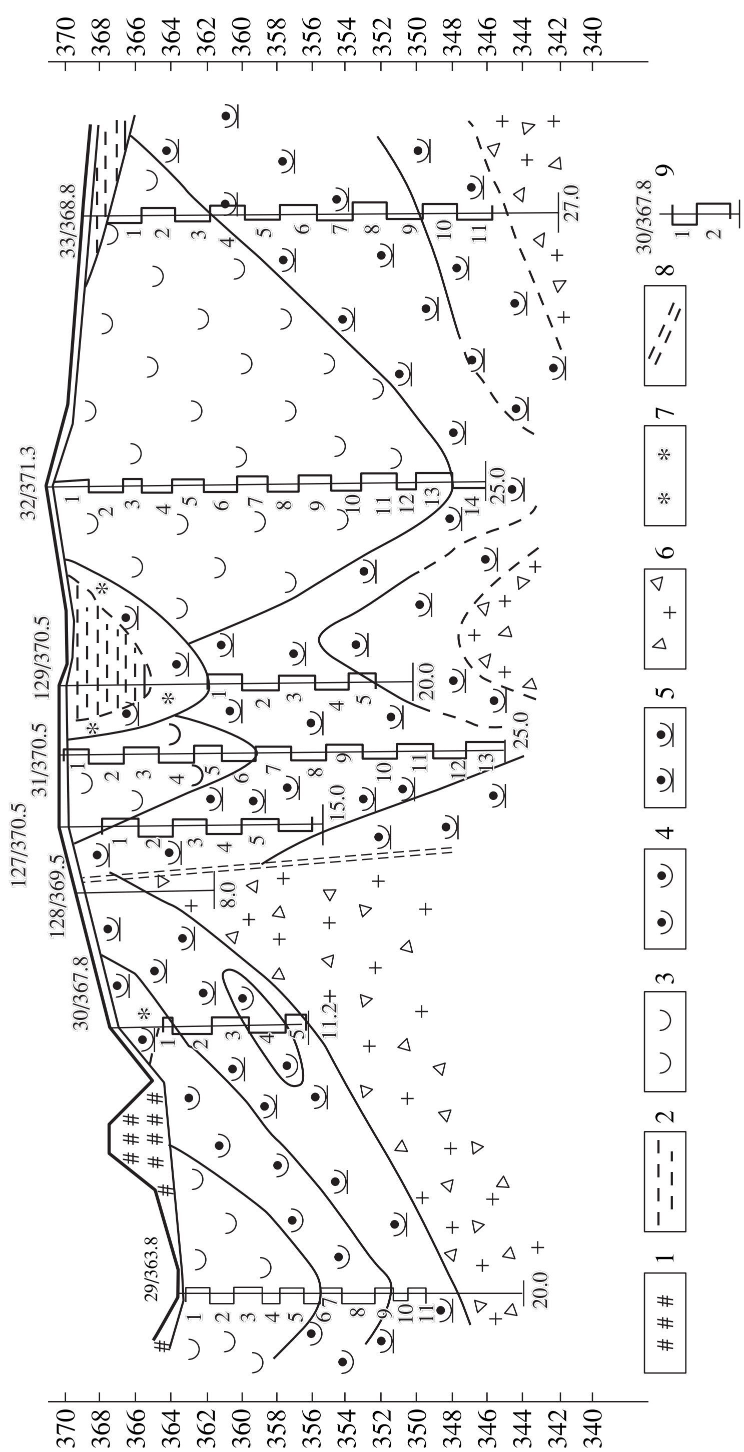

Fig. 2. Geological section of Lode 1 (profile I–I). (1) Overburden; (2) Pliocene sediments; (3) kaolin; (4) alkaline kaolin; (5) variegated residue; (6) granitic rubble; (7) limonitized kaolin; (8) inferred faults; (9) borehole, its number, absolute height of its mouth, sampling intervals, and sample numbers.

