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Geomechanical Justification of Open-Pit Slope Stability and Beneficiation Process Solutions for Rare Earth and Noble Elements

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Abstract

The rapid advancement of high-technology industries critically depends on the supply of rare earth elements (REEs), which constitute strategic raw materials for knowledge-intensive sectors. This study proposes an integrated methodological framework for the development of the Kundybay REE deposit, combining geomechanical substantiation of open-pit slope stability with beneficiation optimization of weathering-crust ores. The novelty of the research lies in the justification of rational pit-wall parameters based on a coupled 3D geological–geotechnical model implemented in the Micromine environment. Structurally disturbed zones were identified and subjected to detailed stability analysis using numerical modeling techniques. Particular emphasis was placed on the delineation of geotechnical domains and factor-of-safety evaluation in Slide2, which enabled refinement of design solutions and optimization of slope geometry. Simultaneously, the study addresses processing challenges of refractory weathering-crust ores through the application of ultrasonic aerohydraulic desliming combined with a vibro-centrifugal separation device. Optimization of slope parameters resulted in a 30 Mt reduction in stripping volume, corresponding to a 16.7% economic gain. The proposed flowsheet achieved a concentrate grade of 948.89 g/t REEs with an overall recovery of 45.66%. The results confirm that integrating geomechanical design with process engineering provides a technically robust and economically efficient basis for REE deposit development.

Keywords: open pit; slope angle; geomechanics; rare-earth ore; particle size class; gravity beneficiation; concentrate; weathering crust ore



Academic Editor: Manoj Khanal

Received: 20 February 2026

Revised: 26 March 2026

Accepted: 7 April 2026

Published: 14 April 2026

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1. Introduction

Rare earth elements (REEs), including lanthanides, yttrium, and scandium, are strategic mineral resources that play a critical role in high-technology industries and the transition to low-carbon and resource-efficient economies. They are essential for manufacturing permanent magnets, energy storage systems, catalysts, optical and laser materials, micro-electronics, and renewable-energy technologies. Their growing importance has led to their classification as critical raw materials, making the development of new REE resource bases

a priority worldwide. In recent years, global demand for individual REEs has increased steadily and has outpaced the demand for non-separated concentrates, intensifying the need for advanced processing routes and the development of previously underutilized deposits. In this context, the Kundybay deposit in Kazakhstan represents a promising REE-bearing weathering-crust system with significant resource potential and a relatively high proportion of yttrium-group elements, enhancing its economic attractiveness.

For Kazakhstan, establishing a domestic REE resource base is of strategic importance in terms of raw-material security, industrial diversification, and export potential. The country hosts considerable forecast REE resources in both primary and technogenic deposits, particularly in Central and Eastern regions. However, despite this mineral potential, industrial processing and technological readiness remain limited. This highlights the need for scientifically grounded approaches that integrate mining safety, economic efficiency, and processing performance. Among prospective occurrences, the Kundybay deposit is distinguished by its association with a Mesozoic weathering crust developed over metamorphic rocks. This geological setting creates both opportunities and challenges. While the ore is enriched in valuable heavy REEs, particularly yttrium-group elements, the host sequence consists of weak, clay-rich, and poorly cemented materials, which complicate both slope stability and beneficiation [1–3].

From a geomechanical perspective, the deposit is characterized by low and variable rock strength, structural heterogeneity, and pronounced sensitivity to water saturation. Moisture infiltration may cause swelling, cracking, and progressive strength degradation, particularly in clay-rich horizons, leading to reduced shear resistance. The alternation of weak weathered materials with stronger underlying rocks creates a complex stress–strain environment that cannot be adequately described by simplified homogeneous models. Under such conditions, overly conservative slope designs increase stripping volumes and reduce economic efficiency, whereas insufficiently justified steep slopes may result in unacceptable geotechnical risks. Therefore, reliable pit-wall design requires detailed geomechanical analysis incorporating realistic geological structures, appropriate strength criteria, and advanced numerical modeling techniques.

At the same time, the efficiency of deposit development depends not only on slope stability but also on the technological behavior of ores during beneficiation. The granulometric composition of mined material and the degree of mineral liberation directly influence processing performance. This is particularly relevant for weathering-crust REE ores, where valuable components are often associated with fine-grained clay fractions, iron-bearing phases, and complex mineral aggregates. Under such conditions, selective disintegration, efficient desliming, and targeted gravity concentration are essential for improving concentrate quality and recovery. Consequently, mining and processing stages should be considered as an integrated system. Pit geometry, fragmentation, ore disintegration, desliming, and concentration form a unified technological chain that determines the overall technical and economic efficiency of deposit development [4–6].

A review of international practice shows that slope design in weathering-crust formations is typically conservative. At deposits such as Mount Weld and Serra Verde, overall slope angles are often limited to 25–35° due to the low strength, high porosity, and plasticity of clay-rich materials. Classical geotechnical studies have demonstrated that neglecting post-peak behavior and residual strength can lead to significant errors in stability assessment. More recent research using nonlinear strength criteria and numerical methods indicates that finite-element and finite-difference approaches provide a more realistic representation of stress redistribution, progressive failure, and hydrogeological effects than conventional limit-equilibrium methods alone.

However, the existing literature on REE-bearing weathering-crust deposits is largely fragmented. Most studies focus either on mineralogical and metallurgical aspects or on geotechnical stability, treating these domains independently. Limited attention has been given to integrated approaches that simultaneously consider geological heterogeneity, slope geometry, fragmentation conditions, mineral liberation, and processing efficiency. This gap is particularly critical for weathering-crust deposits, where both slope stability and beneficiation performance are highly sensitive to moisture conditions, clay content, and structural variability [7–9].

Accordingly, the main research gap addressed in this study is the lack of an integrated methodological framework that simultaneously (i) substantiates geomechanically stable and economically efficient pit-wall parameters for weak, heterogeneous, and water-sensitive rocks, and (ii) evaluates the feasibility of producing a marketable REE concentrate from the same ore type using combined disintegration, desliming, and gravity beneficiation techniques [10–12].

The scientific novelty of this study lies in the integration of geomechanical slope optimization and beneficiation process evaluation within a unified framework for the Kundybay weathering-crust deposit. Unlike conventional approaches that consider mine design and ore processing separately, this study combines: (i) three-dimensional geological modeling and geotechnical domain delineation in the Micromine environment; (ii) numerical stability analysis of pit slopes under structurally heterogeneous and water-sensitive conditions using Slide2 and complementary modeling tools; and (iii) experimental testing of difficult-to-process REE ores using ultrasonic aerohydraulic desliming and a proprietary vibro-centrifugal gravity separation device.

The aim of this study is to develop and substantiate an integrated methodological framework for the efficient exploitation of the Kundybay REE deposit by combining geomechanical optimization of slope parameters with technological justification of beneficiation processes. To achieve this aim, the following research questions are addressed: (1) which pit-wall angles are geomechanically stable and economically justified under the specific conditions of the Kundybay weathering crust; (2) whether selective disintegration combined with desliming and gravity separation can produce a marketable REE concentrate; and (3) to what extent the integrated approach improves overall efficiency in terms of stripping reduction, economic benefit, and recovery of valuable components.

