Mining of Mineral Deposits
Volume 20 (2026), Issue 1, 114-124

https://doi.org/10.33271/mining20.01.112

Industrial quality classification for strategic planning: Economic optimization of the Köprüalan feldspar deposit, Turkey

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Abstract

Purpose. To investigate the mineralogical, geochemical, and technological characteristics of the Köprüalan (Aydın, SW Turkey) feldspar deposit. The study aims to determine its suitability for industrial ceramic applications and to evaluate how quality-based resource management influences both the economic viability and environmental sustainability of the mining operation.

Methods. Geochemical analysis of 222 samples was conducted together with X-ray diffraction (XRD) to determine mineral assemblages. Technological tests, including water absorption and shrinkage measurements, were performed to assess industrial performance. The obtained data were integrated into 3D geological models and geostatistical simulations to evaluate various mine design scenarios, with a focus on optimizing stripping ratios and reducing material handling.

Findings. Results indicate that the deposit consists predominantly of felsic metamorphic rocks with high SiO_2 (64.76-74.87%), elevated alkali oxides ($Na_2O + K_2O$), and low Fe_2O_3 (≤ 1.72%). XRD analysis confirmed a feldspar-rich composition with an average content of 62%. Integration of a multi-tier quality classification into the production sequence significantly increases the project's economic value. Optimized extraction sequences also reduce the stripping ratio, thereby lowering the operational carbon footprint by minimizing waste haulage and energy consumption.

Originality. A novel framework is proposed that transforms static mineralogical classification into a dynamic decision-support system. The approach integrates 3D geological modelling with geostatistical simulations to quantify trade-offs between quality-driven extraction, economic performance, and environmental sustainability in industrial mineral deposits.

Practical implications. Implementation of the proposed quality-tier system enables operators to optimize production planning, reduce waste management costs, and improve the environmental sustainability of industrial mineral extraction through lower green-house gas emissions.

Keywords: *feldspar; ceramic raw materials; mine design; Köprüalan deposit*

1. Introduction

Although feldspars are the most abundant mineral group on Earth, comprising nearly 60% of the continental crust, they present a distinct geological paradox: they are listed as a critical raw material, yet deposits that meet the rigorous chemical and physical purity standards required for modern ceramic manufacturing are scarce [1], [2].

Feldspar formation in igneous environments occurs across an exceptionally wide temperature range from 360 to 1400°C, with distinct formation mechanisms operating in different thermal regimes. The formation and quality of the resulting feldspar depend critically on bulk composition, pressure, and water activity [3]. Feldspars act as the fundamental flux agents in ceramic batches, essential for products such as porcelain tiles and sanitaryware. Their utility stems from their ability to form low-temperature eutectic melts with silica and clay minerals. This resulting liquid phase drives densification via viscous flow, filling interparticle voids and sealing the final ceramic body. The ceramic industry relies heavily on high-quality raw materials, which influence the firing behavior, strength, and aesthetic properties of final products [4], [5]. Continuous exploration and characterization of new raw material reserves are essential to meet growing industry demands and maintain quality standards.

Although characterizing the Köprüalan feldspar-bearing materials under the license of Kalemaden Co. (Aydın, Türkiye; Fig. 1) through XRD and XRF is a foundational component of this research, the study's core contribution lies in bridging the gap between mineralogy and mine optimization. Most contemporary scheduling models focus on homogeneous grade variables in metallic ores [6]. However, industrial minerals like feldspar require a more nuanced approach, as a combination of chemical and physical parameters dictates their economic value.

Received: 8 January 2026. Accepted: 16 March 2026. Available online: 30 March 2026

Mining of Mineral Deposits. ISSN 2415-3443 (Online) | ISSN 2415-3435 (Print)

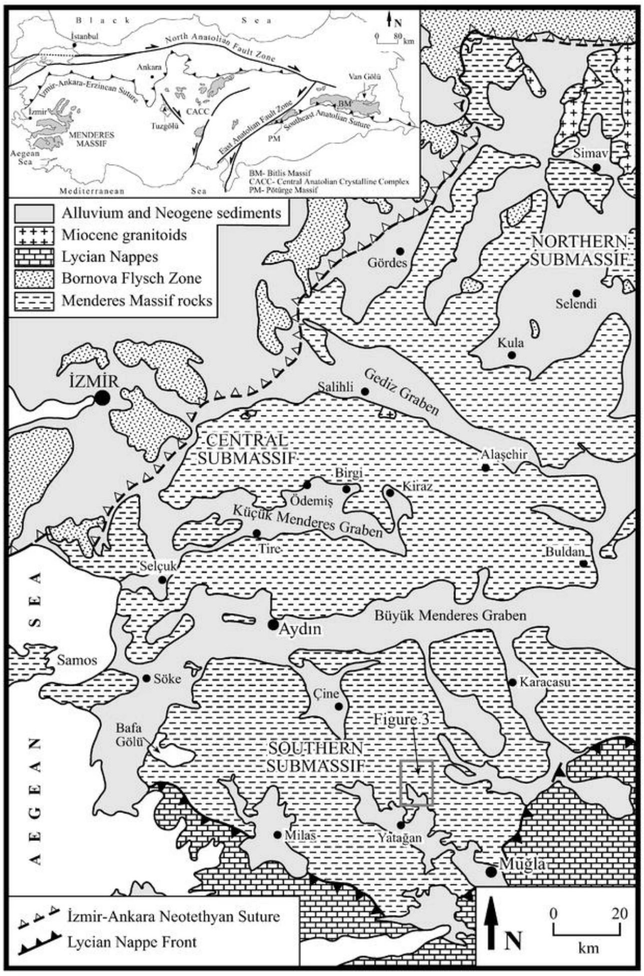

Figure 1. Geological map of the Menderes metamorphic massif after [7] (the red asterisk shows the study area)

Integrating these constraints into the production sequence ensures that selection, processing, and utilization decisions account for a holistic set of criteria, ultimately leading to more sustainable and optimized resource use, in line with the principles established in sustainable mineral resource management frameworks that emphasize integrating multiple discrete activities along the resource value chain [8]. This paper develops a methodology to integrate these multi-parameter constraints directly into the production sequence, providing a more accurate assessment of resource efficiency than traditional single-variable models.

While general mining studies emphasize that maximizing short-term profits often leads to long-term ecological imbalance [9], they typically treat ore as a binary variable (valuable vs. waste). In the specific context of feldspar, the "value" is a spectrum defined by alkali ratios and coloring oxides. By failing to account for this quality spectrum during the initial 3D modeling and block-sequencing phase, companies often engage in blind extraction, resulting in the accidental dilution of premium-grade materials or the unnecessary stripping of overburden for low-value yields.

In the mining sector, adopting circular-economy strategies that include resource recovery systems and digital supply-chain integration significantly enhance the economic and environmental performance of mining operations. Such strategies prioritize resource efficiency and optimize recovery, thereby improving economic returns despite the deposit's inherent mineral content [10]. Recent studies extensively discuss the economic trade-offs in mining, focusing primarily on the conflict between immediate GDP growth and environmental degradation [11]. However, a critical oversight in current industrial mineral research is the failure to explicitly integrate multi-parameter quality classification directly into the production planning phase. As noted by [12], sustainable mining requires data-driven approaches to balance profitability with ecological function. We provide evidence that the economic value of such a deposit is not determined solely by its mineral content, but is also significantly influenced by a production strategy that leverages quality ranking to optimize resource recovery.

Our research demonstrates that incorporating a quality-tier framework into the geostatistical simulation stage serves as both an economic and environmental optimization tool. Economically, it enables targeted extraction, optimizing the stripping ratio and preventing financial losses associated with processing substandard materials [13]. We argue that quality-based production planning is the precise mechanism required to achieve this balance, transforming the Köprüalan deposit into a roadmap for companies seeking to align financial viability with the rigorous sustainability mandates of the future. Thus, the methodology involves constructing an integrated decision framework that merges chemical quality assessments with physical parameter evaluations, employing sophisticated data integration techniques and adaptive predictive models to embed these constraints directly into operational workflows. This results in enhanced resource-efficiency assessments for feldspar compared to traditional approaches that rely on isolated parameter evaluation.

