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History of the Formation of the Tsentral'noe Titanium–Zirconium Sand Deposit in the European Part of Russia

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Abstract—Based on the study of the Tsentral'noe deposit, specific features of the formation of mineral assemblages of complex titanium–zirconium placers are considered. The placers formed during the multiple redeposition of clastogenic minerals from source rocks and younger sedimentary rocks (intermediate collectors of titanium–zirconium minerals). The location of erosion and sedimentation zones significantly varied in the Phanerozoic in the adjacent region, resulting in the development of intricate relationships between different-aged terrigenous rocks (possible intermediate collectors) that provided the formation of new mineral assemblages of clastogenic ore minerals. In addition, erosional processes during the continental evolution of the study region could promote the exposure of more ancient rock complexes, the local washout of crystalline basement rocks, and the delivery of ore minerals from the latter rocks to the coastal zone of sedimentary basins. The aim of this communication is to attract the attention of researchers to the issue of the formation of mineral assemblages of complex placers of heavy minerals with similar hydraulic grain dimension and migration capacity for concentration in a rather narrow grain size range. Such mineral assemblages only slightly inherit the primary compositional features of provenances and primarily reflect changes in the sedimentation environment.

The Tsentral'noe deposit located in the Tambov region is the largest titanium–zirconium deposit in Russia. It has nearly 1 bln m^3 of sand with the following average contents, %: ilmenite 36, rutile 8.3, zircon 7.2, disthene 4.5, and P_2O_5 7. In terms of ore sand reserves, the Tsentral'noe deposit is commensurable with the largest titanium–zirconium deposits in the world and serves as a reference object for understanding the principle trends of the formation of complex heavy mineral placers in the platformal sedimentary cover. The Tsentral'noe deposit was discovered in 1959 and explored in the mid-1960s. However, the deposit was qualified as a subeconomic object in the early 1970s, because technological aspects of the titanium–zirconium sand were insufficiently studied and its exploitation was unfeasible at the wholesale price of that time. Therefore, the Tsentral'noe deposit was excluded from the realm of investigation for a long time. After the breakup of the Soviet Union in 1991, the demand for titanium–zirconium concentrates drastically increased in Russia. At present, both Russian and foreign mining companies consider this deposit a highly attractive object for the investment and a top-priority object for the commercial development (Bykhovskii and Zubkov, 1996).

The Tsentral'noe placer is located mainly in the upper section of the Cenomanian sandy sequence and partly in the basal unit of the Santonian. The placer field, approximately 140 km^2 in area, extends in the submeridional direction over 20 km and varies in width from 2 to 18 km (average 8 km). The ore bed, which is outlined only on the basis of sampling data, lies at a depth of 3.5–22 m and has a thickness of 2–15 m (average 6.1 m).

The Tsentral'noe deposit, located on the western slope of the Cretaceous Penza–Murom Trough at its junction with the Voronezh Massif, is the largest representative of the Upper Cretaceous titanium–zirconium placer sand formation identified by N.N. Ikonnikov as the Rasskazov-type formation (after the name of the adjacent town). The study region, more than 6000 km^2 in area, incorporates four differently investigated Cenomanian and Santonian deposits and more than ten placers that make up the Rasskazov placer district (*Rossypnye*…, 1997) (Fig. 1).

As long as the 1960s, preliminary geological reports on the placer-bearing sedimentary formations in the European part of Russia (Gurvich and Bolotov, 1968 and others) demonstrated that the upper Cretaceous formation is among the major stratigraphic levels of titanium–zirconium placers. Let us remind that these levels are as follows: Middle Devonian, Lower Carboniferous (potential placer-bearing), Middle Jurassic (Bathonian), Lower Cretaceous (Aptian–Albian), Upper Cretaceous (Cenomanian–Santonian and Campanian), Oligocene–Miocene (Poltavian–Sarmatian), and late Pleistocene–Holocene (postglaciation stage) (*Rossypnye*…, 1997). It is worth noting that the titanium–zirco-

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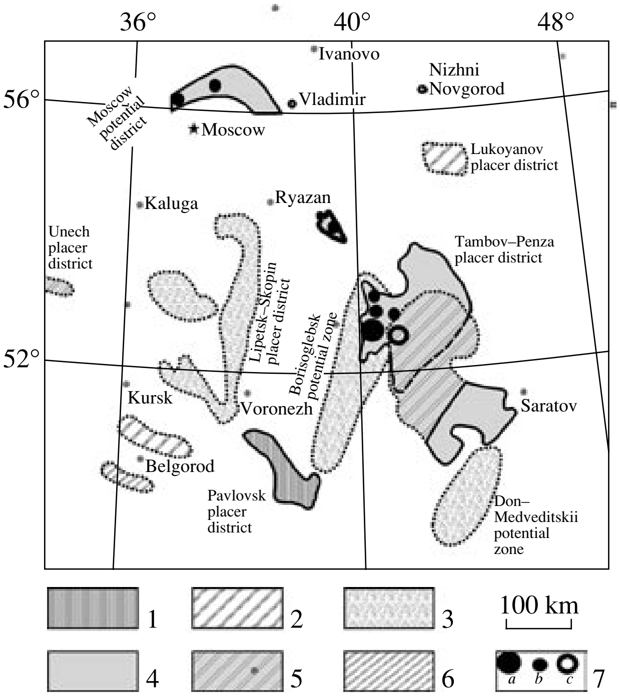

Fig. 1. Position of the Tsentral'noe deposit in the system of titanium–zirconium placer zones and districts of the East European Platform. (1–6) Placer zones and districts with titanium–zirconium placers: (1) Devonian; (2) Middle Jurassic; (3) Lower Cretaceous (Aptian–Albian); (4, 5) Upper Cretaceous: (4) Cenomanian; (5) Santonian and Campanian; (6) Oligocene–Miocene; (7) deposits: (*a*) Tsentral'noe, (*b*) other Cenomanian deposits, (*c*) Santonian Kirsanov deposit (Rasskazov district).

nium placer mineralization was also developed in the middle Riphean (metamorphosed zircon–rutile places of the Srednii Peninsula and "rutilites," i.e., rutile-rich rocks of the Middle Urals) and the Archean (heavy mineral concentrations in the coastal zone of paleobasins in the Kola Peninsula (Patyk-Kara, 2002). The available data indicate that the distribution of productive different-aged formations within the EEP is governed by a distinct zonality related to the migration of sedimentary paleobasins. The distribution of Paleozoic (Devonian and Carboniferous) placers is controlled by coastal zones of marginal shelf seas of the Proto-Ural Ocean; the distribution of Mesozoic and Early Cenozoic placers, by seas of the Tethys and Paratethys (Gurvich and Bolotov, 1968; Patyk-Kara *et al.*, 1999).

The Upper Cretaceous formation has a high phosphorite potential and, therefore, occupies a specific position among the productive placer formations of the East European Platform (Fig. 2). It should be noted that N.N. Ikonnikov divides this unit into the Cenomanian–Santonian (Rasskazov) and the Campanian (Unech) formations. Actually, all of the Upper Cretaceous placer deposits and occurrences simultaneously represent phosphorite deposits, such as deposits of the Unech placer group (Ikonnikov, 1989), or phosphate-bearing objects, such as the Tsentral'noe deposit with persistent nodular and pebble phosphorite units that locally form up to 15-cm-thick interlayer at the top of the placer ore bed (Fig. 3). Some less persistent pebble phosphorite interlayers are also encountered in the underlying ore bed. Bardeeva (1999) demonstrated that the phenomenon mentioned above may be related to the evolution of placer that was subjected to eolian reworking after the Cenomanian regression and the formation of a thick dune complex that makes up the top of the major ore bed. The accumulation of local nodular phosphorite accumulations beneath the major phosphorite-bearing unit is related to the residual concentration of nodular phosphorites in deflation holes. It should be noted that the high phosphorite potential of Upper Cretaceous placers in the East European Platform has not been sufficiently elucidated.

The Tsentral'noe placer deposit is a complex geological body. Its commercial significance is defined by both heavy minerals of ore sand, such as ilmenite, rutile, zircon, and gold (up to 200 mg/m^2), the grain size of which varies from –0.1 to +0.074 mm, and their nonmetallic component, such as quartz sand, glauconite, epidote, garnet, and phosphates of the collophane-francolite group (Bykhovskii *et al.*, 1998; Lushchakov *et al.*, 2001). The placer mineral assemblage is characterized by the persistent subordiante presence of disthene, tourmaline, and staurolite. Diamond of grain size varying from –0.3 to +0.1 mm has been reported by Yu.A. Polkanov and I.F. Kashkarov. Therefore, one can propose some assumptions concerning the migration mode of minerals mentioned above and the origination of mineral assemblages in placers.