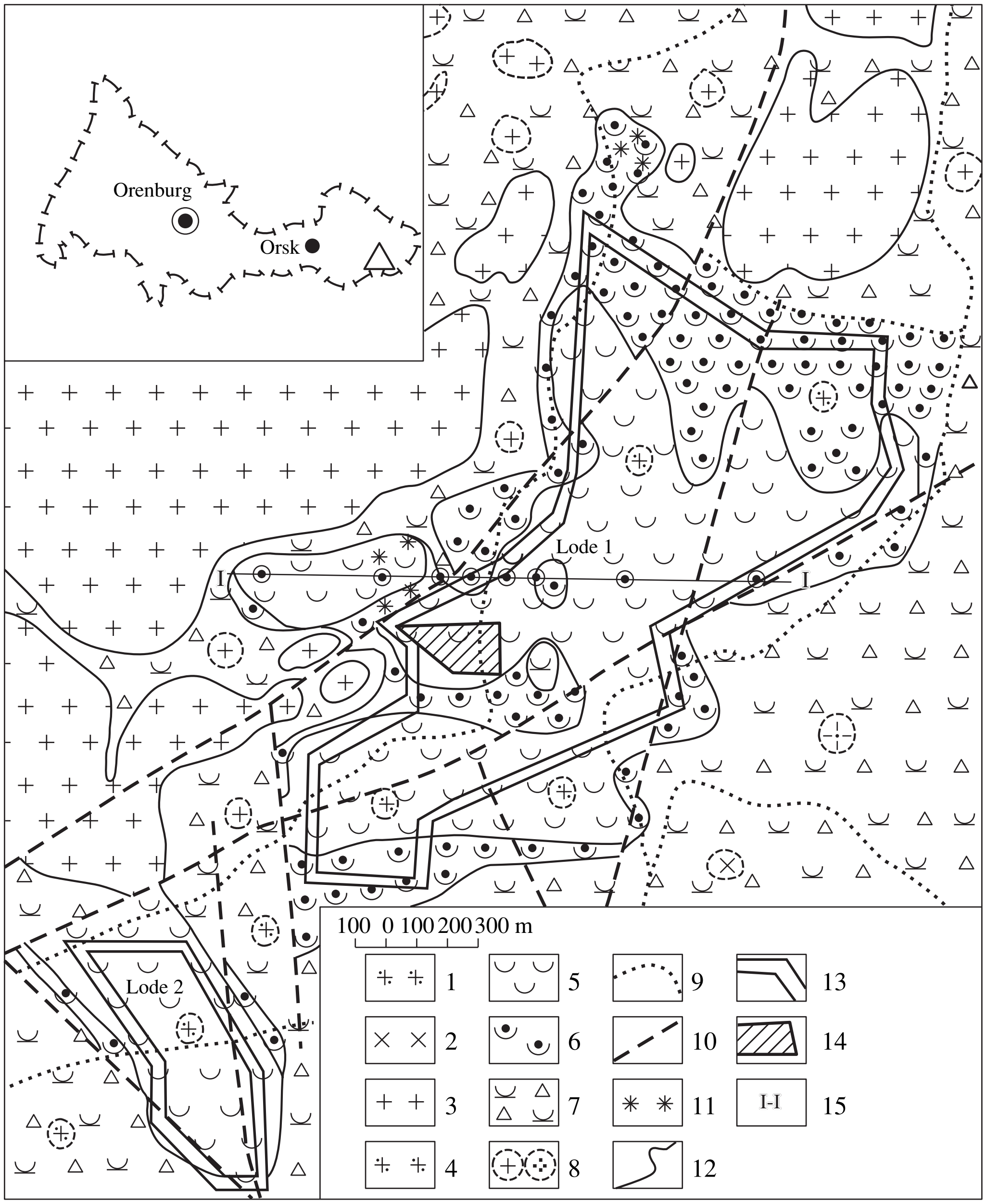

Fig. 3. Schematic geological map of northern part of the South Ushkoty deposit (without the Pliocene–Quaternary cover). (1) Plagiogranite and biotite (occasionally, amphibole–biotite) tonalite; (2) granodiorite; (3) porphyritic two-mica microcline granite; (4) microcline and muscovite leucogranite; (5) kaolin; (6) alkaline kaolin; (7) variegated clay and rubble eluvium; (8) granitic bedrock underlying the weathering crust; (9) conditional boundaries of various granitic rocks; (10) inferred faults; (11) limonitized kaolin; (12) boundary of the weathering crust and kaolin lodes; (13) contour of inferred reserves (category C_2); (14) contour of indicated reserves (category C_1); (15) profile shown in Fig. 2.

zones that can be divided into alkaline kaolin and normal kaolin subzones.

Granitoids of the Upper Ushkoty Pluton, which served as substrate for the weathering crust, formed in three phases: (1) emplacement of plagiogranites and tonalites (with biotite and occasional hornblende) produced as a result of the crystallization of the main volume of acid magma that intruded the intrusive chamber; (2) replacement of plagiogranites by microcline and formation of the porphyritic two-mica granite; and (3) formation of bleached leucogranites as a result of the replacement of the porphyritic rocks by microcline and muscovite under the influence of gaseous emanations in the first and second phases. The leucogranites make up a narrow band in the northern sector of the explored area (Fig. 4), suggesting the existence of a permeable zone that served as a conduit for fluids enriched in alkaline metals and volatile components.

