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Genesis of bauxites in the Valeryanovskaya zone, Kazakhstan

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ABSTRACT

The Valeryanovskaya structural-formational zone is located in the Kostanay region of Kazakhstan and is part of the North Kazakhstan bauxite province. The article discusses the genesis of bauxites and provides structural and petrographic arguments for the lateritic origin of bauxites, previously considered karst. Analogies are given of the structure of bauxite ore bodies and their host formations with the structure of the Shaimerden zinc deposit. The Shaimerden type Bozhi Dar ore occurrence is briefly described and proposed fundamental methods for searching for similar objects based on the idea of the lateritic origin of bauxites.

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1. Introduction

The literature and archive reports (Kazarinov, 1958a; Petrov, 1967; Roslyakov, 1981; Sakharov, 1969; Venkov, 1997; Yevlampyev, 1978; Ishchenko, 2005; Ichshenko et al., 2022; Kalugin, 1984; Bardossy and Aleva, 1990; Karst, 1981; Mikhailov and Petrovskaya, 1959; Esenov and Shalabayev, 2007) presents various perspectives on the genesis of bauxites in general and the bauxites of the western part of the Turgay Depression in particular. These viewpoints do not seem mutually exclusive to us. On the contrary, from a certain perspective, they can significantly complement each other. We base our understanding on the in-situ formation of bauxites in the North Kazakhstan Province under lateritic weathering crust conditions. This hypothesis was proposed by D.A. Venkov in 1997 (Venkov, 1997), but he did not develop it further due to a lack of data: "... bauxite-bearing rocks can be attributed to the lateritic weathering profile, but special studies are required for proof." Existing discrepancies in the interpretation of the origin of bauxites from both Krasny Oktyabr and the Ayat group deposits are based on the study of bauxites and ore-bearing sequences exclusively from the perspective of industrial parameters. This has led to the identification of lithological rock variations and stratigraphic units, which primarily determine their classification according to the GOST bauxite standard while pushing structural, petrographic, and genetic features into the background.

The study of petrographic features of the bauxite-bearing sequence and the bauxites themselves has allowed us to consider them together with the underlying rocks as a single weathering crust with a lateritic profile, developed on volcanogenic-sedimentary rocks of Carboniferous age. Different authors propose various methods for dividing the weathering crust profile into zones. The classical stratigraphic division from bottom to top is as follows:

1. Fresh parent rock, barely affected by weathering.
2. A zone primarily of mechanical rock destruction, leading to rubble formation.
3. An initial decomposition zone where primary silicates break down and transform into hydromicas, hydrochlorites, montmorillonite, and beidellite.
4. An enrichment zone, or mottled zone, typically a dense, variegated clay-like rock.
5. An ochre zone or hematite-gibbsite zone.

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A less detailed classification was proposed by N.A. Roslyakov (Roslyakov, 1981) for kaolinitic-type weathering crusts, structured from bottom to top as follows:

1. Source rocks from which the weathering crust develops.
2. Weakly disintegrated rocks at the initial weathering stages identified as saprolite (saprolites, according to V.P. Kazarinov (Kazarinov, 1958b)).
3. Rocky structural eluvium (clay-rubble zone, as per other authors).
4. Clay structural eluvium.

It should be noted that a complete weathering crust profile is not observed universally in the bauxite deposits of western Turgay. There are instances of missing sections, disruptions in the sequence of zones, and the merging of adjacent zone characteristics within a single rock unit. This is due to variations in composition, heterogeneity of rocks subjected to hypergenic transformation, predisposition or resistance of specific lithological units to weathering, and the conditions under which weathering occurred. Weathering crust zones lack distinct boundaries. Therefore, it is sometimes more practical to describe a zone by its structural-textural characteristics and composition rather than assign it a specific number.

In the western Turgay bauxite deposits, the depth of weathering is often constrained by underlying limestones, which are resistant to weathering. These limestones appear as the zone of unweathered rocks, whereas the overlying silicate-rich clastic rocks are more extensively weathered and correspond to the hydromica zone or even the enrichment (hematite-gibbsite) zone. This explains why, in some cases, certain zones described in conventional classifications are missing.

In studying bauxite-bearing sequences, we have focused not only on identifying geochemical zones and delineating their spatial boundaries but also on determining the educts to clarify the profile structure and the conditions of the parent rock's deposition, as well as its potential stratigraphic affiliation. The educts were identified exclusively based on relict petrographic structures preserved in clay formations of the structural weathering crust. The degree of preservation of relict structures in the educts within the weathering crust formations is not strictly tied to any particular zone within the weathering profile. Occasionally, in zone 4 (the enrichment zone in the classical scheme), relict structures are clearly identifiable, whereas in zone 3 (the montmorillonite or initial rock decomposition zone), they are either absent or only tentatively recognizable.

The bauxite deposits of Western Turgay, particularly Krasny Oktyabr and the Ayat group deposits, are of the same type or, at the very least, share many similarities. The primary feature uniting these deposits is the formation of bauxite in the hypergenic zone. The parent rocks may be either identical or different in composition, age, and genesis. Another common characteristic of these deposits lies in the structural features of the Paleozoic basement: their association with contact zones of silicate rocks with carbonate rocks and the karstification of the latter. Given these similarities, in our study of bauxite genesis, we present data obtained from both the Vostochny Ayat deposit and Krasny Oktyabr.

Sequence of Stages in the Formation of Bauxite Deposits Based on Previous Studies (Yevlampyev, 1978; Ishchenko, 2005; Kalugin, 1984).

1. Karstification of Middle-Upper Visean limestones and weathering of the underlying and overlying volcanogenic-sedimentary rocks (Triassic-Cretaceous period).
2. Re-deposition of Triassic-Cretaceous weathering crusts from volcanogenic-sedimentary Carboniferous rocks into karst sinkholes and depressions, leading to the accumulation of Cenomanian-Turonian variegated clays.
3. Repeated weathering of Cenomanian-Turonian formations, resulting in the formation of bauxite (or the weathering of re-deposited Cenomanian-Turonian bauxites, i.e., sedimentary bauxites).
4. Submergence of the region, leading to the formation of a sedimentary basin with Maastrichtian sands containing marine fauna, Chagan clays, and younger Paleogene-Quaternary cover deposits.

Below, an alternative viewpoint on the origin of bauxite is presented. According to our interpretation, bauxite formed as a result of lateritic weathering of silicate rocks in contact with Visean (Visean-Serpukhovian) limestones (C1v2-s sk), i.e., through lateritic processes. This article presents the results of research conducted during operational exploration

Fig. 1. Clays of the structural weathering crust over finely layered tuffites (Ayat deposit, Quarry6).