MINERAL ASSEMBLAGES IN THE TSENTRAL'NOE DEPOSIT

The mineral composition of ore sand in the Tsentral'noe deposit has been studied from the point of view of its genesis and technological properties by many research institutes (GIREDMET, IMGRE, TsNIGRI, Mekhanobrchermet, and others) and individual researchers (I.E. Sekretarev, A.M. Bolotov, Yu.A. Polkanov, N.N. Ikonnikov, V.V. Bol'shagin, E.N. Levchenko, and others). Their data and our observations indicate that the Tsentral'noe sand has all main properties of ore sand from the complex coastal-marine placers known in the literature as heavy mineral placers or mineral sands (*Rossypnye…*, 1997):

(1) Fine-grained sand dominated by the 0.5–0.02 mm fraction, indicating a high sorting grade of sediments. This grain size class makes up more than 87 vol % of the studied sand and represents the major technological fraction (Fig. 4).

(2) Oligomictic quartz-rich sand (~78 wt %) with minor feldspar and the following complex mineral composition, wt %: ilmenite 1.76, rutile 0.4, leucoxene 0.3, zircon 0.3, garnet 1.2, epidote 0.87, disthene 0.48,

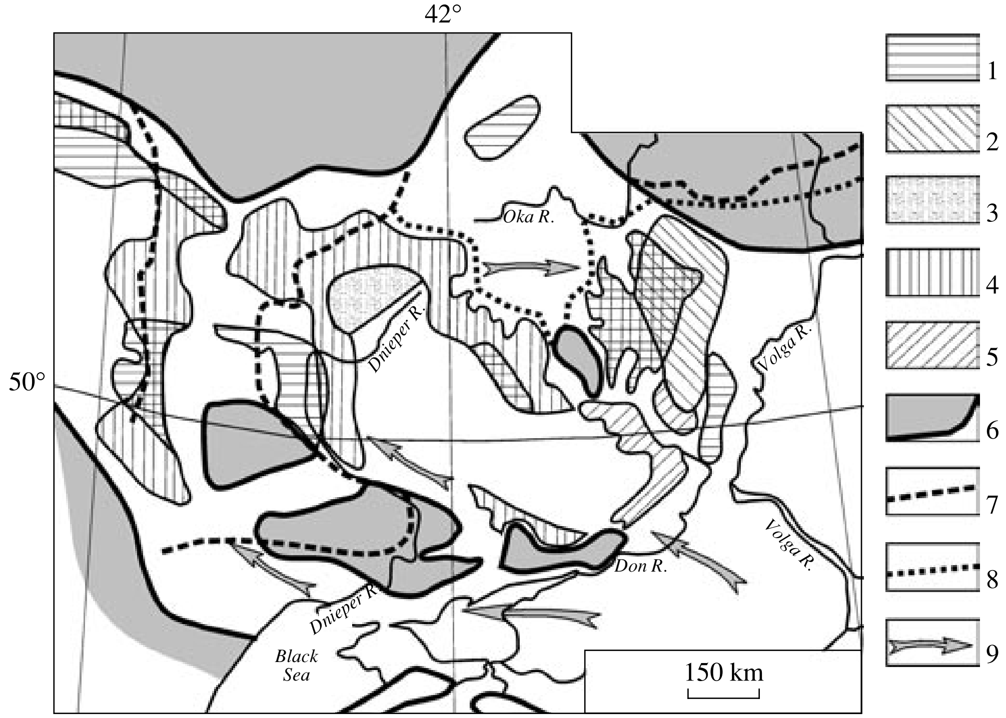

Fig. 2. Distribution of Upper Cretaceous titanium–zirconium placer and phosphorite-bearing sedimentary formations. (1–3) Ti- and Zr-bearing formations: (1) Cenomanian, (2) Santonian, (3) Campanian (with phosphates); (4, 5) phosphorite-bearing formations: (4) Cenomanian, (5) Santonian; (6–8) assumed boundaries of land in (6) Cenomanian, (7) Santonian, and (8) Campanian; (9) direction of marine currents.

tourmaline 0.4, staurolite 0.013, glauconite 6.2, and phosphates 3.8 (based on the GIREDMET data).

(3) Concentration of ore minerals within a very narrow range of grain size distribution (Fig. 4a). Against this background, one can see a smaller-scale fractionation—a significant differentiation of individual heavy minerals reflecting their initial grain size distinctions in the primary source and the subsequent breakdown in the debris flow in accordance with the hydraulic dimension. Figure 4a shows that the major part of ore minerals (≥80%) ranges in grain size from –0.10 to 0.074 mm. One can distinctly recognize in this general pattern the finer-grained zircon fraction (from –0.74 to 0.063 mm), the subordinate cyrtolite fraction (from –0.063 to 0.01 mm), and the coarser-grained tourmaline fraction (from –0.15 to 0.074 mm). Gold flakes have high buoyancy and, therefore, show a wider distribution range (from –0.117 to 0.026 mm).

(4) Grain size distribution of authigenic minerals. Naturally, this parameter is not rigorously controlled by the grain size composition of sediments. For example, glauconite is concentrated in the 0.25–0.63 mm fraction (maximum in the class ranging from –0.15 to 0.074 mm), whereas phosphorite nodules are concentrated in the coarser fraction (0.5 mm) with the prevalence of pebbles more than 2 mm in size.

The distribution of ore minerals in the deposit area is very homogeneous, the average ilmenite : rutile : zircon ratio being equal to 6.2 : 1.2 : 1. However, the rutile and zircon concentrations are relatively higher in the western area, while the ilmenite and disthene concentrations are higher in the eastern area. This is consistent with concepts of the existence of two lithodynamic zones in the placer field—prodelta in the west-northwestern area and alongshore transport zone in the eastern area (Bardeeva, 1999).

The sufficiently high homogeneity of mineral assemblages in the Tsentral'noe deposit is emphasized by the multidimensional statistical parameters of its mineral field expressed by the method of major components (MC). In the case of complex titanium–zirconium placers, this method makes it possible to outline associations of concordant and discordant indicators (minerals) and reveal the character of their spatial distribution (Patyk-Kara and Shevelev, 2000; Patyk-Kara, 2002). In this connection, the following features are important:

(1) the large share of the first (ore) MC (65–67%, up to 90% in some samples) reflecting the high ordering degree of mineral assemblages;

(2) the distinct spatial MC distribution that makes it possible to divide the placer field into two heterogeneous parts. MC 1 includes the major ore minerals (ilmenite, rutile, and zircon)[1] and disthene. These minerals are characterized by high factor loads: 0.889–0.97

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[1] The leucoxene distribution was not analyzed.