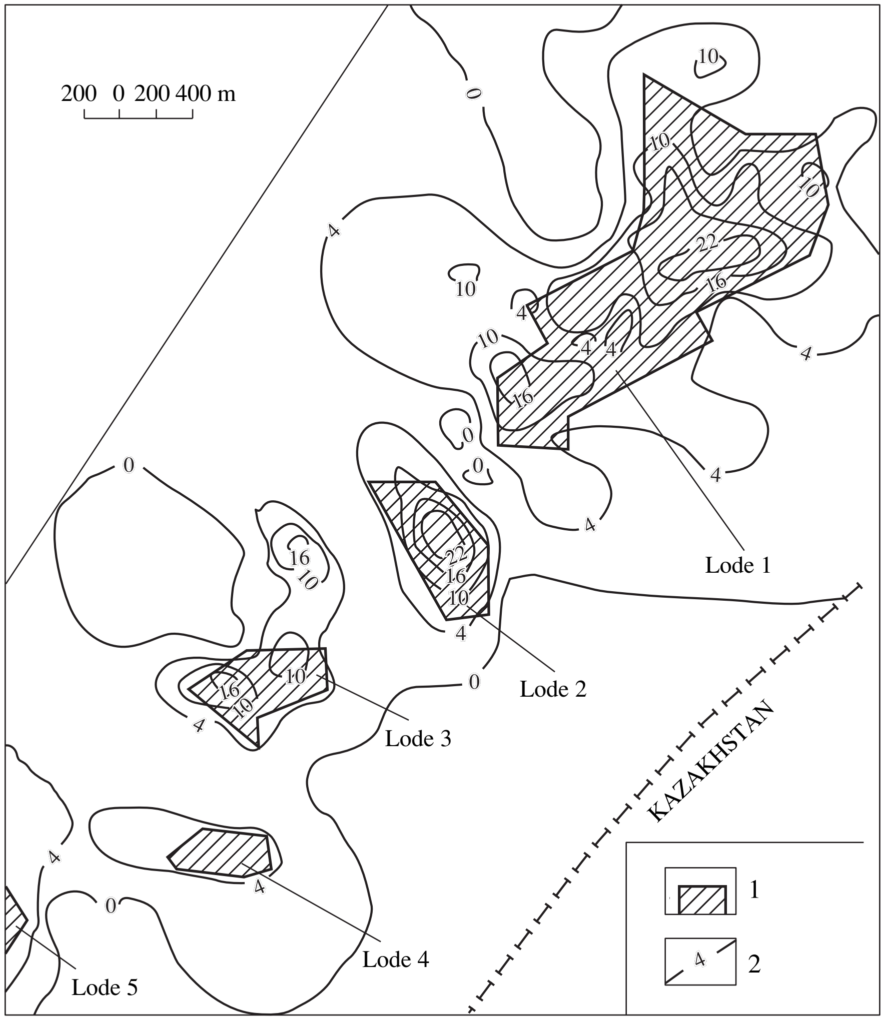

Fig. 4. Kaolin lodes (1) and their isopachs (2).

The mineral composition of two-mica granites corresponds to the normal granite partially corresponding to the plagioclase variety (Table 2). Like plagiogranites, they are marked by porphyritic or equigranular textures with the hypidiomorphic texture often masked by recrystallization.

Leucogranites reveal a more distinct granitic texture due to more prominent differences in the idiomorphism grade of rock-forming minerals in the case of metamorphism. Some varieties contain up to 70% of microcline and approach granosyenite in composition. The leucogranites are characterized by the absence of minerals of F, Li, and B due to depletion of granites of the studied massif in fluorine and fluorophile rare elements (Grabezhev *et al.*, 1980).

It should be noted that the complete weathering crust is generally developed above the leucogranites. The substantially feldspathic composition of this rock and low contents of oxides of Fe, Ti, and Mn are favorable prerequisites for the formation of light-colored (or white) kaolin.

In the lower zone of weathering, the granitic rocks are disintegrated into gruss that becomes enriched upsection in the plagioclase- and biotite-replacing hypergene clayey components (kaolinite and smectite), while microcline, quartz, and muscovite remain unal-

Table 2. Mineral composition of granitic bedrocks, %

Rock-forming minerals	Plagiogranite	Two-mica granite	Leucogranite
Plagioclase	45–60	20–35	15–30
Biotit	5–10	1–5	<1
Hornblende	1–5	–	–
Microcline	5–10	30–40	35–45
Quartz	20–35	25–40	30–45
Muscovite	<1	5–10	up to 5

Table 3. Chemical composition of crude kaolin, %

Component	Natural types		
	Normal kaolin I	Alkaline kaolin II	Normal kaolin III
SiO_2	66–73	65–74	56–687
Al_2O_3	18–22	15–22	22–29
Fe_2O_3	0.5–0.8	0.3–0.7	0.3–1.5
TiO_2	0.07–0.16	0.08–0.12	0.3–0.8
CaO	0.05–0.16	0.05–0.2	0.15–0.5
K_2O	0.05–0.1	2.0–5.6	0.1–0.25
L.O.I.	0.5–2.0	2.9–7.5	7.0–10.5

tered. The disintegrated zone thickness varies from 4 to 8 m and reaches 15 m or more in some boreholes, probably, due to tectonic impacts before the weathering. The upper boundary of the weathering zone is conventionally drawn based on the disappearance of plagioclase due to its replacement by cryptic flaky kaolinite. Biotite flakes lose their color along the margins and split along the cleavage planes, while muscovite becomes turbid. The weathering of biotite is accompanied by the appearance of small gel-type segregations of light green smectite, which occasionally makes up pseudomorphs after the biotite, and the development of anatase leucoxene.

The incipient kaolinization zone, up to 15 m thick, consists of more dilated rocks with a high content of hypergene minerals (mostly, kaolinite). Microcline is stable and only slightly dissolved along the cleavage fissures. Albitic perthites in the microcline are replaced by kaolin. Muscovite loses its transparency and becomes granular. The upper boundary of the incipient kaolinization zone is conventionally drawn based on the disappearance of the hydrated and bleached biotite commonly corresponding to the Fe_2O_3 content decrease to 2%. Owing to the presence of weathered dark-colored minerals, rocks of this zone are greenish, yellowish, or brownish gray corresponding to the iron oxide content of 3–5%. If the initial biotite content in leucogranites is low, the incipient kaolinization zone is vaguely and thin. In contrast, this zone is clearly defined and has a maximum thickness on plagiogranites.

In the weathering crust of microcline granites, the incipient weathering zone is overlain by the alkaline kaolin subzone 2–28 m thick (10 m, on the average). This subzone is not developed in the case of plagiogranite weathering. Due to the selective resistance against weathering, microcline occurs in the alkaline kaolin together with quartz and kaolinite at the initial stage of kaolinization. Muscovite, smectite, iron and titanium oxides, and accessory minerals are present as impurities. If the K_2O content is more than 3.5% and kaolin is colorless, the alkaline kaolin may be utilized as a complex quartz–microcline–kaolinite raw material. The boundary between the alkaline kaolin and the overlying normal kaolin zones is conventionally drawn based on the K_2O content of less than 2% in the kaolinite concentrate.