Fig. 2. Clay formations of the weathering crust: (a) pisolitic (pea-like) clays over unevenly fragmented tuffs; (b) non-pisolitic clays over finely layered tuffites.

of the Vostochny Ayat and Krasny Oktyabr bauxite deposits by TOO "Soyuzshakhtoosushenie."

2. Relict Structures of Bauxite-Hosting Rocks (Bauxite-Bearing Strata)

The relict structures of the parent rocks in the weathered clays of the bauxite-bearing strata exhibit significant diversity. The main types of structures identified include clastic, granular, and magmatic structures.

2.1. Relict Clastic Structures

Relict clastic structures are classified based on the grain size of the clasts in the parent rocks:

Aleurolitic (silt-sized, fractions of a millimeter)
Psammitic (sand-sized, up to 1 mm)
Psephitic (gravel-sized, up to 5 mm)
Coarse clastic (clasts 1 cm or larger)

Additionally, unsorted rocks are observed, containing clasts of all the above-mentioned grain sizes.

Aleurolitic (and aleuropelitic) rock. Under weathering crust conditions, these rocks poorly retain the structure of the parent rocks. In the described strata, the structure is difficult to determine. In rare cases, mainly based on rock coloration, finely layered varieties of fine-clastic rocks can be identified (in Quarry No. 6 of the Ayat deposit), as well as sections of the profile with fine cross-bedding (in the area of ore body 58 at the Vostochny Ayat deposit) (Fig. 1, Fig. 2(b)).

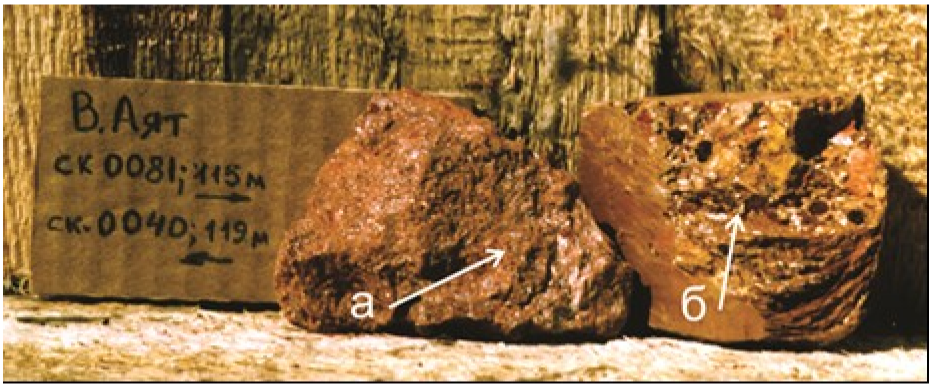

Fig. 3. Relict structures in the red clays of the enrichment zone of the weathering crust: (a) psammitic; (b) unevenly clastic.

Fig. 4. (a) Relict psammitic structure in the red clays of the weathering crust (enrichment zone), (b) Relict psammitic structure in the red clays of the weathering crust (enrichment zone).

Psammitic rocks. The fragments are angular or semi-rounded, ranging in size from 0.5–0.8 mm to 1 mm. The cementing mass is aleuritic. Fragments of splintery and ragged shapes—relics of pyroclastic particles—are often present. The rocks are massive and non-layered. Based on these characteristics and the overall texture, the parent rocks are sandstones and tuffaceous sandstones. (Figs. 3(a), 4a,b).

Psephitic Rocks. The fragments are angular or splintery in shape, very rarely sub-rounded. Their size ranges from one and a half to 5 mm. The cementing mass is psammitic or silt-sized. When the silt-sized cementing mass undergoes clayification, its structure often becomes difficult to determine or even indeterminate. Based on relict structures, fragments are identified as andesitic porphyrites, red-colored siltstones, and rocks with aphyric or indistinctly grained structures. Large fragments exhibit varied colors: cherry, tobacco-green, white, beige, and lilac. However, most relict fragments are white or lightly colored, composed of kaolinite, indicating that their original composition was predominantly feldspathic. The texture and composition of the clays characterize their educts as lithocrystalloclastic tuffs. (Figs. 5a,b,c, 6a).

Coarse-Clastic Rocks. Coarse-clastic rocks are not commonly found in the bauxite-bearing sequence. The fragments, usually irregular in shape, are represented by andesitic porphyrites with a fine-porphyritic, densely spotted texture. The fragment size ranges from 0.5–0.8 cm to several centimeters. The cementing mass is cryptocrystalline with a fluidal texture. The educts of these rocks are identified as lava breccias of andesitic composition (possibly andesite-dacite or trachyandesite?) (Fig. 3b) and coarse-grained breccias (Fig. 5d).

2.2. Granular Structures

Rocks with this type of structure are rarely found in the bauxite-bearing strata. These include a cryptogranular structure of siliceous-iron rocks forming thin (a few centimeters thick) interlayers and a