2. Geological characteristics of the region

The basement of the region between Aydın, Muğla, and Milas consists of metamorphic rocks of the Menderes Massif. These are represented by a Pan-African (Late Neoproterozoic) aged basement core overlain by a Paleozoic to Early Tertiary cover sequence. The geology of the region is compiled from several significant papers [14]-[20]. The Pan-African basement comprises a stratigraphy that includes a partially migmatized metaclastic sequence and polymetamorphic acidic and basic intrusive rocks emplaced within it (Fig. 2).

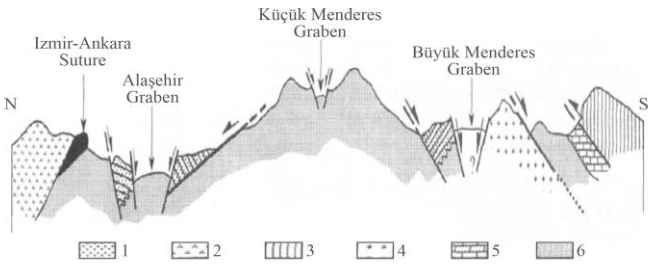

Figure 2. N-S sketch cross-section across the Menderes Massif: 1 – Neogene sediments; 2 – Neo-Tethyan ophiolites and rocks of Sakarya continent and Karakaya complex; 3 – Lycian Nappes; 4 – Augen gneisses; 5 – Mesozoic-Cenozoic marbles; 6 – Palaeozoic schists [21]

The metaclastic units, consisting of paragneisses and conformably overlying schist units, represent the oldest rocks of the Pan-African basement of the Menderes Massif. Field observations and geochronological data indicate that the protoliths of the paragneisses were predominantly litharenitic sandstones. The paragneisses are interbedded with mica schists and biotite-albite schists derived from mudstones and subarkosic sandstones. The paragneisses are overlain by the schist unit, with a conformable, gradational contact. An interlayering of paragneiss and schist characterizes this transition zone. The schist unit is rich in micaschists and contains biotite-albite schist levels derived from subarkosic protoliths. The metaclastic sequence exhibits widespread migmatization across the massif. Anatectic granites occur within the migmatites as shapeless masses with gradational contacts. The cover sequence is composed of metaconglomerates, metaquartzites, and alternations of phyllite-metaquartzite-marble. Overlying the rocks of the Menderes Massif, particularly in the northern regions (between Aydın and Çine) and in the central parts of the massif, are terrestrial sedimentary rocks of Neogene and Pliocene-Plio-Quaternary age.

Within the Menderes Massif, feldspar occurrences are confined to the core gneisses of the massif and are generally located within NE-SW trending (N10-25E) shear zones. These zones are typically 30-50 meters wide and extend up to 500-1000 meters in length. They are bounded at the lower and upper contacts by augen gneisses and/or metagranites. The primary characteristics of these zones are their cataclastic textures and blastomylonitic features (References needed). Albitic feldspar formations have developed either primarily through aplite/pegmatite intrusions or through processes such as migmatization and metasomatism. Feldspar occurrences may consist of either pure albite or a mixed type (comprising both albite and orthoclase/microcline). Mixed-type feldspar occurrences characterize the Köprüalan area (Fig. 3). Within this area, mica schists are found in narrow zones bounded by augen- and banded two-feldspar gneisses (Na- and K-feldspars).

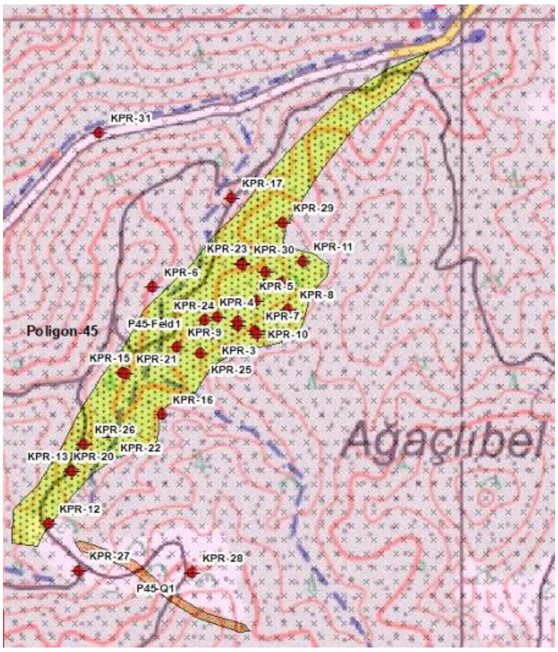

Figure 3. Feldspar zone of the study area (yellow colored field)

Between the gneisses, altered zones transformed into feldspar are observed along fracture zones, as well as light-colored feldspar occurrences conformably associated with the gneisses. The gneisses and the mica schists, which are considered to be primarily associated with them, generally exhibit a NE-SW (N35-50E) orientation and dip 15-50 degrees towards the SE. Towards the northwest part of the area, the dip direction is occasionally reversed, shifting towards the NW. This reversal is likely due to a fault extending along the Eğri Stream.

3. Materials and methods

The primary dataset for this study comprises 222 samples collected from 31 core-drilling operations distributed across the study area (Fig. 3). The characterization studies began with X-ray Diffraction (XRD) and X-ray Fluorescence (XRF) analyses to determine the mineralogical and chemical composition, followed by technological testing to determine water absorption, total firing shrinkage, viscosity, and density. All analyses were performed in Kaleseramik R&D Center Laboratories. By integrating these datasets, the chemical, mineralogical, and technological properties of the deposit were defined and benchmarked against those of other major feldspar deposits worldwide.

Physical quality of ceramic tiles, specifically their dimensions, strength, water absorption, and color, is fundamentally dictated by the chemical interactions between raw materials (clays, fluxes, and fillers) during the firing process. SiO_2 (present as quartz and in the glassy phase) acts as the "filler" in the microstructure of the final product. This specific microstructure contributes to the material's high technical properties, such as low water absorption, chemical and frost resistance, high bending strength, and abrasion resistance [22], [23]. Na_2O and K_2O promote the formation of a viscous liquid phase at high temperatures. This liquid fills pores, reducing water absorption and increasing bulk density. MgO acts as a sintering promoter. When combined with alkaline elements, it forms a less viscous liquid phase, thereby improving densification kinetics. $CaCO_3$ is a defining component of wall tile formulations, introduced by calcite and/or marble. It decomposes into CaO and CO_2, and the resulting CaO reacts with amorphous phases to form crystalline phases, such as anorthite. This reaction sequence produces a small volume of liquid phase and maintains high porosity, which is essential for preventing excessive linear firing shrinkage [24]. The presence of Iron (Fe_2O_3) and Titanium (TiO_2) oxides negatively impacts the whiteness of the fired body [25].

To link these material properties to industrial utility, the reserves were evaluated using Kale Ceramic Co.'s quality classification system, which categorizes raw materials based on specific chemical, mineralogical, and physical criteria. To assess the impact of these quality classes on economic viability, a comprehensive resource modeling workflow was implemented. A 3D model of the orebody was first constructed from lithological cross-sections. Subsequently, geostatistical analyses were conducted to define the spatial continuity ranges, and the study area was discretized into a block model, with ore properties interpolated via kriging. Finally, hypothetical open-pit mine designs were developed to demonstrate how targeting different quality tiers directly affects the project's economic metrics, specifically stripping ratio.

3.1. Geochemistry of Köprüalan feldspar-bearing materials

The geochemical data provided in Table 1 reveal significant insights into the lithological and compositional characteristics of the sampled areas, offering a robust framework for interpreting the geological history and rock-forming processes within the study region.

