Geological Characteristics and Prospecting Potential of Andranovato Bauxite in Madagascar

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Funding: A Project Supported by Scientific Research Fund of Hunan Provincial Education Department (22B0963).

Abstract: Madagascar is rich and underdeveloped in bauxite, the Andranovato bauxite is a laterite-type bauxite. The primary rock is aluminum-rich quartz syenite. The ore body occurs in the Neogene strata, covering the plateau, with irregular shape and mostly controlled by topography. There are four layers of red soil, bauxite, semi-weathered layer and bedrock. The ore has high quartz content and is earthen, sandy, honeycomb, nodular, bean shaped, etc., which is cemented by aluminum-bearing minerals under leaching action. The main ore minerals have been altered into bauxite, kaolinite, goethite, and hematite. The aluminum-rich protolith, hot and humid climate, favorable topographic features, good drainage system and plant desilication provide favorable conditions for the Andranovato bauxite mineralization.

Keywords: Madagascar; Bauxite; Geological Characteristics; Metallogenic Regularities

1. Introduction

Bauxite resources in more than 40 countries on five continents[1-2], according to the mineral summary released by the USGS in 2020, the world's total bauxite resources are 55~75 billion tons, of which 17.6~24 billion tons are in Africa, 12.7~17.2 billion tons are in Oceania, 11.5~15.7 billion tons are in South America and the Caribbean, 9.9~13.5 billion tons are in Asia and 3.3~4.5 billion tons are in other regions, accounting for roughly 32% in Africa, 23% in Oceania, 21% in South America and the Caribbean, 18% in Asia, and 6% in other regions [3]. The laterite type and karst type are the two basic types of bauxite, and the laterite type has the largest reserves, accounting for about 90% of the world's total reserves [4]. Central Africa is an important laterite bauxite mineralization belt, and the rich bauxite resources are mainly distributed in Guinea, Madagascar and other countries [5].

2. Regional Geological Background

Madagascar is located in the south-eastern corner of Africa, across the Mozambique Channel from the African continent. The landform is high in the middle and low in the east and west sides, which is approximately symmetrical. The western part is a gentle basin, the central part is a plain and plateau, and the eastern part is a long and narrow basin, with obvious step drop. The island's climate is clearly divided into zones, with the eastern and northern coastal areas being hot and humid all year round, with an average annual temperature of 24°C and a tropical rainforest climate; the central part of the island is mild and cool, with an average annual temperature of 18.3°C and a highland climate, with a clear distinction between the dry season and the rainy season; the western coastal and south-central areas are arid and have little rainfall, with an average annual temperature of 26.6°C and a tropical grassland climate; and the southern region is mostly semi-arid climate.

Madagascar, located on the western margin of the Rodinia supercontinent [6], is a complex block of multi-sourced, multi-component blocks, comprising in general three major systems: the Precambrian metamorphic crystalline basement, the Late Paleozoic-Early Mesozoic sedimentary cover, and the Mesozoic-Cenozoic volcanic sedimentation[7-8].The study area is located on the western side of the Tsaratanana Plateau, east of the Mahajanga Sedimentary Basin in Madagascar, and the geological and tectonic evolution in the region has gone through three major stages, namely, the Archean Cratonization, the activated orogeny within the Proterozoic-Early Paleozoic Craton, and tectonic rifting after the Late Paleozoic. The exposed strata can be broadly categorized into basement and caprock. Magmatic rocks are exposed over large areas, and large-scale magmatism occurred mainly before the Late Proterozoic. During multi-stage tectonic movement and tectonic deformation, accompanied by a large number of granite-diorite and mafic-ultramafic rocks intruded into Archean metamorphic rocks, forming the initial basement of the platform.

