

Research Article

Comparative Mineralogical and Chemical Characterization of Kombelcha and Bombowha Kaolin Deposits, Ethiopia

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Abstract

The investigation into the mineralogical and chemical properties of Ethiopian kaolin deposits is essential for transitioning the national manufacturing sector from a reliance on imported raw materials to domestic resource utilization. This study provides an exhaustive comparative characterization of the Kombelcha and Bombowha kaolin deposits, representing two distinct geological and environmental origins. Analytical techniques, including X-ray Diffraction (XRD), Differential Thermal Analysis (DTA), Scanning Electron Microscopy (SEM), and wet chemical analysis, were employed to delineate the characteristics of the raw materials and their behavior during high-temperature treatment. Kaolinite is the primary mineral phase in both deposits, yet the Bombowha occurrence is uniquely distinguished by the presence of halloysite and gibbsite, which are absent in Kombelcha. Chemically, the Bombowha kaolin exhibits higher purity, with Al_2O_3 content exceeding 35% and total iron and alkali impurities below 3%. In contrast, the Kombelcha kaolin averages 32% Al_2O_3 with significantly higher Fe_2O_3 (2.75%) and total alkalis (1.50%). Firing tests reveal that the Kombelcha deposit vitrifies at 1150°C, whereas the Bombowha deposit maintains refractoriness up to 1250°C. The study further evaluates the efficacy of kyanite additions (5–15%) in controlling firing shrinkage. Genetic evidence suggests that Kombelcha is a product of in-situ weathering of granite, while Bombowha originates from a complex interplay of hydrothermal alteration and subsequent weathering of pegmatitic and granitic dikes. These findings provide a scientific framework for the industrial application of these clays in ceramics, refractories, and paper manufacturing.

Keywords

Kaolin, Mineralogical Characterization, Mullite, Refractoriness, Kyanite, Hydrothermal Alteration

1. Introduction

The strategic assessment of industrial mineral resources is a critical component of national economic planning, particularly for developing nations seeking to reduce trade deficits and promote industrial self-sufficiency. In Ethiopia, the Ethiopian Institute of Geological Survey, established as a major entity for

mineral evaluation, has identified significant potential in non-metallic minerals, including gold, rare earths, tantalum columbite, and industrial clays such as kaolin, bentonite, and diatomite. Kaolin, colloquially known as china clay, is an exceptionally versatile industrial mineral primarily composed of the hydrous alu-

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minum silicate mineral kaolinite, defined by the chemical formula $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$. Its utility spans multiple industries, including ceramics, paper, paint, plastics, rubber, and pharmaceuticals, owing to its chemical inertness, high whiteness, and specific rheological properties [1].

Historically, Ethiopian manufacturing industries have depended on expensive imported raw materials for ceramic and paper production. The discovery and systematic evaluation of local deposits, such as those at Kombelcha and Bombowha, offer a pathway toward import substitution. The global kaolin market, which saw a production of approximately 25.7 million tons as early as 1988, is dominated by nations such as the United States, England, Brazil, and Australia, who export highly refined paper-coating grades. [2] For Ethiopia to enter this competitive landscape or even to satisfy internal demand, a nuanced understanding of the mineralogical and chemical nature of its domestic resources is required. [3].

This research focuses on two significant Ethiopian kaolin deposits: Kombelcha, located in the north, and Bombowha, situated in the south. The Bombowha deposit, identified in the early 1980s during infrastructure development, has been recognized as a high-quality material for the ceramic industry. [1, 4] Conversely, the Kombelcha deposit, while economically viable, presents challenges due to higher concentrations of iron and alkali oxides, which necessitate specific beneficiation strategies to improve brightness and firing performance. By conducting a side-by-side comparative characterization, this study elucidates the differences in mineralogy, chemistry, and technological behavior that result from their diverse environmental and geological origins.

1.1. Geologic and Tectonic Setting

The geological framework of Ethiopia is characterized by a complex history of Precambrian basement deformation, Mesozoic sedimentation, and Cenozoic volcanism associated with the formation of the East African Rift System (EARS). The kaolin deposits investigated in this study are primarily hosted within the older crystalline basement and its associated intrusive bodies. [4].

1.2. Kombelcha Geological Context

The Kombelcha area is underlain by the oldest rock units in Ethiopia, comprising the Precambrian basement. These lithologies include granite, granitic gneiss, and various gneissic rocks. The basement is unconformably overlain by Mesozoic sedimentary sequences, specifically the Adigrat sandstone and Hammaneli limestone, which are found in the peripheral parts of the district. The entire sequence was later intruded by basaltic flows. [4].