Table 1. Geochemistry of the Köprüalan feldspar-bearing materials

Value	Min	Average	Max
LOI	0.35	1.01	4.58
SiO_2	50.03	72.01	82.35
Al_2O_3	10.15	14.99	21.89
TiO2	0.13	0.31	1.02
Fe_2O_3	0.03	1.69	14.54
CaO	0.14	0.57	3.2
MgO	0.01	0.51	8.83
Na_2O	0.23	4.22	11.28
K_2O	0.68	4.38	7.84
P_2O_5	0.1	0.23	1.45

When examining the minimum values, the mixed feldspar content falls below the threshold with a total alkali value of 4.75%. In contrast, the maximum values reveal significantly high concentrations of Na_2O, K_2O, and total alkalis. The maximum iron content reaches 14.54%, while MgO levels can reach 8.83%, corresponding to highly micaceous (biotite, phlogopite) gneisses. Elevated levels of CaO and iron also indicate the presence of rare pyroxenes and amphiboles. The source of CaO is attributed to both plagioclase minerals (oligoclase and andesine) and amphibole phases. To better understand these relationships, variations in chemical composition should be compared with mineralogical data using XRD (X-ray Diffraction) analyses.

3.2. Mineralogical characterization of Köprüalan feldspar-bearing materials

As introduced in the sections above, the Köprüalan feldspars are represented by orthoclase/microcline and albite-bearing gneisses. From the perspective of ceramic production, the minerals to consider in the Köprüalan material are quartz, total feldspars, and total micas. The XRD analyses from the Köprüalan deposit reveal a mineralogical assemblage dominated by feldspars, averaging 62% and primarily comprising albite, orthoclase, and microcline, which align with the geochemical prevalence of alkali oxides (Na_2O, K_2O) and high SiO_2. Quartz (27% average) further corroborates the silicic nature of the deposit. The presence of micas (10% average), including biotite, phlogopite, annite, and muscovite, suggests that the protolith contains some iron and magnesium. At the same time, trace minerals such as pyroxene, amphibole, and hornblende reflect minor mafic inputs. The varieties of these rocks, particularly those low in mafic minerals such as biotite and phlogopite (leuco-feldspathic gneisses), are used as mixed feldspar.

3.3. Technological characterization of Köprüalan feldspar-bearing materials

Density, viscosity, water absorption, and shrinkage analyses were also conducted on core samples to assess the potential of the study area as a ceramic raw material. Technological test results for the Köprüalan feldspathic material are presented in Table 2, including minimum and maximum values.

3.4. Köprüalan feldspar-bearing materials as a raw material for the ceramic industry

Köprüalan Feldspar has significant potential as a raw material for the ceramic industry, driven by a geochemical profile that rivals those of established commercial deposits worldwide. Compared with the feldspar sources currently used in the industry, as shown in Table 3, the Köprüalan samples exhibit a favorable oxide balance, essential for high-quality wall and floor tile production. Specifically, the Köprüalan deposit exhibits a balanced fluxing capacity, with Na_2O (4.53%) and K_2O (4.32%) levels comparable to, or exceeding, the total flux values of widely utilized deposits. Crucially, the Fe_2O_3 (1.72%) and TiO_2 (0.33%) contents suggest that Köprüalan is particularly suitable for ceramic bodies where firing color is critical.

Köprüalan's suitability for feldspar-bearing materials is further supported by quality classifications established by leading industry players (e.g., Kale Ceramic Co.). These classifications confirm that the Köprüalan deposit falls within the ranges required for premium ceramic manufacturing. While variations in oxide levels may occur, the deposit's high silica (71.06%) and moderate alumina (15.39%) content align it closely with standard recipes for vitrified tile bodies, minimizing the need for extensive processing or formulation adjustments compared to lower-grade alternatives.

Table 2. Technological properties of the Köprüalan province

		Viscosity (cps)	Density (gr/lt)	Water absorption (%)	Shrinkage (%)
Albite (Mica-bearing albite / mica-bearing feldspar)	Min	51	1607	41.92	1.71
	Max	314	1727	19.87	11.87
Gneiss / Feldspathic gneiss	Min	52	1615	0	3.32
	Max	955	1732	16.08	11.87

Table 3. Comparison of the study area with feldspar deposits of different parts of the world

Oxides	Köprüalan	Turkey (Menderes Massif) [26]	Turkey (Çine) [27]	Italy (Sardinia) [4], [28]	Thailand (Lan Sang) [29]
SiO_2	71.06	62.23	69.53	70.79	68.38
TiO_2	0.33	1.00	0.29	0.37	0.41
Al_2O_3	15.39	16.76	18.25	14.35	15.34
Fe_2O_3	1.72	5.85	0.10	3.13	2.43
MnO	0.05	0.02	–	0.06	–
MgO	0.70	2.48	0.15	0.69	0.84
CaO	0.57	2.06	0.70	1.72	2.95
Na_2O	4.53	2.37	10.10	3.21	3.33
K_2O	4.32	3.19	0.28	4.13	3.96
P_2O_5	0.26	0.23	0.25	0.22	–
LOI	1.06	2.68	0.35	1.00	1.21
Total	99.99	98.87	100.00	99.67	98.85

3.4.1. Chemical content

The chemical composition of the mineral reserve is critical for determining its suitability for ceramic applications, as it influences the firing behavior, strength, and aesthetic properties of the final product. Reserves with chemical compositions within these ranges are suitable for premium ceramic products like tiles and sanitaryware. Key chemical parameters and their typical ranges for quality classifications are given in Table 4.

Table 4. Quality classification with respect to chemical content (%)

Content / Quality class	$Na_2O + K_2O$	SiO_2	Al_2O_3	Fe_2O_3	TiO_2
Ultra-high	> 11	< 68	> 20	< 0.35	< 0.4
High	11-9	68-70	20-17	0.35-1	0.4-0.6
Medium	9-7	70-74	17-14	1-2	0.6-0.8
Low	< 7	> 74	< 14	> 2	> 0.8

3.4.2. Mineral content

The mineralogical composition determines the reserve's processing behavior and compatibility with ceramic formulations. A balanced mineral profile within these ranges ensures optimal processing and high-quality ceramic output. Reserves with higher feldspar and moderate quartz content are particularly valued for their fluxing and stability properties. The key mineralogical parameters and their typical ranges for quality classifications are given in Table 5.

Table 5. Quality classification with respect to mineralogical content (%)

Content / Quality class	Mica	Feldspar	Quartz
Ultra-high	< 5	> 85	< 10
High	5-9	85-55	10-30
Medium	9-18	55-25	30-50
Low	> 18	> 25	> 50

3.4.3. Physical properties

Physical properties dictate the material's performance during processing and the quality of the final ceramic product. The key parameters and their ranges for quality classification are given in Table 6; these categories are established in relation to worldwide standards, specifically ISO 13006, which defines the technical requirements for ceramic tile classification, and the ISO 10545 series, which standardizes the testing methodologies for physical and chemical properties.

Table 6. Quality classification with respect to physical properties

Content / Quality class	Viscosity, cps	Density, g/L	Color, L%	Water absorption, %	Shrinkage, %
Ultra-high	< 75	< 1650	> 85	< 0.35	> 12
High	75-100	1650-1675	85-65	0.35-6	12-9
Medium	100-120	1675-1690	65-50	6-11	9-5
Low	> 120	> 1690	< 50	> 11	> 5

4. Results and discussion

4.1. 3D modeling of feldspar body

Before the exploratory data analysis, a three-dimensional geological model was constructed to define the volumetric boundaries of the feldspar mineralization and the host rock units (Fig. 4).

The plan view illustrates the surface projection of these units, revealing the lateral extent of the albite-rich zones. At the same time, the accompanying cross-sections provide a vertical perspective that demonstrates the subsurface geometry and structural continuity of the deposit. In this framework, these lithological wireframes are treated as hard boundaries to ensure that the subsequent quality distribution reflects the true structural dip and orientation of the ore body. Specifically, the deposit is differentiated into three primary lithological units based on their mineralogical characteristics and industrial potential. The Albite unit comprises albite-dominated felsic gneisses with low mica and mafic mineral concentrations, making it the primary focus for high-quality raw material extraction. This is distinguished from the M-Albite unit, which consists of micaceous albite-dominated gneiss; in this domain, the increased presence of mica minerals necessitates more rigorous processing considerations. Finally, the F-Gneiss unit comprises the broader feldspathic gneiss sequences that form the surrounding geological and metamorphic matrix. By establishing these spatial boundaries within the 3D environment, the model facilitates a precise transition from descriptive geology to a structured geostatistical evaluation, enabling more accurate estimation of the deposit's total industrial volume and resource distribution.