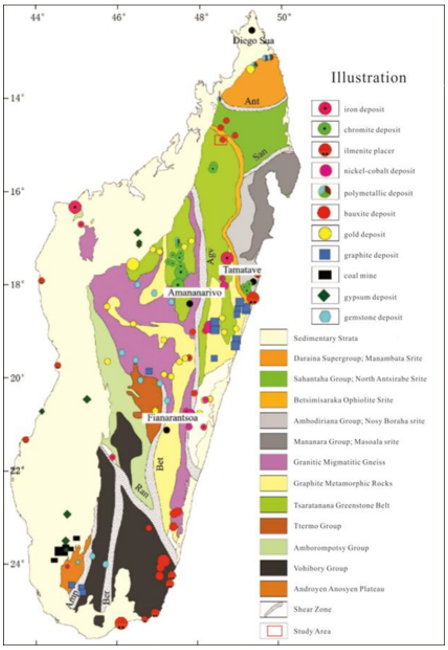

Figure 1: The distribution of the main mineral deposits in Madagascar [8].

The majority of the secondary enrichment deposits in the area are related to lateritization of the crystalline basement. Mainly including bauxite deposits in the Manantenina, Farafangana and Tampoketsa areas, and lateritic nickel deposits in the Antampombato area and near Alaotra and Valozoro.

3. Geological Characteristics of ore District

3.1 *Stratum*

The Andranovato ore district is located on the west side of the Tsaratanana Plateau, with an altitude of 1000 ~ 1500m, which is a typical plateau hilly landform. The exposed stratum is relatively simple, which can be divided into two parts: basement and caprock. The basement is Precambrian complex, mainly migmatized intermediate-acid rock; the caprock can be divided into the post-Cretaceous silica-alumina weathering crust and the Quaternary sandy soil and alluvial deposits. Due to being in a long-term uplifted state and experiencing varying degrees of weathering and erosion, and not receiving sedimentation from the Late Paleozoic to Mesozoic, the cover layer in the area is mainly composed of modern sediments from the Tertiary and Quaternary systems.

The Tertiary sediments in the mining area are widely distributed, unconformably covering the basement of the Precambrian, and are the host layers for bauxite ore. This layer is stable and continuous, and is generally produced in a layered or quasi layered manner. Its shape is strictly controlled by the terrain and base morphology in the vertical direction; Its form is mainly influenced by structural and topographical factors horizontally, and its planar form is relatively complex. Based on its differences, it can be divided into two segments:

Upper Tertiary (N): mainly composed of light reddish brown to yellowish earth like and clumpy bauxite layers, with a small amount of iron manganese nodules and quartz particles. The boundary with the underlying Tertiary strata is blurred, showing a gradual and transitional relationship.

Lower Tertiary (R): mainly composed of semi weathered rock debris layers with a small amount of clay and gravel, distributed in hills and mountainsides; In some valleys or wetland areas, there are varying degrees of semi consolidated white to light red terrestrial sedimentary sandstones directly covering the basement.

Quaternary sediments are mainly composed of modern alluvial deposits and residual slope deposits, mainly consisting of red light brown sandy soil, gravel, and loam, distributed in valleys, terraces on both sides of rivers, or flat terrain, with a thickness of 1-2 meters. According to the chronological order of its formation, it can be further divided into two sections:

Holocene (Qh): Distributed in the valleys of water systems, with a gray black humus layer and medium to high soil maturity, containing a large amount of organic matter and plant roots. In some areas, there are also accumulated large amounts of gravel and iron manganese nodules.

Pleistocene (Qp): Distributed in hills and mountainsides, mainly consisting of brown high alumina iron manganese alum clay layers. Containing spherical, nodular, and earthy bauxite, iron manganese nodules, quartz particles, etc.; There are thin semi consolidated sediments at the bottom of some valleys, containing a large amount of gravel and iron manganese nodules.

3.2 Structure and Magmatic Rock

The structure in the study area is not well-developed, mainly developing two sets of northeast and northwest trending fault structures in the southwest, causing small-scale shear and displacement of the basement complex.

The basement in the area is composed of medium to acidic mixed rock, with its composition gradually transitioning from migmatite and granite gneiss to remelted granite. The main rock type is quartz syenite, with sporadic distribution of migmatites plagioclase granite.