To answer these questions, the study includes comprehensive geological, mineralogical, and geotechnical characterization of the ore-bearing massif; identification of structural and geotechnical domains; numerical modeling of slope stability with consideration of hydrogeological effects and strength degradation; laboratory- and pilot-scale testing of ore processing using staged disintegration, desliming, and gravity concentration; and quantitative evaluation of the technical and economic performance of the proposed solutions.

The results demonstrate that the combined application of advanced geomechanical modeling and targeted beneficiation strategies provides a more reliable and efficient basis for the development of REE-bearing weathering-crust deposits than conventional approaches. The study contributes to both the methodology of open-pit design in weak heterogeneous formations and the development of processing technologies for complex REE ores, offering a scientifically grounded framework applicable to similar deposits worldwide.

2. Object and Subject of the Study

The object of this study is the rock mass of the Kundybay rare earth element (REE) deposit planned for open-pit mining. The study focuses on assessing pit-wall stability and substantiating rational slope angles under specific geological and geotechnical conditions. The subject is the stress–strain state of the rock mass and key controlling factors, including

structural heterogeneity, water sensitivity, and strength properties of the weathering crust. The aim is to justify geomechanically stable and economically efficient slope parameters for integrated deposit development. The deposit is located in the Zhitikara District, Kostanay Region, Kazakhstan, within a gently undulating plain (300–370 m elevation).

The Kundybay deposit is located in northern Kazakhstan (Figure 1), approximately 300 km from Kostanay and 50–70 km from Zhitikara. Favorable development conditions are determined by proximity to a railway station, availability of water from the Zhelkuar River, and existing power infrastructure, as well as regional mining expertise. Geologically, the deposit is confined to the junction of the Mariinskaya and Milyutinskaya synclines within the Kusakan uplift. REE mineralization is hosted in a 20–40 m thick Mesozoic weathering crust over Precambrian rocks. Ore zones average ~30 m in thickness (up to 67.8 m), with elevated heavy REE content (up to 26.7%), and exhibit complex, laterally fragmented distribution (Table 1).

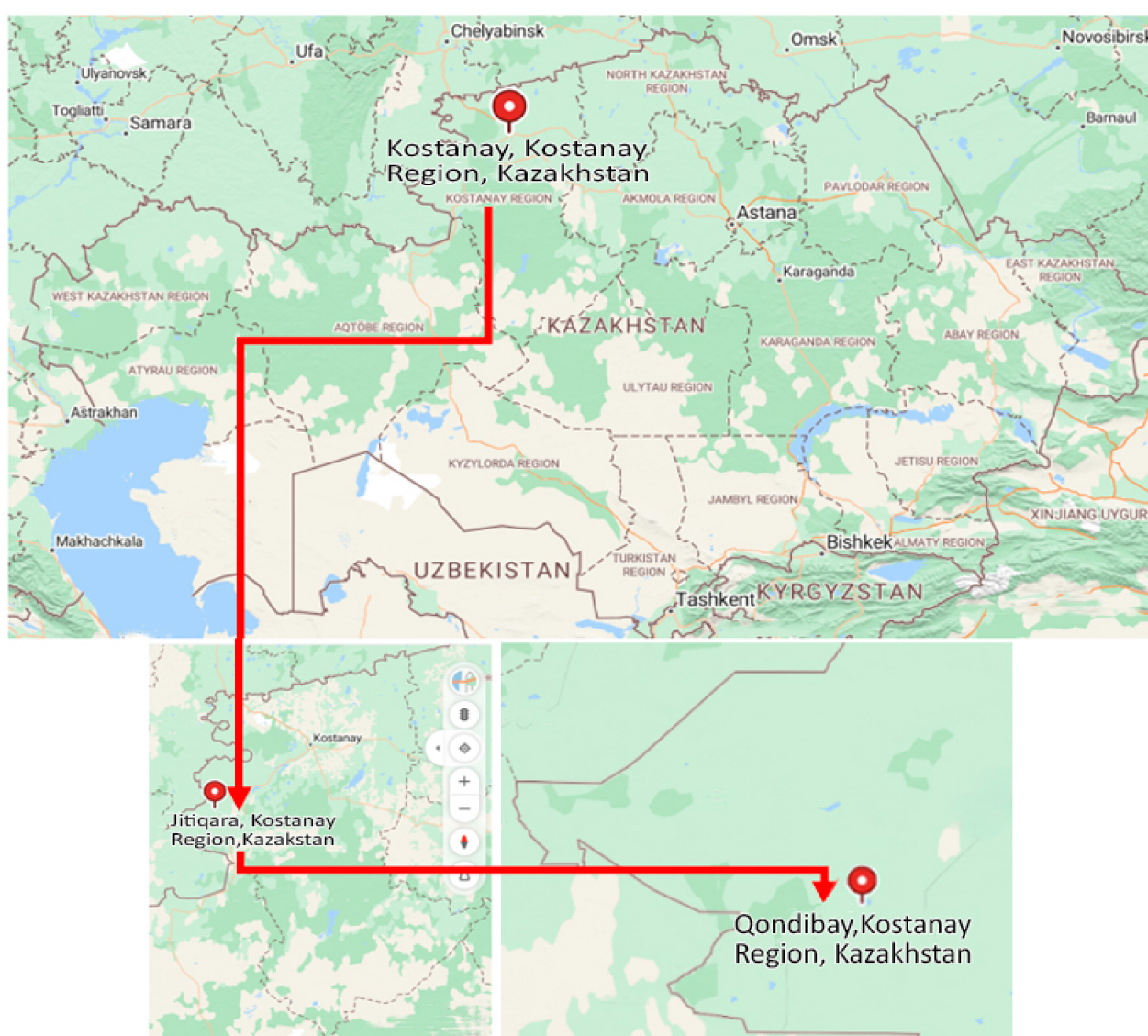


Figure 1. Location of the Kundybay deposit.

Kundybay ores have no direct industrial analogs in terms of composition and mining conditions, which required early technological studies by Soviet and Kazakhstani researchers. Despite being formally classified as a simple engineering–geological object, mining within the weathering crust involves significant geomechanical risks. The ore-

hosting massif consists of loose, clay-rich, weakly cemented rocks, posing major challenges for slope stability. The hydrogeological regime is critical, as clay shales exhibit high water sensitivity and swelling capacity (up to 84.7%), leading to strength degradation under saturation. In addition, low dry density (1.58–1.83 g/cm³) and high porosity (up to 50%) necessitate the use of nonlinear strength criteria in geomechanical modeling (Table 2).

Table 1. Distribution of total rare earth contents in lithological rock varieties across the ore bodies of the Kundybay deposit (within geological boundaries).

Ore Body	Amphibolites and Their Weathering Crust		Gneisses and Their Weathering Crust		Diabases and Their Weathering Crust		Shales and Their Weathering Crust		Total by Ore Bodies	
	%	Avg. Content. $\Sigma\text{TR}_2\text{O}_3$, %	%	Avg. Content. $\Sigma\text{TR}_2\text{O}_3$, %	%	Avg. Content. $\Sigma\text{TR}_2\text{O}_3$, %	%	Avg. Content. $\Sigma\text{TR}_2\text{O}_3$, %	%	Avg. Content. $\Sigma\text{TR}_2\text{O}_3$, %
Southern area of the first ore body	10.7	0.038	77.4	0.038	2.5	0.048	9.4	0.04	100	0.038
Northern area of the first ore body	8.2	0.03	28.4	0.029	3.2	0.037	60.2	0.03	100	0.030
Second ore body	89.7	0.035	9.9	0.03	0.4	0.015	-		100	0.034
Third ore body	41.2	0.034	44.0	0.028	8.3	0.039	6.5	0.034	100	0.032
Fourth ore body	9.7	0.039	66.7	0.033	3.9	0.035	19.7	0.031	100	0.033
Total for the deposit	20.3	0.036	58.8	0.035	3.0	0.04	17.9	0.033	100	0.035

Table 2. Physicomechanical properties of cohesive rocks.

