= MINERALOGY ===

Sources of Substance and Genetic Relation of Soil and Bauxite-Bearing Horizons in the Laterite Profile of the Weathering Crust (of the Fouta Jallon–Mandingo Province, Republic of Guinea)

M. A. Makarova^a, E. S. Shipilova^a, N. M. Boeva^a, D. A. Vnuchkov^a, and Academician N. S. Bortnikov^a

Received March 4, 2023; revised April 30, 2023; accepted May 4, 2023

Abstract—For the first time, a granulometric analysis of lateritic soils was carried out and the sources of the substance involved in the formation of the degradation zone in the bauxite-bearing laterite profile of the bauxitebearing province of Futa Jallon-Mandingo were identified. Throughout the province, on the stony rocks of the lateritic covers, the soil horizon occurs everywhere—the uppermost element of the vertical profile of the weathering crust. In the soil horizon, most of the components become mobile, leaching processes predominate, and laterites are mobilized and redistributed. The study of these continental formations made it possible to establish the genetic relationship between the soil horizon of the weathering crust and the underlying bauxite ores, and to determine the degree of influence of soil composition on the processes of bauxite formation.

Keywords: laterites, weathering crust, soil horizon, bauxite, Fouta Djallon–Mandingo **DOI:** 10.1134/S1028334X23600986

INTRODUCTION

In tropical zones, with a high average annual temperature, a high amount of precipitation, and seasonal wet climate promote the migration of weathering products, their accumulation, and the formation of a thick weathering crust. A soil loose layer of the lateritic weathering crust is the uppermost zone of a classical lateritic profile. It is termed a degradation zone or a degradation horizon [1, 2]. Various hypotheses explain the formation of the upper horizon of the lateritic bauxite-bearing profile. It is considered that it is a result of the degradation of the underlying material of cuirrase (autochthonous origin), colluviation, and reworking of the material from landscape slopes (allochthonous origin), and a mixed origin together with material from deeper horizons of the same profile due to gain of small mineral particles after the activity of termites [1].

It is suggested that termites make a significant contribution to the formation of laterites [3]. The soil layer and underlying rocks are penetrated by a network of their channels increasing the penetration of the weathering profile and promoting bauxitization [4]. Termites tunnel deeply for water that is often used as evidence of their upward transportation of mineral particles [5]. The higher SiO_2 content of the soil layer is explained by the upward removal of clay and sandyclay material by termites for their mounds from the lithomarge of the weathering crust [6].

The Fouta Diallon-Mandingo (FDM) province is confined to wet savannah and forest savannah. The climate on this territory is tropical, seasonally wet, with alternating wet (June-October) and dry (November–May) seasons of the annual cycle. The average annual temperature varies from 24 to 30° C [7, 8]. From the end of November to the middle of March, the territory undergoes the very dry and dusty, hot and draining northeastern Harmattan [9]. Because the wind passes a desert, it picks up and transfers numerous dust particles 0.5-10 µm in size. The climate conditions promote an increase in temperature of soil solutions leading to hydrolysis of minerals in the soil horizon, their disintegration, the formation of cavities, and fragmentation as a result of collapse. The soils also host secondary minerals: kaolinite, goethite, gibbsite, etc. [10].

Scientists who applied the mass balance equation to the chemical analysis of the weathering profile of the West Australian bauxites showed that the enrichment of bauxite ore in Al could be caused by the accumulation of aeolian dust from chemically mature soils of other regions. Due to the high porosity of bauxites,

^a Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry, Russian Academy of Sciences, Moscow, 119017 Russia

^{*}e-mail: boeva@igem.ru



Fig. 1. Maps of plant cover (a) and thicknesses of soil cover (b) on the Vuasso beauval.

their structure is favorable for the transportation of mineral grains. Aeolian dust penetrates through the soil to the underlying layers by the root channels of plants, thereby enriching the ore in Al and Fe [11]. The aeolian contribution also explains a higher amount of quartz and alumosilicates in soils [12, 13].