Quartz syenite is mostly light gray white in color, with a semi-euhedral grain structure and block structure. Striped or gneiss-like structures can be seen in local areas, and bauxite mineralization can also occur after weathering.

4. Prospecting Potential Analysis

4.1 Ore-forming Parent Rock

The ore body is produced in the weathered crust of quartz syenite rich in aluminum, containing silicon, aluminum, and iron. The initial laterite type ore body formed after weathering of aluminum rich rocks is continuous and stable layered, with a single ore body length and width of over 10 km and an area of over a hundred square kilometers. The ore body has been eroded and cut by long-term water flow, and its shape is relatively complex, showing irregular, bay shaped, serrated, short axis shaped, branched, etc. The shape of the ore body is strictly controlled by terrain and water systems. The ore body is preserved on flat hills and mountaintops, with the thickest thickness. The ore body in the water system valleys is washed and transported, presenting a "mineral free skylight".

The ore body is clearly divided vertically, and from the surface downwards, it can generally be divided into four major layers: red soil layer, bauxite layer, semi weathered layer, and bedrock layer. The description is as follows:

4.1.1 Red Soil Layer

1) Quaternary (Q) humus layer

Gray brown, black, mainly composed of clay, loam, and organic matter, containing plant roots, visible gibbsite mineral nodules, and weathered remnants of the original rock.

2) Hard shell layer

Hard shell layer also known as iron cap or hard cap, not commonly seen in the area. It is a red soil cemented with hematite, limonite, and bauxite, intermittently exposed on the surface, consisting of silicon and iron cementation, porous, worm like, and block like structures. The main mineral components include hematite and limonite, trihydrate alumina, kaolin, clay, and opal.

3) Kaoling soil red (sticky) soil layer.

There are two types of colors found in the mining area: 1. Light yellow soil yellow (dry color) and yellow deep yellow (wet color). 2. Light red red (dry color), red brown red (wet color). Mainly composed of particle scale like and mud soil like structures; Soil like, powder like, and mud like structures. The main mineral components are kaolinite, quartz, trihydrate alumina, goethite, clay minerals, and carbonaceous materials. Locally visible nodules or remnants of the original rock.

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4.1.2 Bauxite Layer

There are 5 layers in the standard, but the bauxite in this mining area often lacks 1 to several layers.

1) Porous gibbsite bauxite: Hard texture with well-developed pores, presenting reddish brown, dark red, and mottled colors. The ore texture has cementation, mud crystal-microcrystal and clastic texture, and the ore structure is pisolitic (oolitic), brecciated and honeycomb or porous, with cementitious material of silicon and iron.

2) Yellow to light yellow soil gibbsite bauxite: The ore is extremely uneven composition and is loose and fragile. The ore has cementation, mud crystal-microcrystal and clastic texture, soil or semi-soil, brecciated structure. Quartz (or opal) as a heteromorphic crystal, embedded in a collection

of soil gibbsite bauxite with a particle size of 1-n mm. The visible black carbon (particles ≤ 1 mm) is also unevenly distributed. Breccia or clumps are mainly composed of mineral nodules of trihydrate alumina or weathered remnants of the original rock. Main mineral components: gibbsite, clay minerals (kaolinite), iron minerals (goethite, limonite), quartz, white (water) mica.

3) Purple red and deep red soil gibbsite bauxite: The ore is similar to fine sandstone, has soil texture, soil and block structure, and occasional layered structure. Quartz (or opal) as a heteromorphic crystal, embedded in a collection of soil gibbsite bauxite with a particle size of 1-n mm. The visible black carbon (particles ≤ 1 mm) is also unevenly distributed. Main mineral components: gibbsite, clay minerals (kaolinite), iron minerals (goethite, hematite), quartz, white (water) mica. This type of ore has high grade and good quality, and can be distinguished by the naked eye.

4) Light red to light yellow soil gibbsite bauxite: The ore has cementation, mud crystal-microcrystal and clastic texture, soil or semi-soil, massive structure. The composition of the ore is extremely uneven. This layer shows the presence of trihydrate alumina mineral ooids and bean shaped nodules, with occasional weathered remnants of the original rock. Main mineral components: trihydrate alumina, quartz, kaolinite, white (water) mica, with small amounts of limonite and goethite.