4.2. Geostatistical analysis

To understand the geochemical relationships within the Köprüalan feldspar deposit, a multivariate correlation analysis was conducted on the major oxides. Figure 5 illustrates the correlation matrix, highlighting strong negative correlations between SiO_2 and Al_2O_3 and between SiO_2 and Na_2O. This inverse relationship is characteristic of feldspathic mineralization, where an increase in silica content typically indicates a transition towards quartz-rich zones, thereby reducing the alumina and sodium concentrations essential for high-quality feldspar. These correlations justify selecting SiO_2 as the primary variable for geostatistical modeling, as it serves as a robust proxy for overall mineralogical quality.

Experimental semi-variograms were calculated for SiO_2, which constitutes over 70% of the deposit volume and serves as the distinct indicator of ore quality. An anisotropic spherical model was fitted to the experimental data to capture the spatial continuity of the mineralization. As shown in Figure 6, the variogram analysis reveals geometric anisotropy with a major range of approximately 63 m, a minor range of approximately 23 m, and a significantly shorter vertical range of approximately 9 m. This structural trend suggests a stratiform or lenticular depositional environment where mineralization is continuous along the strike but varies rapidly in the vertical direction. The nugget effect is relatively low, indicating good continuity at short distances.

Based on the parameters derived from the variogram modeling, a 3D search ellipsoid was constructed to define the neighborhood for block model estimation (Fig. 7). The ellipsoid is oriented with an azimuth of 45.0° and a dip of -15.0°, aligning with the geological trend of the feldspar body. The dimensions of the ellipsoid (63, 23 and 9 m) correspond to the major, minor, and vertical ranges of the variogram model, respectively. This anisotropic search volume ensures that the chemical content estimation prioritizes samples along the axis of greatest continuity, thereby increasing the reliability of the resource model before classifying the ore types according to the quality rankings presented in Table 4.

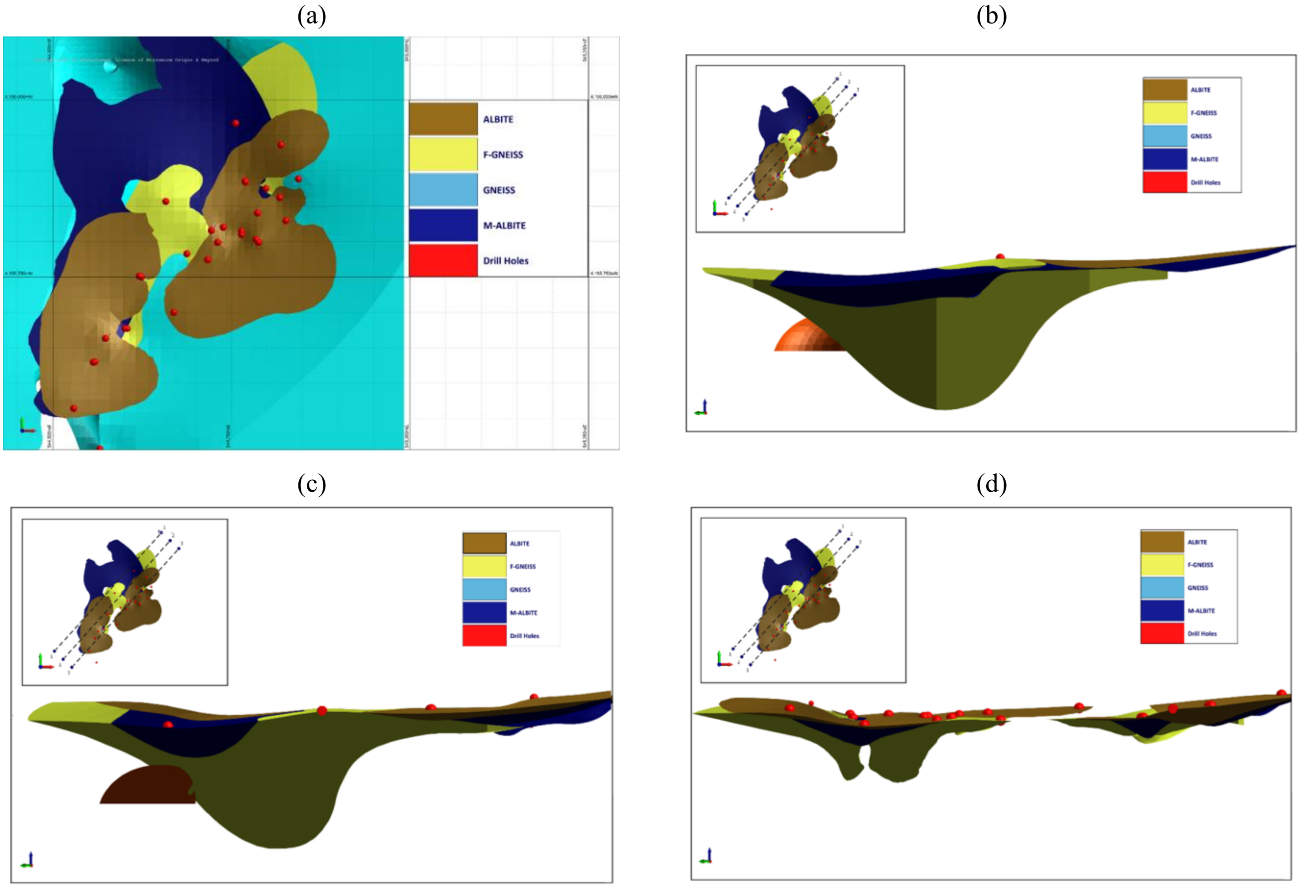

Figure 4. Lithological modeling of the study area: (a) top view; (b) cross section 1-1; (c) cross section 2-2; (d) cross section 3-3