The normal kaolin zone (40 m, average 11 m) consists of quartz and kaolinite with a variable admixture of partly kaolinized muscovite. The white variety, particularly, the kaolinite products obtained after the concentration of kaolin (i.e., concentrated or fractionated kaolin), are the most valuable raw mineral. Beneath the sedimentary cover of the weathering crust, kaolin is enriched in limonite and calcite. The illuviation of alien clayey material and humus is also observed. Therefore, one can outline a local infiltration unit from tens of centimeters to a few meters thick. The infiltrated kaolin is commonly characterized by low grade.

The results obtained make it possible to propose two modifications of weathering crust formed after the (1) microcline-bearing granite and (2) the plagiogranite and similar rocks (without or with a very low content of microcline). Correspondingly, one can recognize three natural types of kaolin: (1) normal kaolin formed after the microcline-bearing leucogranite (hereafter, kaolin I), (2) alkaline kaolin formed after the same initial rock (kaolin II), and (3) normal kaolin formed after the plagiogranite and biotite granite (kaolin III).

It is commonly accepted that the natural types of mineral deposits make up geologic bodies characterized by specific occurrence mode and volume depending on their mineral composition, structural-textural features, color, physicomechanical, and other properties. The natural types of kaolin at the South Ushkoty deposit fit well these conditions. They are clearly separated in space and, as will be shown below, characterized by specific compositions and properties.

THE CRUDE KAOLIN

The white and grayish white, greasy kaolin (occasionally, with a cream tint) is the most valuable raw mineral. Its mineral composition is governed by the initial mineral composition of the granitic bedrock and the type of subzone in the weathering profile. Therefore, the natural types of crude kaolin vary in the chemical (Table 3) and modal mineral (Table 4) compositions.

The normal kaolin is a product of the strong weathering of all granitic rocks. Relict minerals are represented by the inequigranular quartz. The contribution of muscovite is subordinate and variable. The alkaline kaolin also contains close proportions of quartz and latticed microcline with completely kaolinized perthites. The microcline includes numerous microcavities related to hydrolytic dissolution. The clayey matrix (40–60% of kaolin) largely consists of the cryptic flaky kaolinite with the polycrystalline (vermicular) intergrowths. Sericite microflakes are discernible under crossed nicols.

Compositional variations of the crude kaolin reflect proportions of the major components (kaolinite, quartz, microcline, and muscovite). The contents of iron and titanium oxides are also important. The alkaline kaolin is characterized by elevated K_2O content and lower loss on ignition. Kaolin III differs from kaolin I by a slight depletion in silica and enrichment in Al_2O_3 and TiO_2 relative to the variety formed after microcline granite.

If the crude kaolin contains more than 1.5% Fe_2O_3, its grayish white or light gray color is supplemented with yellow and cream tints. The pink tint appears if the iron oxide content is very high. The color of kaolin depends on the total sum of oxides of Fe, Ti, Mn, Cr, and Ni (oxides of Fe and Ti play the major role). The radionuclide analysis demonstrated that the A_{eff} value of crude kaolin samples varies from 72.6 to 328.5 TBq/kg (155.86, on the average). The thorium component directly related to the Th content in the granitic bedrock provides the greatest contribution.

The commercial crude kaolin (CK) from the Zhuravlinyi Log (ZhL) deposit (rank KS-ZhL) has the following chemical composition (%): SiO_2 63.1, Al_2O_3 20.71, Fe_2O_3 0.59, TiO_2 0.22, (CaO + MgO) 0.57, (K_2O + Na_2O) 0.80, SO_3 0.08, and L.O.I. 7.70. The corresponding mineral composition is as follows (%): kaolinite 45, quartz 42, mica 6, potassium feldspar 6, and carbonates 1. The crude kaolin of this rank is suitable for the production of porcelain, glazed pottery, and building ceramics. Comparison of the above composition with the data from Tables 3 and 4 shows that kaolin I from the Upper Ushkoty Pluton is close to rank KS-ZhL. This crude kaolin can be used for the production of acid refractories, while the colorless variety can be used for the production of glazed pottery. In general, the field of crude kaolin utilization is rather restricted. Therefore, the main attention is usually focused on the economic evaluation of the concentrated kaolin characterized by a more persistent composition and properties.

Grains smaller than 63 μm were separated from 464 section samples of the crude kaolin and used as concentrated kaolin samples. The calculations showed that the average yield of the concentrated kaolin was 41–51% (45.7%, on the average) from crude kaolin I, as much as 45.7–65.8% (57.5%, on the average) from crude kaolin III, and 23.1–49.7% (39.0%, on the average) from the alkaline kaolin II.

It should be admitted that the dressing of fractions –63 or –56 μm does not warrant the recovery of concentrated product with the Al_2O_3 content of >36% specified by several state standards owing to a high content of the fine-dispersed quartz and microcline. At the current state of dressing technology, it is expedient to carry out the kaolin concentration based on –20 μm fraction, which provides the maximal removal of impurities and stabilizes the composition and quality of the dressing product.

Table 4. Mineral composition of crude kaolin, %

Mineral	Natural types		
	Normal kaolin I	Alkaline kaolin II	Normal kaolin III
Kaolinite	45–50	30–35	55–65
Quartz	48–52	45–48	30–40
Microcline	1–2	18–20	1–2
Muscovite	1–3	1–2	1–2
Others	1–2	1–2	1–3

THE CONCENTRATED KAOLIN

The concentrated kaolin samples were studied with the application of chemical analysis, X-ray diffraction, thermographic analysis, optic microscopy, and other methods. When examining the chemical composition, the main attention was focused on the contents of Al_2O_3 and K_2O, as well as iron and titanium oxides, which govern the color of kaolin before and after its thermal processing. The quantitative proportions of kaolinite and mineral impurities in the mineral composition were also scrutinized.

