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GEOLOGY

The Main Processes and Stages in the Formation of the Unique Sangaredi Deposit of Bauxites (West Africa)

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Abstract—In the course of additional exploration of the lower horizons of the unique Sangaredi deposit in West Africa, nonlaterized deposits of the Sangaredi series of all major lithological types were found. The lithological composition of redeposited bauxitized deposits of the Sangaredi series varies from conglomerate- and gritstone—bauxites to sandstone-like and clayey bauxites, which facially represent water-sedimentary (alluvial and lacustrine) continental deposits. The appearance of such a propitious redeposited parent substrate predetermined the formation of sedimentary-lateritic bauxites as a result of subsequent laterization. In this article the main processes are characterized and the stages of the formation of extra-quality bauxites of the unique Sangaredi deposit are substantiated.

Keywords: bauxites, lithological type, stage of formation, Sangaredi, sedimentary-laterite origin
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The unique Sangaredi deposit is situated in Fouta-Djallon—Mandingo in West Africa on the left bank of the Kogon River in the Republic of Guinea. This deposit is well-known to a wide range of the experts in bauxites [1–5].

The unique qualities of these bauxites, their great thicknesses, a mineral composition that is different from classical lateritic bauxites, and the high content of boehmite lead to debates about the origin of the Sangaredi deposit. The majority of researchers of the second half of the last century confidently referred the origin to the sedimentary type. These ores were related to alluvial, lacustrine, and boggy deposits due to the presence of clastic texture and gel-morphic and oolitic formations [1, 2, 6–9]. On the basis of the flattened form of small pebbles and gravels, part of the horizons of this structurally complex deposit was related to the coastal-marine beach type [1].

At the beginning of this century, a group of French colleagues [5] again considered the Sangaredi deposit and other deposits of this region as sedimentary occurrences on the Eocene surface. These sedimentary formations were considered to have been redeposited from the Cretaceous surface, which is situated several hundred kilometers to the east, on the top of the Fouta-Djallon Plateau. However, neither the age of the surface nor the sedimentary origin of the occurrences was factually substantiated in this light.

The first attempt to reconstruct a geological model of the deposit was made in 1985 [3]. The study of tens of core sections and the geomorphological position of the occurrences allowed us to assume for the first time that the redeposited substrate of alluvial and alluvial—lacustrine facies was affected by epigenetic changes and subsequent laterization.

In 1986, Puliken and Malm expressed a similar opinion with regard to subsequent lateritic bauxitization of the sedimentary continental formation (Sangaredi series) [4]. It should be noted that Puliken guided the geological works on the deposit for several years. He had a good understanding about the structure of bauxite occurrences unlike the researchers who had only visited this object and generally studied it on the basis of rock samples. In Australia, at the Weipa deposit, where pisolitic bauxites were studied, the formation of bauxites was substantiated not only in situ, but also as a result of redeposition of heavily weathered rocks with subsequent laterization [10].

Until 2012, the authors of some publications assumed that the formation of the Sangaredi deposit was stadial and polygenic [11, 12]. The following stages were considered:

—accumulation of material and redeposition of lateritic weathering crusts lying topographically higher;