No.	Parameter	Quaternary Clays and Loams (Tokhtarovskoye)	Quaternary Clays and Loams (Komarovskoye)	Miocene Clays (Komarovskoye)	Clayey Products of Weathering Crust (Komarovskoye)	Clayey Products of Weathering Crust (Tokhtarovskoye)	Clayey Products of Weathering Crust (Milyutinskoye)
1	Natural moisture, %	13.9–19.9/16.9 (2)	12.8–24.0/17.1 (6)	8.8–24.1/16.4 (21)	1.3–30.7/16.6 (84)	1.0–50.7/13.3 (73)	8.9–47.4/23.6 (19)
2	Density of mineral fraction, g/cm ³	2.63–2.64/2.635 (2)	2.50–2.76/2.64 (6)	2.54–2.89/2.69 (22)	2.70–3.18/2.87 (84)	2.60–2.92/2.70 (73)	2.58–3.76/3.08 (19)
3	Skeleton density, g/cm ³	1.69–1.77/1.73 (2)	1.57–1.92/1.73 (6)	1.48–2.03/1.80 (21)	1.45–2.81/1.83 (84)	1.17–2.16/1.78 (73)	1.26–2.22/1.58 (19)
4	Porosity, %	33.0–35.7/34.4 (2)	29.3–37.7/34.3 (6)	24.6–49.3/32.4 (21)	3.1–49.7/35.4 (84)	20.0–50.0/33.4 (72)	26.0–62.0/50.2 (19)
5	Swelling, %	12.6 (1)	8.5–26.4/15.4 (6)	4.4–30.5/16.0 (17)	0–60.2/10.9 (65)	1.8–31.4/12.6 (24)	8.3–84.7/23.6 (18)
6	Cohesion, 10 ⁵ Pa	0.55 (1)	0.23–0.90/0.58 (5)	0.17–2.00/1.15 (19)	0.10–2.10/0.73 (57)	0.20–2.30/1.10 (25)	0.30–1.23/0.823 (11)
7	Compressibility coefficient, 10 ^{−5} Pa ^{−1}	0.006 (1)	0.0073–0.0146/0.0110 (2)	0.0050–0.0408/0.0189 (15)	0.0037–0.0377/0.0171 (47)	0.003–0.019/0.0110 (22)	0.0031–0.0423/0.0127 (8)

Kundybay ores have no direct industrial analogs in terms of composition and mining conditions, necessitating dedicated technological studies. Although classified as a simple engineering–geological setting, mining within the weathering crust involves significant geomechanical risks. The massif is composed of loose, clay-rich, weakly cemented rocks, creating challenges for slope stability. Hydrogeological conditions are critical, as clay shales exhibit high water sensitivity and swelling (up to 84.7%), leading to strength degradation under saturation. Low dry density (1.58–1.83 g/cm³) and high porosity (up to 50%) require the application of nonlinear strength criteria in geomechanical modeling.

3. Integrated Methodology for the Investigation of Rare Earth Elements at the Kundybay Deposit

The integrated methodology for investigating REEs at the Kundybay deposit is a multi-stage framework combining mining geomechanics and mineral processing, based on an end-to-end design approach from pit stability to ore processing. The first stage focuses on geomechanical substantiation of rational pit-wall parameters for a clay-rich weathering crust dominated by kaolinite and illite. Slope stability analysis is critical for ensuring operational safety and improving economic efficiency through optimized slope angles.

The subsequent stage involves ore preparation and compositional analysis, including drying, homogenization, and sample reduction to obtain representative portions. Detailed mineralogical, X-ray phase, and microstructural analyses identify REE occurrence forms,

showing their concentration in fine-dispersed fractions associated with iron oxides and aluminosilicates.

The integrated methodology for investigating REEs at the Kundybay deposit is developed as a multi-stage framework (Figure 2) combining geomechanical substantiation (Stage I) with technological testing of ores (Stages II–III). The approach is based on end-to-end design, linking pit-wall stability with downstream processing efficiency.

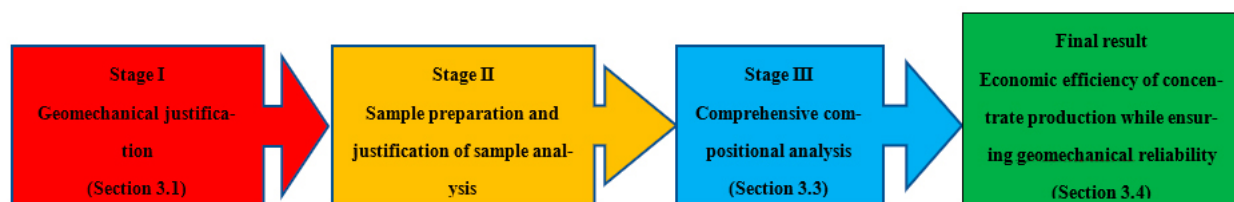


Figure 2. Flowchart of the integrated methodological framework for investigating the Kundybay.

At the initial stage (Section 3.1), a detailed geomechanical assessment is conducted. This is critical due to the loose and weakly consolidated nature of the weathering crust hosting the mineralization. Evaluation of physical and mechanical properties, together with slope stability calculations, allows the definition of safe and technically justified pit boundaries, forming the geotechnical basis for further analysis.

The next stage (Section 3.2) involves sample preparation and primary characterization. Representative material is subjected to crushing, grinding, homogenization, and staged reduction to obtain reliable analytical fractions, minimizing uncertainty in technological assessment.

A key component (Section 3.3) is comprehensive compositional analysis using ICP-MS, XRF, and SEM. These methods identify REE occurrence forms, size-class distribution, and mineral associations, providing the basis for beneficiation design. Technological testing includes desliming (removal of -0.045 mm fraction), where over 70% of REEs are concentrated, followed by heavy-liquid separation to determine optimal processing parameters.

The principal advantage of the approach lies in integrating geomechanical and technological criteria. This enables optimization of pit design with an economic benefit of 16.7% while maintaining required safety factors, thereby reducing risks and improving overall efficiency of deposit development.

3.1. Geomechanical Justification of Rational Open-Pit Wall Parameters at the Kundybay Deposit

For the geomechanical substantiation of rational pit-wall parameters (Stage I, Figure 2) at the Kundybay deposit, a multi-stage methodology combining digital modeling and numerical stability analysis was implemented, as shown in Figure 3.

At the first stage, a high-resolution integrated 3D geological model was developed in the Micromine (version 2023.5) software environment. The model incorporated the wireframes of the ore bodies (the Third and Fourth ore bodies) together with the block distribution of rare earth element grades, thereby providing the basis for subsequent geomechanical calculations.