5) Variegated color soil gibbsite bauxite: The ore has subhedral-euhedral, cementation, mud crystal-microcrystal texture, rare pisolitic (oolitic)texture, soil or semi-soil, structure. This layer shows remnants of the original rock or quartz clusters.

4.1.3 Semi Weathered Layer (Also Known as Humus Layer)

Mottled, in the form of mud or soil, with original rock fragments and gravel mixed in. Quartz particles can be seen locally, while plagioclase has partially weathered into kaolin, distributed in clusters or stars. The main minerals include gibbsite, quartz, kaolinite, hematite, and limonite, secondary minerals include montmorillonite, ilmenite, mica, etc.

4.1.4 Bedrock Layer

The lithology is quartz syenite, with a weathered surface that is light brown or grayish white. The fresh surface is mostly light flesh red with a hint of grayish white. It has a medium to coarse grained porphyritic structure and blocklike structure, with occasional bandlike structures in some areas. The mineral composition is mainly alkaline feldspar and quartz, with a small amount of dark minerals such as biotite, which can be further divided into lithology.

4.2 Ore Characteristics

The ores in the area are mostly brownish red, some of which are grayish yellow, grayish white and variegated. They often have residual structures such as sand, soil, bean and oolitic, and stomatal, spotted and honeycomb structures. According to the main natural types and characteristics of the ore, it can be divided into the following five categories:

1) Light reddish brown soil ore: It is widely distributed in the area, and the texture is loose and easy to break. The diameter of the block is one to dozens of cm, and there are many stomatal structures with a pore size of 0.5 ~ 2 mm.

2) Brownish yellow sandy ore: It is often produced in the residual ore layer at the top of the hill, or located in the lower part of the light reddish brown soil ore. The structure is scattered, and the block diameter is one to more than ten cm. It has many stomatal structures with a pore size of 0.5-2

mm. The hardness is slightly larger than that of the soil ore, and the residual fine-grained porphyritic texture of the quartz syenite can be seen locally.

3) Pale red-brownish yellow porphyritic (honeycomb) ore: mostly exposed to the surface, distributed on coarse-grained quartz syenite, with a pore diameter of several millimeters and a large size of nearly 1 cm. There is no filling in the circular hole, and some of the hole wall has a yellow film, and limonite and illite particles can be seen with the naked eye.

4) Dense massive ore, brownish yellow, brownish red, grayish yellow, irregular mass, denser, similar to hard clay, with tiny holes, blocks of centimeters, slightly higher hardness.

5) The brown-red and white spotted ore, with round pores and a pore diameter of 1 ~ 2 mm, often coexists with light red-brown earthy ore.