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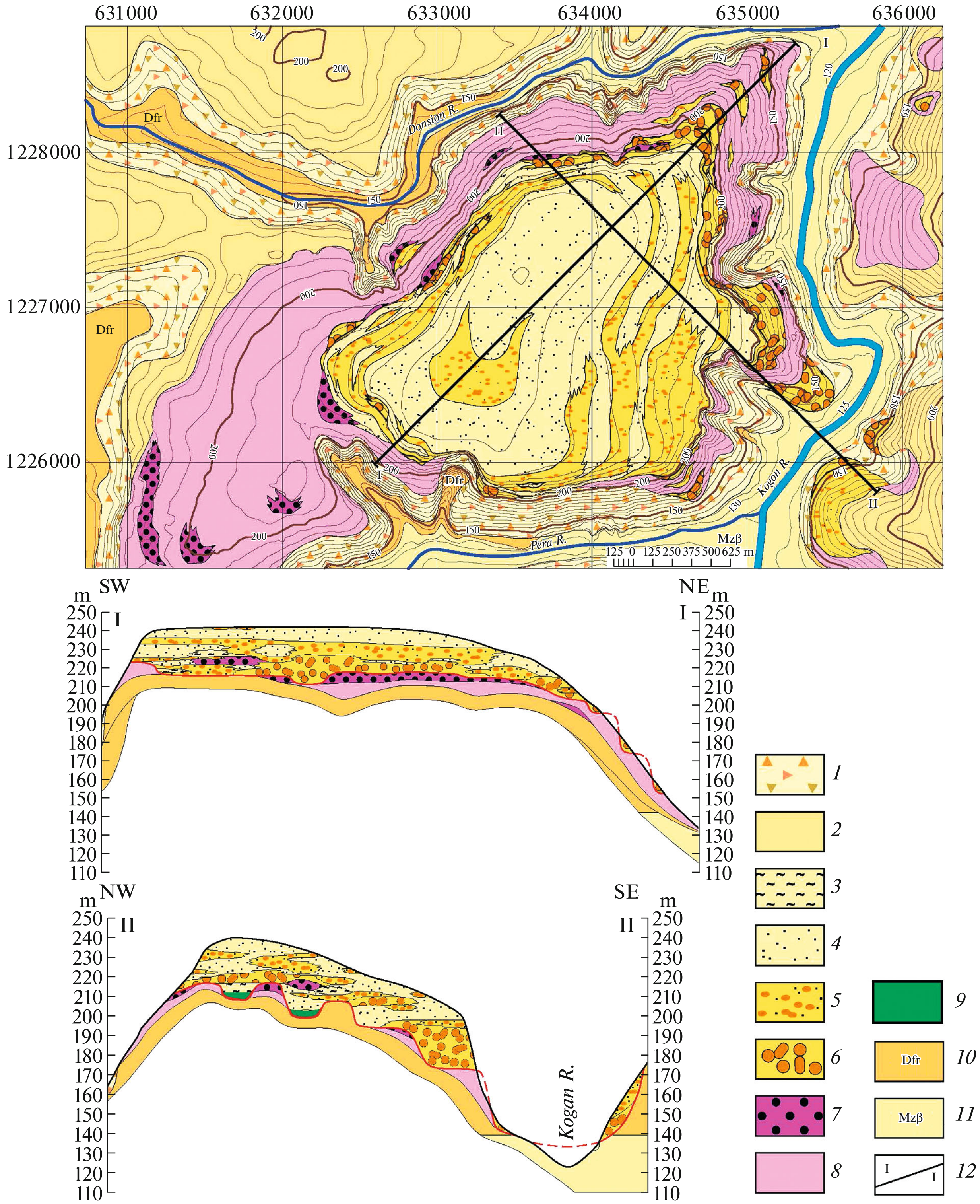

Fig. 1. The geological map and longitudinal and transverse sections of the Sangaredi deposit. (*1*) Deluvial-proluvial aprons of slopes; (*2*) classical bauxites and laterites in situ on the Devonian silty claystone; (*3–6*) sedimentary–lateritic bauxites: (*3*) on sedimentary clays, (*4*) on psammitic deposits; (*5*) on gravel deposits; (*6*) on pebble and gravel–pebble deposits; (*7–8*) infiltration-metasomatic bauxites: (*7*) oolitic bauxites, (*8*) gel-morphic and gelified bauxites; (*9*) nonlaterized deposits of the Sangaredi series; (*10, 11*) parent rocks: (*10*) the Devonian silty claystone of the Faro Formation, (*11*) dolerites of the Mesozoic trappean formation; (*12*) lines of the sections.