For geomechanical substantiation of pit-wall parameters (Stage I, Figure 2) at the Kundybay deposit, a multi-stage methodology combining digital modeling and numerical stability analysis was applied (Figure 3). First, a high-resolution 3D geological model was developed in Micromine, integrating wireframes of the Third and Fourth ore bodies and block distributions of REE grades to support geomechanical calculations. Second, geological–structural zoning and representative calculation profiles (A–A, B–B, C–C) were defined to capture the most critical sections of the planned pit, including Quaternary sediments and weathering-crust materials. Third, the rock mass was modeled as an

elastoplastic medium with residual strength properties. Fourth, slope stability was analyzed in Slide2 using the limit-equilibrium method for angles between 30° and 50°, verifying factors of safety against regulatory requirements. Finally, geomechanical results were integrated with economic considerations, identifying 35° as the optimal pit slope angle, which ensures the required safety factor while minimizing stripping volumes. This multi-stage approach provides a technically sound and economically efficient basis for pit design in weak, heterogeneous weathering-crust rocks.

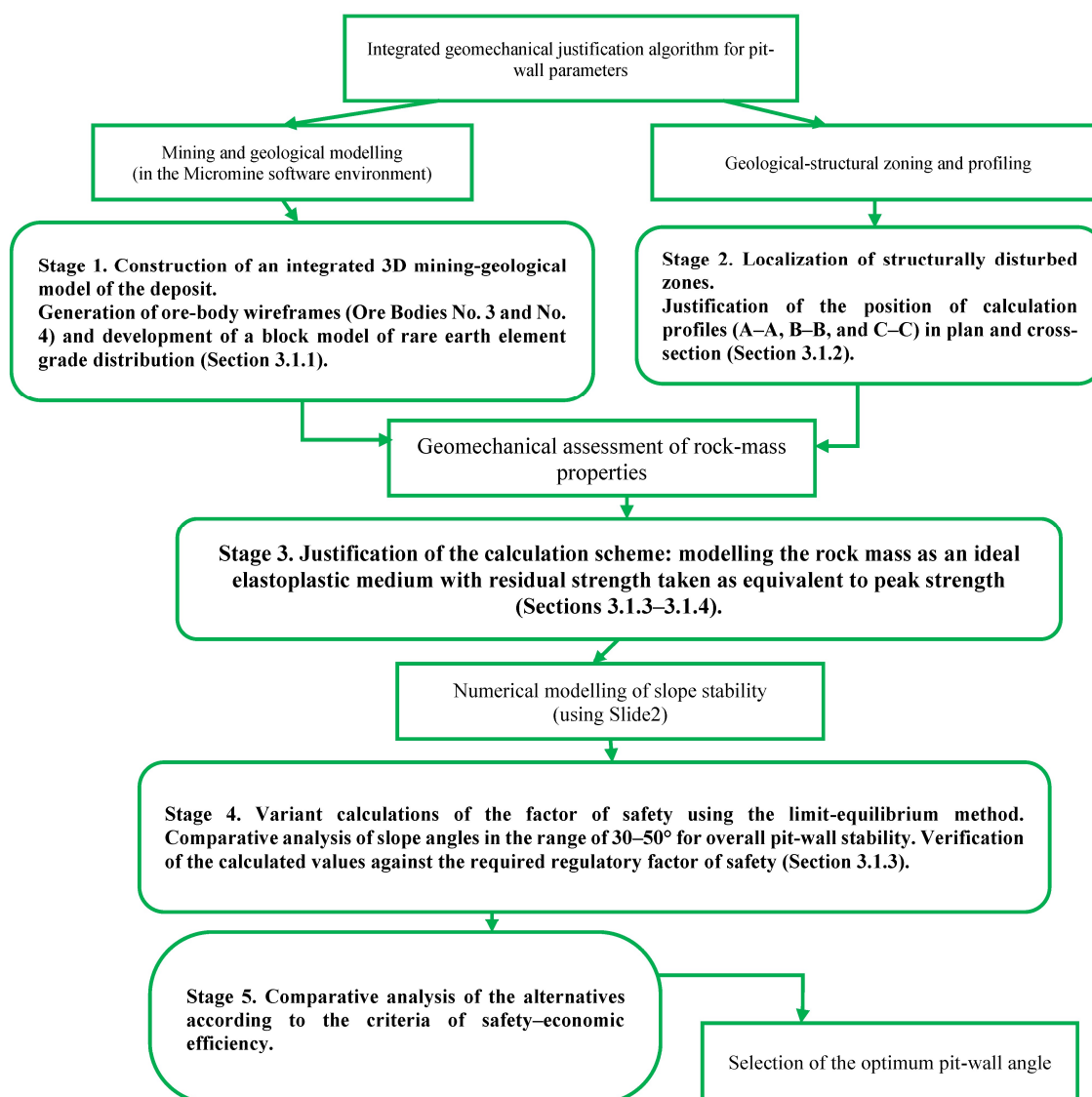


Figure 3. Algorithm for comprehensive geomechanical substantiation of open-pit wall parameters.

The geomechanical justification workflow (Figure 3) is based on iterative modeling in the environments. Within Stages 4 and 5, a variant analysis of slope angles was Micromine (v.2023) and Slide2 (v.9.00) software performed. The transition from the conservative design angle of 35° to the substantiated range of 45–55° (Stage 5) made it possible to achieve a direct reduction in stripping volume by 30 Mt. This result confirms the effectiveness of numerical modeling for identifying deformation-prone zones and optimizing pit-wall geometry.

3.1.1. Development of an Integrated 3D Model of the Kundybay Deposit in Micromine

The geomechanical justification workflow (Figure 3) relies on iterative modeling in Micromine and Slide2. During Stages 4 and 5, slope angles were analyzed, and increasing the design angle from the conservative 35° to a substantiated 45–55° range reduced stripping volumes by 30 Mt, demonstrating the effectiveness of numerical modeling in identifying deformation-prone zones and optimizing pit geometry.

For the integrated 3D model of the Kundybay deposit, geological and economic data from Asbestovoe GRP LLP (2021) were used, including maps, cross-sections, sampling plans, and reserve tables. Materials were georeferenced in Micromine, with borehole inclinometry data refined through visual verification. A total of 14,213 data points from 817 boreholes supported modeling. In the Third ore body, the weathering crust overlies mainly gneisses (41%) and amphibolites (44%), with rare earth oxide contents increasing from amphibolites (224 g/t) to gneisses (244 g/t) and shales (372 g/t), reflecting a consistent stratigraphic pattern.

Originally, four ore bodies were identified, with the First and Second fully mined out. The Third and Fourth ore bodies are under industrial development, and the Third ore body was selected as the main focus for this study, serving as the basis for geomechanical and technological assessment (Figure 4).