The FDM bauxite-bearing province is the largest in the world. The study of the soil horizon, which is the uppermost element of the vertical section of its weathering crust, allows the determination of the degree of influence of the composition of soils on processes of bauxite formation. The horizon is composed of gray loams and lateritic and bauxitic clasts and is saturated with roots and relics of plants. The solid lateritic rocks inside and below the soil undergo disintegration, dissolution, and redistribution of matter along the fractures [14].

The high amount of organic plant substance and microbiota under conditions of seasonal saturation with rain water and dry periods between rains is responsible for the chemical and biochemical mobilization of the matter of lateritic covers and its redistribution.

The loose formations of the soil layer are a zone of physical mobilization of the material, which affects the redeposition and accumulation of various genetic types of continental formations, and manage the possible localization of mechanically sedimentary bauxites [15].

In our study, we analyzed samples collected in areas of the provinces where cuirrase was eroded and bauxites were under the soils. We conducted for the first time granulometric analysis of lateritic soils and identified the sources of matter for the formation of the upper horizon of the bauxite-bearing lateritic profile.

MATERIALS AND METHODS

The FDM bauxite-bearing province is located in the westernmost part of Africa. The territory is a step plateau with deep river and creek valleys [16, 17]. The flat, gently wavy, and gently step summits of remnants and individual watershed arrays (beauvales) of the northwestern spurs of the Fouta Djallon Plateau on rocks of lateritic covers are ubiquitously covered by present-day soils of variable thickness and intercalation of areas of grass, bushes, and forests.

The maximum (up to 1.5 m) thickness of the soil horizon is observed in forests, especially on flat slopes and benches of the beauval surfaces. This is especially evident from the example of the Vuasso deposit (Figs. 1a, 1b). On a flattened beauval surface, the thickness is typically 0.1-0.3 m reaching 0.5-1.0 m in local pockets and holes. There are also local linear zones (confined to fracture zones), where the thickness of the soil horizon on the slopes of beauvales increases and reaches 1 m or more.

The upper part of the soil horizon is formed by a dark gray to black sandy-clayey mass, which contains small angular grus clasts (10-15%) of unaltered or ferruginous small-gravel bauxites. A subsurface part to a depth of 10–15 cm is penetrated by a fine root system of grass and rare trees; the amount of roots can reach 30-40% and even 50% near the surface. Down through the depths, the soil gradually becomes brownish gray without a sharp boundary. The amount of grus clasts of pebble and, to a lesser extent, boulder size increases and can reach 50-60%. The size and amount of clasts increase to deep levels. They also include a significant amount of concentrically zoned concretions: soil ferruginous pisolites with the size ranging from a few millimeters to 1 cm (rarely, 2.0– 2.5 cm). The basement of the soil horizon exhibits a conditional zone, which is strongly enriched in coarse clastic material: from 20-40 to 70-80 vol % is composed of round ferruginous clasts and angular boulders of bauxites and laterites up to 10-15 (rarely 40-50) cm in diameter. Small fractions (matrix) consist of a gray or brownish loamy–sandy mass similar to the matrix of the middle zone. The lower boundary of loose formations is extremely uneven, depends on the hilly surface of the lateritic cover, and is complicated by fractures, pockets, and inliers.

For the study of the soil horizon, we used the results of field work and laboratory analyses of rocks of a loose cap from some bauxite deposits in the basins of the Kogon and Tingilinta rivers of the FDM bauxitebearing province in the northwestern part of the Republic of Guinea.