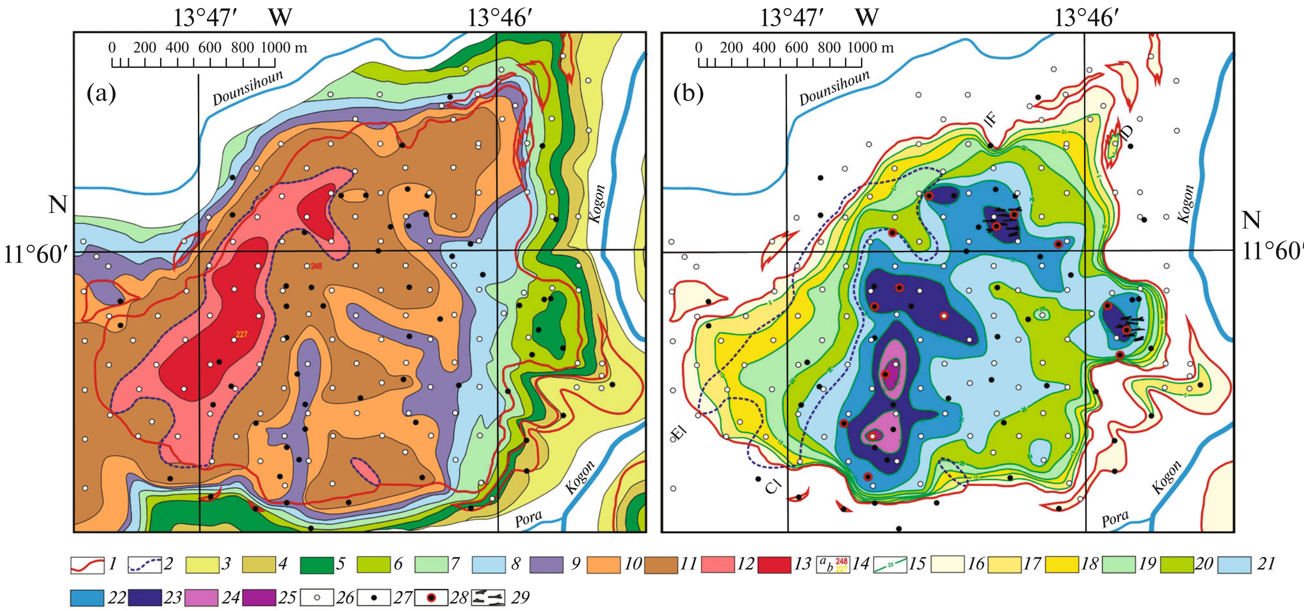

Fig. 2. The maps (a) of the floor relief and (b) the thickness of the Sangaredi series of the Sangaredi deposit. (*1*) Contours of the preserved deposits of the Sangaredi series; (*2*) contours of local highlands of the floor of the Sangaredi series; (*3–13*) fields of the absolute elevations of the floor relief of the Sangaredi series, m: (*3*) from 135 to 150, (*4*) from 150 to 160, (*5*) from 160 to 170, (*6*) from 170 to 180, (*7*) from 180 to 190, (*8*) from 190 to 195, (*9*) from 195 to 200, (*10*) from 200 to 205, (*11*) from 205 to 215, (*12*) from 215 to 220, (*13*) more than 220; (*14*) the maximal absolute elevations of (*a*) modern surface of the bowal and (*b*) the floor relief of the Sangaredi series; (*15*) an isoline of the Sangaredi series thickness and its value; (*16–25*) fields of thickness of the Sangaredi series, m; (*16*) less than 5, (*17*) from 5 to 10, (*18*) from 10 to 15, (*19*) from 15 to 20, (*20*) from 20 to 25, (*21*) from 25 to 30, (*22*) from 30 to 35, (*23*) from 35 to 40, (*24*) from 40 to 45, (*25*) more than 45; (*26–28*) borehole mouths: (*26*) drilled in 1976, 1977, (*27*) drilled from 2010 to 2012, (*28*) intersected the poorly laterized and resilicated deposits of the Sangaredi series; (*29*) lignites.