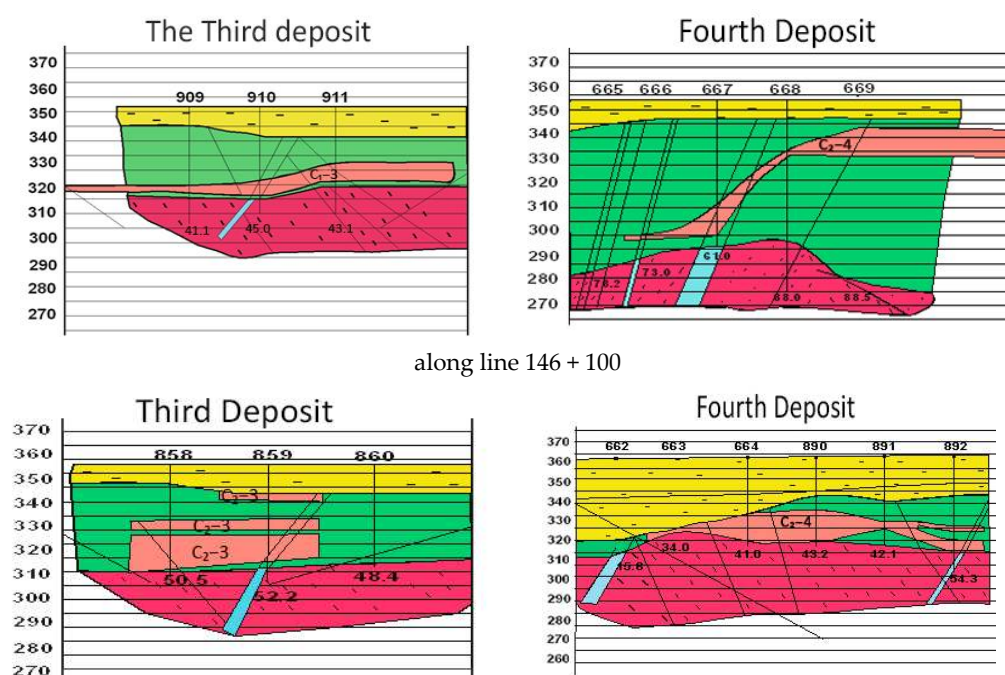


Figure 4. Geological cross-sections of the Third and Fourth ore bodies along lines 146 + 100 and 147 + 150.

Analysis of the block models shows that the Second ore body has the most uniform distribution of yttrium and rare earth oxides, with a thickness of 20–25 m, making it the most laterally consistent unit within the deposit (Mining Plan, 2020–2021). In contrast, the Fourth ore body exhibits high variability, with elevated yttrium and REE zones (0.06%–0.09% and higher) mostly in the upper horizons and no clear spatial pattern.

The Third ore body, the focus of this study, displays pronounced heterogeneity. High-grade zones are concentrated in the middle and lower horizons, while the upper part mostly falls below the cutoff grade (<0.03%). REE content increases with depth, and the ore-body thickness varies from 40 to 55 m. The integrated 3D mining–geological model of the Kundybay open pit uses a color scheme to visualize host rock composition and origin. Mafic metamorphic rocks (amphibolites) are shown in green shades, with tonal

variations distinguishing leucocratic and melanocratic types. The gneiss complex is pink to reddish, with hatching indicating biotite to garnet-bearing varieties and red patches reflecting fenitization. Lilac and violet denote schists and serpentinites, the latter marking major tectonic zones.

The spatial correlation between REE-enriched zones and host amphibolites and gneisses provides a basis for interpreting ore-body morphology and optimizing mining parameters, accounting for pronounced geological heterogeneity and geochemical variability. This understanding supports targeted extraction and efficient pit design under complex deposit conditions.

The block–wireframe model serves as a digital twin of the Kundybay deposit, supporting reserve re-evaluation and pit-wall stability analysis (Figure 5) by accounting for actual excavation geometry and geological heterogeneity. Figure 6 presents an integrated wireframe of the Third and Fourth ore bodies within the designed open pit, illustrating the transition from a static geological model to dynamic mine planning. Red denotes the host massif, yellow and beige indicate Quaternary and weathering-crust horizons, and blue shows the mined-out pit volume.

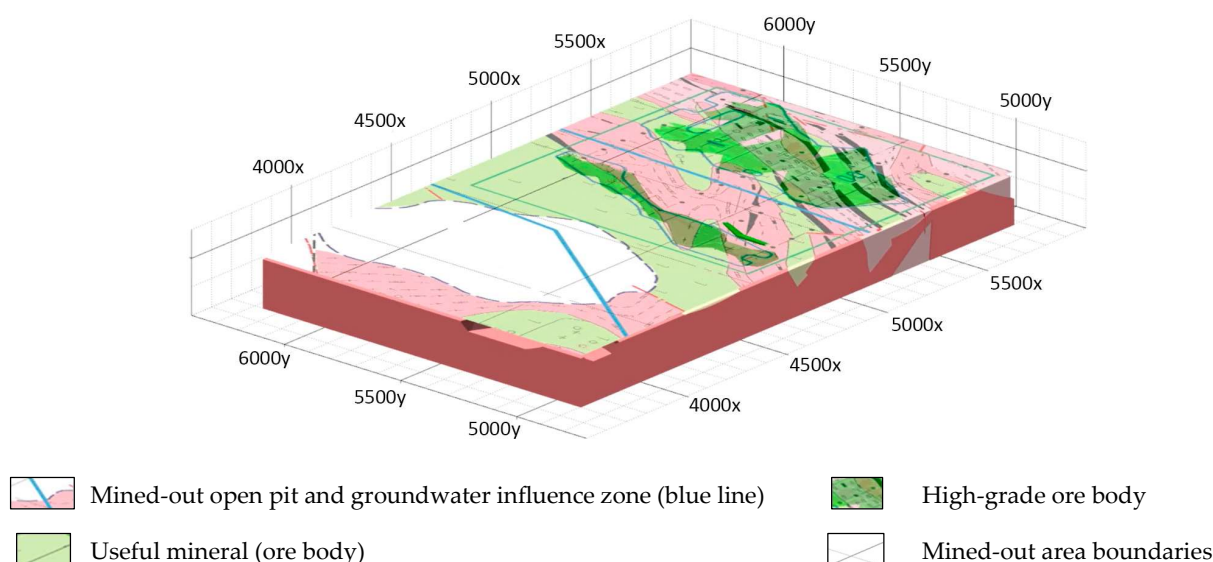


Figure 5. General integrated 3D model of the mining–geological space of the Kundybay open pit.

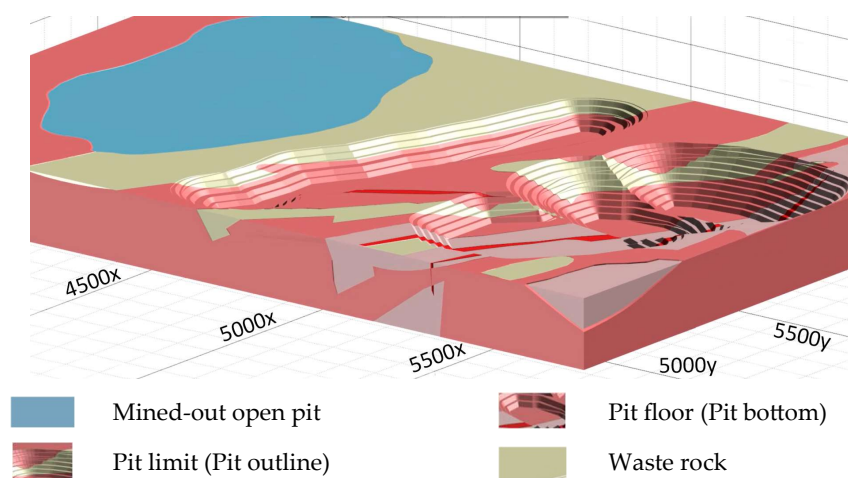


Figure 6. Wireframe model of the Third and Fourth ore bodies within the current open-pit contour.