For detailed study of the composition and physical-mechanical properties of the loose cap rocks and underlying bauxites, we analyzed (i) the volumetric mass, the coefficient of disintegration, and the natural moisture (the moisture of rocks was analyzed in the second half of the dry season and in the first half of the rainy season) and (ii) the granulometric composition using dry sieving through sieves of fractions of (mm) +100, +50...-100, +25...-50, +10...-25, +5...-10, +2...-5, +1...-2, +0.5...-1, +0.25...-0.5, and 0...-0.25. The fractions of <math>+0.1...-0.25, +0.04...-0.1, and -0.04 mm were selected using laser diffraction on a "FRITSCH" ANALYSETTE 22 sizer (Germany).

The laboratory studies included X-ray diffractometry (XRD) on an Ultima-IV diffractometer (Rigaku, Japan) and analysis of the chemical composition on an AxiosAx "RANalytical" X-ray fluorescent spectrometer (the Netherlands).

In total, we studied 18 soil samples collected at seven deposits of the FDM province: NDangara (P-1, P-2, P-4, P-6, P-8), Tiapikoure (P-18), Bourore (P-17, P-18), Vuasso (P-20, P-21), Bunde-Vaade (P-11–P14), Paravi (P-9, P-10), and Koobi (P-15, P-16).

RESULTS

Loose formations always contain particles of different fractions and size classes: from boulders (>100 mm) to silty and clayey fractions. The proportion between different fractions in the studied samples varies widely depending on landscape types. Two sample groups are distinguished:

(i) Samples (11) of group 1 were collected in the marginal parts of the beauval or on the slopes of the local hills. Their granulometric composition is characterized by a significant role (12-45%) of small (<1 mm) fractions.

(ii) Samples (7) of group 2 were collected on the flattened beauval surface. Their granulometric composition is strongly dominated by particles of >8 mm (53–90%). The sandy and smaller fractions (<1 mm) are subordinate (2-5%).

Table 1. Granol	umetric com	position of	different	fractions
of present-day lo	oose formatio	ns (%)		

Fractions, mm	Margins and slopes of beauval	Flattened surface of beauval	All landscapes							
Coarse-gravel, pebble, and boulder fractions										
>100	8.2	5.8	7.3							
50-100	6.9	10.8	8.4							
25-50	10.4	16.3	12.7							
12-25	12.5	25.5	24.4							
8-12	10.7	16.8	13.4							
Total	48.8	75.1	66.2							
Coarse-sandy, small- and medium-gravel fractions										
5-8	8.9	8.3	13.1							
2-5	10.6	7.5	9.6							
1-2	3.4	2.0	2.9							
Total	22.9	17.8	25.6							
Small- and medium-sandy fractions										
0.5-1	10.0	0.5	6.9							
0.25-0.5	6.9	0.8	4.9							
< 0.25	7.7	2.2	5.9							
Total	24.6	3.6	17.7							

The landscapes cannot adequately be classified into two groups; thus, these sample groups should be considered the endmembers of a series, which includes the intermediate variants of proportion of fractions with a more even distribution of particles of different sizes and predominance of the medium fractions from 2 to 8 mm.

The chemical composition of samples of the soil cover, as well as its comparison with that of underlying bauxites, is shown in Table 2. The soil horizon is characterized by an increase in the SiO_2 content and a corresponding decrease in the Al_2O_3 content. Note the accumulation of Fe in the soil cover, as well as a minor but constant decrease in the Ti content.

These features are typical of almost all samples irrespective of the landscape types and characterize the soil cover in general. There are, however, significant differences in the chemical composition of fractions of the loose cap of different sizes (Table 2).