The kaolin in Kombelcha occurs as extensive blankets or mantles overlying the parent granite bodies. The intensity of kaolinization is non-uniform and is influenced by the structural, textural, and morphological characteristics of the host

rock. Intensive alteration is most prominent along the flanks of deeply dissected gullies, where groundwater flow and chemical leaching are maximized. The field evidence, supported by the gradual transition from fresh rock to clay, indicates that the Kombelcha kaolinite is a product of in-situ (residual) weathering of the granite. [4-6].

1.3. Bombowha Geological Context

The Bombowha kaolin deposit is hosted by kaolinized pegmatites and granitic dikes that intrude a sequence of deformed Precambrian amphibole schists and granites. These pegmatites exhibit diverse and irregular forms, penetrating the host metamorphic rocks in complex patterns. The distribution of these bodies often correlates with the prominent joint systems of the area, with some pegmatites following systematic jointings while others are related to non-systematic fractures. [7, 8].

Unlike the blanket-like deposits of Kombelcha, the Bombowha kaolin exhibits features that suggest a dual origin. Field evidence and mineralogical suites indicate that the deposit formed through both hydrothermal alteration where hot fluids circulated through the pegmatitic dikes and subsequent in-situ weathering under tropical conditions. This complex genesis has resulted in a deposit of high chemical purity and unique mineralogical characteristics, including the presence of halloysite and gibbsite, which are typical indicators of advanced leaching and specific hydration states. [9].

2. Materials and Analytical Methodology

A rigorous experimental protocol was followed to ensure the accuracy and comparability of the mineralogical and chemical data.

2.1. Sample Preparation and Mineralogical Analysis

Samples were collected from various pits and depth intervals in both the Kombelcha and Bombowha regions. For mineralogical identification, clay fractions of less than $63\ \mu\text{m}$ were separated through sedimentation. X-ray Diffraction (XRD) was performed using a Phillips Diffractometer with Ni-filtered $\text{Cu K}\alpha$ radiation at a scanning rate of 1° per minute within the range of 5° to $45^\circ 2\theta$. Oriented and random powder mounts were used to identify the primary clay minerals and subordinate phases. Crystallinity indices were calculated following Hinckley's method to assess the structural ordering of the kaolinite. [10, 11].

Differential Thermal Analysis (DTA) was conducted on the sub- $63\ \mu\text{m}$ fraction using a heating rate of 10°C per minute under static atmospheric conditions, with $\alpha\text{-Al}_2\text{O}_3$ as the reference material. This technique provided critical information regarding dehydroxylation temperatures and phase transformations. Morphological and textural studies were performed

using Scanning Electron Microscopy (SEM) at magnifications ranging from 2000 to 10,000 times on the sub-20 μm fraction to observe crystal habits such as "books" or "tubes" [11].

2.2. Chemical and Physical Testing Protocols

The bulk chemical composition of the kaolin was determined using standard chemical analysis methods to quantify major oxides, including SiO_2 , Al_2O_3 , Fe_2O_3 , CaO , MgO , Na_2O , K_2O , TiO_2 , and P_2O_5 , along with Loss on Ignition (LOI). Firing properties were evaluated in accordance with the Indian Standard for testing refractory materials (IS: 1528). [11] Test specimens were prepared at a molding pressure of 25 MPa and fired in the temperature range of 950°C to 1250°C with a one-hour soaking time. Parameters measured included linear thermal shrinkage, apparent porosity, bulk density, and brightness (reflectance).

The influence of kyanite as an additive was also examined. Kyanite was added in proportions of 5%, 10%, and 15% to evaluate its effectiveness in offsetting the shrinkage of the kaolinitic body at 1250°C. The newly formed high-temperature phases were subsequently analyzed by XRD to determine the extent of mullite formation [10].

3. Mineralogical Characterization Results

The mineralogical analysis reveals significant commonalities and striking differences between the two Ethiopian deposits, reflecting their distinct geological histories.

3.1. XRD and Crystallinity Comparisons

Kaolinite is identified as the predominant mineral in both the Kombelcha and Bombowha deposits, characterized by strong basal reflections at 7.16 Å and 3.58 Å. In both areas, trace to subordinate amounts of illite/muscovite, feldspar (both plagioclase and K-feldspar), and quartz are present. However, the Bombowha deposit is uniquely characterized by the presence of gibbsite ($\text{Al}(\text{OH})_3$) and halloysite. [4].