The 3D wireframe model (Figure 6) visualizes ore morphology isolated from the geological background for precise analysis. The Third ore body (dark blue) is elongated and aligned with tectonic zones and the axial weathering crust, while the Fourth ore body (light blue) is lens-shaped, reflecting supergene REE distribution influenced by parent-rock type. This wireframe defines the digital boundaries of the ore bodies (Figure 7). Combined with a digital terrain model based on recent geodetic surveys, it provides a complete 3D representation of the Third and Fourth ore bodies within the current pit contour.

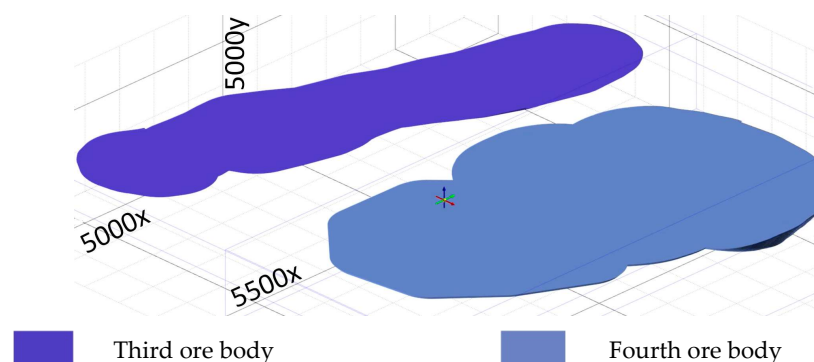


Figure 7. Wireframe model of the Third and Fourth ore bodies defining their spatial position at the Kundybay deposit.

The next step involved constructing a block model constrained by the wireframes, enabling spatial interpolation of REE grades. A fragment of the Third ore body block model illustrates the distribution of total yttrium and rare earth oxides. Analysis of the longitudinal section (Figure 8) confirms a key characteristic: the systematic increase in grade with depth. This block model provides a quantitative basis for ore-body evaluation and supports subsequent geomechanical and technological assessments for efficient pit design and resource extraction.

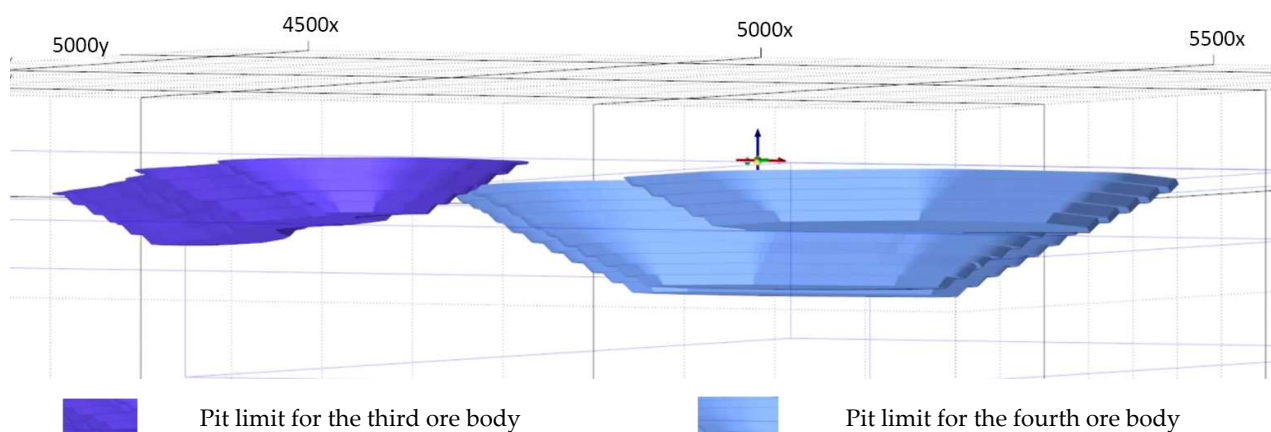


Figure 8. Longitudinal section of the block model of the Third and Fourth ore bodies, showing the distribution of total yttrium and rare earth oxide contents.

The next step involved constructing a block model constrained by the wireframes, enabling spatial interpolation of total yttrium and rare earth oxide grades. A fragment of the Third ore body model (Figure 8) illustrates grade distribution, confirming the systematic increase in REE content with depth. Using over 14,000 geological data points in Micromine, a refined digital geotechnical model was developed, integrating borehole inclinometry and weathering-crust data. Structural-domain analysis showed that existing faults do not promote pit-wall failure, supporting slope steepening to 45–55° and reducing stripping volumes.

Micrographs and EDS elemental maps (Figure 9) reveal the heterogeneous structure of weathering-crust ore. The main matrix consists of dispersed kaolinite–illite aluminosilicates, with Fe and Ti oxide microinclusions. Grain morphology is dominated by angular, irregular particles up to 0.2 mm, reflecting advanced hypergene alteration. Rare earth elements (Sm, Eu, Gd, Dy, Ho, Tm, Yb) occur both in discrete REE micro-minerals and as a dust-like, ion-adsorbed fraction associated with clay surfaces. These observations confirm two key forms of valuable components, providing a critical basis for designing beneficiation processes and optimizing recovery in the weathering-crust ores.