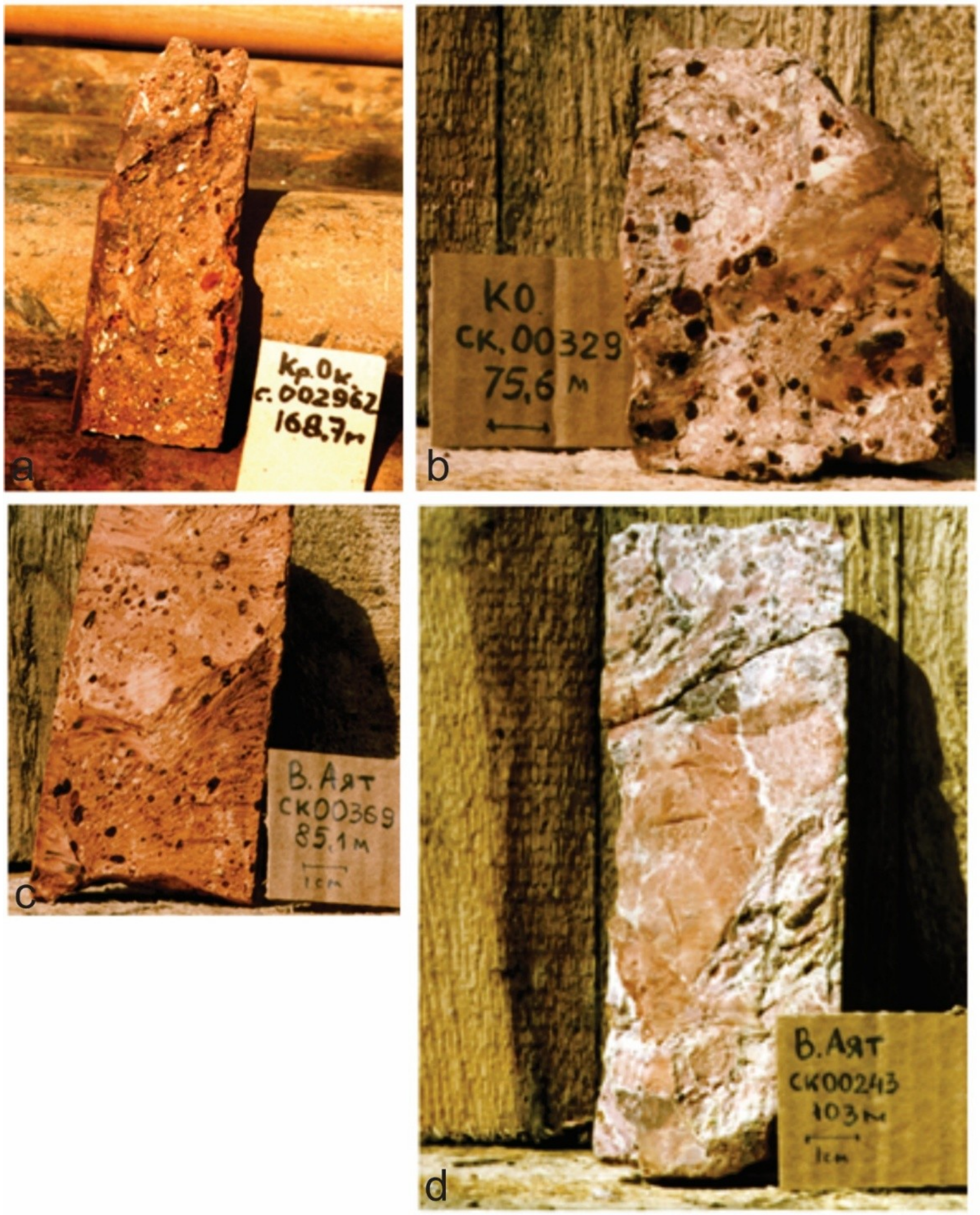

Fig. 5. Sparse-Pisolitic Clay of the Enrichment Zone of the Weathering Crust, developed from unevenly clastic lithocrystalloclastic tuffs. Lithoclasts are larger in size, with reddish and dirty-gray coloration, while crystalloclasts are small and white, (b) Pisolitic (Pea-Like) Clay of the Weathering Crust, developed from psephitic crystalloclastic tuffs. The white-colored fragments are kaolinized feldspars, (c) Pisolitic (Pea-Like) Clay with Relict Psammitic Structure of the Parent Rocks, (d) Weathering Crust Clay Developed from Coarse-Clastic Breccia.

mosaic granular structure of microquartzites, described in two boreholes in the southern part of the ore body 58 at the Vostochny Ayat deposit. It should be noted that the siliceous rocks described here, embedded within the clays, exhibit structures of unaltered rocks rather than relict structures. This is likely due to the resistance of siliceous rocks to weathering, which allowed them to remain unchanged under the conditions of the weathering crust.

2.3. Relict Structures of Igneous Rocks

Porphyritic Structure: The rocks are fine-plated and densely porphyritic. The porphyritic inclusions are small (1–2 mm in size) and have tabular, prismatic, or irregular shapes. Phenocrysts make up 30–40% of the rock. The groundmass is aphanitic and homogeneous, with its color varying across different zones of the weathering crust—from red in the ochre zone to gray and turquoise in the montmorillonite

Fig. 6. (a) Relict Structure of Lithoclastic Tuffs in Pisolitic Clays of the Weathering Crust Enrichment Zone. The clasts are white and red, angular, and splintery in shape. Notably, pisolites (concretions) are present both in the cementing matrix and within the clasts of the original rock, (b) Relict Psephitic Structure in Red Crustal Clays of the Ochre or Enrichment Zone.

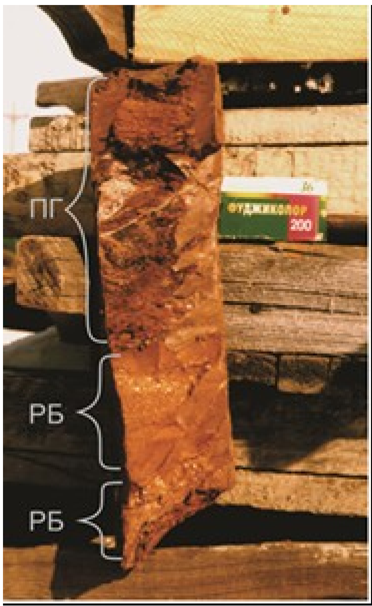

Fig. 7. Bouma Sequences ( ) Preserved in Crustal Clays from Parent Turbidites and Pisolithic Clays ( ) Derived from Coarser Clastic Rocks (Tuffs).

zone. It is possible that the original unweathered parent rocks also had different colors across different layers and horizons.Based on the relict structures, the rocks are identified as andesites, possibly extending to andesite-basalts (Figs. 8b, 9).

Hypidiomorphic Granular Structure: Visually, based on the texture within the clays, this structure resembles that of dioritic porphyrites. The grain size reaches up to 0.5 cm. Both feldspars and dark-colored minerals have been transformed into clay. Weathering crust clays with a relict hypidiomorphic granular structure derived from diorites have been documented at the Vostochny Ayat deposit, in the southwestern part of ore body 58.

3. Composition of the Parent Rocks of the Pre-weathering Basement

Based on the relict structures preserved in clayey weathering crust formations, only the original rock

Fig. 8. (a–c) Weathering Crust Clays Developed from an Interbedded Sequence of Lava Breccias (LB), Gray Andesites (GA), and Red Andesites (RA) with a Densely Porphyritic Fine-Lath Structure.

Fig. 9. Transition from the Enrichment Zone to the Montmorillonite Zone within a Monotonous Andesite Sequence. Enrichment Zone: 1 – Base of Tuffs; 2 – Roof of Fine-Lath Andesites. Transitional Zone: 3 – Fine-Lath Andesites. Montmorillonite Zone: 4 – Fine-Lath Andesites. 1–4: Clays with Relict Structures.