The chemical composition of the concentrated kaolin is shown in Table 5.

As can be seen, the concentrated product of the alkaline kaolin is steadily depleted in alumina in comparison with that of the normal kaolin. It has also been established that the concentrated kaolin III contains much more TiO_2 and approximately two times lower Fe_2O_3 content than the concentrated kaolin I. The K_2O content in the alkaline kaolin II is always 4–10 times higher than in the normal kaolin, because the numerous microcline grains in the crude alkaline kaolin become brittle due to the kaolinization of perthites and intracrystalline dissolution of the microcline and break down into small particles, most of which are of the same size as kaolinite particles. Therefore, the higher the microcline content in the crude material, the greater the amount of microcline transferred into the concentrate. The statistical processing of three samplings characterizing the concentrated kaolin has shown the persistent negative correlations in the SiO_2–Al_2O_3, SiO_2–L.O.I., Al_2O_3–K_2O, and K_2O–L.O.I. systems and the positive correlation in the Al_2O_3–L.O.I. system. At the same time, the Fe_2O_3–Al_2O_3 (negative) and TiO_2–Al_2O_3 (positive) correlations are significant in the concentrated kaolin III and insignificant in kaolin types I and II. This discrepancy is explained by the specific chemical composition of kaolin III that differs from kaolin I by a wide variation of the Fe_2O_3 and TiO_2 contents and low background K_2O content. The contents of toxic elements in the concentrated product are insignificant and permissible.

Grain size distribution. Concentrated products of the alkaline kaolin II demonstrate the highest dispersion. The content of particles smaller than 2 μm varies

Table 5. Comparison of chemical compositions of concentrated kaolin extracted from different types of crude kaolin

Statistical characteristics	SiO_2			Al_2O_3			Fe_2O_3		
	1*	2	3	1	2	3	1	2	3
Average	48.4	51.3	48.7	35.9	52.86	35.95	0.76	0.81	0.36
Standard deviation	1.31	1.22	1.54	0.89	1.31	0.47	0.19	0.15	0.26
Coefficient of variation	2.71	2.38	3.16	2.48	3.98	1.30	25.0	18.5	72.2
Statistical characteristics	TiO_2			K_2O			L.O.I.		
	1	2	3	1	2	3	1	2	3
Average	0.12	0.13	0.85	0.82	3.11	0.18	13.04	11.05	13.43
Standard deviation	0.036	0.05	0.43	0.37	0.61	0.048	0.68	0.65	0.54
Coefficient of variation	33.3	38.5	51.8	45.1	19.6	80.0	5.2	5.9	4.0

Note: (1) Normal kaolin I; (2) alkaline kaolin II; (3) normal kaolin III.

Table 6. Mineral composition of the concentrated kaolin (based on XRD data)

Crude kaolin type	Kaolinite minerals	Quartz	Microcline	Muscovite (sericite)	Mixed-layer minerals
Normal kaolin proper	82–98 / 88	3–12 / 6.5	0–4 / 0.5	0–8 / 5	–
Alkaline kaolin	64–86 / 77	5–12 / 7	3–23 / 9	0–12 / 7	Traces
Micaceous alkaline kaolin	31–60 / 50	10–18 / 10	0–42 / 14	21–30 / 24	0–5 / 2
Clay and rubble	31–54 / 50	7–10 / 9	16–42 / 25	10–13 / 11	2–10 / 5

Note: Numerator and denominator show the range and average value, respectively.

from 35 to 67% in these products and from 20 to 43% in products of the normal kaolin. Some recrystallization of kaolinite can be expected in the upper subzone of the weathering profile. It should be noted that the least dispersion is typical of products of kaolin III with <2 μm fraction occupying no more than 30%. In general, the concentrated kaolin may be regarded as a moderately dispersed material. It cannot be ruled out that the long-term processing of the concentrated kaolin by methods providing the splitting of kaolinite crystals along the cleavage planes (delamination) can substantially increase its dispersion.

Mineral composition. The concentrated kaolin mainly consists of minerals of the kaolinite group (mixture of isostructural kaolinite varieties with various degrees of structural perfection and a subordinate amount of 7Å-halloysite). In addition to the kaolinite minerals, the concentrated kaolin contains particles of the relict quartz, microcline, and sericite. The XRD method was applied to determine the proportions of the aforementioned minerals commonly occurring as subcolloidal particles. We analyzed 40 samples covering the entire range of Al_2O_3 and K_2O proportions. The quantitative assessment of mineral composition of the concentrated kaolin samples was carried out with the computer processing of XRD results (Ivoilova and Gorbachev, 2000). The results obtained (Table 6) show that both sericite and potassium feldspar occur in the majority of samples. Sericite is absent only in 5 samples, while potassium feldspar is missing in 14 samples. This indicates that mica is more stable under conditions of kaolin weathering. The variation of components is as follows (%): kaolinite 31–94, sericite 0–23.5, potassium feldspar 0–42%, and quartz, 3–21%. The mixed-layer minerals largely detected in the clayey and rubble products of weathering are less common in the alkaline kaolin. The content of K-bearing minerals is no more than 8% in the concentrated product of the normal kaolin and 8–30% in the product from the alkaline kaolin contain. Sericite accounts for 20–30% of the concentrate in some samples.