Gibbsite formation in Bombowha is attributed to the warm and humid climate and intensive leaching environment, which favors the removal of silica and the concentration of aluminum hydroxides. It is more frequently encountered in the stratigraphically higher horizons of the deposit. Halloysite, with its characteristic tubular morphology, appears more selective to the pegmatitic parental material at Bombowha. [4, 7].

Table 1. Comparison of Kombelcha and Bombowha deposits based on XRD.

Mineralogical Phase	Kombelcha Content (%)	Bombowha Content (%)
Kaolinite	75 - 85	85 - 90
Halloysite	Absent	2 - 5
Gibbsite	Absent	1 - 3
Illite / Muscovite	5 - 10	2 - 4
Plagioclase	2 – 5	1 - 3
K-Feldspar	1 – 3	1 - 2
Quartz	2 – 5	1 - 3
Others	< 5	< 1

Crystallinity index values show that both deposits possess moderate to high structural ordering. However, in both Kombelcha and Bombowha, the structural ordering of kaolinite tends to decrease as the grain size decreases. This suggests that the finer particles may have undergone more intensive mechanical or chemical degradation during the weathering process. [10].

3.2. Thermal Analysis (DTA) and Textural SEM Observations

The DTA curves for both deposits exhibit a characteristic

endothermic peak at approximately 587°C, corresponding to the dehydroxylation of kaolinite into amorphous metakaolinite. The peaks for Bombowha samples are nearly symmetrical, indicating better crystallinity compared to typical sedimentary kaolins. An exothermic peak at 950°C signals the transformation of metakaolinite into a spinel phase or mullite nuclei. Bombowha samples specifically show a sharp endothermic peak at 95°C, likely due to hygroscopic water or allophane, and a small endothermic peak at 320°C, confirming the presence of gibbsite. [13].

SEM imaging provides visual confirmation of these miner-

alogical findings. The Kombelcha kaolin consists of well-preserved, expanded "books" of kaolinite, with book lengths reaching 15 μm and individual flakes ranging from 1 to 3 μm . Pitted surfaces on subordinate feldspar crystals in Kombelcha indicate a state of partial alteration. In contrast, the Bombowha morphology is dominated by elongate tubes and books. The halloysites at Bombowha are up to 4–5 μm in length and 0.25 μm in diameter, exhibiting a tabular to tubular shape with a length-to-width ratio of approximately 20:1 [7, 8].

3.3. Geochemical Characterization Results

The bulk chemical composition is the primary determinant of the industrial grade of kaolin. The comparative data highlights the high-purity nature of the Bombowha deposit compared to the more impurity-rich Kombelcha deposit [1].

3.3.1. Major Oxide Analysis

Chemical analysis indicates that alumina (Al_2O_3) content is significantly higher in the Bombowha kaolin, generally exceeding 35%. The primary impurities iron oxide, titanium oxide, and total alkalis account for less than 3% in Bombowha. This low iron content ($\text{Fe}_2\text{O}_3 < 1\%$) is critical for maintaining high brightness and whiteness in ceramic and paper applications. [1, 4].

In contrast, the Kombelcha kaolin contains a lower average alumina content of approximately 32%, with significantly higher iron (average 2.75%) and total alkali (average 1.50%) concentrations. These elevated impurity levels suggest that the Kombelcha material would require more intensive beneficiation to achieve the quality required for fine ceramics [4].

Table 2. Chemical oxides analysis of Kombelcha and Bombowha deposits.

Chemical Component	Bombowha (Typical Range%)	Kombelcha (Typical Range%)
SiO_2	43.10 - 46.61	47.30 - 48.50
Al_2O_3	35.35 - 37.58	31.90 - 34.30
Fe_2O_3	0.29 - 0.54	1.94 - 3.29
CaO	0.02	0.40 - 0.90
MgO	0.05 - 0.06	0.20 - 0.40
Na_2O	0.44 - 1.39	0.20 - 1.60
K_2O	0.53 - 1.68	1.10 - 1.90
TiO_2	< 0.01	0.57 - 0.74
LOI	12.73 - 14.57	11.20 - 12.50

3.3.2. Variation with Depth

A distinct geochemical trend is observed in the Kombelcha deposit regarding depth. There is a gradual increase in both total alkali and iron content with increasing depth. This corresponds to a decrease in the percentage of the finer clay fractions in deeper horizons. The potassium oxide (K_2O) content, ranging between 1% and 2%, is a useful indicator of the degree of alteration of primary alumino-silicate minerals; these values suggest that alteration in the deeper parts of the Kombelcha deposit is incomplete. In Bombowha, the alumina content remains relatively high throughout the sampled intervals, further supporting the idea of a high-grade, intensively altered resource. [7, 12].