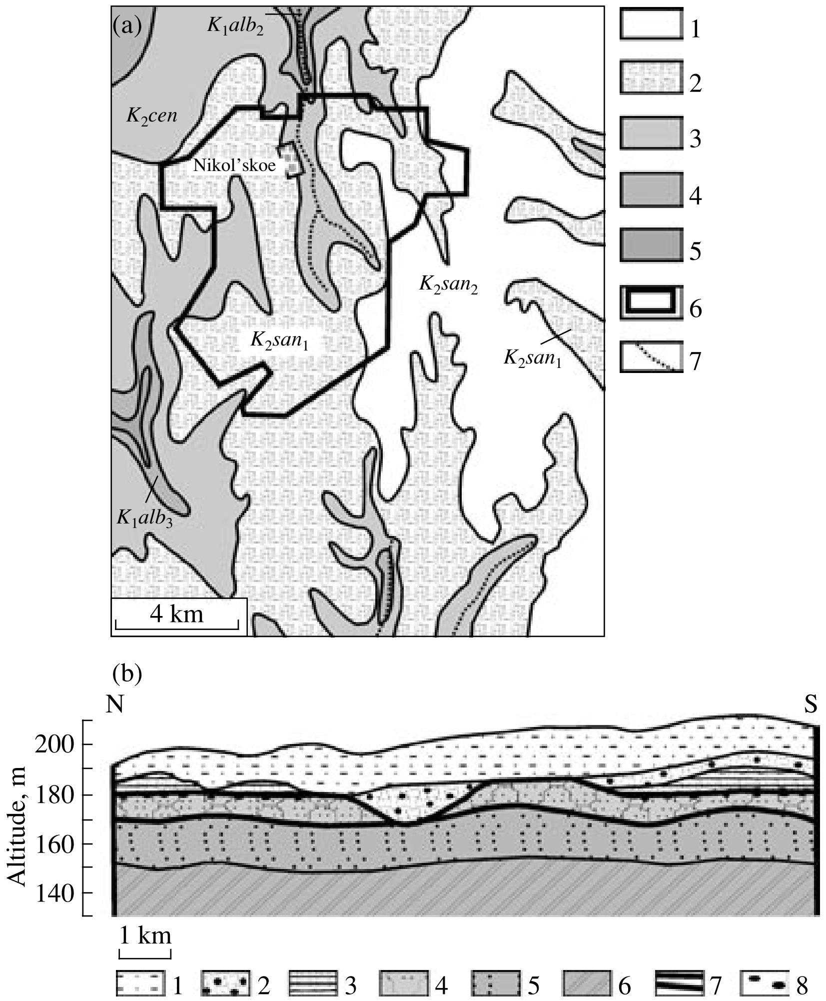

Fig. 3. Structure of the Tsentral'noe titanium–zirconium sand deposit. Based on (Sekretarev and Kitaev, 1971) and later data. (a) Plan view. (1–5) Cretaceous sediments: (1) upper Santonian, (2) lower Santonian, (3) Cenomanian, (4) upper Albian, (5) middle Albian; (6) contour of the placer deposit; (7) present-day streams. (b) Principle section. (1) upper Quaternary loam; (2) middle Quaternary sand, loam, and clay with detritus; (3) Santonian sand and friable sandstone; (4–6) Cenomanian sediments: (4) sand, (5) clayey sand, (6) clay-rich sand and silt; (7) productive placer unit; (8) phosphorite units.

(ilmenite), 0.71–0.98 (rutile), 0.77–0.96 (zircon), and 0.69–0.93 (disthene). The northwestern area of the placer field is marked by the highest MC 1 values; the southern and eastern area, by the lower values. The analysis of the composition of MC 2 and MC 3 shows that they reflect the breakdown of minerals of the major ore association in accordance with local features of the sedimentation environment. For example, MC 2 expressed as the statistical parameter $[\mathrm{ilm}_{0.57}/\mathrm{zr}_{\mathrm{zr}0.29}\ \mathrm{ru}_{0.29}]$ unravels a certain antagonism of the ilmenite behavior relative to zircon and rutile, while MC 3 shows the antagonism of zircon (occasionally, in association with disthene) relative to ilmenite and rutile. The statistical parameters reflect different migration capacities of these minerals in the debris flow and, consequently, specific features of the internal structure of the Tsentral'noe deposit (Fig. 5). The breakdown of ore association into the antagonistic minerals (ilmenite versus zircon and rutile) is observed in the central zone and southeastern periphery of the deposit. The latter area, presumably, represents a littoral zone where the concentration of minerals was controlled by the alongshore debris flow. This type of breakdown is missing in the prodelta zone.

POSSIBLE PATHWAYS OF THE MIGRATION OF ORE MINERALS

Works of I.E. Sekretarev, S.I. Gurvich, A.M. Bolotov, V.I. Belyaev, N.N. Ikonnikov, and other researchers have established that Cenomanian and Santonian placers of the Rasskazov district—Type 2 district, according to (Gurvich and Bolotov, 1968)—are exclusively related to the intermediate sedimentary collectors located on slopes of platformal structures beyond uplifts of the crystalline basement. This fact makes virtually senseless the issue of the prospecting for primary sources of placer mineralization and compels us to search the explanation of its mineral assemblages in the geological history of the region, the multiple rearrangement of the provenance, and specific features of intermediate collectors (Fig. 6).

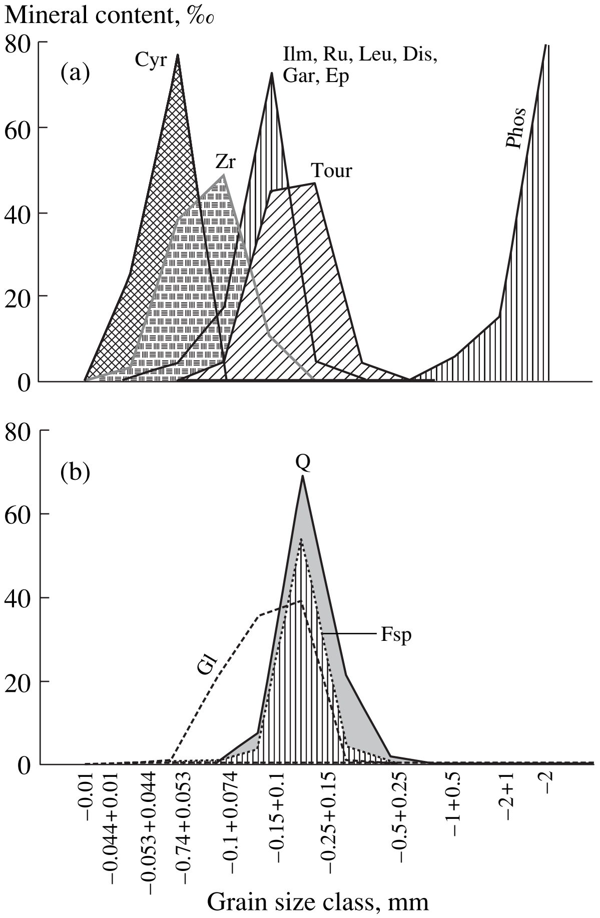

Fig. 4. Grain size distribution of placer-forming (a) heavy minerals and phosphates and (b) light minerals in the Tsentral'noe deposit. (Ilm) ilmenite, (Ru) rutile, (Leu) leucoxene, (Zr) zircon, (Dis) disthene, (Cyr) cyrtolite, (Gar) garnet, (tour) tourmaline, (Ep) epidote, (Phos) phosphates, (Q) quartz, (Gl) glauconite, (Fsp) feldspar.

After a rather prolonged (~130 Ma) continental evolution in the Early Paleozoic (Middle Devonian–Middle Carboniferous), the study region was subjected to processes of subsidence owing to destructive events at the eastern periphery of the East European Platform. Beginning from the Eifelian, the region underwent prolonged transgression that resulted in the accumulation of terrigenous–carbonate sediments. During this episode, the material was delivered from the spacious Baltic–Sarmatian zone (Lower Cambrian terrigenous and terrigenous–carbonate rocks) in the northern area, the Voronezh Massif with the crystalline basement uplift in the southern area, and the small Ul'yanov Uplift in the eastern area. The area of these provenances significantly reduced in the course of transgression in the Givetian and Frasnian–Famennian (Fig. 6a). Therefore, one can assume that crystalline rocks occupied a very small area during the short-term hiatus in the Early Carboniferous and the materials were mainly delivered from areas composed of terrigenous–carbonate rocks. Owing to the progressive deepening of the Donetsk aulacogen and associated transgression in the Early Carboniferous, crystalline rocks of the Voronezh Massif were buried under the sedimentary cover in the Visean and Tournaisian, and the materials were derived from a northern area (Orel and Kursk region). The studied placer area gave way to an occasionally flooded land composed of terrigenous–carbonate rocks. This area was incorporated in the Late Carboniferous into the Bryansk–Kursk Uplift that separated sedimentary basins of the Donetsk aulacogen and Moscow syneclise (Fig. 6b). The land constantly expanded toward the east and existed over approximately 150 Ma (up to the Lower Jurassic). This period was probably characterized by the local (low-scale) exposure of crystalline basement rocks and the introduction of ore minerals.

Beginning from the Bajocian, the study area underwent a new (approximately 100-Ma-long) evolution stage related to shelf seas at the northern periphery of the Tethys. The major provenance composed of Paleozoic terrigenous–carbonate and Upper Permian red-colored terrigenous rocks was located in the north. However, the materials were also derived from the southern submeridional uplift that extended to the Voronezh Massif and gradually diminished in area. The study area was surrounded by other island sectors (e.g., area located west of Tambov, the Nizhni Novgorod area, and others) marked by the erosion of rocks of the sedimentary cover. Since the end of the Middle Jurassic (after Callovian) and in the first half of the Early Cretaceous (including the Neocomian), the study area underwent a relative uplift and served a clastic material provenance for the eastern Ul'yanov–Saratov Trough (Fig. 6c). Beginning from the Aptian, Cretaceous sedimentary basins generally evolved in an inherited manner relative to the Middle Jurassic basin. The sea occupied the Caspian and Moscow syneclises, periodically invaded the Dnieper syneclise, and joined the Vyatka–Pechora Basin via the submeridional strait. In the Aptian–Albian, the materials were mainly derived from the Belarus–Moscow Uplift, where primarily Upper Carboniferous carbonate and Permian terrigenous rocks were eroded, the Cis-Ural Massif composed of Permian and Middle Jurassic rocks, the western land (slopes of the Ukrainian Shield), and the southern land (slopes of the Voronezh Massif where crystalline rock windows could exist in the Paleozoic rock field). Jurassic rocks were eroded in local uplifts, whereas Lower Cretaceous sediments were washed out during the regressions (Fig. 6d). The short-term hiatus between the Lower Cretaceous and Upper Cretaceous (Cenomanian) episodes was probably limited by an insignificant differentiation of the primary Albian coastal-marine plain.