The average Hinckley index (integral estimate of the coefficient of kaolinite structure ordering) is 0.8–0.9 (occasionally, as much as 1.0–1.2). The presence of

7Å-halloysite with a tubular morphology (based on SEM observations) decreases the Hinckley index. Mica (sericite) is present in most of the samples as a partly kaolinized muscovite or hydromuscovite of $2M_1$ polytype.

According to the NGR data, iron mainly occurs in the concentrated kaolin in the mineral form (mainly, oxides). The isomorphic iron admixture in kaolinite minerals and sericite is of subordinate importance. This fact allows us to suggest a positive result of the concentrated kaolin refining with chemical and biochemical bleaching.

Titanium occurs in the concentrated kaolin mainly as anatase leucoxene. However, it should be noted that the content of titanium minerals is maximal (3–4%) in the dressing product of kaolin derived from the weathering of biotite-rich granitoids.

Virtually all the samples of concentrated kaolin meet the normative requirements for CaO and SO_3 contents. The contents of water-soluble salts of Ca, Mg, and Na in the aqueous extracts are also lower that the permissible limits.

Properties of the concentrated kaolin are functions of their chemical and mineral compositions, dispersion, crystal chemistry of kaolinite minerals, and specific impurities (e.g., coaly organic matter).

Whiteness (percentage of ray reflections in the blue region of spectrum), both before and after the roasting to 1350°C, is the parameter limiting the usage of concentrated kaolin in the production of paper, fine ceramics, and other materials. The measured whiteness of three natural kaolin types is given in Table 7.

Table 7. Average coefficients of concentrated kaolin whiteness (%)

Coefficient of whiteness	Natural types of kaolin		
	I	II	III
Average	78.2/80.6	76.8/67.6	72.4/80.4
Maximum	88.2/87.5	85.5/80.5	84/86
Minimum	58.3/74.1	59.5/45.5	52/64
Standard deviation	7.9/4.7	6.0/7.3	11.2/6.6
Coefficient of variation	10.1/5.8	7.8/10.8	15.5/8.2

Note: Numerator and denominator characterize the dry kaolin and roasted kaolin, respectively.

It is evident that the concentrated products obtained from kaolin types I and II are similar in terms of whiteness before the roasting and occupy the leading position, whereas the concentrated crude kaolin III has a lower whiteness. After the roasting, the kaolin becomes paler in the case of types I and III and darker in the case of kaolin II mainly due to the presence of fusible microcline. The statistical analysis confirms a negative correlation of the kaolin whiteness with the Fe_2O_3 and TiO_2 contents, which is most prominent in kaolin III (Table 8). Therefore, products of kaolin types I and II are presumably most suitable as fillers for paper and other materials.

Rheological properties characterize ability of the concentrated kaolin to make up stable water suspension with the necessary density or to form plastic mass (paste). With respect to *plasticity*, the concentrated kaolin from the South Ushkoty deposit may be referred to as a nonplastic or low-plastic clayey raw material. Therefore, it reveals a low *mechanical bending strength in dry state* ranging from 0.15 to 2.25 MPa (commonly, 0.6–0.7 MPa). The *structure formation threshold* virtually does not depend on any other parameters of the concentrated kaolin and varies from 1.04 to 1.16 g/m^3. The predominance of samples with a rather high structure formation threshold (~1.1 g/m^3 or higher) indicates the possibility to obtain stable suspension of sufficient density. The fluidization was studied in 43 samples of kaolin I in order to minimize the influence of feldspar. About 30% of these samples turned out to be poorly fluidized. They are close, if not identical, to the fluidized kaolin in terms of chemical and mineral compositions. The poor fluidization of kaolin, which is probably related to electrochemical effects and governed by the charge of solvate shells, may hamper the preparation of ceramic slip.

Ceramic properties. The complete shrinkage at roasting up to 1350°C varies from 9.2 to 16.8%. Correspondingly, water absorption by the ceramic crock varies from 13.9% at the K_2O content of <2% to 6–7% at the K_2O content of 2–5%. Thus, the caking ability of the concentrated kaolin depends on the quantitative proportions of kaolinite and alkali-bearing minerals (potassium feldspar + muscovite). Results of the statistical processing of data on ceramic properties of kaolin are shown in Table 8.

One can see that Fe_2O_3 and TiO_2 reveal a positive correlation, while these components have a negative correlation with the water absorption. The average water absorption is rather high (about 14%) and indicates that the concentrated kaolin samples are generally characterized by a low caking ability despite the presence of K_2O-bearing minerals.

The *refractoriness* of kaolinite concentrates obtained from crude kaolin types I and II is rather high (1755°C, on the average). The concentrates containing >2% K_2O are less refractory (1730°C or lower).

Sandy dressing wastes. The utilization of wastes is highly desirable for the environmental and economic reasons. The yield of >63 μm fraction during the dressing of composite crude kaolin samples varies from 37 to 73.2%. The yield from the crude kaolin of types I and II is 60.4 and 60.2%, respectively (average of 32 samples). The average yield from crude kaolin III amounts to 44.2%. The grain size of sands separated from the crude kaolin of types I and II corresponds to the average grain size module of 2.6 (2.1–4.4). This module equals 2.2 (1.0–3.5) for crude kaolin III. Hence, the medium-, coarse-, and very coarse-grained sands prevail in the

Table 8. Correlation between the components of concentrated kaolin and its ceramic properties ($N = 60$)