(educt) can be identified for a specific interval. The analysis of educts as a whole provides insight into the structure of the pre-weathering Paleozoic basement. Previously, the variegated clays containing bauxites were classified as a stratigraphic unit of Cenomanian-Turonian age. These clays are mainly red, with various shades, streaks, spots, or clayey inclusions of other colors.

Based on the relict structures of the parent rocks throughout the entire volume of variegated clays, the following formations or horizons are identified (most likely of Visean and Serpukhovian age):

- Lithoclastic tuffs (Vostochny Ayat, borehole 00243, depth 104.2 m; borehole 00264, depth 92.7 m; Krasny Oktyabr, borehole 002962, Fig. 5a – depth 168.7 m and Fig. 6a – depth 172.8 m).
- Crystaloclastic psephitic tuffs of andesitic composition and tuffaceous sandstones containing pyroclastic material (Vostochny Ayat, borehole 0040, depth 119 m, Fig. 6b).
- Rhythmically layered flyschoid formation – within rhythms with a thickness of 3–5 m, the size of clasts decreases from 1–2 cm at the base to 1 mm at the top. The formation is capped by thin-bedded siltstones and silt-sandstones (Vostochny Ayat, borehole 00177).

- A package of turbidites with Bouma sequences of 5–10 cm thickness (Vostochny Ayat, borehole 0082, depth 98 m, Fig. 5b).
- Andesitic porphyrites (Krasny Oktyabr, boreholes 4300=003026, 002962, Figs. 8b, 9).
- Lava breccias – large (up to 5–10 cm) clasts with an aphanitic relict structure, cemented by material retaining relict fluidal texture (Figs. 8a,c, left, Krasny Oktyabr, borehole 002962).

Thus, various silicate Paleozoic rocks of different compositions and ages, which were altered to clay and colored red in the ocher zone and enrichment zone of the Mesozoic weathering crust, were assigned to a single stratigraphic unit—the Cenomanian-Turonian variegated clays. Below is the justification for considering the variegated clay sequence as an in situ structural weathering crust.

3.1. Correlation of Stratigraphic Boundaries in Parent Rocks with the Boundaries of Weathering Zones

In borehole 4300 (003026), the correlation between the boundary of red (variegated) clay development and the stratigraphic boundaries of the parent rocks is particularly illustrative. Clays with relict porphyritic structures occur at depths of 61.0–82.8 m, while red clays are found between 57.5–65.4 m. This means that the lower boundary of the red (variegated) clays lies within the andesite sequence (Fig. 9). This observation contradicts the interpretation of these clays as "reworked" weathering crusts. In the upper part of the red clays, a diverse clastic structure of tuffs is preserved. Thus, the ocher and enrichment zones encompass both the roof of the andesites and the overlying tuffs. Above the red clays, light gray kaolinitic clays and light gray clayey bauxite are found, corresponding to the kaolinite zone of the weathering crust. Below, clayey formations with a relict porphyritic structure exhibit beige and bluish-gray coloration, characteristic of the hydromica zone (see Table 1). Borehole 4300 (003026) presents a complete profile of the weathering crust (from top to bottom): kolinite zone; enrichment zone; hydromica zone; clayey-rubble zone; unweathered rocks. The weathering crust has developed over various rock types, including igneous rocks. Petrographically diverse rocks, such as andesitic porphyrites and polymictic tuffs, belong to the same weathering zone (the iron-enrichment zone), acquiring a red coloration. Their variegated appearance is explained by their relict porphyritic structure. Meanwhile, the lower boundary of the enrichment zone (the so-called "variegated clays") occurs within the andesite horizon (Table 1). From the above, it follows that "variegated clays" cannot be considered a separate stratigraphic unit. The inclusion of similar rock types in different weathering zones is also observed at the Vostochny Ayat deposit (ore body 57). Boreholes 00195 and 00196 intersect a clayey structural weathering crust developed in rocks of three tuffogenic-sedimentary sequences. These sequences are clearly distinguished by structure and color (Tables 2 and 3). The rock compositions within these sequences are identical in both boreholes. However, the upper part of the interbedded sequence in borehole 00196 falls within the enrichment zone, acquiring a rare pitted texture and a red color while retaining the relict structure of the original rocks. This once again emphasizes that "variegated clay" is, in essence, a weathering product of an undisturbed Late Carboniferous sequence (in situ formations), forming the enrichment zone in a lateritic weathering crust.

In rare cases, we observe the development of the entire weathering crust profile within a monotonous rock sequence, where identical rock types with the same structure appear in different weathering zones. In borehole 003069 (Krasny Oktyabr), a gradual transition is observed from bright red-orange, sparsely pitted clays with a relict fine-fragmental tuffaceous structure to unweathered or weakly weathered tuffs (solid, light beige) that retain their primary fine-fragmental tuffaceous structure.

Here, the monotonous tuff sequence with a uniform structure throughout the section extends across different weathering zones. This allows for tracing the attenuation of the weathering process with depth in the same parent rock and the gradual transition from clays with a relict fine-fragmental structure to solid parent fine-fragmental tuffs.

The tuffs overlie altered brecciated medium-grained and unevenly grained multicolored limestones (gray, yellow, and brown, with white calcite nests). The contact dip is subvertical. The contact between the tuffs and limestones is stratigraphic, with a thin (up to 1 cm) transitional (basal) layer containing not only tuffaceous fragments but also small psammitic limestone clasts (Figs. 10, 11, 12a,b,c,d).

Table 1. Correlation of the stratigraphic boundaries of Paleozoic educts with the boundaries of weathering crust zones (Krasny Oktyabr, well 4300g =003026).