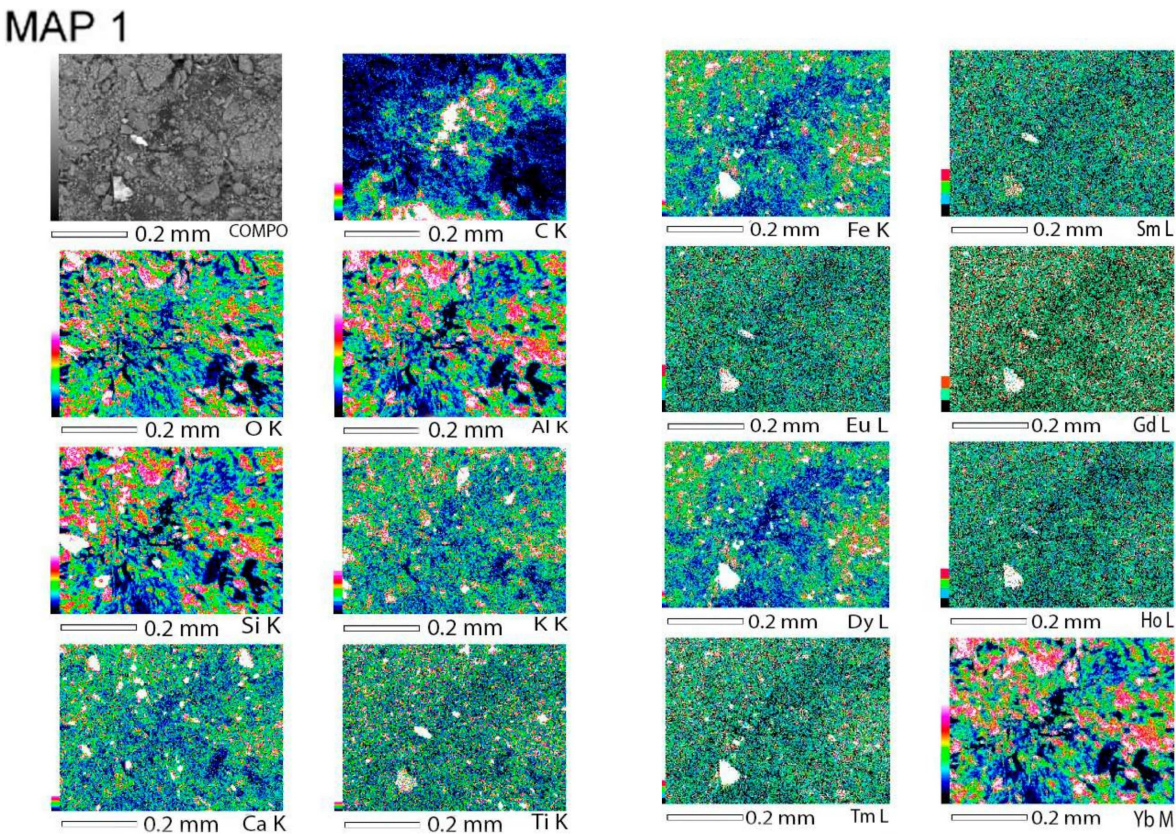


Figure 9. Results of EDS mapping of the samples.

Based on the integrated interpretation of the elemental distribution maps and EDS spectra, the principal mineral phases and the main morphological characteristics of the ore were identified. The summarized results of the elemental diagnostics of the different sample regions and their mineralogical interpretation are presented in Table 3.

Table 3. Elemental composition and mineralogical interpretation of the identified phases based on EDS mapping results.

Region/Phase Designation	Identified Elements (EDS)	Interpreted Mineral Composition	Distribution Characteristics and Morphology
Region A (Matrix)	Si, Al, O, (K, Mg)	Kaolinite, illite, aluminosilicates	Fine-dispersed mass forming the main matrix of the weathering-crust host rock.
Region B (Microinclusions)	Ce, La, Nd, P, (Ca)	Monazite, REE fluorocarbonates	Point-like high-contrast inclusions, 5–20 μm in size, associated with phosphorus.
Region C (Oxide phases)	Fe, Ti, Mn, O	Hematite, ilmenite, manganese oxides	Patchy accumulations and replacement rims around grains of primary minerals.
Region D (Heavy minerals)	Zr, Si, O	Zircon	Idiomorphic grains with well-defined boundaries, resistant to chemical weathering.

Slight variations in weighted-average Σ REE content (307.73–320 g/t) were observed due to experimental factors, such as sieve analysis of bulk samples and desliming of crushed material. Variations within 3%–4% are acceptable for heterogeneous weathering-crust REE ores. The 3D block model refines both geometry and REE grades, providing a detailed view of spatial distribution, valuable-component localization, and ore-zone delineation within specific geological and lithological settings.

3.1.2. Investigation of Deformation-Prone Zones at the Kundybay Deposit (Third Ore Body)

Geomechanical analysis focused on the Third ore body within the fault-influenced zone, a key risk for mine design. Using the Micromine block-wireframe model with imported fault geometry, results showed the fault redistributes stress, concentrating strain and reducing rock mass strength locally, creating zones of decreased stability that must be considered in pit-wall design (Figures 10 and 11).

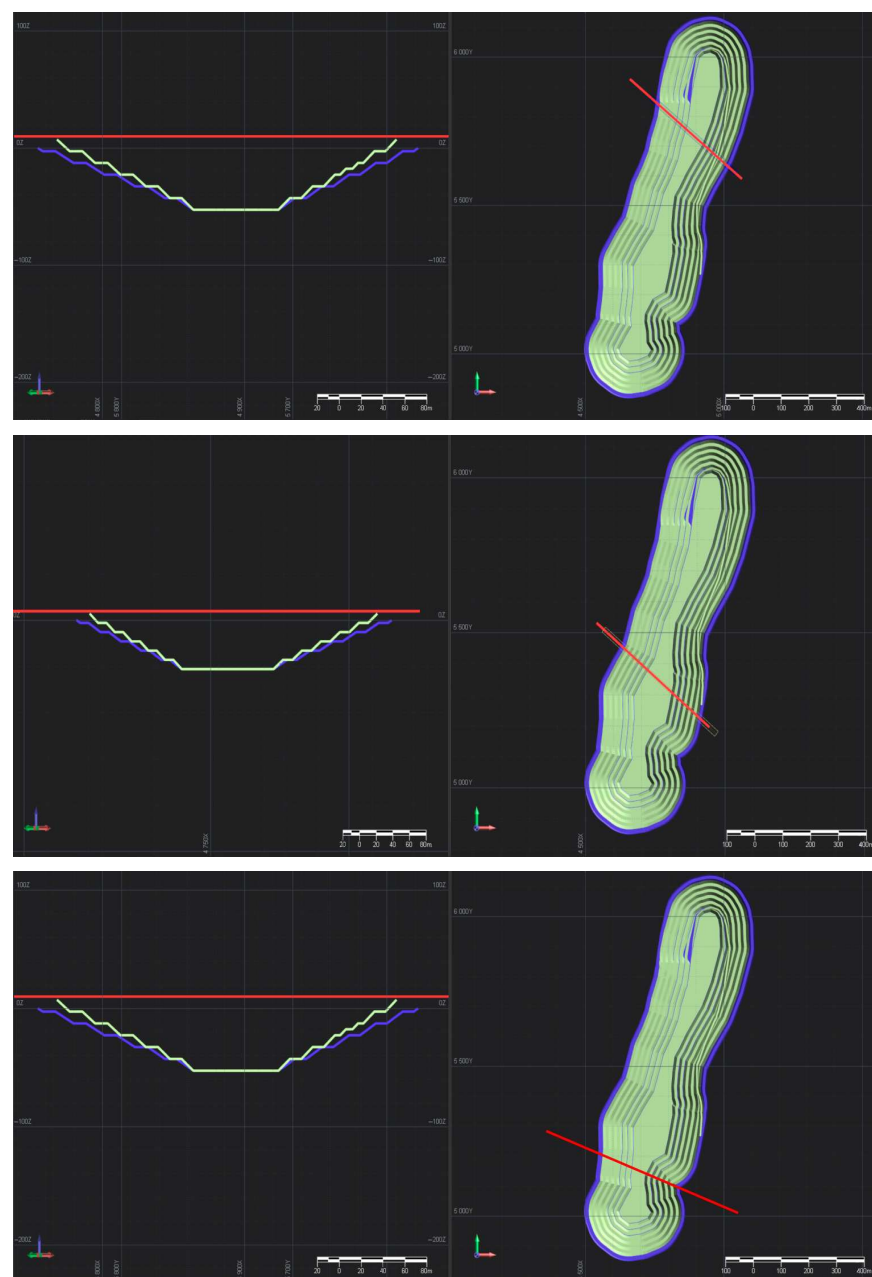


Figure 10. Graphic layout of the transverse sections in plan view and cross-section in the Micromine software environment.