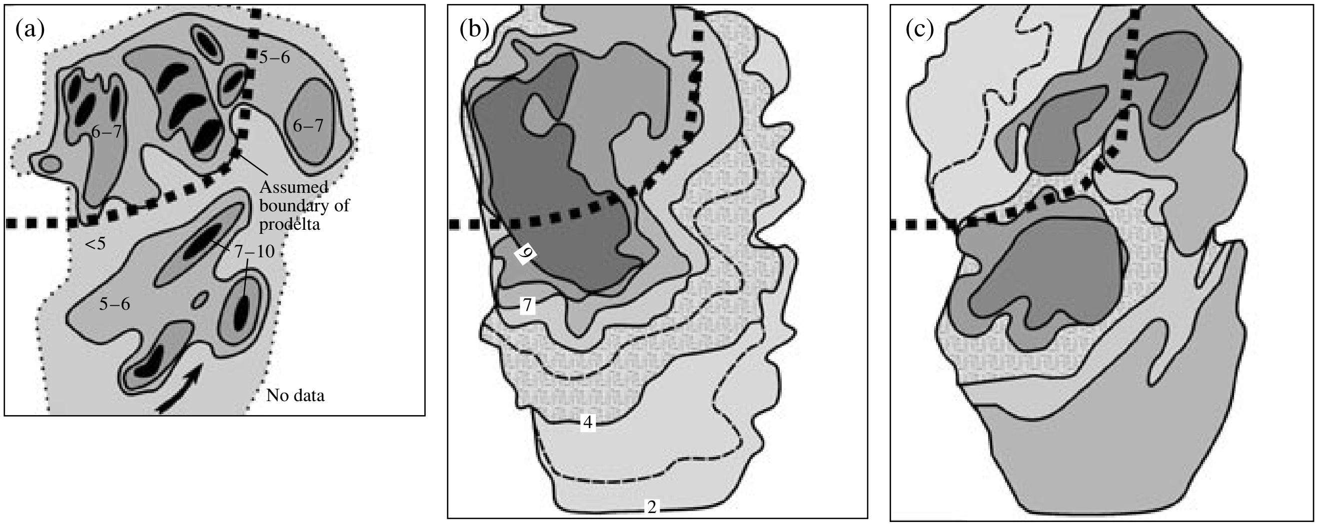

Fig. 5. Geochemical zonation in the Tsentral'noe deposit. (a) Major (ore) component of type 1 (MC 1) [ilm$_{0.9}$ zr$_{0.85}$ ru$_{0.8}$ dis$_{0.7}$]; (b) major component of type 2 (MC 2) [ilm$_{0.57}$/zr $_{0.29}$ ru$_{0.29b}$]; (c) major component of type 3 (MC 3).

The maximal development of the Cenomanian basin was marked by the formation of a large bay in the Dnieper syneclise area and the supply of its coastal zone with sediments from slopes of the Ukrainian Shield where crystalline rocks were still exposed. This bay joined the eastern open sea via a system of straits separated by an archipelago that existed at the site of the Voronezh and Tambov massifs (Figs. 2, 6e). These islands could significantly affect water mass circulation in the bay and govern the direction of the major transport material by alongshore debris flows. The primary plain was drained by probably E- and SE-oriented river valleys during the subsequent regression.

According to modern concepts, placers of the Rasskazov district, including the Tsentral'noe deposit, formed at the regressive stage of the Cenomanian basin when the coastline was located within the Tambov district and the coastal zone received materials mainly from rivers that drained the spacious land extending from the Belarus Uplift in the west to the Volga and Cis-Ural regions in the east. This land represented a hillocky denudation plain, the surface of which was composed of Devonian–Carboniferous terrigenous–carbonate rocks and Permian, Jurassic, and Lower Cretaceous terrigenous rocks. The Tsentral'noe deposit formed in the prodelta of one of the valleys that drained the land. The valley cut the accumulative coastal-marine plain composed of Lower Cretaceous sand and older sediments of the transgressive stage of the Cenomanian basin. Another source could be represented by ancient rivers that originated on slopes of the Ukrainian Shield and intersected the primary coastal-marine plain composed of Aptian–Albian and Cenomanian sediments. The northeastern slope of the Voronezh Massif, which was buried under the Carboniferous–Permian sedimentary cover by that time, could serve as an additional provenance. Thus, at the onset of the formation of the Tsentral'noe deposit and other Cenomanian placers of the Rasskazov district, fresh portions of clastogenic minerals of crystalline rocks could be transported by transit rivers from remote sources, the nearest source (Ukrainian Shield) being located more than 900 km away. It should be remembered that a thick kaolinitic weathering crust was developed on the Ukrainian Shield at that time.

The north-northeastern direction of material transport prevailed in the placer field during its formation. This is indirectly indicated by the mineral space structure of the placer field. As mentioned above, based on specific features of the distribution of ore association composed of the major ore minerals, the placer field may be divided into two zones—the coastal (prodelta) zone and the outer zone marked by the influence of the alongshore debris flow on the submarine slope (Bardeeva, 1999). Other researchers also support the concept of the formation of the studied placer in a low-energy environment of the coastal shallow-water zone that was responsible for the relative homogeneous distribution of ore minerals and the absence of prominent bedding and lithological boundaries of the ore bed (Belyaev and Ivanov, 2000).

Thus, the above assumptions based on the analysis of regional paleogeographic maps *(Atlas…*, 1962 and others) suggest that crystalline rocks—primary sources of clastogenic minerals of the ore association—ceased to play any significant role in the formation of sedimentation paragenesis of heavy minerals in the Carboniferous. However, the adjacent territory was subjected to an appreciable rearrangement of the discharge source and sedimentation zones in the Phanerozoic, resulting in intricate relationships between different-aged terrigenous rocks (the possible intermediate collectors) during