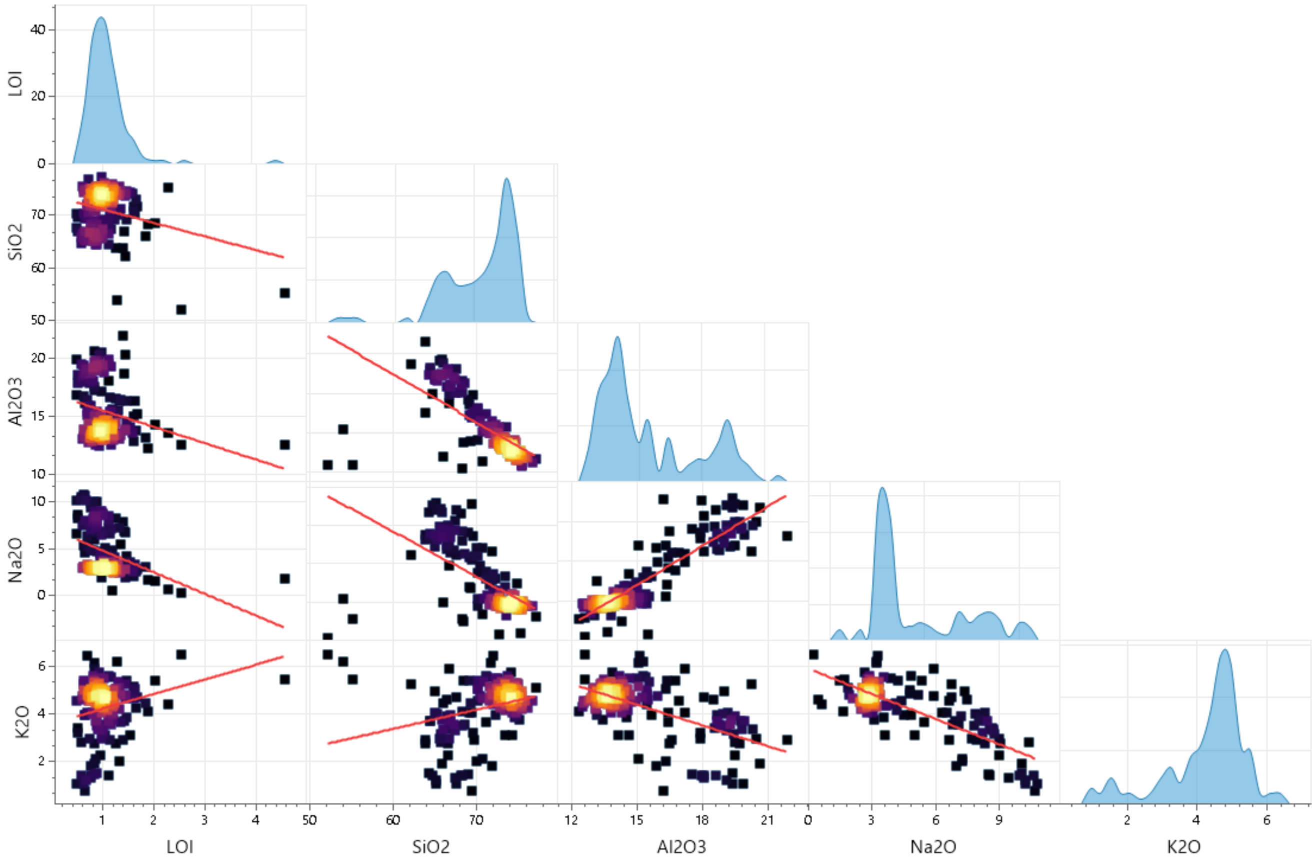

Figure 5. Correlation between major oxides

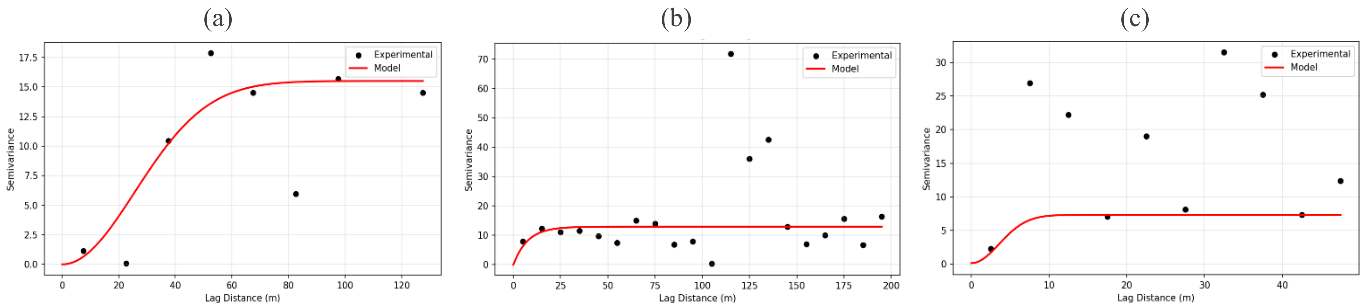

Figure 6. Semi variogram analysis of SiO_2 content: (a) major axis; (b) minor axis; (c) vertical axis

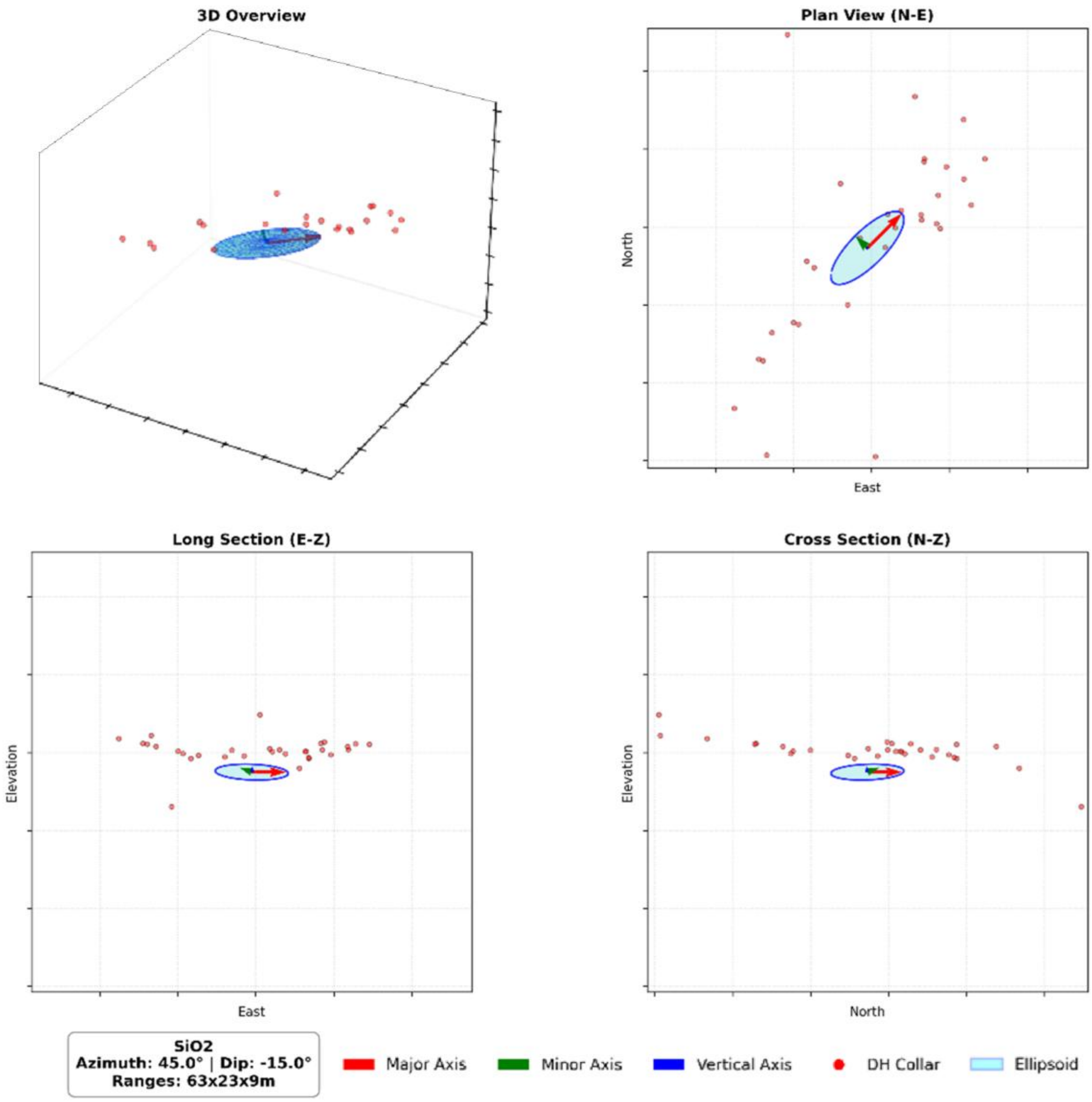

Figure 7. 3D search ellipsoid

4.3. Effect of quality classes on the economic value of the mineral reserve

In the economic architecture of open-pit mining, the distinction between profitability and loss is often drawn by the volume of non-revenue-generating waste material that must be displaced to access the orebody. Determining the pit's geometric boundaries directly dictates the stripping ratio, a metric that serves as the primary lever for controlling operational costs. It is the strategic minimization of this stripping ratio that secures the project's financial health [30]. Consequently, the spatial distribution of quality classes becomes a decisive economic factor; by aligning excavation schedules to prioritize high-grade zones, the operation can effectively lower the stripping ratio required to recover a unit of value. This section evaluates how integrating quality classification into the pit design drastically enhances the project's overall profitability by reducing capital expenditures wasted on overburden removal. The quality classification of the ore zone (Fig. 8) reveals a critical constraint regarding the in-situ characteristics of the deposit.

As summarized in Table 7, the distribution of ore types is heavily skewed towards lower grade intervals; "Ultra-High" and "High" quality classes comprise a mere 0.0057 and 3.21% of the total volume, respectively, while "Medium" and "Low" quality materials account for over 96% of the reserve.