The XRD showed that gibbsite, goethite, hematite, quartz, boehmite, anatase, kaolinite, feldspar, chlorite, montmorillonite, ilmenite, rutile, and hydromica are the major minerals of soils. The most important and typical interplanar distances for the minerals include 4.82 and 4.34 Å for gibbsite; 4.18, 2.69, and

Fractions, mm	Landscape	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	TiO ₂	LOI	RO	R ₂ O	P ₂ O ₅	Σ		
Bauxite	Slope (7 samples)	1.06	51.75	15.97	3.52	26.90						
	Top (11 samples)	1.25	48.62	20.47	3.34	25.54						
Coarse-gravel, pebble, and boulder fractions												
>8	Slope	1.35	52.55	17.39	3.34	24.54	0.02	0.02	0.18	99.39		
	Тор	1.16	50.42	21.15	2.81	23.62	0.02	0.02	0.23	99.42		
Coarse-sandy, small-, and medium-gravel fractions												
5-8	Slope	1.53	48.73	24.80	2.45	21.58	0.02	0.02	0.23	99.35		
	Тор	1.83	45.30	33.63	2.45	16.81	0.02	0.01	0.31	99.35		
2-5	Slope	8.23	44.00	23.98	2.77	19.98	0.05	0.06	0.25	99.32		
	Тор	2.73	37.32	40.64	2.43	15.81	0.04	0.04	0.35	99.37		
1-2	Slope	29.89	32.10	17.57	2.56	16.65	0.17	0.22	0.22	99.38		
	Тор	7.11	37.18	35.10	2.39	17.17	0.08	0.07	0.32	99.40		
		Sr	nall- and	medium-s	sandy frac	tions						
0.5-1	Slope	38.75	28.11	12.04	2.41	17.39	0.19	0.28	0.20	99.36		
	Тор	24.82	27.43	22.20	2.12	22.31	0.15	0.23	0.25	99.51		
0.25-0.5	Slope	40.20	27.48	10.84	2.38	17.80	0.19	0.29	0.20	99.36		
	Тор	35.76	26.8	13.3	2.31	20.4	0.45	0.34	0.241	99.60		
		•	Silty a	nd clayey	fractions							
0.1-0.25	Slope	42.99	25.40	9.56	2.28	13.17	0.39	0.29	0.23	94.31		
	Тор	42.11	16.60	6.90	1.92	0.28	1.13	0.44	0.47	69.85		
0.04-0.1	Slope	42.38	24.89	9.29	2.41	18.41	1.20	0.36	0.34	99.27		
	Тор	47.53	15.81	5.58	1.66	26.84	1.03	0.41	0.41	99.28		
< 0.04	Slope	50.13	21.72	7.68	2.17	15.66	1.06	0.31	0.40	99.13		
	Тор	51.40	14.57	4.99	1.66	24.84	0.87	0.45	0.41	99.19		

 Table 2. Chemical composition (wt %) of material of various fractions of the soil cover (average for all deposits) and underlying bauxites

RO = CaO + MgO, $R_2O = K_2O + Na_2O$.

2.45 Å for goethite; 2.69, 1.69, and 2.51 Å for hematite; 3.34, 4.25, and 1.81 Å for quartz; 3.51, 1.89, and 2.37 Å for anatase; 2.34, 1.3, and 1.85 Å for boehmite; 7.13, 1.49, and 3.56 Å for kaolinite; 3.18, 3.80, and 4.0 Å for orthoclase; 6.9, 4.6, and 3.5 Å for chlorite; 11.5, 1.49, and 4.45 Å for montmorillonite; 2.74, 2.53, and 1.72 Å for ilmenite; 1.68, 3.24, and 2.48 Å for rutile; and 1.48, 2.54, and 4.41 Å for hydromica.

In the mineral composition, the coarse and medium fractions correspond to underlying bauxites: 54.2-61.4 wt % of gibbsite, 3.7-7.5 wt % of boehmite, 2-4.3 wt % of hematite, 3.5-8.2 wt % of goethite, 2.3-4.2 wt % of kaolinite, 1.5-2.0 wt % of quartz, 1-2 wt % of anatase, and 1-2 wt % of rutile.

An important feature of the mineral composition of small fractions is related to the presence of minerals atypical of the underlying bauxites and unstable in the weathering profile: chlorite and K-feldspars (Table 3). Clay minerals (kaolinite and montmorillonite) make up a noticeable amount (>5%), which is also atypical of the upper part of the lateritic cover.