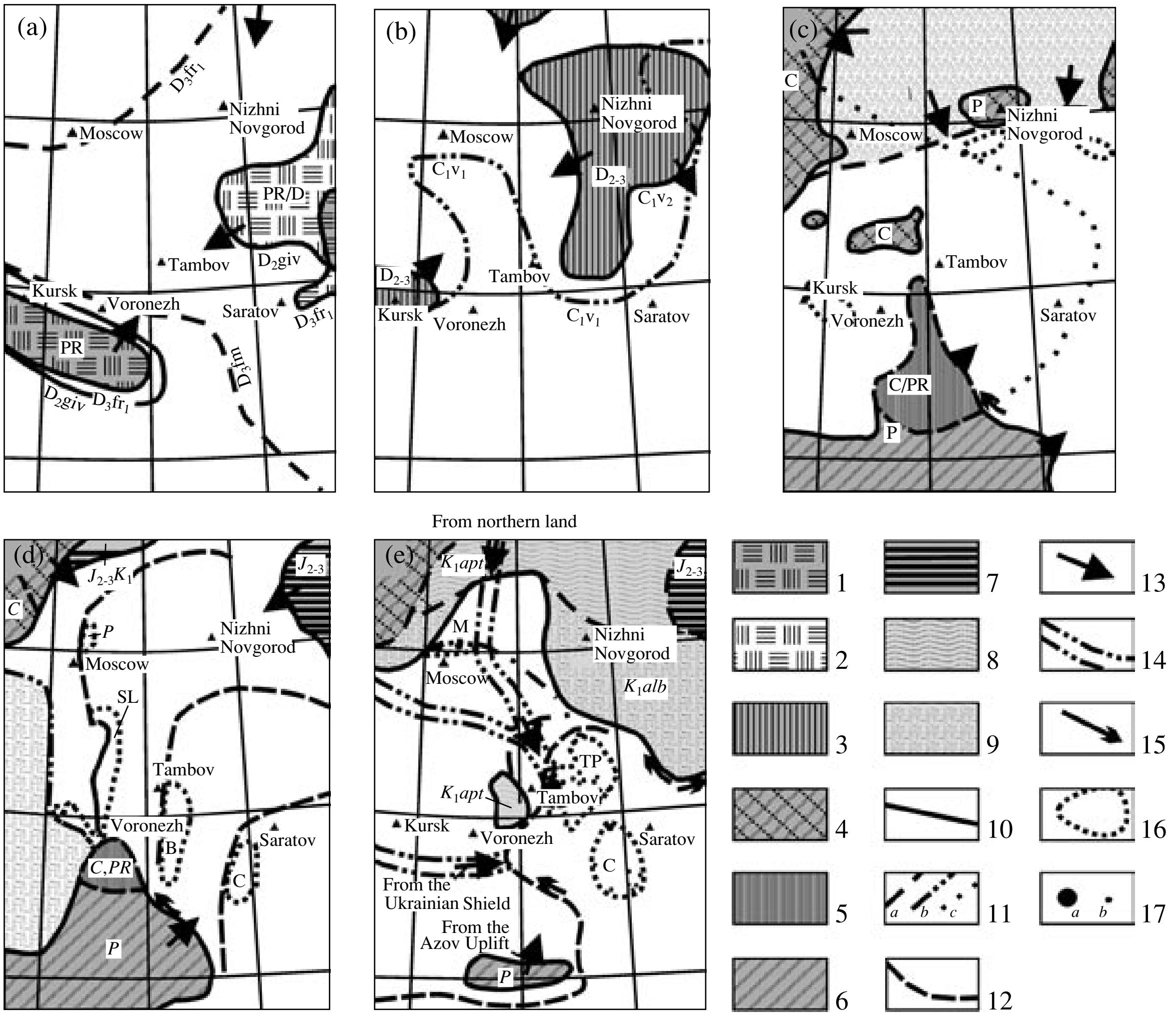

Fig. 6. Paleogeographic scheme of the study area showing the possible pathways of migration and redeposition of clastic material involved in the formation of the mineral composition of Cenomanian placers in the Rasskazov placer district. (a) Devonian; (b) Middle Carboniferous; (c) Middle Jurassic; (d) Lower Cretaceous (Aptian–Albian); (e) Upper Cretaceous (Cenomanian). (1–9) Type of discharge zones: (1) crystalline basement rocks,(2) crystalline basement rocks partially overlain by Devonian sediments; (3–9) sedimentary rocks of the cover: (3) Devonian, (4) Carboniferous, (5) Carboniferous and assumed windows of the crystalline basement rocks, (6) Permian, (7) Jurassic, (8) Lower Cretaceous (Aptian), (9) Lower Cretaceous (Albian); (10) assumed boundary of the sedimentary basin; (11) boundary of the assumed basin of another age: (*a*) Frasnian and Famennian (scheme a), (*b*) early Visean (scheme b), (*c*) Permian (scheme c); (12) assumed phases of coastline stabilization (schemes d and e); (13) assumed direction of material transport; (14) assumed paleovalleys (scheme e); (15) assumed direction of alongshore displacement of detritus; (16) placer domains; (17) deposits: (*a*) Tsentral'noe deposit, (*b*) small placer deposits and occurrences (scheme e).

the formation of new mineral assemblages of clastogenic ore minerals. In addition, more ancient rock complexes could be exposed during the continental evolution and erosion leading to the local washout of crystalline basement rocks, removal of ore minerals from primary rocks (sources), and their transportation to the coastal zone of sedimentary basins.

These processes are evident from the typomorphic features of minerals of the ore association. However, their interpretation should take into consideration the long-term history of evolution in the sedimentary process.

TYPOMORPHIC FEATURES OF THE MAJOR ORE MINERALS

As mentioned in our previous work (Patyk-Kara *et al.*, 2001), one should differentiate the following two important points. Typomorphic indicators of placer minerals (crystal habit, color, composition of the major components and trace elements, and so on) are inherited from the primary source. Therefore, they can be used as indicators of the source of placer. In contrast, the properties developed during the placer formation serve as indicators of the environment of material transport, concentration, and redeposition (degree of roundedness, microtexture of surface, intensity of secondary

Table 1. Chemical composition of ilmenite in ore sand of the Tsentral'noe deposit

	Oxides															
	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	Cr_2O_3	MnO	FeO	CuO	ZrO_2	Nb_2O_5	MoO_3	SnO_2	Total
8/TS-1	–	–	0.38	–	–	0.14	66.13	–	1.74	30.49	–	0.37	–	–	–	99.24
8/TS-2	–	–	0.62	–	–	0.16	66.50	–	0.59	31.97	–	–	–	–	–	99.84
8/TS-3	0.58	–	0.35	–	–	–	54.34	–	0.50	42.19	0.25	–	0.58	–	0.52	99.30
8/TS-4	0.27	0.26	0.75	0.64	–	0.23	66.33	0.36	0.33	30.27	–	–	–	–	–	99.44
8/TS-5	–	0.31	0.51	0.29	–	0.17	62.37	–	2.51	33.53	–	–	–	–	–	99.70
8/TS-6	–	0.29	0.75	–	0.11	–	51.19	–	1.93	44.75	–	–	–	–	–	99.01
8/TS-7	0.23	–	0.62	0.47	–	0.25	64.68	–	1.61	31.22	–	–	0.63	0.49	–	100.19

Note: Based on results of the LINK-ISIS analysis at the IGEM (L.O. Magazina, analyst). (–) Not detected.

alterations, and so on). These features are sufficiently well deciphered by electron microscopy. In turn, the secondary morphogenetic features of placer minerals can be subdivided into two groups. The first group includes features developed during the transportation and redeposition of the clastogenic material, i.e., during the removal from the enclosing rock, integration of ingrowths, rounding of grains, and development of specific microtexture indicating the nature of transportation environment (Krinsley *et al.*, 1973). The second group includes features acquired by placer minerals after their precipitation or related to postore processes, such as deflation and superimposed weathering under subaerial conditions.

The interpretation of data on the mineralogical and technological analyses of ore sand should take into consideration its following features.

Despite a narrow range of grain size distribution of the major ore minerals (Fig. 4), one can note some specific features of their distribution.

Ilmenite is dominated by the fraction ranging from –0.1 to 0.044 mm. It is also occasionally found in the coarser fractions ranging from –0.25 to 0.02 mm. However, the Ti-bearing phases are rarely present as pure ilmenite in such fractions. It is more often present as ilmenite ingrowths with quartz, leucoxene, and authigenic phosphates and glauconite. The analysis of geometric parameters of ilmenite grains shows the predominance of ilmenite grains with the elongation coefficient ranging from 1 to 2. At the same time, the average elongation coefficient shows a low variation (1.33–1.6) in all grain size ranges. The roundedness is also rather stable (0.6–0.7) and becomes slightly higher in the coarser fractions, suggesting that the larger grains were more rounded. Ilmenite is present as differently altered varieties. This is indicated by its physical properties, such as lower density, disappearance of the metallic luster typical of the unaltered variety, development of the dull surface, chemical composition–high contents of TiO_2 (58–67%) and Fe_2O_3 (10–15%) and low FeO contents (25–32%) (Table 1). The SEM and XRD data demonstrate that ilmenite is mainly composed of a fine-dispersed banded and patchy aggregate consisting of ilmenite and pseudorutile with a variable Fe/Ti ratio (Fig. 7). The two-phase texture is related to the alteration of the primary ilmenite, in which a part of Fe^{2+} is oxidized and leached, resulting in the appearance of the pseudorutile phase (Grey and Reid, 1975; Grey *et al.*, 1999). The present state of the knowledge of ilmenites in the Tsentral'noe deposit is not sufficient to differentiate the alterations in terms of their inheritance from the weathering crust or primary placer. However, Bardeeva (1999) revealed that the share of altered (leucoxenized) ilmenite grains considerably increases in the upper portion of placer composed of the dune complex at the subaerial development stage. The placer includes ilmenite grains of different shapes, size, roundedness, and alteration degree, indicating the heterogeneity of provenances and different modes of their transport or the replacement of provenance, which included sedimentary and metamorphic rocks and older ancient intermediate collectors, in the course of placer formation.