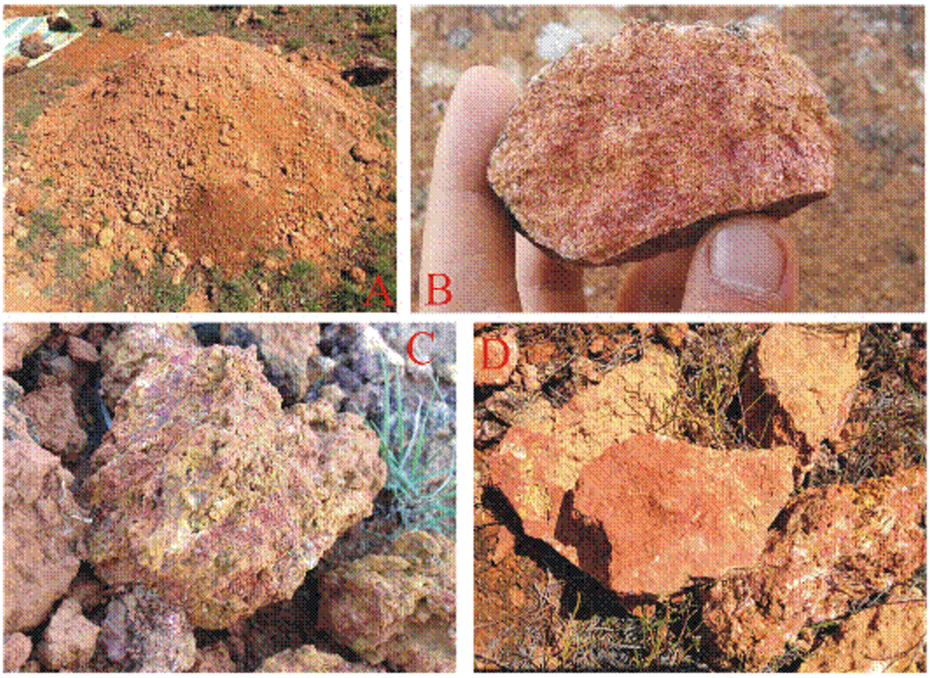

Figure 3: Andranovato bauxite ore photos: A. Reddish brown earthy bauxite ore; B. Sandy bauxite ore; C. Bauxite ore with stomatal structure; D. Dense massive bauxite ore

4.3 Mineral Characteristics

Bauxite in the area is the product of strong weathering and alteration of quartz feldspar, most of the protolith composition and structural structure can not be recognized, and only quartz, clay, and a small amount of iron and opaque minerals can be seen with the naked eye. Most of the minerals have been altered to gibbsite, kaolinite, etc. under the microscope, and the outlines of the minerals are no longer distinguishable. Kaolinite is a microscopic scale-like texture aggregates, mostly clumped, striated distribution, from the protolith feldspar alteration, the alteration process has a small amount of limonite precipitation of fine-grained, can be seen in the original mineral contours, locally visible better crystallization of flake kaolinite. Gibbsite is in the form of microscopic scales, fine streaks, etc., dispersed among the kaolinite minerals with a uniform distribution. Limonite is mostly precipitated in parallel short fine lines. It is speculated that dark minerals may be precipitated along cleavage, and the original dark minerals may be mostly biotite. Some are in the shape of other particles, with a particle size of 0.2-1 mm and star distribution, which may be transformed from iron-containing metal minerals.

4.4 Chemical and Mineralogical Composition of Ores

The statistical analysis of the shallow well (borehole) samples in the study area shows that the proportion of shallow wells (boreholes) that meet the requirements of bauxite is 77.44% [9].Beneficiation test and Bayer alumina dissolution test (Table 1) showed that the average content of effective alumina in the ore was 44.41% .The content of active silicon is low, only 2.83% on average.The average effective Al/Si ratio is 15.69.The average content of gibbsite is 67.62 %.Quartz (inert silicon, not involved in the Bayer dissolution reaction) content is higher, with an average of 15.86%.The content of boehmite is low, with an average of 0.13%.The dissolution rate of alumina is 92.92%, and the alkali content of the dissolved red mud is not high, only 5%. The results of phase composition of 2 ~ 5 mm bauxite block ore showed that the average content of gibbsite is 67.54%, the content of hematite is 2.49%, the content of aluminum goethite is 5.19%, the content of kaolinite is 6.52% (one of them is 50.6%), the content of quartz is 15.86%, and the content of diaspore is 0.13% [10].

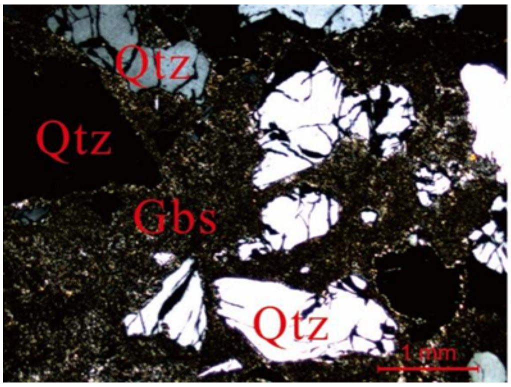

Figure 3(a): Microphotographs of bauxite ore. Gibbsite dispersed between quartz particles (+).