Indices	Average	Minimum	Maximum	Standard deviation	Coefficient of variation
Al_2O_3,%	34.75	27.53	37.41	1.77	5.1
K_2O,%	1.32	0.01	4.04	1.21	91.7
Fe_2O_3,%	0.71	0.04	2.85	0.35	49.3
Complete shrinkage	13.17	9.20	20.40	1.86	14.2
Water absorption	13.87	0.40	29.40	6.42	46.3

Matrix	Al_2O_3	K_2O	Fe_2O_3	Complete shrinkage
Al_2O_3	1.00			
K_2O	–0.77	1.00		
Fe_2O_3	–0.44	0.41	1.00	
Complete shrinkage	–0.45	0.16	–0.05	1.0
Water absorption	0.68	–0.69	–0.30	–0.56

first case, while the medium-grained sand (with the occasional coarse- and fine-grained varieties) dominates in the second case. The chemical composition of sands (Table 9) is consistent with proportions of quartz and K_2O-bearing microcline and muscovite (sericite). Microcline is detected in fractions ranging from 1.6 to 0.063 mm. Its maximum content (15–20%) is inherent to the alkaline kaolin (occasionally, up to 30%). The muscovite (sericite) content is very variable and depends on its content in the granitic bedrock. The mica is mainly represented by the fine-flaky variety (sericite). The relatively coarse-flaky sericite (fractions ranging from –1.0 to +0.63 mm) contains 7.5% K_2O. The sericite content shows an inverse correlation with the grain size of sand and commonly does not exceed 5% (occasionally, up to 20%). The degree of sericite kaolinization also inversely correlates with the particle size and the K_2O content drops to 4–5%. Pseudomorphs of kaolinite after biotite (not more than 5%) are noticed in the sands obtained during the concentration of crude kaolin III. The ore minerals commonly occur as black, dark brown, and brown grains in the fraction smaller than 0.315 mm. The DTMA and XRD data indicate the presence of goethite, hematite, magnetite, maghemite, lepidocrocite, and ilmenorutile that account for no more than 0.5% Fe_2O_3 in the sand.

The pure quartz concentrate (1.25–0.4 mm) obtained from the sand by rubbing and crushing can be used for the production of glass, ceramics, welding and molding materials, and so on. The fine-grained fractions, typical of alkaline kaolin, are polymineral (quartz–feldspar, sericite–quartz, or sericite–quartz–feldspar) materials that can mainly be used in building works. However, valuable commercial products (concentrates of high-quality white microcline and light fine-grained mica) may also be obtained with the application of special separation methods. Microcline is used in the production of ceramics and glass, while muscovite (sericite) may be utilized to produce paints, wallpaper, ruberoid, technical rubber, cement, and others.

Table 9. Major components in sands, %

Natural types of crude kaolin	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	R_2O	L.O.I.
I	94.86	2.6	0.45	0.05	0.6	0.70
II	90.74	4.5	0.50	0.03	2.74	0.22
III	97.40	1.0	0.6	0.02	0.02	0.65

THE QUALITATIVE CHARACTERISTICS OF DRESSING PRODUCTS

The kaolinite concentrate was assessed from the point of view of its utilization in four principal industrial fields of industry (fine ceramics, paper, technical rubber and synthetic materials, and refractory materials). The assessment was conducted for three natural (economic) types of crude kaolin described above based on the following basic parameters: Al_2O_3, Fe_2O_3, and TiO_2 contents; coefficient of whiteness; and concentrated product yield (<63 μm fraction). The indices shown in Table 10 are compared with the limit values specified by the Russian state standards (GOST): 21286-82 for ceramics, 19285-73 for paper, and 19608-84 for technical rubber.

The estimated reserves in Lode 1 can be distributed in the following way: 68.4% of the concentrated normal kaolin can be utilized for the production of ceramics (including 25.4% for the porcelain production). The concentrated normal kaolin and alkaline kaolin can also be used in the following fields: 63.8 and 42.8%, respectively, as filler for paper and cardboard; 95.7 and 68.7%, respectively, for the production of refractory materials; 98.8 and 97.8%, respectively, for the production of technical rubber, artificial leather, and textile.

Table 10. Major indices of concentrated kaolin from the South Ushkoty deposit

Indices, %	Kaolin type									
	I (normal kaolin formed after microcline leucogranites)			II (alkali kaolin formed after microcline leucogranites)				III (normal kaolin formed after plagiogranites and biotite granites)		
	Aver.	σ	V	Aver.	C	σ	V	Aver.	σ	V
Al_2O_3	35.9	0.89	2.48	32.86	3	1.31	398	35.95	0.47	1.30
Fe_2O_3	0.76	0.19	25.0	0.81	0	0.15	18.5	0.36	0.26	72.2
TiO_2	0.12	0.04	33.3	0.13	0	9.05	38.5	0.83	0.43	51.8
Coefficient of whiteness	78.2	7.9	10.1	76.8	7	6.0	7.8	72.4	11.2	15.5
Yield of concentrated kaolin	45.7			39.87	3			57.5		

Notes: (σ) Standard deviation; (V) coefficient of variation.

The economic characteristics for the deposit as a whole (five lodes) are close to or slightly lower than the values given above: 65.3% for ceramics (including 22% for porcelain); 60.6 and 42.8%, respectively, for paper and cardboard; 97.5 and 69%, respectively, for refractory materials; and 99.3 and 97.9%, respectively, for technical rubber.

At the current state of the art, kaolin of the South Ushkoty deposit ranks between its counterparts from the Soyuznoe deposit (Kazakhstan) and the Zhuravlinyi Log deposit (Chelyabinsk region, Russia) in terms of high-quality varieties required for the production of ceramics and paper.