Zircon is mainly concentrated in the grain size class ranging from –0.14 to 0.06 mm (more than 90%). In all fractions, the zircon grains are significantly variable in terms of elongation. They vary from the nearly equant grains (elongation 1.01) to strongly elongated and prismatic ones (elongation 2.4–3). The roundedness varies from 0.35 (angular crystal fragments) to 0.83 (rounded semiprismatic grains). However, we failed to decipher any relationship between the roundedness value and grain size class. The average statistical value of the roundedness is constant (0.7). According to A.N. Surkov (private communication), the major mass of zircon (72%) is represented by the 0.05–0.1 mm fraction that can be subdivided into two subfractions (0.06–0.07 and 0.09 mm).

The diversity of zircon grains (both the zircon and hyacinth varieties with the Zr/Hf ratio ranging from 33 to 42 and the rounded varieties are present) indicate the diversity of provenance (Fig. 8a), including the granite-series rocks and metasedimentary rocks of the crystalline schist and rutilite types. In addition to the Y-rich

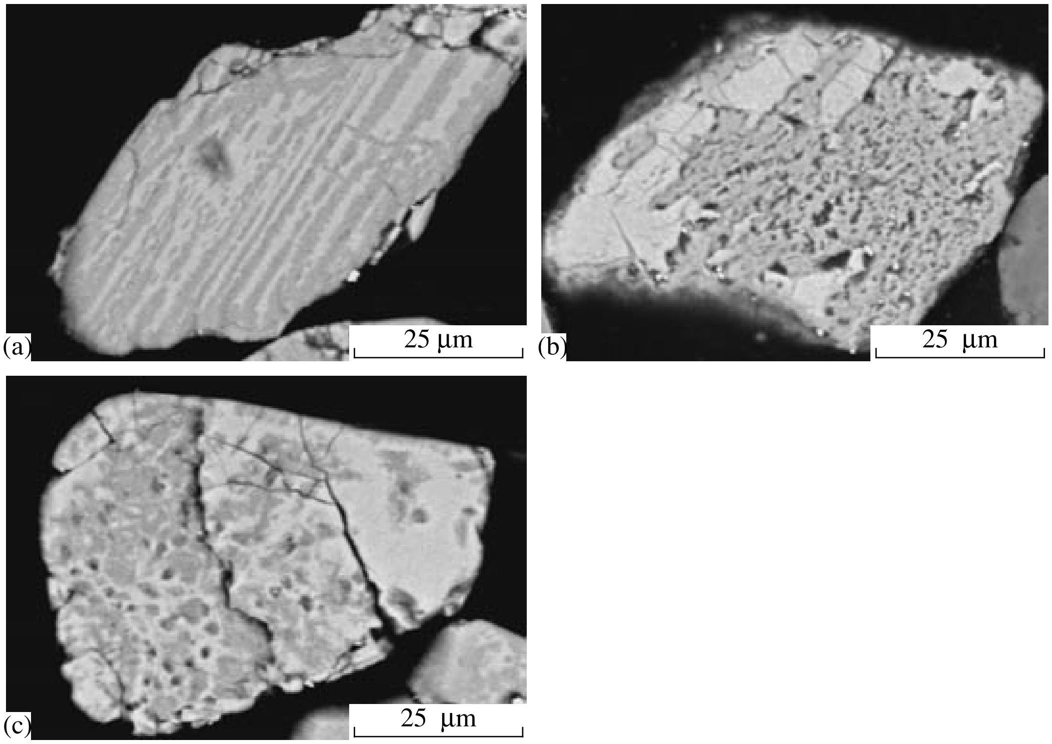

Fig. 7. SEM (reflected electron) images of altered ilmenite grains from the titanium–zirconium sand. (a) Banded texture of ilmenite grain (light) associated with pseudorutile (dark); (b) two-phase texture of altered ilmenite (light) associated with pseudorutile (dark); (c) patchy texture of two-phase ilmenite showing Fe-rich (light) and Ti-rich (dark) zones (L.O. Magazina, analyst).

zircon typical of granitoids, the Ce-rich variety derived from alkaline rocks is also found in the placer. One can occasionally observe the coexistence of both varieties. Well-rounded and perfectly rounded grains, including the grains with traces of eolian reworking, make up 45–75% (Fig. 8b). Subrounded prismatic grains with smoothed edges and faces account for 10–25%. Subangular and angular crystal fragments are also present. The rounded grains are dominated by the lilac-colored variety typical of ancient metamorphosed sedimentary rocks (in particular, such zircon grains are observed in Riphean rutilites of the southern Urals and Kokchetav Massif). According to T.B. Pyatibratova (private communication), the ratio of different zircon types varies across the section.

Rutile is mainly observed as free grains (more than 90%) concentrated in the grain size class ranging from –0.14 to 0.06 mm. In the coarser fractions, particularly the 0.25-mm class, rutile is present as ingrowths with quartz and authigenic minerals. This mineral shows a statistically significant distribution of grains with different coefficients of elongation in various grain size classes. The finest fractions are dominated by more elongated rutile grains (average elongation coefficient 1.72). According to A.N. Surkov (private communication), the detailed grain size analysis of rutile confirmed the predominance of 0.05–0.15-mm fraction that can be divided into two subfractions (0.06 and 0.09–0.1 mm), indicating the existence of two cycles of rutile deposition. Rutile is present as two major varieties with different shades of red and black colors. Some rutile grains are neogenic formations related to the decomposition of ilmenite and leucoxene.

According to T.B. Pyatibratova and A.N. Surkov (private communication) who scrutinized the grain size distribution of rounded grains of the major ore minerals (ilmenite, rutile, zircon, disthene, and tourmaline), one can outline the bimodal distribution of grains with different degrees of roundedness against the general grain size distribution described above, indicating that the minerals underwent several redeposition cycles before being concentrated in the placer or they formed in various energy environments.

Garnet. Ore sand of the Tsentral'noe deposit contains abundant angular and subrounded almandine grains. Their share relative to the rounded garnet variety is significantly higher than that of zircon grains. As mentioned above, zircon mainly occurs as spherical grains with a very high degree of roundedness (Fig. 8). This fact deserves special attention and compels one to assume that the placer accumulation was obviously accompanied by the input of a certain portion of fresh material that could be derived from crystalline rocks. Since the Voronezh Massif was already buried under a thick sedimentary cover by that time, the Ukrainian Shield could be the most plausible source of angular material, while an unspecified number of sublatitudinal

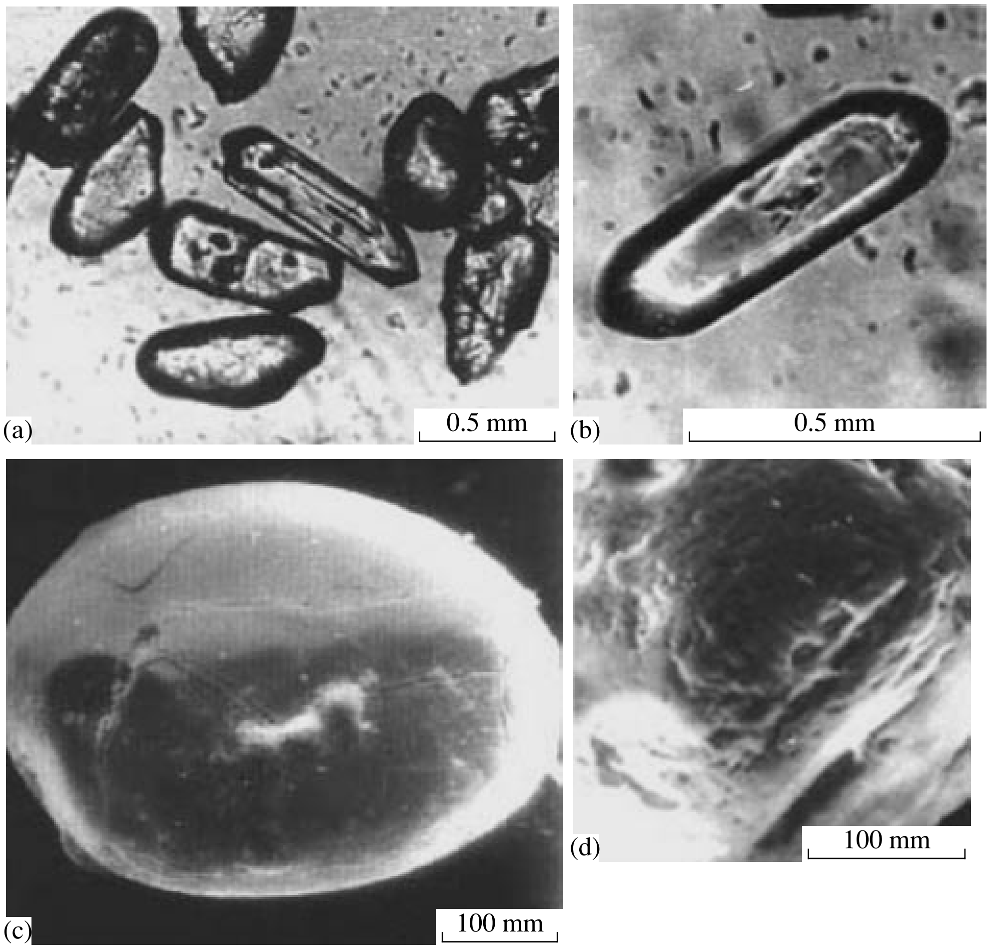

Fig. 8. Morphology of zircon grains from ore sand of the Tsentral'noe deposit. (a) Grains of variable habit and roundness; (b) subrounded prismatic grain; (c) well-rounded grain with traces of eolian reworking; (d) fragment of rounded grain surface with traces of water transport.

rivers flowing from its slopes could transport the sedimentary material. However, the material was presumably transported over approximately 1000 km even in this scenario.