—whitening, reduction, and removal of iron from deposits at the stage of the flow-through watering under conditions of a hot and humid climate, luxuriant vegetation, and a biologically active environment, i.e., in a gleyey geochemical setting; these processes had to be accompanied by resilication of bauxite fragments;

—subsequent laterization of sedimentary whitened deposits in the post-Middle Miocene time due to the

Table 1. The composition of different facies deposits of the Sangaredi series according to the intensity of lateritic weathering

Intensity of laterization of deposits of the Sangaredi series		for sedimentary clays				for sandy deposits				for gravel deposits				for pebble and gravel–pebble deposits			
		Number	SiO_2	Al_2O_3	Fe_2O_3	Number	SiO_2	Al_2O_3	Fe_2O_3	Number	SiO_2	Al_2O_3	Fe_2O_3	Number	SiO_2	Al_2O_3	Fe_2O_3
$SiO_2 < 2$	%	69	1.1	57.7	7.8	168	0.8	59.4	5.5	208	0.8	60.3	4.4	48	0.6	63.3	2.2
	kg/m^3		20	1062	143		16	1169	108		14	1080	78		12	1229	43
$2 < SiO_2 < 5$	%	7	3.5	59.3	5	16	3.3	58.1	6.2	18	3.6	58.8	5.6	11	3.6	61.1	4.5
	kg/m^3		57	954	81		57	1005	107		61	994	94		67	1117	82
$5 < SiO_2 < 10$	%	10	6.8	55.4	4.5	14	6.4	56.2	6.6	23	7.1	57.4	5.8	12	7.9	58.6	5.1
	kg/m^3		109	892	72		113	983	115		124	1004	101		147	1089	94
$10 < SiO_2 < 15$	%	6	14	53.6	2.3	4	12.1	53.9	5	5	11.2	55.8	4.7	3	13	54.5	4.6
	kg/m^3		211	809	35		190	846	78		194	966	82		220	920	78
$15 < SiO_2 < 20$	%	9	16.6	51.9	3.6	11	17.2	51	3.4	5	16.9	52.9	4.9	3	18.1	52.4	3.2
	kg/m^3		257	804	55		272	805	54		272	851	79		319	928	56
$SiO_2 > 20$	%	1	43.5	38.6	1.6	1	41	38.8	3.7	1	42.1	35.9	5.1	1	43.5	37.4	3.2
	kg/m^3		631	559	24		624	590	56		648	552	79		697	598	52

Input/removal was calculated in relation to the underlying rocks of the weathering profile.

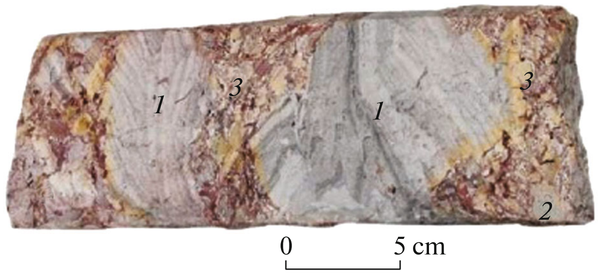

Fig. 3. Resilicated rock with a relict conglomerate-breccia texture. (*1*) Kaolinized fragments of silty claystone, (*2–3*) fragments of bauxites resilicated to kaolinite clay: (*2*) pebble, (*3*) gravel.

descent of the base level resulting in the consistent occurrence of deposits in the hydrogeological vadose and infiltration zone.

The entire system of the logical geological–geomorphological, mineralogical, and geochemical substantiations lacked factual confirmation.

By documenting the core boreholes, we managed to reconstruct a geological model of the deposit, which is shown on a geological map and sections (Fig. 1).

In the course of additional exploration of the lower horizons of the Sangaredi deposit, 15 core boreholes encountered almost nonlaterized deposits of the Sangaredi series, which are parent rocks of all main lithological types represented by gravel–pebbles, sands, and clayey deposits. As might be expected, these boreholes occurred in local depressions of the floor microrelief of the Sangaredi series, on the flat top of the Sangaredi paleo-bowal (Fig. 2). It was earlier assumed that the deposits that were unaffected or poorly affected by laterization were mostly kaolinite rocks, which were both whitened (Fe_2O_3 content was rarely more than 3–6%) and resilicated high-alumina (Al_2O_3 35–42%) rocks. A clastic conglomerate-gritstone structure is shown on the image of a core from the basal horizon (36.7 m below the surface) of the Sangaredi series (Fig. 3). Numerous whitish rounded inclusions were rounded fragments of bauxites. At