Lateritic Profile Zone of the Weathering Crust	Characteristics of the Hypergene Product (Weathering Crust Formations)	Characteristics of the educt: Relict structures and determination of the parent rock		Depth of distribution	Notes
Loose Cover Deposits				0–53,7	
Kaolinite Zone	Gray clayey bauxite	Indeterminate		53,7–54,9	Profile of the Weathering Crust
	Gray kaolinitic stiff plastic massive clay	Indeterminate		54,9–57,5	
Enrichment zone	Clayey ferruginous formations of various shades of red, also known as “pestrotsvetka.”	Irregular brecciated, tuffogenic structure. Angular, unsorted fragments; rare admixture of ash material.		57,5–61	
		Fine-porphyritic, densely spotted structure.		61–65,4	
Hydromica Zone	Clay formations of dirty yellow shades.	Porphyritic inclusions of tabular or isometric shape (clay-altered plagioclases).		65,4–70,1	
	Clay formations of brown color with various shades.			70,1–71,2	
	Clay formations of dirty-green color.		*Tuff litho-vitroclas*	71,2–73,4	
Clay-gravel zone (saprolite zone)	Light gray clay-gravel formations with slight shades of green and blue, containing areas of highly weathered rocks that have retained their fracture separations.		*Andesiti porphyrites Andesiti porphyrites*	74,4–82,8	
Saprolite zone, complicated by interbedding of rocks with varying resistance to weathering in the original (Carboniferous) section.	Limestone fragments in a clay matrix.			82,8–83,7	
	Pink, altered, cavernous limestones.			83,7–87,3	
	Coarse fragments of gray and pink limestones in a clay matrix.			87,3–90,3	
	Dense clay formations of greenish-brown color.	Fine-porphyritic, densely porphyritic structure.			
		Porphyritic inclusions of tabular or isometric shape (kaolinized plagioclases). 4o		90,3–90,9	
Unweathered rocks.	Pinkish-gray, gray cavernous limestones.			90,9–97,9	

Table 2. Comparison of Stratigraphic Boundaries of Paleozoic Educts with the Boundaries of Weathering Crust Zones (Vost. Ayat, Borehole 00195).

Weathering Crust Profile Zone	Characteristics of Hypergene Products (Crust Formations)	Educt Characteristics: *Relict* Structures and Determination of Parent Rock		Depth Distribution	stratigraphic sequence
Loose cover deposits				0–84,3	
Kaolinite zone	bluish-gray kaolinitic clays	Psammitic (poorly preserved)	Sandstones, silt-sandstones	84,3–86,0	Light sandstone
Clay-structured (hydromica zone)	Clay formations that have preserved the layering and color of the original rocks	Coarse-fragmental lithoclastic (fragments up to 1.5 cm); psammitic.	Interbedding of lithotuffs*, tuff lavas*, and lilac and greenish-gray sandstones. Layer thickness 20–30 cm.	86,0–89,0	Tuffogenic-sedimentary interbedding sequence.
		Psammitic, aleuritic.	Interbedding of greenish and lilac sandstones and siltstones.	89,0–92,0	Lilac-green sandstone.
Saprolite zone	Clay-gravel formations that have retained the color of the original rocks.	Unevenly clastic.	Massive coarse-clastic lithotuffs of yellow-green and tobacco colors	92,0–95,8	Coarse-clastic tuffogenic.

*Tuffs and tuff-lavas of andesitic composition.

Table 3. Correlation of the Stratigraphic Boundaries of Paleozoic Educts with the Boundaries of Weathering Crust Zones (East Ayat, Borehole 00196)

Weathering Crust Profile Zone	Characteristics of the Hypergenesis Product (Weathering Formations)	Characteristics of the Educt: Relict Structures and Identification of the Parent Rock		Depth of Distribution	stratigraphic sequence
Loose Cover Deposits				0–86,3	
Enrichment Zone	Rare-nodular brown-red clay	Not preserved		86,3–87,9	Interbedded tuffogenic-sedimentary unit
	-	Not preserved		87,9–90,5	
		Psammitic	Sandstone	90,5–92,0	
Clayey structural (hydromica zone)	Clay formations that have preserved the layering and coloration of the original rocks.	Coarse-fragmental; lithoclastic (fragments up to 1.5 cm); psammitic.	Interbedding of lithotuffs*, tuffolavas*, lilac and greenish-gray sandstones**. Layer thickness 20–30 cm.	92,0–108,3	Lilac-green sandstone.
Saprolite zone	Clay-gravel formations that have retained the color of the original rocks.	Unevenly clastic	Massive coarse-clastic lithotuffs of yellow-green and tobacco colors	108,3–113,3	Coarse-clastic tuffogenic

*Tuffs and tuff lavas have an andesitic composition.

** In the upper part of the interval, layers of coarse-clastic tuffs (weathering crust clays on them) acquire a red coloration and a rare-nodular structure, while psammitic varieties remain unaffected by these changes. That is, actual lateritization (bauxitization) develops selectively, preferably affecting the coarse-clastic rock varieties.

Fig. 10. Multicolored Limestone.

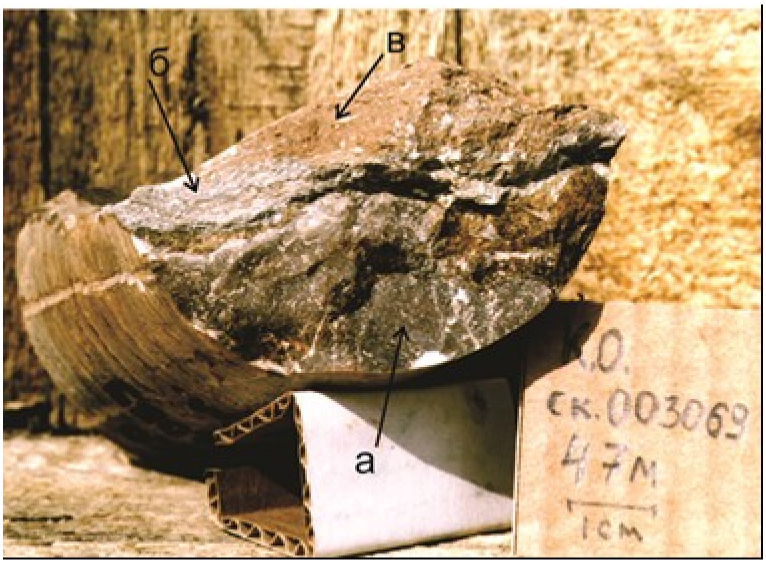

Fig. 11. Stratigraphic Contact of Limestone with Fine-Clastic Tuffs: a – limestone; b – thin basal layer containing both tuffaceous clastic material and small limestone fragments; c – fine-clastic tuffs.

Fig. 12. (a) Clastic Rocks of the Basal Layer, (b) Hard Unweathered Fine-Clastic Tuffs, (c) Clay of the Structural Weathering Crust on Fine-Clastic Tuffs. The Relict Structure Fully Corresponds to the Primary Structure in the Unweathered Fine-Clastic Tuffs (Fig. 12b). Weak Iron Enrichment: Montmorillonite Zone of the Weathering Crust, (d) Clay of the Structural Weathering Crust on Fine-Clastic Tuffs.