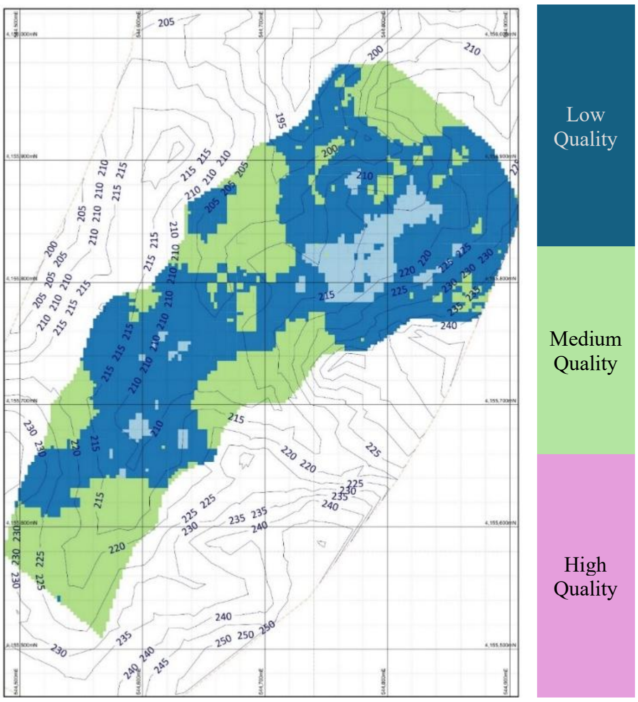

Figure 8. Quality distribution across the feldspar zone

This distribution indicates that the direct extraction of high-grade final products is not feasible at the current stage of the reserve body, and that downstream mineral processing is required to upgrade the run-of-mine material to meet premium market specifications.

Table 7. Amount of material classified according to the chemical content

Quality class	Volume (%)
Ultra-High	0.0057
High	3.21
Medium	40.81
Low	55.97

Classifying the mineral reserve into distinct quality classes and developing a targeted production plan significantly enhances its economic value by optimizing resource utilization and meeting market demands for high-value ceramic products. To demonstrate this, three distinct mine plans (Fig. 9) have been designed to focus on producing materials of varying quality classes. The initial design aims to encompass all quality classes, whereas the second design omits the low-quality class, and the third design exclusively targets the high and ultra-high classes. Variations in the stripping ratio (Fig. 10) across these production scenarios elucidate the critical role of quality classes in determining the economic viability of the mineral reserve.

The diagram in Figure 11 illustrates the ore and waste distribution across three mine designs, highlighting the impact of quality classes on economic viability.

Design 1 includes all quality classes (low, medium, high, ultra-high) with a high stripping ratio (0.68 m^3/t) and significant waste (55%). Design 2 excludes the low-quality class, reducing waste to 15% and the stripping ratio to 0.1 m^3/t, while focusing on medium and high/ultra-high classes.

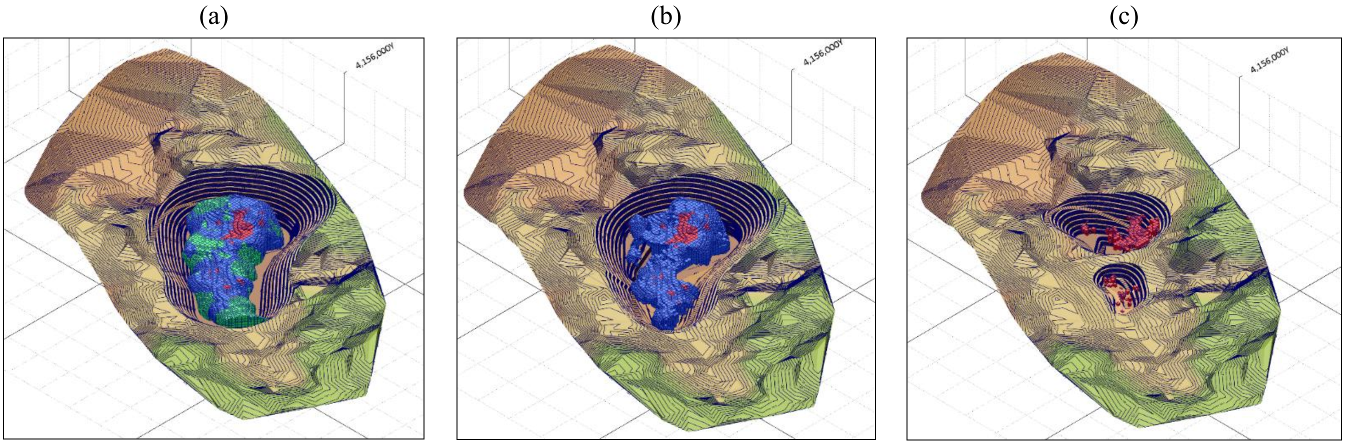

Figure 9. Different mine production plans with respect to quality classes: (a) all classes; (b) excluding low class; (c) targeting high & ultra-high classes

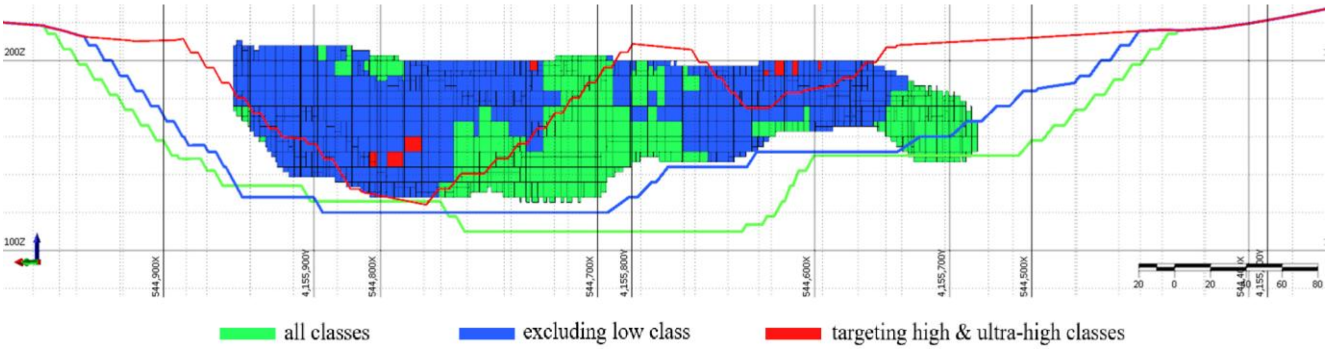

Figure 10. Cross-section of pit designs

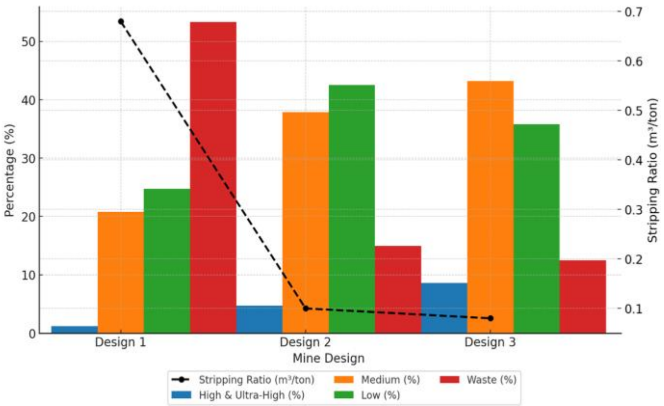

Figure 11. Ore, waste and stripping ratio comparison of pit designs

Design 3 targets only high- and ultra-high-grade ore, further reducing waste to 10% and maintaining a low stripping ratio (0.08 m³/t), demonstrating that prioritizing higher-grade ore improves efficiency and economic value. The technical efficiency of the proposed quality-tier framework is most evident when analyzed through the lens of operational cost reduction. As shown in Figure 11, the transition from a bulk extraction scenario to a quality-driven targeted strategy results in a significant decrease in the stripping ratio from 0.68 to 0.08 m³/t. To contextualize this improvement within the Turkish mining sector, [31] indicates that waste management costs (WMC) constitute a substantial burden on mining operating costs in Turkey, often exacerbated by high land-use fees and the technical requirements of waste storage facilities. This optimization does not merely lower the cost per tonne of ore produced; it effectively lowers the deposit's "break-even" quality threshold. Consequently, our model confirms that treating quality as a selective mining constraint enhances the project's financial resilience against the high waste-handling costs characteristic of the Turkish mining regulatory environment.