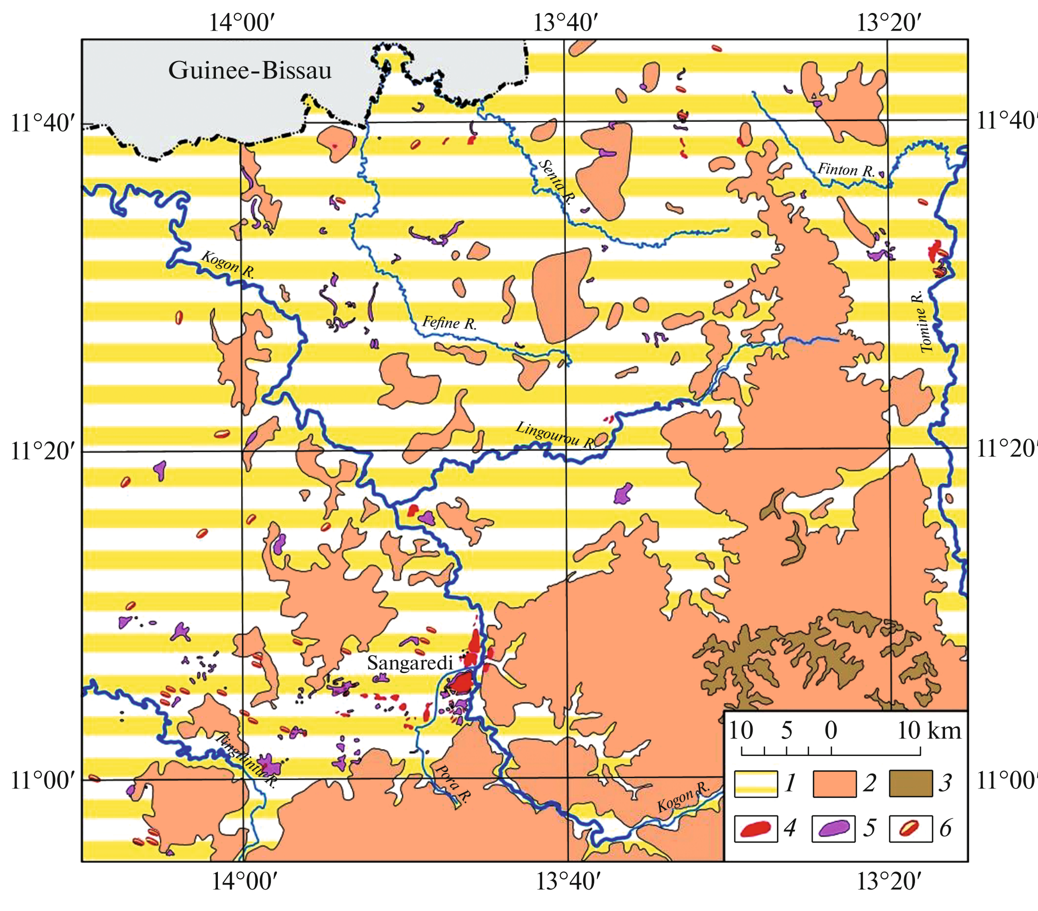

Fig. 4. The paleogeographic scheme of the area between the Tingilint–Kogon–Tominé rivers by the end of the Middle Miocene. (*1*) The area of the probable distribution of the Middle Miocene accumulative plain–alluvial–lacustrine plain (deposits of the Sangaredi series); (*2*) pre–Middle Miocene planation surfaces of Late Eocene and Oligocene ages; (*3*) fragments of the African Surface; (*4*) preserved deposits of the Sangaredi series (bauxitized); (*5*) gel-morphic bauxites on the whitened parent rocks at the bottom of the Sangaredi series; (*6*) scattered pebbles from basal conglomerate–bauxites on pebble stones of the Sangaredi series.