Gold. Technological tests of the gold potential of ore sand carried out in laboratories of the TsINIGRI and GIREDMET indicate that gold is represented by at least two types. The free gold is extracted by gravity separation (not more than 14%) and flotation (not more than 23%). The bound gold apparently associates with the authigenic minerals. The free visible gold is present in all fractions ranging from –0.5 to 0.044 mm, the maximal concentration being confined to the class ranging from –0.14 to 0.074 mm. This grain size class is dominated by completely free gold flakes with the equant patchy (occasionally, ellipsoid), moderate or well-rounded shape and corrosion surface. These typical clastogenic gold flakes bear indications of grinding during the transportation (hatches). Holes in the microrelief are coated with silica, hydroxides of Fe and Al, and halogenides of Ca, Na, and K. The halogenides locally overlap the oxide coating. Silver is virtually absent in the rim of gold flakes. One can easily reconstruct the migration pathway of such particles. The high degree of their roundedness and the removal of Ag from their surface, coupled with the abundance of oxide overgrowths, testify to the rather prolonged transportation and redeposition of gold with its periodic residence in the subaerial environment and subsequent burial in the marine medium. This is evident from the presence of a marine salt coating on the gold flake surface. The assumptions formulated above suggest that the clastogenic gold can be derived from sedimentary rocks of the northern land that contained gold dissemination delivered from the Baltic Shield and Urals (this assumption is supported by the presence of Au in sediments of the Kama–Vyatka region) or auriferous rocks of the Ukrainian Shield. Analyses made in laboratories of the TsNIGRI suggest quite a different form of free gold concentrated in the fraction ranging from –0.5 to 0.14 mm. The mineral is observed as interstitial lamellas with fine marginal bends and regeneration signs (overgrowths of ultrafine spherical gold particles). One can also see skeletal crystals without any signs of rounding and grinding. In other words, the free gold is a product of early diagenetic and epigenetic processes in the ore sand rather than clastogenic processes. This following fact supports this inference. The gold occasionally associates with glauconite, apatite, and clay minerals. One can also see its intricate ingrowths with quartz cemented by iron hydroxides. The quartz in such ingrowths is observed as curvifaced grains that represent dissolution structures. Results obtained at the TsNIGRI have also revealed the presence of thin gold coating on zircon grains. This variety presumably relates to the gold bounded in the clayey matrix, phosphates, and other authigenic minerals. The total content of these minerals in the Tsentral'noe deposit is estimated at 60–69.

AUTHIGENIC MINERALIZATION

Glauconite and phosphates are the major authigenic minerals in the ore sand of the Tsentral'noe deposit.

Glauconite (*n*%) is concentrated in the grain size class ranging from –0.25 to 0.063 mm with a peak at –0.15/0.074 mm. It is observed as dark green, less common black rounded grains, occasional equant grains with smoothed faces, and rare botryoidal grains. Sirotin *et al.* (2004) studied the REE distribution in glauconites of the Tsentral'noe district and revealed that, like all counterparts in the Cenomanian terrigenous formation of the central Russian Platform, glauconites of the Tsentral'noe deposit reflect the humid environment of that time with a deep heating of coastal water.

Glauconite occurs in Cenomanian and lower Santonian sediments as disseminated grains in phosphorite nodules. This mineral is a constant component of the sandy and clayey varieties of ore sand of the Tsentral'noe deposit. The glauconite distribution in the section is irregular, the maximal concentration being confined to the phosphorite-bearing beds. Glauconite is present as several varieties: dark green rounded equant or botryoidal grains with ilmenite or quartz inclusions; Fe-poor globular mass making up pseudomorphoses after feldspars and micas in leached radiolarites; pale green fine-grained mass (associated with clay minerals) characterized by mosaic extinction. The major portion of glauconite is represented by the granular variety, 0.05–0.75 mm in size, with a green color of variable intensity depending on the Fe content. The mineral composition of sand testifies to the development of glauconite both in the phosphorite formation zone at the early sedimentation stage and in the deposition zone of sediments of the sandy–clayey fractions, i.e., beyond the phosphorite zone. The glauconite-bearing sand formed at different distances from the coastline, resulting in the compositional and morphological variations of glauconite grains.

Phosphate minerals account for more than 3% of the ore sand and as much as 10*n*% in the coarse-grained (more than 2.5 mm) fractions They make up complex nodular aggregates (Table 2) with other authigenic minerals, and clastogenic minerals of sand. The share of clastogenic minerals in the nodules ranges from 30 to 80%, the maximal content being typical of fine-grained phosphorites (75–80%). The average share of ore minerals in the nodules is approximately 4%.

Phosphorites of the Tsentral'noe deposit are located in two (upper Cenomanian and lower Santonian) units. The upper phosphorite bed is confined to the base of the Santonian sequence and included in the stripped rocks of the titanium–zirconium sand. The lower bed located at the top of the upper Cenomanian sequence includes quartz sand with sandy phosphorite pebbles and fragments of phosphatized fauna and shark teeth fossils ("shark unit"). The main phosphorite fraction is 0.5 mm in the upper bed and 2 mm in the lower one. The phosphorites are enriched in organic remnants, 50 mm or less in size, composed of sponge skeletons, gastropod and pelecypod cores, and phosphatized wood fragments and coprolites. The phosphorites of the Tsentral'noe deposit occur as disseminated grains (pellets) and nodules. The phosphates are represented by earthy cryptocrystalline, compact oolitic, and angular modifications. The most common light-colored phosphate makes up pellets in the cement of fragments and phosphatized sandstone nodules. The phosphates represent a complex (polycomponent) mixture of ultramicroscopic phases that gradually recrystallized into apatite and fluorite. The microscopic study of phosphatized rocks made it possible to recognize the cryptocrystalline, radial-fibrous (with low birefringence), equant (powdered), and crystalline (apatite-type) varieties that reflect different stages of the phosphorite crystallization. In the sandy–clayey varieties, the phosphates make up basal cement with the authigenic silica as radiolarian and sponge spicule remnants replaced by opal and fine-dispersed siliceous–phosphate mixture. In the sandy varieties, phosphorites usually occur as radial-fibrous accretions. Results of the chemical analysis show that nodular phosphorites are enriched in Fe relative to the fine-grained variety. Results of the quantitative spectral analysis indicate that the Au content in the phosphorites is 0.5 g/t.

The study of phosphate-bearing rocks in Upper Cretaceous sequences of the Tsentral'noe deposit is very interesting for the reconstruction of the environment and mechanism of phosphate formation. The relationship of chemogenic and biogenic processes is the crucial point in this aspect. The nature of phosphorites, including the granular variety characterized by the maximal phosphorus concentration in the Earth's sedimentary cover, remains a debatable issue (Shkol'nik, 1999; Kholodov and Paul, 2001; Baturin, 2003).