Boehmite is dominant over gibbsite in contrast to the more abundant gibbsite in primary rocks. This is explained by the higher solubility of gibbsite, as well as the influence of fires [18]. The fine fraction contains a significant amount of the X-ray amorphous phase (up to 55 wt % in some analyses) and OM (3.3–4.7 wt %). The termite mounds on the surface are made up of lay-

DOKLADY EARTH SCIENCES Vol. 511 Part 2 2023

Fractions, mm	Quartz	Bochmite	Gibbsite	Anatase	Kaolinite	Goethite	Orthoclase	Chlorite	Montmorillonite	Ilmenite	Rutile	Hematite	Hydromica	X-ray amorphous phase
< 0.005	5	7	5	2	11	8	Ν	Ν	Ν	Ν	1	Ν	5	56
0.005 - 0.04	32.5	5.5	4	2.5	5	3.5	2	1.5	<5	Ν	Ν	3	2	39.5
0.04-0.1	27.6	5.8	3	2.4	6.4	3.8	2.8	2.3	Ν	Ν	Ν	2	—	45.6
0.1-0.25	19.8	5	3	2	5.3	4.3	3	1.6	<5	2	Ν	2	2	55.6

Table 3. Mineral composition of fractions of the soil horizon (wt %)

N means not found.

ered gray and dirty gray material up to 15 cm thick, which consists of kaolinite and traces of humus.

Small and fine fractions of the soil layer can be transported to the bauxite horizon along the fractures, often to a significant depth (to a few meters). The clayey material with roots from caverns at a depth of 4.5-5.0 m contains 29.5-36.6 wt % Al₂O₃, 10.9-15.1 wt % Fe₂O₃, and 32.5-36.5 wt % SiO₂. This material corresponds to a medium sandy fraction.

The granulometric composition of soils varies widely and depends on the landscape types. In the marginal parts of the beauval, the small fractions (<1 mm) play a significant role, reaching 25% in total, whereas their total content on the flattened surface is <5% (Fig. 2). The content of the fraction of 12–25 mm (21–24%) (mostly, soil pisolites) is consistent in all samples.

DISCUSSION

Irrespective of the landscape types, the soil cover exhibits increasing contents of Si, Fe, P, and K. Significant differences are observed only between fractions of different sizes (Fig. 3).

The coarse clastic fractions (>8 mm) contain >47 wt % Al₂O₃ (Fig. 3a), 15–31 wt % Fe₂O₃ (Fig. 3b), and <1.5 wt % SiO₂ (Fig. 3c). In composition, they generally correspond to underlying rocks of the lateritic cover (Table 2). It is evident that the large clasts in loose mass are local in origin and they formed mainly as a result of the formation of residual deposits without their significant transportation.

The main feature of the medium- to small-gravel and coarse–sandy fractions (1-8 mm) is related to the higher Fe₂O₃ content (up to 45 wt %) and the maximum content is typical of samples taken from the tops of beauvales (Fig. 3b, Table 2). The composition of



Fig. 2. Differences in the granulometric composition of samples of soil cover of various landscape types on example of the Dangara deposit. P-1, P-4, and P-8, samples taken on the slopes of the beauval; P-2 and P-6, samples taken on the flattened surface of the beauval.

DOKLADY EARTH SCIENCES Vol. 511 Part 2 2023



Fig. 3. Chemical composition of the soil horizon of different size fractions of the bauxite horizon with samples from the soil (circles) and bauxite (triangles) horizons.

these fractions is significantly affected by ferruginous pisolites, the size of which, as a rule, corresponds to small- and medium-gravel fractions.

The coarse-gravel and small-gravel fractions also have a decreasing Al_2O_3 content (to 40 wt % and lower); therefore, they dilute the ore, being trans-

ported to the bauxite along fractures. The same fractions also contain a higher amount of SiO_2 , especially in slope samples (to 30 wt %).