The sandy dressing wastes can be used to obtain pure quartz and high-quality microcline concentrates. This will enhance the potential value of the South Ushkoty deposit and its appeal for investors.

CONCLUSIONS

The total indicated and inferred reserve (category $C_1 + C_2$ in the Russian classification) of eluvial kaolin in Lode 1 of the South Ushkoty deposit has been estimated and approved at 38494.4 kt (including 22494.0 kt of alkaline kaolin).

The deposit merits a more detailed exploration and the subsequent development.

Kaolin from this deposit is fit for the wet electrolyte-free concentration combined with the refinement of sandy waste by sieving (<0.14 mm fraction), flotation, drying, and magnetic separation to obtain the pure quartz and high-quality microcline concentrate together with the kaolinite concentrate.

It should be added that the hydrogeological, geoengineering, and mining characteristics of the South Ushkoty kaolin deposit are favorable for its open pit mining. This is indicated by the shallow depth of kaolin lodes, satisfactory stability of overburden and kaolin, and insignificant inflow of groundwater (maximum 1.04 m^3/day).

The building and breaking-in of the mining- dressing plant on the basis of the South Ushkoty deposit would be an appreciable contribution to the creation of a self-sufficient source of kaolin in the Russian Federation and the growth of economic potential of the Orenburg region. The calculated technicoeconomic parameters of such enterprise indicate that it will be highly efficient.

The South Ushkoty deposit is characterized by the favorable geographic setting, proximity to railways, favorable parameters of kaolin composition and properties, and a sufficiently developed infrastructure. Therefore, it is expedient to start the exploitation of this deposit as soon as possible. This will promote the creation of a new mineral base for the production of high-quality kaolin materials in the Orenburg region and satisfy the demand of domestic consumers. Prospects of the Transural Orsk region for the discovery of new eluvial kaolin deposits are far from being exhausted. The discovery of the South Ushkoty deposit actually confirmed the previously forecasted high potential of the eastern Orsk region (Adamov, Dombarov, Svetlin, and Yasnensk administrative districts of the Orenburg region). The possible kaolin resource (category P_2 in the Russian classification) of this territory is estimated at 1 Gt, and no less than 10% of this quantity corresponds to the high-quality kaolin.

REFERENCES

Belov, V.V., Genetic, Mineral, and Industrial Types of Kaolin Deposits in the Urals and Their Relationship to Ancient Weathering Crust, *Kory vyvetrivaniya Urala* (Weathering Crusts in the Urals), Saratov: Saratov. Univ., 1969, pp. 195–197.

Blokhintseva, V.P. and Ivanov, V.V., Mugodzhary: A New High-Quality Kaolin Resource Base, *Genezis i resursy kaolinov i ogneupornykh glin* (Genesis and Resources of Kaolin and Fireclay), Moscow: Nauka, 1990, pp. 105–111.

Gorbachev, B.F., Regularities of Formation and Localization of Kaolin Deposits in the Weathering Crusts, *Usloviya* *formirovaniya kor vyvetrivaniya i ikh mineral'nykh mestorozhdenii* (Formation Conditions of Weathering Crusts and Associated Mineral Deposits), Moscow: Nauka, 1983, pp. 22–28.

Gorbachev, B.F. and Vasyanov, G.P., Geological Criteria for the Prediction and Exploration of Residual and Allogenic Mineral Deposits in Weathering Crusts of the Urals, *Sov. Geol.*, 1970, no. 10, pp. 96–107.

Gorbachev, B.F. and Vasyanov, G.P., Kaolins and Their Spatial Distribution in the Mugodzhary, *Litol. Polezn. Iskop.*, 1974, no. 5, pp. 18–26.

Gorbachev, B.F., Kornilov, A.V., and Gonyukh, V.M., The Comprehensive Assessment of the Quality of Kaolin, *Razved. Okhr. Nedr*, 2000, no. 9, pp. 38–40.

Grabezhev, A.I., Biryukov, V.M., and Fedorov, V.I., Metallogeny of the Western Part of the East Mugodzhary Uplift, *Ezhegodnik-1979* (Yearbook-1979), Sverdlovsk: Inst. Geol. Geokhim. Ural. Nauchn. Tsentra Akad. Nauk SSSR, 1980, pp. 119–121.

Ivoilova, E.Kh. and Gorbachev, B.F., The Computer Analysis of Kaolin Composition, *Razved. Okhr. Nedr*, 2000, no. 9, pp. 35–36.

Metodicheskie rekomendatsii po sredne- i krupnomasshtabnomu prognozirovaniyu mestorozhdenii elyuvial'nykh kaolinov (Methodical Recommendations for Medium- and Large-Scale Forecast of Eluvial Kaolin Deposits), Kazan: VNIIgeolnerud, 1984.

Petrov, V.P., Kaolin Deposits of the USSR, *Kaolinovye mestorozhdeniya i ikh genezis* (Kaolin Deposits and Their Origin), Moscow: Nauka, 1968, pp. 7–12.

Prognoznaya otsenka zon gipergeneza na tverdye poleznye iskopaemye pri geologicheskoi s'emke masshtaba 1 : 50000–1 : 200000 (Prognostic Estimation of Metallic Mineral Resources of Hypergene Zones during the Geological Mapping at a Scale of 1 : 50000–1 : 200000), Mikhailov, B.M., Ed., St. Petersburg: Nedra, 1998.

Stepanov, A.P. and Gerasimenko, L.F., Kaolins of the Orenburg Region of the Urals, *Kaoliny* (Kaolins), Moscow: Nauka, 1974, pp. 61–66.