3.3.3. Technological and Fired Properties

The behavior of kaolin during firing determines its suitability

for the ceramic and refractory industries. This study identifies critical differences in the vitrification behavior and mechanical strength of the two deposits.

3.3.4. Shrinkage, Porosity, and Vitrification

The presence of fluxes such as iron and alkalis significantly influences the firing characteristics. Kombelcha kaolin shows high shrinkage and low porosity at lower temperatures compared to Bombowha. Specifically, a sharp increase in porosity and a decrease in bulk density for certain Kombelcha samples at 1150°C suggest the onset of vitrification, where pore spaces expand due to the formation of a glassy phase. [8].

Bombowha kaolin, however, remains highly refractory up to 1250°C. The slight increase in porosity and decrease in bulk density observed between 950°C and 1050°C in Bombowha samples are attributed to structural adjustments during the transformation of metakaolinite to gamma-alumina, rather than premature melting. [12].

3.3.5. Brightness and Reflectance

The brightness values of both deposits improve with increasing temperature, but the effect is more pronounced for the Kombelcha kaolin. Initial brightness is much higher for Bombowha due to its lower iron content (Fe_2O_3). For the Kombelcha samples, the higher initial iron and titanium concentrations limit the brightness of the raw clay, making it less suitable for high-end paper coating without bleaching or magnetic separation. [14].

3.4. Mechanical Strength and Phase Transformations

The modulus of rupture (MOR) increases significantly at 1250°C for both deposits, corresponding to the formation of high-temperature crystalline phases. XRD analysis of fired samples indicates that mullite ($3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$) begins to form at 1150°C. At 1250°C, mullite is the dominant mineral phase for the Bombowha kaolin, with subordinate amounts of cristobalite and glassy phases. [15].

Kombelcha kaolin also develops comparable amounts of mullite but contains a higher proportion of cristobalite. This is due to the higher excess silica in the Kombelcha parent material. Cristobalite formation is significant as it can influence the thermal expansion and mechanical stability of the fired ceramic body.

3.4.1. Effect of Kyanite Additions on Firing Properties

Kyanite (Al_2SiO_5) is often added to ceramic bodies to control shrinkage and enhance refractoriness. This study analyzed the addition of kyanite in proportions of 5% to 15% at 1250°C.

3.4.2. Linear Firing Shrinkage and Specific Gravity

The addition of small amounts of kyanite resulted in a gradual decrease in linear firing shrinkage, with the minimum shrinkage values corresponding to the highest kyanite concentration (15%). This confirms that kyanite effectively offsets the shrinkage of the kaolinitic body, likely due to the volume expansion associated with kyanite's transformation to mullite and silica.

The specific gravity values of the samples also increased with kyanite addition. Samples containing the higher proportion of kyanite and cristobalite exhibited the highest specific gravity. However, XRD analysis showed that at 1250°C with a one-hour soaking time, the transformation of kyanite to mullite was not entirely complete, suggesting that higher temperatures or longer soaking times might be required for full conversion. [16].

Table 3. Linear firing shrinkage analysis.

Kyanite Addition (%)	Linear Firing Shrinkage (%)	Main Fired Phases (XRD)
0	9.0 - 11.5	Mullite, Cristobalite, Glass
5	8.2	Mullite, Residual Kyanite
10	7.5	Mullite, Residual Kyanite
15	6.8	Mullite, Residual Kyanite

4. Discussion on Genesis and Formation Mechanisms

The distinct properties of the Kombelcha and Bombowha deposits are inherently linked to their genetic origins and the specific environmental conditions during their formation.

4.1. In-Situ Weathering of Granite (Kombelcha)

The Kombelcha deposit is a classic example of residual kaolin formed through the in-situ weathering of granitic basement rocks. The hydrolysis of feldspars and micas under acidic groundwater conditions led to the depletion of mobile cations and the concentration of alumina as kaolinite. The

depth profiles showing increased alkali and decreased clay content support this supergene weathering model. [17] The relatively high iron and alkali content at Kombelcha is inherited from the parent granite, which contains more ferromagnesian minerals and residual primary feldspars compared to the Bombowha parent rocks.