The environmental significance of the proposed multitier quality system extends beyond economic metrics, primarily through reductions in the carbon footprint associated with waste haulage. According to [32], energy consumption and greenhouse gas emissions in open-pit operations are intrinsically linked to the scale of excavation and the efficiency of the haulage cycle. In their assessment of energy conservation potential, they highlight that optimizing the pit limit and reducing the transport of non-valuable material are essential strategies for mitigating a mine's carbon intensity.

By applying these principles to the Köprüalan deposit, reducing waste material directly translates into lower diesel consumption and lower atmospheric emissions. This reduction in the stripping ratio represents a form of "source-level energy conservation", where the geological model itself serves as a tool for decarbonization. Consequently, our findings support the argument that quality-driven production planning is a critical technical lever for achieving modern environmental sustainability targets, as it effectively aligns operational productivity with carbon-emission mitigation in the industrial minerals sector.

Taken together, this evidence confirms that the economic value of mineral or material deposits is dynamic and can be substantially improved through targeted production strategies that exploit quality rankings and optimize resource recovery pathways. Optimizing how and when materials of varying qualities are extracted and processed can increase resource utilization efficiencies and profitability beyond what could be achieved from the mineral content alone.

5. Conclusions

The investigation of the Köprüalan feldspar-bearing materials confirms its significant potential as a high-grade source for the ceramic industry, particularly for floor and wall tile production. The geochemical and mineralogical signatures not only align with the geological evolution of the Menderes Massif but also rival established commercial deposits globally in terms of fluxing capacity and low impurity levels. However, this study demonstrates that the industrial utility of the deposit is best realized through a systematic quality classification framework rather than traditional bulk characterization.

The transition from material characterization to economic modeling reveals that the project's viability is not a static property of the mineral content but a function of selective mining strategies. By utilizing 3D spatial continuity analysis and quality-tiered mine designs, it was shown that strategic resource recovery significantly improves economic performance and reduces operational overheads compared to non-targeted extraction. Consequently, the Köprüalan deposit serves as a model for how integrating technological characterization with quality-driven mine planning can maximize the value of critical industrial raw materials.

Looking forward, several avenues for further research emerge from this study to refine the integration of mineral quality into mining operations. Future work should focus on multi-scenario economic analysis, using stochastic modeling to assess the project's sensitivity to fluctuating market demand and energy prices. Such an approach would enable an even more resilient production schedule that adapts to the varying price points across different quality tiers. Additionally, there is a clear opportunity to conduct a detailed life cycle assessment. This would explicitly quantify the environmental benefits of the suggested quality-tier classification, specifically measuring the reduction in greenhouse gas emissions and cumulative energy demand achieved through optimized stripping ratios and reduced haulage. Finally, integrating real-time sensor-based sorting technologies could be explored to validate the 3D quality models during the active extraction phase, further bridging the gap between digital geological twins and physical mine production.

Author contributions

Conceptualization: KH, CAÖ, ŞCG; Data curation: YY, MK; Formal analysis: KH, YY, ŞCG; Funding acquisition: CAÖ, ŞCG, KH; Investigation: KK, ŞCG; Methodology: KH, CAÖ, ŞCG; Project administration: CAÖ, KK; Software: KH; Supervision: CAÖ, ŞCG, KK; Validation: CAÖ, ŞCG; Visualization: KH; Writing – original draft: KH, CAÖ; Writing – review & editing: KH, CAÖ, ŞCG., YY, KK. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Acknowledgements

The authors would like to express their gratitude to the Kaleseramik Research-Development Center and Kalemaden Industrial Raw Materials Co. for their technical support, provision of materials, and use of laboratory facilities during this study. In addition, the authors would like to thank Levent Can and Aykut Keskin for their valuable efforts and technical support during the data preparation phase of this study.

Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

References

[1] Dondi, M., Conte, S., Molinari, C., & Zanelli, C. (2025). Mineral resources for the ceramic industry: survey of feldspathic raw materials in Italy. *Minerals*, *15*(1), 87. https://doi.org/10.3390/min15010087

[2] Grohol, M., & Veeh, C. (2023). *Study on the critical raw materials for the EU 2023*. Final report. Luxemburg, Luxemburg: Office of the European Union, 158 p. https://doi.org/10.2873/725585

[3] Carten, R.B. (1986). Sodium-calcium metasomatism; chemical, temporal, and spatial relationships at the Yerington, Nevada, porphyry copper deposit. *Economic Geology*, *81*(6), 1495-1519. https://doi.org/10.2113/gsecongeo.81.6.1495

[4] Bordicchia, F., Marini, C., & Bornioli, R. (2004). Raw feldspar materials in Sardinia, an overview. *Industrial Ceramics (Italy)*, *24*(2), 71-79.

[5] Silva, A.C., Carolina, S.D., Sousa, D.N., & Silva, E.M.S. (2019). Feldspar production from dimension stone tailings for application in the ceramic industry. *Journal of Materials Research and Technology*, *8*(1), 1-7. https://doi.org/10.1016/j.jmrt.2018.02.011

[6] Huang, S.W., Hu, N.L., Li, G.Q., & Hou, J. (2020). Optimization model of underground mining production scheduling with grade uncertainty. *Zhongguo Youse Jinshu Xuebao/Chinese Journal of Nonferrous Metals*, *30*(12). https://doi.org/10.11817/j.ysxb.1004.0609.2020-37688

[7] Özer, S., Sözbilir, H., Özkar, İ., Toker, V., & Sari, B. (2001). Stratigraphy of Upper Cretaceous-Palaeogene sequences in the southern and eastern Menderes Massif (western Turkey). *International Journal of Earth Sciences*, *89*(4), 852-866. https://doi.org/10.1007/s005310000142

[8] Liu, Y., Qin, K., Zhao, J., Zhou, Q., Shi, R., He, C., & Gao, Y. (2023). Feldspar traces mineralization processes in the Qongjiagang giant lithium ore district, Himalaya, Tibet. *Ore Geology Reviews*, *157*, 105451. https://doi.org/10.1016/j.oregeorev.2023.105451

[9] Samimi Namin, F., Shahriar, K., & Bascetin, A. (2011). Environmental impact assessment of mining activities. A new approach for mining methods selection. *Gospodarka Surowcami Mineralnymi*, *27*, 113-143.

[10] Zhu, W., Kong, D., Ye, Q., Zhang, X., Tian, D., & Solangi, Y.A. (2025). Enhancing environmental sustainability in the mining industry: circular economy strategies for resource management and digital integration. *Land Degradation & Development*, *36*(9), 2887-2901. https://doi.org/10.1002/ldr.5539

[11] Camara, A.D., Konaté, A.A., Solié, L., Hébélamou, J., & Bah, I. (2025). Analysis of the impacts of bauxite mining on the environment and the socio-economic activities of the population of the rural commune of Tanènè, Boké prefecture. *Mineral Economics*, 1-20. https://doi.org/10.1007/s13563-025-00565-z

[12] Hasözdemir, K., Meral, M., & Kahraman, M.M. (2025). Revolutionizing open-pit mining fleet management: integrating computer vision and multi-objective optimization for real-time truck dispatching. *Applied Sciences*, *15*(9), 4603. https://doi.org/10.3390/app15094603

[13] Antony Jose, S., Calhoun, J., Renteria, O.B., Mercado, P., Nakajima, S., Hope, C.N., Sotelo, M., & Menezes, P.L. (2024). Promoting a circular economy in mining practices. *Sustainability*, *16*(24), 11016. https://doi.org/10.3390/su162411016

[14] Bozkurt, E. (1996). Metamorphism of Paleozoic schists in the southern Menderes massif: Field, petrographic, textural and microstructural evidence. *Turkish Journal of Earth Sciences*, *5*(2), 105-121. https://doi.org/10.55730/1300-0985.1742