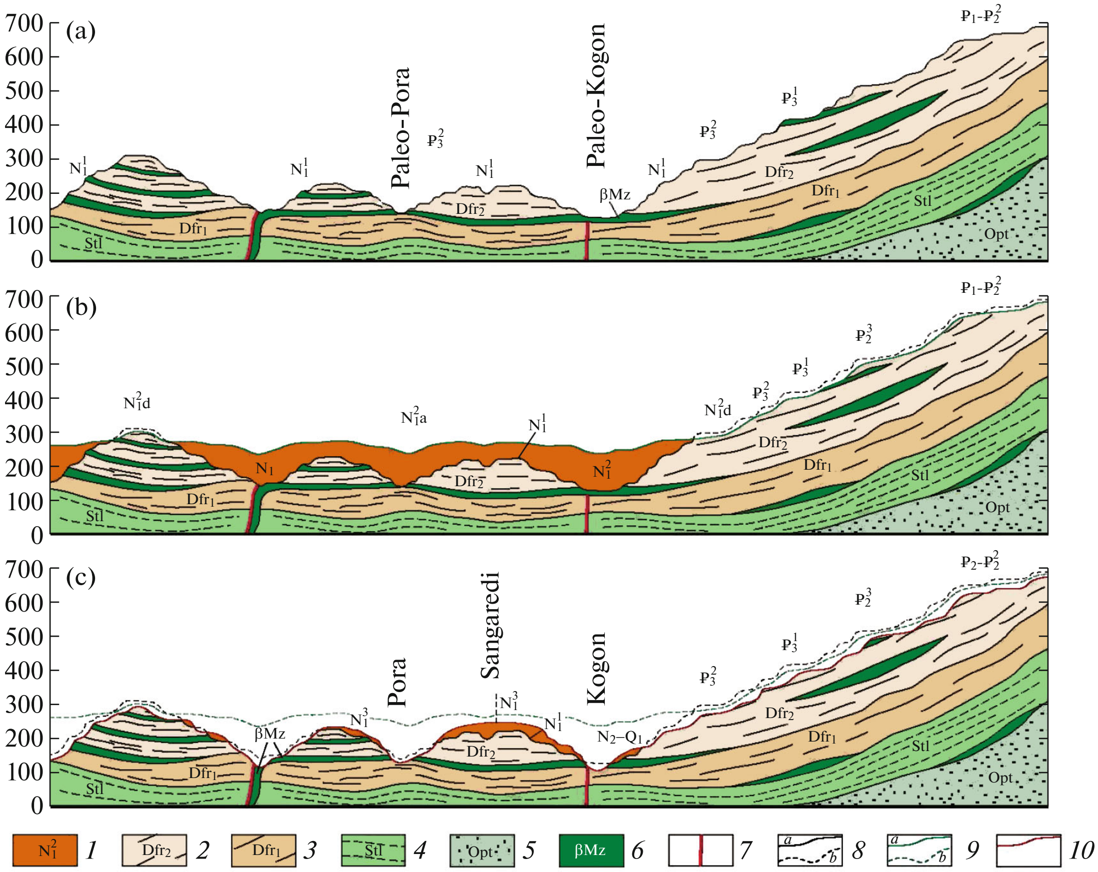

Fig. 5. The scheme of the geomorphological cycles on the western slope of the Fouta-Djallon–Mandingo morphostructure by (a) the end of the Early Miocene, (b) the end of the Middle Miocene, and (c) the present time. (*1*) Alluvial and alluvial–lacustrine deposits of the Sangaredi series, which formed the accumulative plain in the Middle Miocene; (*2*–*5*) terrigenous–sedimentary deposits of the platform cover of the Guinea syneclise in the Bowe synclinal: (*2*, *3*) the Devonian siltstones, claystones, and fine-grained sandstones of the Faro suite of the upper (*2*) and lower (*3*) members; (*4*) the Silurian silty claystones of the Telimele Formation; (*5*) quartz sandstones uneven-grained, the Ordovocian gritstones and conglomerates of the Pita suite; (*6*) sills and dikes of dolerites and conga-diabases of the Mesozoic trappean formation; (*7*) faults; (*8*–*10*) relief lines of relief: (*8a*) by the end of the Early Miocene, (*8b*) assumed on the sections of the following stages, (*9a*) by the end of the Middle Miocene, (*9b*) assumed at the following stage, (*10*) modern relief.

present, this is clay, which is easily broken down by hand. In the chemical composition of an interval sample, the SiO_2 content is 43.54% and the Al_2O_3 content is 37.39%, which corresponds to kaolinite with a small amount of free alumina. The Fe_2O_3 content is 3.22%, and the Al_2O_{3mono} content is only 0.2%. Initially in situ, this clastic rock could not be almost completely kaolinitic and low iron. Such a composition is caused by resilication and whitening.