The medium- and small-sandy (0.25-1 mm) fractions are characterized by a strongly variable chemical composition, which is mainly expressed in the



Fig. 4. Distribution of chemical elements by various fractions. Elements related to processes of laterite formation (a), aeolian gain (b), and authigenic soil mineralization (c).

increasing content of SiO₂ (to 42–49 wt %), as well as the content of RO (from 0.02-0.05 to 0.19-0.36 wt % mostly in chlorite) and R₂O (from 0.04-0.05 to

0.2-0.4 wt % mostly in the form of K-feldspar). The Al₂O₃ content decreases to 23-30 wt %. The Fe content also decreases (7-19 wt %, on average).

DOKLADY EARTH SCIENCES Vol. 511 Part 2 2023

The elements and compounds atypical of rocks of the lateritic cover (first, SiO_2) thus play a significant (often dominant) role in sandy fractions. It is evident that the sandy fractions accumulate with a significant role of aeolian gain of the material.

The small and fine fractions (<0.25 mm) exhibit similar features: the SiO₂ content increases to 40– 43 wt % (to 53 wt % in fine fractions), as do the RO (to 0.9–1.2 wt %) and R₂O (to 0.3–0.4 wt %) contents. The Al₂O₃ content decreases to 21–23 wt % (to 16 wt % in the finest fractions) and the Fe content also decreases to 6–8 wt %.

The components of loose formations can conditionally be subdivided into three groups of different genesis and affinity to certain size classes (Fig. 4). Group 1 includes Al₂O₃, Fe₂O₃, and TiO₂ typical of underlying bauxites (autochtonous material, residue) (Fig. 4a). Their higher contents are observed in the coarse fractions composed of rocky clasts. Group 2 includes elements and compounds atypical of the lateritic cover: first of all, SiO₂, as well as CaO, MgO, and K₂O (Fig. 4b). They accumulate in small fractions in the form of chlorite, K-feldspar, kaolinite, and montmorillonite. Their accumulation is related to aeolian activity. Group 3 (Fig. 4c) includes that part of Fe that accumulates in soil pisolites and is focused in small-gravel fractions (2-10 mm). This group also includes V. In addition to newly formed organic clayey X-ray amorphous phases, they should be ascribed to authigenic mineralization related to soil processes.

Our studies thus showed that the soil horizon of the lateritic bauxite-bearing profile of the FDM province is of continental origin of the residual and talus genetic type, which form at the expense of physical destruction and chemical leaching of the underlying rocky bauxites and laterites, as well as by aeolian gain.

CONCLUSIONS

The soil horizon is studied in various geomorphological conditions during field and laboratory analytical work. Our studies support the following conclusions.

(1) The present-day loose formations occur almost ubiquitously on bauxite deposits of the FDM province. The soil horizon has a variable thickness (from a few centimeters to 1-2 m) and a complex morphology, first of all, an uneven lower boundary with underlying bauxites.

(2) The present-day soils are polygenic characterized by four main constituents: Fe–Al residual and residual-talus material, which forms due to destruction of underlying rocks of the lateritic cover; allochtonous aeolian material atypical of the underlying laterites; authigenic mineralization: ferruginous pisolites and ferruginous envelopes on bauxitic and lateritic clasts; newly formed and soil regeneration of clayey material related to the decomposition of the plant mass, as well as mobilization of Al and Si upon weathering of aeolian material; and organic matter, which occurs as organic acids and organic compounds, as well as the fragments of plant root systems.

(3) The soil horizon occurs directly on bauxites and laterites and represents the rear zone of a supergene metasomatic column, which is the lateritic weathering crust. The soil horizon exhibits mobility of most components, dominant leaching processes, and mobilization and redistribution of the material. The loose formations are first to interact with atmospheric precipitation, which results in their downward transportation together with an infiltration front of rain water of laterites.