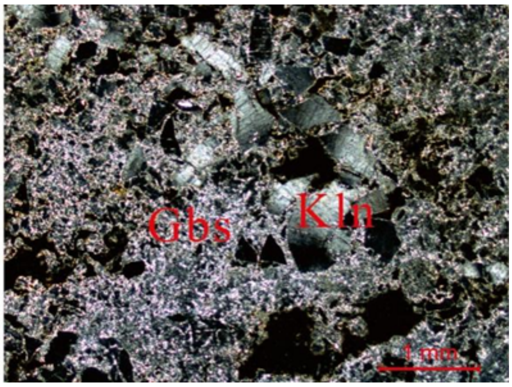

Figure 3(b): Microphotographs of bauxite ore. Gibbsite dispersed between kaolinite (+).

Qtz: Quartz; Gbs: Gibbsite; Kln: Kaolinite

Table 1: Main Chemical Composition of Bauxite Ore Obtained from Different Enterprise.

Enterprise	Total Al_2O_3	Effective Al_2O_3	Total SiO_2	Active SiO_2	A/S	Fe_2O_3	Number of samples
Aluminum Corporation of France		39.87		5.29	10.79		800 pieces (6-10 sieve)
ALS Guangzhou Company		45		2.66	16.92	7.31	20 pieces (unscreened)
China Aluminum (Shandong)		44.41	15.86	2.83	15.69	15.69	13 pieces (unscreened
Inner Mongolia Geological Prospecting Third Company	30.24						72 pieces (unscreened)
Sichuan Provincial Bureau of Geology and Mineral Resources	31.33		35.00				11 pieces (unscreened)

Content unit: %, screening degree unit: mm, content values are average.

5. Prospecting Potential Analysis

5.1 Ore-forming Parent Rocks

The formation of laterite bauxite is more strictly controlled by the parent rock. Most of the world's laterite bauxite raw rocks are mafic rocks, because of its low SiO_2 content, easy to form high quality bauxite with high Al/Si ratio. Ore-forming parent rocks in the area are aluminum-rich neutral rocks with high porosity, strong permeability, poor surface stability of plagioclase feldspar and other minerals, and high alumina content, the parent rock formed bauxite after a long period of weathering, and desiliconized aluminum-rich action. However, the quartz anorthosite has a high SiO_2 content, and the desilication is difficult to be thorough, so it is unfavorable to the further enrichment of Al. As a result, the bauxite produced in the ore district is mostly characterized by fine quartz particles, and the Al content of the ore in the study area is medium and the Si content is high compared with that of the ideal laterite-type bauxite.

Bauxite ore bodies in the study area are produced in the upper silica-alumina-iron weathering crust of quartz anorthosite, mostly located at the top of the mountain or the upper part of slopes with moderate gradient, and the ore bodies in the ravines are of poor quality or without ore. Therefore, the bottom plate of the ore body is quartz orthoclase, which is the mother rock of bauxite; the surface of hills and slopes with small gradient is mostly covered with sandy soil and gravelly soil of the fourth system, and the soil is mostly brownish-red in color due to the high iron content in local sections, which is typical of red soil.1-3 m thick.

According to the analysis of the existing shallow boreholl test data and field observation, the bauxite layer in the area has clear boundaries with the overlying laterite layer (ferromanganese alumina layer) and vague boundaries with the underlying semi-weathered rock layer, and the ore body is distributed continuously between the laterite layer and the semi-weathered bedrock layer, with few intercalations. Horizontally, the ore body is relatively continuous, but there are unweathered boulder and bedrock exposed locally.

5.2 Climatic Conditions

The mining area has a tropical grassland climate, with an average annual temperature of 24~32°C. The dry and rainy seasons are distinct, and the annual precipitation is >3000 mm, which is concentrated in January—March of the rainy season. Strong sunshine and large temperature differences between day and night during the dry season favor the physical weathering of the protolith. The abundant precipitation and hot and humid climate during the rainy season contribute to the chemical and biological weathering of rocks, prompting the decomposition of aluminosilicates in the protolith, the soluble alkali and alkaline-earth metals as well as SiO_2 to dissolve in alkaline solutions and be taken away, and the hydration of Al_2O_3 and Fe_2O_3 to form insoluble hydroxides that accumulate in the weathered crust.