4.2. Hydrothermal and Weathering Hybrid (Bombowha)

The Bombowha deposit exhibits a more complex genesis. The hosting within pegmatite dikes and the alignment with joint systems suggest that initial kaolinization was triggered by hydrothermal fluids. Hydrothermal alteration often results in high-purity kaolin deposits because the fluids can be highly selective and carry fewer impurities than surface weathering

agents. [18].

Subsequently, these hydrothermal products were subjected to intensive surface weathering. The presence of gibbsite and halloysite indicates a highly leached, warm, and humid environment typical of tropical weathering. [1] This dual-stage process hydrothermal "pre-conditioning" followed by intensive weathering explains the high alumina content (>35%) and the low level of impurities found at Bombowha, as the pegmatitic parent rock was already naturally low in iron and titanium.

4.3. Industrial Implications and Future Outlook

The findings of this research have significant implications for the development of the Ethiopian mineral industry.

4.3.1. Suitability for Ceramic and Refractory Applications

The high refractoriness and purity of the Bombowha kaolin make it an ideal candidate for fine ceramics, including bone china and high-voltage porcelain insulators. [19] Its ability to remain stable up to 1250°C without excessive glass formation allows for the production of high-strength, dimensionally stable ceramic components.

Kombelcha kaolin, while less pure, is well-suited for heavy clay products such as floor and wall tiles, sanitaryware, and bricks. Its lower vitrification temperature (1150°C) can lead to energy savings during the firing process for industries that do not require the high refractoriness of fine porcelain. However, to be used in high-grade applications, Kombelcha kaolin would require beneficiation to remove iron and improve brightness [20].

4.3.2. Comparison with Other Ethiopian Deposits

When compared to other Ethiopian deposits, such as Alemtena (weathered volcanic tuffs) or Bensa (weathered rhyolitic ignimbrite), the Kombelcha and Bombowha deposits are notable for their association with the Precambrian basement. [21] Deposits formed from volcanic precursors often have higher silica-to-alumina ratios and different impurity suites (e.g., higher TiO_2 or P_2O_5) compared to those formed from granites and pegmatites. [22] This diversity in Ethiopian kaolin sources provides a broad spectrum of raw materials that can be blended or selected for specific industrial needs. [23].

5. Conclusion and Recommendations

5.1. Conclusion

The comparative mineralogical and chemical characterization of the Kombelcha and Bombowha kaolin deposits highlights the critical role of geological provenance and alteration mechanisms in determining the industrial utility of clay minerals. Kaolinite is the dominant phase in both, but the Bom-

bowha deposit is superior in terms of alumina content and purity, enriched with halloysite and gibbsite due to a complex hydrothermal and intensive weathering history. Kombelcha, a residual granite-weathering product, provides a massive resource characterized by higher iron and alkali content, making it suitable for vitrified ceramic products.

The firing behavior further differentiates the two: Kombelcha vitrifies early at 1150°C, while Bombowha remains refractory at 1250°C. The addition of kyanite serves as an effective strategy for controlling firing shrinkage, particularly in the more flux-rich materials. These results confirm that Ethiopia possesses diverse kaolin resources capable of supporting a range of industries, from heavy construction ceramics to fine porcelain and high-duty refractories. Strategic beneficiation and targeted application of these deposits will be essential for achieving national industrial goals and reducing reliance on imported mineral raw materials.

5.2. Recommendations for Beneficiation

To maximize the value of these resources, particularly the Kombelcha deposit, future research must prioritize a multifaceted approach to beneficiation. [7] Implementing magnetic separation is critical to reducing iron oxide (Fe_2O_3) content, which would directly enhance the fired color and optical brightness of the raw material. [24] This can be further augmented by chemical leaching techniques specifically using organic acids like oxalic acid which have demonstrated significant potential in stripping iron oxides from Ethiopian kaolins to boost whiteness. Finally, the integration of particle size separation through wet-sieving or hydro-cyclone processing is essential; because the kaolinite is naturally concentrated in finer fractions, these methods effectively eliminate coarse quartz and feldspar impurities, thereby increasing the overall alumina percentage and refining the clay for high-end industrial use. [25].

Abbreviations

DTA	Differential Thermal Analysis
MOR	Modulus of Rupture
SEM	Scanning Electron Microscopy
XRD	X-Ray Diffraction

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Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing

Wakjira Tesfaye: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization

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Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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