The Relict Structure Corresponds to That of the Underlying Crustal Clays (Fig. 12c) and the Primary Structure of the Un-weathered Fine-Clastic Tuffs (Fig. 12b). Significant Iron Enrichment: Enrichment Zone in the Weathering Crust. The presence of a basal layer suggests the subhorizontal positioning of the limestone surface at the beginning of the deposition of clastic rocks and also rules out the direct juxtaposition of these rocks against a steeply dipping limestone surface. This indicates that the rocks underwent a phase of tectonization after the deposition of clastic material onto the limestone. Accordingly, it can be inferred that the clastic rocks significantly predate peneplanation, crust formation, and karstification in the limestones (i.e., they are pre-Triassic), which excludes the accumulation of redeposited sedimentary material in karst depressions.

A steeply dipping stratigraphic contact between limestone and tuffaceous sandstones, along with the transition of the latter from a solid state into clay upwards from the contact, is also observed in borehole 003103 (Krasny Oktyabr). Notably, the clays have preserved the relict structure of the tuffaceous sandstones, which is completely identical to that of the underlying solid rocks. Unlike borehole 003069, the contact here features thin interbedding of limestone and unweathered tuffaceous sandstones, indicating the concordant deposition of the tuffaceous sandstones on the limestones of the Sokolovskaya Formation (C1v2-s sk). Thus, the variegated bauxite-bearing clays formed as a result of weathering, specifically from the rocks of the Kurzhunkul Formation – C1s kr (lateritic weathering crust).

4. Formation of Bauxites (Origin of Bauxites)

In previous studies (Yevlampyev, 1978; Ishchenko, 2005; Kalugin, 1984), lithological varieties of Cenomanian-Turonian age rocks (such as clayey bauxite, bauxitic clay, variegated dense-pisolitic clay, etc.) were classified based on petrochemical characteristics, including Al_2O_3 and Fe_2O_3 content, as well as the Al_2O_3/SiO_2 ratio. These are the parameters by which a rock can be classified as industrially viable bauxite according to GOST standards. However, these varieties do not have distinct geological boundaries.

Fig. 13. Tectonic contact along line A–B–C–D between rock bodies transformed in the weathering crust into red variegated clays (1) and white kaolinitic clays (2). The A–B–C–D fault predates the weathering crust formation process.

In our study, lithological differentiation of clayey rocks is based on petrographic characteristics, primarily color:

- White and light-colored varieties—predominantly kaolinitic.
- Red varieties—high in iron, typically exhibiting pisolitic structure.
- Dark-colored varieties—containing unweathered fragments of Paleozoic rocks.

It is widely recognized that during the laterization of rocks in the weathering crust, chemical elements migrate and accumulate in zones where they form the most stable compounds. Aluminum and iron, therefore, concentrate in areas with the highest oxidation potential, typically near the surface or in zones of increased permeability, such as faults, fractures, and lithological contacts.

In tectonic contact zones between limestone and silicate rocks, the clayey weathering crust reaches its greatest thickness (linear weathering crusts). This has been noted in nearly all, if not most, past studies of bauxite deposits in Western Turgay. The karstification of limestone at these contacts leads to the formation of voids and cavities, which enhance the permeability of zones to surface waters with high oxidation potential (elevated concentrations of oxygen, organic acids, etc.). Additionally, the chemical reaction products of karst formation may act as catalysts for the clay formation process and the coagulation of pisolites (nodules) in the clays when their component concentrations reach sufficient levels.

It is in this sense that we interpret the karstic nature of the region's bauxites, excluding the redeposition of clastic material into karst depressions. This also explains the presence of pisolitic structures in both the ore and host rocks—an unusual feature for typical lateritic bauxites. As the distance from limestone contacts increases, the thickness of the weathering crust on silicate Paleozoic rocks significantly decreases, and the enrichment zone becomes less pronounced.

However, the presence of limestone is not the sole criterion determining the distinctiveness of ochre and enrichment zones. As noted earlier, the classical sequence of weathering crust zones can be disrupted. This is likely influenced by the chemical composition of the parent rocks and their texture (porosity, uniformity, fragment size, etc.). Under equal conditions, pisolitic structures tend to form during the weathering of heterogeneously clastic tuffogenic rocks. This leads to the selective development of enrichment zones along specific layers.

For example, in borehole 0082, body 58 (Eastern Ayat), the contact between red clays formed from fine-clastic rocks and clays formed from coarser, heterogeneously clastic rocks marks the boundary of pisolite formation. A 15 cm layer of clay derived from the heterogeneously clastic rocks exhibits a pisolitic, nodular structure, while the overlying and underlying clays derived from siltstones lack nodules (Fig. 7).

Selective and irregular geochemical zonation of the weathering crust, associated with the composition of parent rocks, is also observed at the Ayat deposit. In the quarry wall, red bauxitic clays (enrichment zone) are found in direct contact with white kaolin clays (kaolinitic zone) (Fig. 13). The contact is subvertical, sharp, and linear, indicating its tectonic origin. Strong, unweathered rocks of different

Fig. 14. (a) Dark gray coarse-grained unweathered tuffaceous sandstones with a psammitic structure (left) and clayey weathering crust formations derived from them, preserving a relict psammitic structure (right), (b) Disruption of the sequence of weathering crust zone development: red clays of the enrichment zone (E.Z.) occur at a depth of 37 m, above kaolinitic clays (K) found at a depth of 38.8 m. Both the white and red clays have developed from fine-fragmented, thin-bedded rocks (tuffites, argillites).

compositions were brought into contact along a fault before peneplanation and weathering began, confirming the pre-weathering age of the fault. Over time, these rocks transformed into clays that differ both in appearance and composition, which, according to the classical scheme, belong to different zones of the weathering crust profile.

It is also important to note that aluminum and iron concentrations do not always coincide. This is evidenced by the presence of gray (low-iron) pisolitic bauxites in the kaolinitic zone, indicating that aluminum enrichment zones do not always correspond to iron enrichment zones.

Under equal conditions (monotony of the weathered sequence, isotropy of the space where weathering occurs, uniform water saturation, etc.), the classic weathering crust profile and the position of bauxites within it are maintained. However, with sharp fluctuations in these factors, the picture becomes significantly more complicated, and we sometimes encounter unpredictable behavior of the weathering crust profile, including disruptions in the sequence of zones and the appearance of bauxites "out of place." (Figs. 14a,b, 15a,b,c)

1-7 – Clays, 8 – Clay-gravel formations, 9 – Solid limestone.