The application of scanning electron microscope for the study of ultramicrotexture of phosphates from the Tsentral'noe deposit revealed the presence of different microbial groups, including the most common fragments of sponge spicules and foraminiferal tests and the less common microbial of coccoidal mats and

Table 2. Mineral composition of phosphorites from ore sand of the Tsentral'noe deposit (based on the GIREDMET and IMGRE data)

Minerals	Grain size class, mm				
	+10	+5	+2.5	+1.0	+0.56
Phosphates	50–55	45–46	40	15–20	5–20
Glauconite	5	6	7	3.5	5
Zeolites	1	1	1	0.5–1	1
Iron hydroxides	0.5	0.5	0.5	0.5	0.5
Clayey aggregates	–	–	–	0.5–1	0.5
Quartz	35	40–42	45–47	65–70	75–80
Feldspars	0.5	0.5	0.5–1.0	1.0	1.5
Ore minerals	4	4	4	0.5–1.0	1.0
Other clastogenic minerals	0.5	0.5	0.5	0.5	0.5

cyanobacteria (Fig. 9). This fact indicates the presence of primary biogenic formations replaced to a variable extent by phosphates. Generally, phosphate grains in the phosphorite occur as detritus, i.e., fragments of different organisms. Thus, phosphorites of the Tsentral'noe deposit commonly represent clastic rocks (Gorelikova *et al.*, 2001). According to (Malenkina, 2003), the replacement of organic remnants by calcium phosphate began immediately after their bacterial decomposition. The replacement of silica and carbonate by phosphorus started in the nonlithified sediment, because an amorphous substance was phosphatized.

DISCUSSION

Thus, multiple rearrangements of land and sea by the Cenomanian time promoted the following scenario of mineral assemblage evolution in the complex coastal-marine placers. There is no doubt that sedimentary rocks developed within the spacious land extend-

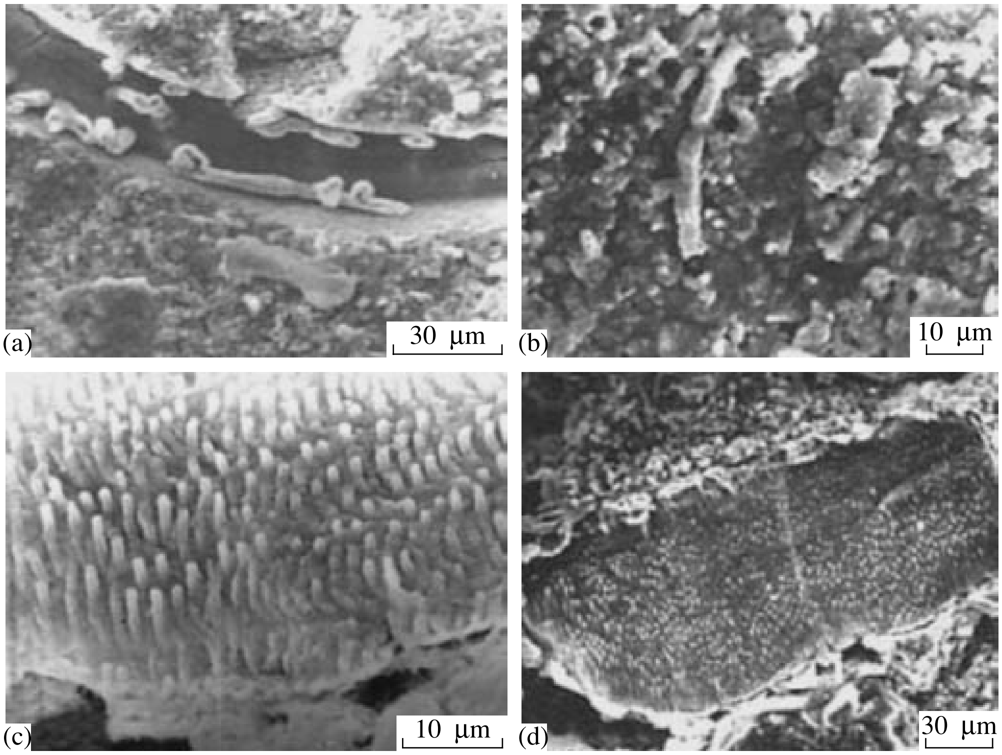

Fig. 9. SEM (reflected electron) images of nodular phosphorites from the Tsentral'noe deposit. (a) Texture of phosphate with cyanobacteria; (b) microbial remnants of coccoidal mats; (c) phosphate with cyanobacterial mats; (d) phosphate with organogenic fragments (E.A. Zhegallo, analyst).

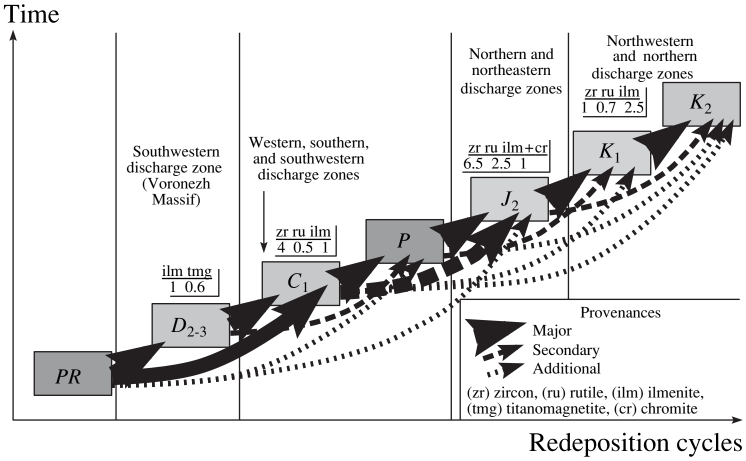

Fig. 10. Scheme of the input and redeposition of clastogenic materials in the ore sand of the Tsentral'noe deposit. Mineral abbreviations: (ilm) ilmenite, (tmg) titanomagnetite, (ru) rutile, (zr) zircon, (cr) chromite. Numerals denote the ratio of ore minerals.

ing from the Belarus Uplift (Devonian–Carboniferous rocks) to the left bank of the Volga River (Jurassic–Lower Cretaceous rocks) played the major role. The paleoislands existing at the site of the present-day Voronezh Massif made a subordinate contribution. At the regressive stage of the Cenomanian basin evolution and the consequent formation of the Tsentral'noe deposit and other late Cenomanian placers of the Rasskazov district, a major portion of the detritus was delivered to the coastal zone as a result of the fluvial erosion of sediments of the primary (Cenomanian) coastal-marine plain.

According to this scenario, one should expect a certain inheritance of the signature of older placers (e.g., the high chromite content in Jurassic placers of the Middle Volga region or the high staurolite content in Aptian placers of the Ryazan–Skopin zone and the Orlov–Tambov Uplift) by mineral assemblages of the Cenomanian placers. However, such features are missing (Gurvich and Bolotov, 1968). Hence, the Aptian sand was buried under the sea in the Cenomanian and it was not eroded. It is worth noting that the major ore minerals of the upper Cenomanian placers have a smaller median grain size, relative to the counterparts in the Aptian sand primarily formed in the high-energy environment of the beach zone. The upper Cenomanian mineral assemblages of ore sand are also characterized by high contents of feldspars and a high proportion of epidote. The latter feature, atypical for older placers, can indicate a rather intense weathering of rocks in the discharge zone. The majority of researchers believe that ore minerals in the placers mentioned above were mainly derived from Permian rocks of the northern land, whereas the Voronezh Massif was only an additional provenance. The proposed basic scheme of the successive redeposition of heavy minerals in the sedimentation zone that existed at the site of the present-day Rasskazov placer district (Fig. 10) shows the stage-by-stage introduction of new intermediate collectors (sources of heavy minerals), but also the retention of the influence of older sedimentary complexes with their inherent mineral assemblages.

The present communication does not consider the epigenetic processes that followed the deposition of the major productive portion of the upper Cenomanian sand and the subaerial (conventionally, Turonian) dune complex and the consequent redeposition of a part of ore minerals in the Santonian basal layers. These aspects are scrutinized in (Bardeeva, 1999; Patyk-Kara *et al.*, 1999; and others). The aim of the present communication is to attract the attention of researchers to the issue of the formation of mineral assemblages in complex placers of heavy minerals. These assemblages are developed in the course of a long-term transportation and multiple redeposition of clastogenic particles with similar hydraulic dimensions, migration capacities, narrow grain-size concentration ranges. *These basically new mineral assemblages only insignificantly inherit the primary features of mineral assemblages in the provenance. They primarily reflect successive changes in the sedimentation environment.* The influence of provenance boils down to the appearance of certain mineral assemblages that supplement the primary ore mineral assemblage, while the major ore (ilmenite–leucoxene–rutile–zircon) association remains universal for all types of complex placers of heavy minerals. The high correlation of minerals in the above association reflects the degree of gravitational separation of clastogenic particles and serves as an indicator of the maturity of the ore (placer) formation process.

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