[15] Candan, O., Koralay, O.E., Akal, C., Kaya, O., Oberhänsli, R., Dora, O.Ö., Konak, N., & Chen, F. (2011). Supra-Pan-African unconformity between core and cover series of the Menderes Massif/Turkey and its geological implications. *Precambrian Research*, *184*(1-4), 1-23. https://doi.org/10.1016/j.precamres.2010.09.010

[16] Catlos, E.J., & Cemen, I. (2005). Monazite ages and the evolution of the Menderes Massif, western Turkey. *International Journal of Earth Sciences*, *94*(2), 204-217. https://doi.org/10.1007/s00531-005-0470-7

[17] Hetzel, R., Romer, R.L., Candan, O., & Passchier, C.W. (1998). Geology of the Bozdag area, central Menderes Massif, SW Turkey: Pan-African basement and Alpine deformation. *Geologische Rundschau*, *87*(3), 394-406. https://doi.org/10.1007/s005310050218

[18] Oberhänsli, R., Candan, O., Dora, O.Ö., & Dürr, St.H. (1997). Eclogites within the Menderes Massif/western Turkey. *Lithos*, *41*(1-3), 135-150. https://doi.org/10.1016/s0024-4937(97)82009-9

[19] Satir, M., & Friedrichsen, H. (1986). The origin and evolution of the Menderes Massif, W-Turkey: A rubidium/strontium and oxygen isotope study. *Geologische Rundschau*, *75*(3), 703-714. https://doi.org/10.1007/bf01820642

[20] Sengör, A.M.C., Satir, M., & Akkök, R. (1984). Timing of tectonic events in the Menderes Massif, western Turkey: Implications for tectonic evolution and evidence for pan-African basement in Turkey. *Tectonics*, *3*(7), 693-707. https://doi.org/10.1029/tc003i007p00693

[21] Bozkurt, E., & Graham Park, R. (1999). The structure of the Paleozoic schists in the Southern Menderes Massif, Western Turkey: A new approach to the origin of the Main Menderes Metamorphism and its relation to the Lycian Nappes. *Geodinamica Acta*, *12*(1), 25-42. https://doi.org/10.1080/09853111.1999.11105329

[22] Martín-Márquez, J., De la Torre, A.G., Aranda, M.A.G., Rincón, J.M., & Romero, M. (2009). Evolution with temperature of crystalline and amorphous phases in porcelain stoneware. *Journal of the American Ceramic Society*, *92*(1), 229-234. https://doi.org/10.1111/j.1551-2916.2008.02862.x

[23] Njindam, O.R., Njoya, D., Mache, J.R., Mouafon, M., Messan, A., & Njopwouo, D. (2018). Effect of glass powder on the technological properties and microstructure of clay mixture for porcelain stoneware tiles manufacture. *Construction and Building Materials*, *170*, 512-519. https://doi.org/10.1016/j.conbuildmat.2018.03.069

[24] Kara, A., Özer, F., Kayaci, K., & Özer, P. (2006). Development of a multipurpose tile body: Phase and microstructural development. *Journal of the European Ceramic Society*, *26*(16), 3769-3782. https://doi.org/10.1016/j.jeurceramsoc.2005.11.009

[25] Genç, Ş.C., Kayacı, K., & Yıldırım, Y. (2021). Mineralogical and technological properties of the Konya clays, Central Turkey. *Journal of Thermal Analysis and Calorimetry*, *147*(2), 1887-1897. https://doi.org/10.1007/s10973-020-10463-x

[26] Etzel, T.M., Catlos, E.J., Cemen, I., Ozerdem, C., Oyman, T., & Miggins, D. (2020). Documenting exhumation in the Central and Northern Menderes Massif (Western Turkey): New insights from garnet-based P-T estimates and K-feldspar 40Ar/39Ar geochronology. *Lithosphere*, *2020*(1), 8818289. https://doi.org/10.2113/2020/8818289

[27] Wyszomirski, P., Gacki, F., & Szydłak, T. (2012). Turkish feldspar raw materials in Polish production of ceramic tiles. *Gospodarka Surowcami Mineralnymi – Mineral Resources Management*, *28*(1). https://doi.org/10.2478/v10269-012-0001-7

[28] Idini, A., Fancello, D., Mameli, P., Ferrero, S., Cuccuru, S., & Casini, L. (2025). A mineralogical perspective on the granite alkali feldspar megacrysts paradox. *Lithos*, *516-517*, 108229. https://doi.org/10.1016/j.lithos.2025.108229

[29] Wonglak, S., Sutthirat, C., & Assawincharoenkij, T. (2020). Petrochemistry of Lan Sang metamorphic suites. *ScienceAsia*, *46*(4), 481. https://doi.org/10.2306/scienceasia1513-1874.2020.066

[30] Hu, Y., Li, C., Li, J., Long, D., & Wang, Y. (2022). A slope stability based realm optimization analysis for an open pit mine in cold region: Taking Jiguanshan molybdenum mine for example. *Geofluids*, *2022*, 1-12. https://doi.org/10.1155/2022/2150610

[31] Yıldız, T.D. (2020). Waste management costs (WMC) of mining companies in Turkey: Can waste recovery help meeting these costs? *Resources Policy*, *68*, 101706. https://doi.org/10.1016/j.resourpol.2020.101706

[32] Zhou, L. (2023). Towards sustainability in mineral resources. *Ore Geology Reviews*, *160*, 105600. https://doi.org/10.1016/j.oregeorev.2023.105600

Класифікація промислової якості для стратегічного планування: економічна оптимізація Кьопрюаланського польовошпатового родовища, Туреччина

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Мета. Дослідити мінералогічні, геохімічні та технологічні характеристики польовошпатового родовища Кьопрюалан (Айдин, південно-західна Туреччина). Дослідження спрямоване на визначення його придатності для промислового використання у keramічному виробництві, а також на оцінку впливу управління ресурсами на основі якості на економічну ефективність та екологічну стійкість гірничого підприємства.

Методика. Геохімічний аналіз 222 проб виконано у поєднанні з рентгенодифракційним аналізом (XRD) для визначення мінеральних асоціацій. Для оцінки промислової придатності матеріалу проведено технологічні випробування, зокрема визначення водопоглинання та усадки. Отримані дані інтегровано у тривимірні геологічні моделі та геостатистичні симуляції для оцінювання різних варіантів проєктування гірничих робіт з акцентом на оптимізацію коефіцієнта розкриву та зменшення обсягів переміщення матеріалу.

Результати. Встановлено, що родовище складене переважно кислими метаморфічними породами, які характеризуються високим вмістом SiO_2 (64.76-74.87%), підвищеним сумарним вмістом лужних оксидів ($Na_2O + K_2O$) та низьким вмістом Fe_2O_3 (≤ 1.72%). Рентгенодифракційний аналіз підтвердив польовошпатовий склад сировини із середнім вмістом польового шпату 62%. Визначено, що інтеграція багаторівневої класифікації якості у послідовність відпрацювання суттєво підвищує економічну цінність проєкту. Доведено, що оптимізовані послідовності видобутку також зменшують коефіцієнт розкриву, що, своєю чергою, сприяє зниженню вуглецевого сліду виробництва завдяки скороченню обсягів транспортування розкривних порід і споживання енергії.

Наукова новизна. Запропоновано новий підхід, який перетворює статичну мінералогічну класифікацію на динамічну систему підтримки прийняття рішень. Цей підхід поєднує тривимірне геологічне моделювання та геостатистичні симуляції для кількісної оцінки компромісів між видобутком, орієнтованим на якість, економічною ефективністю та екологічною стійкістю розробки родовищ промислових мінералів.

Практична значимість. Запровадження запропонованої багаторівневої системи якості дає змогу оптимізувати виробниче планування, знизити витрати на поводження з відходами та підвищити екологічну ефективність видобутку промислових мінералів шляхом скорочення викидів парникових газів.

Ключові слова: *польовий шпат; керамічна сировина; проєктування гірничих робіт; родовище Кьопрюалан*

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