(4) Due to their composition, first of all, the higher SiO_2 content and organic matter, the soil horizon partly dilutes the underlying bauxite ore. The greater part of SiO_2 in bauxites is evidently due to the soil horizon, which penetrated the ore body along fractures.

(5) Our studies allowed us to reveal a genetic link between the soil horizon of the weathering crust and the underlying bauxite ores and to determine the degree of influence of the composition of soils on processes of bauxite formation. Granulometric analysis of the lateritic soils was conducted for the first time. It was found that the material involved in the formation of the degradation zone of the bauxite-bearing lateritic profile was sourced from rocks that are related to the processes of formation of laterites, aeolian elements, and those involved in the formation of new soil mineralization.

FUNDING

This work was supported by a state contract of the Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry, Russian Academy of Sciences (Moscow), project no. 121041500220-0. The analytical studies were conducted in the ANALITIKA Center for Collective Use, Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry, Russian Academy of Sciences.

REFERENCES

- 1. Y. Tardy, *Pétrologie des Latérites et des Sols Tropicaux* (Masson, Paris, 1993).
- 2. A. Beauvais, Geoderma 150, 379–388 (2009).
- 3. A. B. Machado, in *Proc. 2nd Int. Seminar on Laterisation Processes* (Sao Paulo, 1983), pp. 251–254.
- R. R. Anand, M. F. Aspandiar, and R. R. P. Noble, Ore Geol. Rev. 73 Part 3, 394–416 (2016).
- 5. A. E. Petts, S. M. Hill, and L. Worrall, Geochem.: Explor., Environ., Anal. 9, 257–266 (2009).
- 6. V. M. Yakushev, Pochvovedenie, No. 1, 113–115 (1968).

2023

- V. I. Mamedov, A. A. Chausov, E. A. Okonov, M. A. Makarova, and N. M. Boeva, Geol. Ore Deposits 62 (2), 163 (2020).
- 8. V. I. Mamedov, N. M. Boeva, M. A. Makarova, E. S. Shipilova, and F. Melnikov, Minerals **12**, 389 (2021).
- 9. L. Z. Prokh, *Wind Dictionary* (Gidrometeoizdat, Leningrad, 1983), p. 218 [in Russian].
- T. V. Tursina and I. A. Sokolov, Byull. Pochv. Inst. im. V. V. Dokuchaeva, No. 62, 22–35 (2008).
- G. H. Brimhall, C. J. Lewis, J. J. Ague, W. E. Dietrich, J. Hampel, T. Teague, and P. Rix, Nature **333**, 819–824 (1988).
- 12. R. V. Abramov, in *Sedimentary Conditions in the Atlantic Ocean* (Nauka, Moscow, 1971), pp. 7–31 [in Russian].
- 13. M. Mainguet, J.-M. Borde, and M.-C. Chemin, Trav. Inst. Geogr. Reims, No. 59–60, 15–27 (1984).

- M. A. Makarova, V. I. Mamedov, N. M. Boeva, E. S. Shipilova, D. A. Vnuchkov, and N. S. Bortnikov, Geol. Rudn. Mestorozhd. 65 (3), 1–17 (2023).
- V. I. Mamedov, A. A. Chausov, and M. A. Makarova, Moscow Univ. Geol. Bull. 72 (2), 286–295 (2020).
- V. I. Mamedov, E. S. Shipilova, N. M. Boeva, A. D. Slukin, M. A. Makarova, D. A. Vnuchkov, and N. S. Bortnikov, Dokl. Earth Sci. **491** (2), 204–209 (2020).
- 17. E. S. Shipilova, V. I. Mamedov, and N. M. Boeva, Geol. Ore Deposits **64**, 106–124 (2022).
- 18. G de Weisse, in *Proc. Symp. Bauxites, Oxydes, Hydroxydes d'aluminium* (Zagreb, 1964), Vol. 568, No. 1, pp. 7–29.

Translated by I. Melekestseva