Table 1 shows the factual data on the changes in the chemical composition for each lithological type (pebble stones, gritstones, sands, and clays) of the source parent rocks according to the intensity of their lateritic bauxitization. In terms of the chemical composition, all lithotypes of parent rocks are both whitened and resilicated with an extremely high ferruginous module ranging from 7 to 24 and with a very high content of alumina.

As was assumed earlier [3], only the appearance of such a propitious redeposited (sedimentary) parent substrate and its subsequent laterization predetermined the formation of this extremely high-quality sedimentary-lateritic bauxites—the unique Sangaredi deposit.

In the northwestern part of the province, detailed mapping and exploration drilling revealed no more than 195 bodies of different sizes and occurrences of deposits that were transformed in bauxites of the highest quality. The largest occurrence is preserved in the Sangaredi deposit, after which the series itself was named [1, 6].

The geological–geomorphological mapping on the left bank of the Kogon River and in the area between the Kogon and Tominé rivers allowed us to generate a paleogeographic map (Fig. 4) for the end of the Middle Miocene [11, 13] and to draw the scheme of the geomorphological cycles (Fig. 5) of the western slope of the highlands in the region of the deposits of the Sangaredi group.

These materials show that, at the end of the Early Miocene, the first stage of the neotectonic rise was completed resulting in lowering of the base level; after that, in the Middle Miocene, an inversion occurred and the base level rose. As a result, clastic material from the broken down weathering mantles, which occurred topographically higher, filled the valley bottoms and, later, overlapped the low watersheds. Therefore, an accumulative plain with pre–Middle Miocene residual mountains was formed. The elevations of the accumulative plain (in modern measurements) were 270–400 m. The Kogol River paleochannel was at elevations of 134–137 m in the area of the Sangaredi deposit.

The thickness of deposits along the axes of the main rivers of the region was 150–170 m. In the Late Miocene, the territory started rising again (the second phase of the neotectonic stage), and the accumulative plain was dissected resulting in complete erosion and destruction of the Sangaredi deposits.

Therefore, we obtained for the first time direct rather than indirect evidence that the Sangaredi deposit did not result solely from sedimentary processes: this deposit is a polygenic and polychronic formation. However, the sedimentary stage of its formation, when epigenetic changes occurred in the gleyey geochemical setting at the sediment stage, played a very important role in the formation of the new extremely propitious parent substrate. However, such unique bauxite occurrences could not exist without the impact of intensive and sufficiently long lateritic weathering.

Therefore, the Sangaredi deposit is a product of sedimentary–lateritic origin.

No sedimentary occurrences of high-quality low-silica bauxites were revealed in alluvial, lacustrine, and coastal marine sediments over many decades of exploration and mapping this largest bauxite-bearing province [14, 15]. There is no evidence of the existence of sedimentary low-silica bauxites either.

The average content of aluminum in the deposits of the Fouta-Djallon–Mandingo province is 24%, which is three times larger than a clarke of Al in the Earth's crust. When refining the high quality bauxites from contaminants (silica, alkaline, and alkali-earths), the total content of these components in bauxites of the Fouta-Djallon–Mandingo province is no more than 2.5%, on average; in the average composition of parent rocks, it is about 70%, and to obtain bauxite, the total amount of contaminants has to be reduced by 28 times.

Therefore, bauxite is not so much the concentration of aluminum as the highest degree of refining of the parent rocks from contaminants. In the process of ordinary redeposition, it is impossible to provide a high degree of the separation of gibbsite, kaolinite, and quartz, especially in fine clastic deposits [15]. Therefore, the factual and theoretical data obtained allow us to substantiate confidently the sedimentary-laterite origin of the Sangaredi deposit bauxites.

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