Section from top to bottom:

Non-pisolitic clays:

1. Over coarse sandstones containing ash (86.0 m).
2. Over medium- to fine-grained sandstones (89.1 m).
3. Over unevenly fragmented tuffs (94.0 m).

4–5. Over psephitic tuffs (97.3 and 98.5 m, respectively).

Pisolitic clays:

6–7. Over psammito-psephitic tuffs (99.0 and 100.4 m, respectively).

Clay-gravel formations:

8. Over psephitic tuffs. Hard fragments of unweathered rocks are present (102.0 m).

Limestone:

9. Solid gray limestone with white calcite veins (103.0 m).

5. Reworking (Erosion) of the Weathering Crust and Redistribution of Material Within the Crust

In several quarries, beneath the coarse-grained glauconite-quartz sands of the Upper Cretaceous, a layered, horizontally bedded sequence composed of lignite-kaolinite clays can be observed. The Upper Cretaceous sands lie unconformably over this sequence, with a parallel discordance marked only by a thin basal horizon at the base.

This horizon, which contains pebbles of chert and, less frequently, bauxite, is discontinuous along its strike and has a thickness of up to 0.5 m. The lignite-kaolinite sequence rests with an erosional contact on the underlying bauxite-bearing formations, reaching a thickness of up to 10 m.

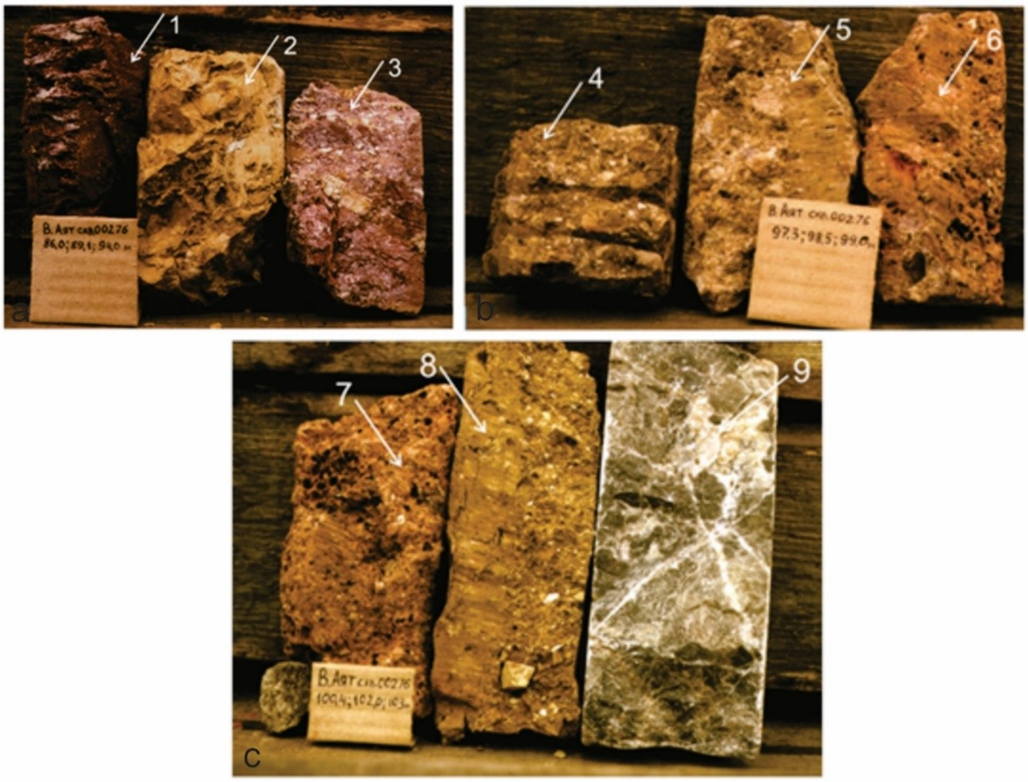

Fig. 15. (a-c) Core from borehole 00276 (Eastern Ayat) demonstrating the development of weathering crust clays over tuffogenic rocks of the tuffogenic member, which overlies limestones.

It appears that this sequence represents a reworked deposit, formed through the erosion and redeposition of an already mature weathering crust, which took place just before the development of the Late Cretaceous marine basin. This kaolinite-lignite sequence is widespread and frequently encountered in drill cores. When it lies atop primary kaolinite clays (the kaolinite zone of the weathering crust), distinguishing a boundary between them based on drill core alone is challenging. As a result, identifying it as a separate stratigraphic unit (formation) without meticulous paleontological research is virtually impossible.

During the drilling of exploration wells in bauxite-bearing formations, frequent occurrences of drill bit failures and loss of drilling fluid are observed. This indicates the heterogeneity of the clays, with the presence of voids, cavities, and decompressed zones. Caverns and voids at the contact with limestones and within the limestones are common occurrences. Often, the cavities in the limestones are filled with clayey material. Under conditions of water saturation of the clays and limestones, the cavities are filled with material from the surrounding clays. Breccia from collapses, the structures formed by the filling of the cavities, and landslide blocks with fresh slip surfaces in the clays can be found. These material movements characterize the evolution of the weathering crust and the actual processes of crust formation, although they sometimes form rocks with signs of reworking.

A characteristic example of this is the pebble-type bauxite ("pea stone") found in Eastern Aiat, body 58, well 0084, at a depth of 133.6 m. The surrounding bauxite-bearing clays retain the relic structure of tuffs and sandstones, meaning that the parent rocks indicate the conditions of their formation in the unstable geodynamic environment of volcanic belts. Among the clays, bodies of clayey and stony bauxite are found. Some areas of clayey bauxites also retain a relic tuffaceous-clastic structure.

In the stony bauxites, areas of "pea stone" bauxite are noted. Externally, the rock appears as a conglomerate of pisoliths on a film cement. (Fig. 16a) Such washing of pisoliths is possible in the calm conditions of a mature continental crust. The discrepancy between the geodynamic setting and the ideal, perfect preservation of pisoliths excludes their transport and sedimentary origin. In certain areas of the "pea stone," the inter-pisolith matrix is preserved. Its

Fig. 16. (a) Bauxite "pea gravel": A «conglomerate» of pisoliths cemented by a film or contact cement, (b) Smooth "polished" surface of the interpisolitic matrix in bauxite – a result of its leaching from the rock, (c) Filling of the interpisolitic space in bauxite with newly formed carbonate (white).

surface is smooth and wavy, which is typical for dripstone forms. This indicates dissolution and leaching of the inter-pisolith matrix during local movement of groundwater. (Fig. 16b)

In another case (Eastern Aiat, body 58, well 0032, depth 87.3 m), "washed" pisoliths are cemented by newly formed carbonates. (Fig. 16c)

The result of similar local collapses, landslides, and filling of cavities is the formation of rocks represented by pisolitic clays with fragments of stony bauxites. No relic structures were found in such rocks.