5.3 Topographic and Geomorphic Conditions

Drainage and topographic conditions are also very important controlling factors in the formation of lateritic bauxites [11]. Only under the topographic and geomorphic conditions consisting of rocks with low elevation differences, good drainage conditions and high permeability, it is possible to form high grade gibbsitic bauxite [12]. Sadleir and Gilkes and Loughnan and Sadleir have both emphasized the need for good drainage systems for bauxite mineralization to reduce the residence time of

SiO_2-containing solutions [13]. The overall topography of the mine site is not undulating and the slope is generally gentle. The weathered crust of the rocks is located above the submerged surface, and the pattern of gullies and some natural landslides and gullies form a better drainage system, which is conducive to the high rainfall during the rainy season for the drainage of desilication and precipitation enrichment of aluminum-containing minerals. The laterite-type bauxite in the district is mainly distributed on the hilltops and slopes with a topographic height of over 1100 m and relatively large cuts, and the greater the difference in height between the slopes of the low hills where the ore bodies are located, the better the water permeability and the higher the mineralization rate. On hilltops and hills are mostly residual types with little vertical variation. In the hillside, especially near the water system for the slope, floodplain type, its vertical upward change is large, generally with multiple layers. The topographic and geomorphic features of the mining area are conducive to the downward infiltration and drainage of surface water, leaching of alkali metals and alkaline earth metals that are easily soluble in water, and the hydration of Al_2O_3 and Fe_2O_3, which are difficult to be soluble in water, to form gibbsite and hematite and limonite residual deposits or piles up in the weathered crust on the surface to form the ore body.

Based on the study of remote sensing quantitative mineral search of surface laterite-type bauxite in the region, Cheng gong et al. realized remote sensing quantitative inversion of surface bauxite by using remote sensing data and an appropriate amount of ground sampling and analytical data, which can accurately and quickly determine the center of mineralization anomalies, and provide an important basis for the next step of mineral exploration.

6. Conclusion

(i) Andranovato bauxite mine in Madagascar is a laterite-type (gibbsitic) bauxite, which is produced on top of aluminum-rich quartz anorthosite, and is endowed with the upper Tertiary strata (silica-aluminum-iron weathering crust). The initial ore body of laterite type formed after the weathering of rocks is in the form of continuous and stable layers with obvious layering structure from the surface downwards, i.e., four layers, namely, laterite layer, bauxite layer, semi-weathered layer and bedrock.

(ii) The main natural types and characteristics of ores can be categorized into earthy ores, sandy ores, porous (honeycomb) ores, dense massive ores and speckled ores. The ore minerals are mainly gibbsite and kaolinite, and kaolinite is a microscopic squamous mass aggregate, which is mostly distributed in clusters and streaks.

(iii) Bauxite block gibbsite alumina average content of 67.54%, the average effective alumina content of 44.41%, alumina dissolution rate of 92.92%, low alkali content of dissolved red mud, it is easy to select, low reactive silica, low impurity, higher effective alumina-silica ratio, easy to smelting, and the effective content of the ingredients of the high-quality trihydrate-type bauxite.

(iv) The distinct dry and rainy seasons and good topography and drainage system in the mining area, coupled with the biological weathering of plants and the removal of iron and desiliconization, are conducive to the leaching and migration of easily soluble elements such as Fe, Si, etc., during the weathering process of quartz anorthosite, so that difficult-to-soluble aluminium-containing minerals will be gradually enriched in situ, and ultimately become minerals.

(v) Based on the topography and geomorphology, surface vegetation and the degree of development of ferroaluminous weathering crusts, combined with the quantitative inversion of surface bauxite remote sensing, it can provide markers for finding minerals.

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