Very distinct traces of redeposition are often observed at the very roof of the bauxite-bearing ore-bearing sequence*. Here, a redeposited mixture of the bauxite-bearing sequence rocks and the overlying Late Cretaceous sands is present. Essentially, these rocks can already be classified as the basal layer of the Maastrichtian sands.

6. Structure of the Pre-weathering Paleozoic Basement and Its Relics in Bauxite-Bearing Weathering Crusts

All previous studies of the bauxite deposits in Western Turgai have noted the fold-block structure of the Paleozoic basement. This explains the presence of genetically diverse rock formations of different ages in contact with each other. During exploration and delineation at the East Ayat bauxite deposit (body 58), we encountered limestones of various ages and facies associations beneath the bauxite-bearing weathering formations. These include:

- Gray, dense, organogenic limestones (C1t2 –v)
- Multicolored, fine- to medium-grained, fully crystalline, marbleized limestones (of uncertain age)

- Black bituminous limestones with interlayers of black siltstones (D2 – D3fr)

The fact that bauxite-bearing weathered clays are underlain by limestones of different ages implies that all Paleozoic silicate rocks that were exposed to the surface during the Mesozoic (pre-Turonian) peneplain underwent weathering and bauxitization upon contact with these limestones. This includes rocks affected by hydrothermal processes, contact metamorphism, metasomatism, and faulting—zones of particular interest for mineral exploration.

A striking example of this phenomenon is the Shaimerden zinc deposit, which is associated with a volcanic vent that intrudes Upper Tournaisian limestones (Venkov, 1997). Since there was no underlying limestone to limit weathering, the silicate rocks of the vent underwent deep clay formation due to weathering processes. The weathering crust profile is well-preserved. In the upper part, within the enrichment zone, red pisolitic clays formed over the vent rocks, containing bauxite bodies. The zinc ores at Shaimerden consist of gray-green weathering crust clays and mineralized carbonate rocks, with zinc concentrations reaching several tens of percent.

The origin of zinc is undoubtedly associated with the vent system, but the high concentrations may have a secondary nature, resulting from its migration to the lower zones of the weathering crust profile. Zinc is unstable under high oxidation potential conditions. The existence of a vent system, to which the Shaimerden deposit is confined, suggests the presence of stratified extrusive comagmatic rocks of similar composition within the post-Tournaisian volcanogenic formations.

Based on this assumption, we attempted to find Shaimerden analogs among the bauxite-hosting clays and sampled saprolite-zone weathering crust clays underlying the bauxite-bearing formations in the northern part of the Krasny Oktyabr deposit. This led to the discovery of the Bozhiy Dar zinc occurrence. We chose this name not for its economic significance (which can only be determined through targeted studies) but because industrial zinc concentrations were found in the lower part of the weathering crust, beneath the bauxite zone and directly on top of the underlying limestones. This finding establishes a prospecting concept for zinc (and possibly other minerals) directly beneath bauxite ore bodies, supporting the potential for integrated mining of these deposits.

Another reason for naming the occurrence Bozhiy Dar ("God's Gift") is that during our research, clergy from three Orthodox churches and a monastery in different cities of Kazakhstan prayed for our success. Below is a brief overview of the Bozhiy Dar occurrence.

In borehole 0077 (exploration line 026+25), clays lying on limestone, including a thin (~10 cm) limestone interlayer, contain between 3.08% and 26.95% zinc, with an average content of 10.7% over 15.3 m. In neighboring boreholes (25 m apart) on the same exploration line, zinc concentrations in clays are as follows:

- Borehole 0091 (northwest of 0077) – maximum 1.09%
- Borehole 0090 (southeast of 0077) – 1.48% to 4.68% (average 2.8% over 5.2 m)

On exploration line 027+25 (borehole 0086), about 75 m northeast of borehole 0077, the maximum zinc content is 1.17%. The clays resemble those at the Shaimerden deposit, are underlain by limestone, and overlain by red-colored clays with relict unweathered tuffaceous sandstones. Thus, full-scale zinc exploration (and potentially for gold and other valuable minerals) can be conducted during bauxite exploration by deepening 30% of boreholes to the Paleozoic basement. This would increase the average borehole depth by 20–40 m beyond the standard depth used for bauxite exploration. Independently of bauxite exploration, the search for Shaimerden-type deposits in the region should focus on bauxite-bearing areas. In such locations, within local grabens or graben-synclines, the weathered volcanic rock sequence is more complete than outside these structures. We briefly mention gold, as there have been cases of its discovery in red clays at the Ayat bauxite deposit and the East Ayat deposit. In the latter, significant gold was recovered from drill core samples taken from red clays near a carbonaceous interlayer.

*[Here, the term "ore-bearing formation" does not carry a stratigraphic meaning. It refers to the complex of ores and their host rocks.]

7. Conclusion

The results of this study confirm that the bauxite deposits of the Valeryanovskaya structural-formational zone formed predominantly through *in situ* lateritic weathering of Paleozoic volcanogenic-sedimentary rocks in contact with Visean limestones, rather than through redeposition into karst depressions. Detailed petrographic analysis of relict structures within bauxite-bearing clays demonstrates that these formations represent a true weathering crust profile, in which classical lateritic zones kaolinite, hydromica, enrichment (hematite-gibbsite), and saprolite are preserved to varying degrees. The so-called "variegated clays," previously treated as separate stratigraphic units of Cenomanian–Turonian age, are better understood as the enrichment zone of this lateritic crust.

Variations in weathering profiles, selective development of pisolitic structures, and irregular zonation are explained by lithological heterogeneity, tectonic activity, and local karst processes, which enhanced permeability and promoted bauxitization but did not determine the primary mechanism of ore formation. Importantly, the comparison with the Shaimerden zinc deposit and the identification of the Bozhiy Dar zinc occurrence highlight the metallogenic significance of these weathering crusts, suggesting that bauxites may serve as exploration markers for concealed polymetallic mineralization.

Thus, the reinterpretation of Western Turgay bauxites as lateritic rather than karstic in origin not only resolves longstanding genetic debates but also broadens the prospecting framework for both bauxite and associated mineral resources in northern Kazakhstan.

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