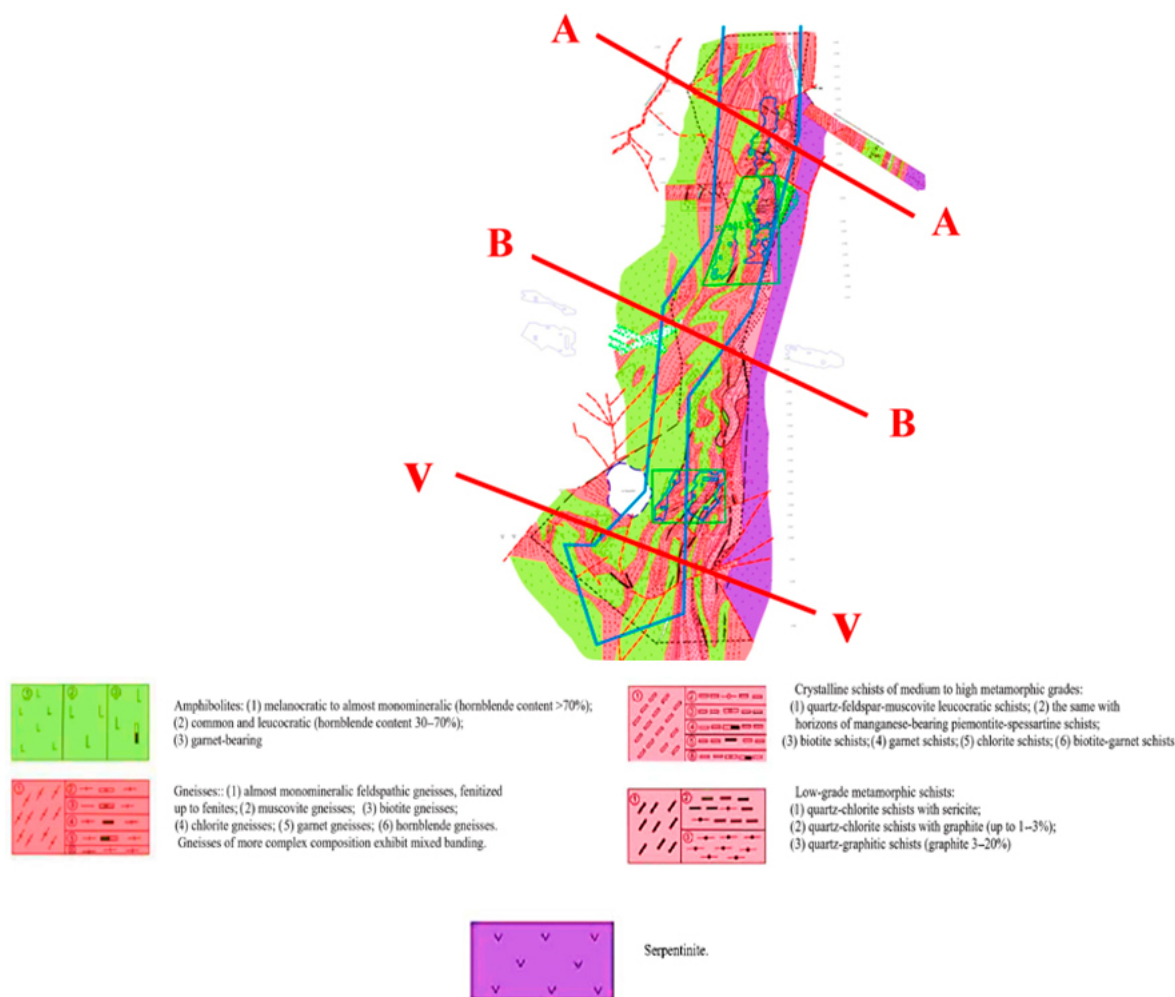


Figure 11. Geological–structural cross-section of the Third ore body with legend and profile lines (A–A, B–B, and V–V) selected for stability analysis (scale 1:200,000).

Figure 12 shows the plan-view scheme used for the subsequent stage of the investigation, including the profile lines (A–A, B–B, and V–V) selected for detailed geomechanical analysis. The selected profiles intersect the zones expected to be most critical in terms of stability, including structurally disturbed sectors and areas influenced by the tectonic fault crossing the ore body. According to the block model interpretation, these sections represent the most stress-sensitive parts of the projected pit and therefore provide the most representative basis for detailed stability assessment.

The integrated 3D model unified static geological data and dynamic mining calculations, transforming information from 817 boreholes into a coherent geotechnical framework. High-resolution ore-body and host-rock wireframes enabled verification of tectonic influences on rock mass stability and supported evidence-based optimization of pit-wall angles. This geotechnical analysis substantiated rational bench and pit-wall slopes (35° and 45°) while accounting for geological and strength heterogeneity, using critical sections (profiles A–A, B–B, and V–V) defined during 3D modeling (Figure 12).

Figure 13 compares two pit-wall options along profile A–A. The pink line shows the existing, gentler slopes, designed for extra stability but increasing stripping volumes. The blue line represents the geotechnically optimized contour, with slopes up to 35° in the middle horizons. This adjustment, supported by refined rock properties and sufficient load-bearing capacity even in weathered zones, reduces non-productive stripping while maintaining the required factor of safety, providing the reported economic benefit.

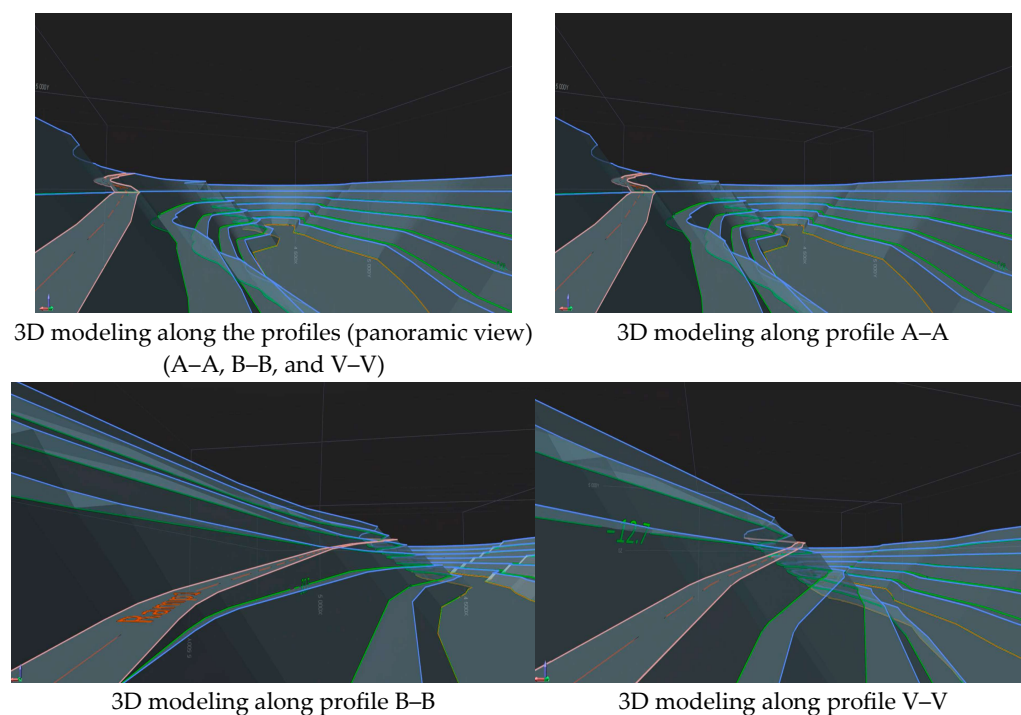


Figure 12. Results of predictive modeling and the influence of the tectonic fault along the selected profiles.

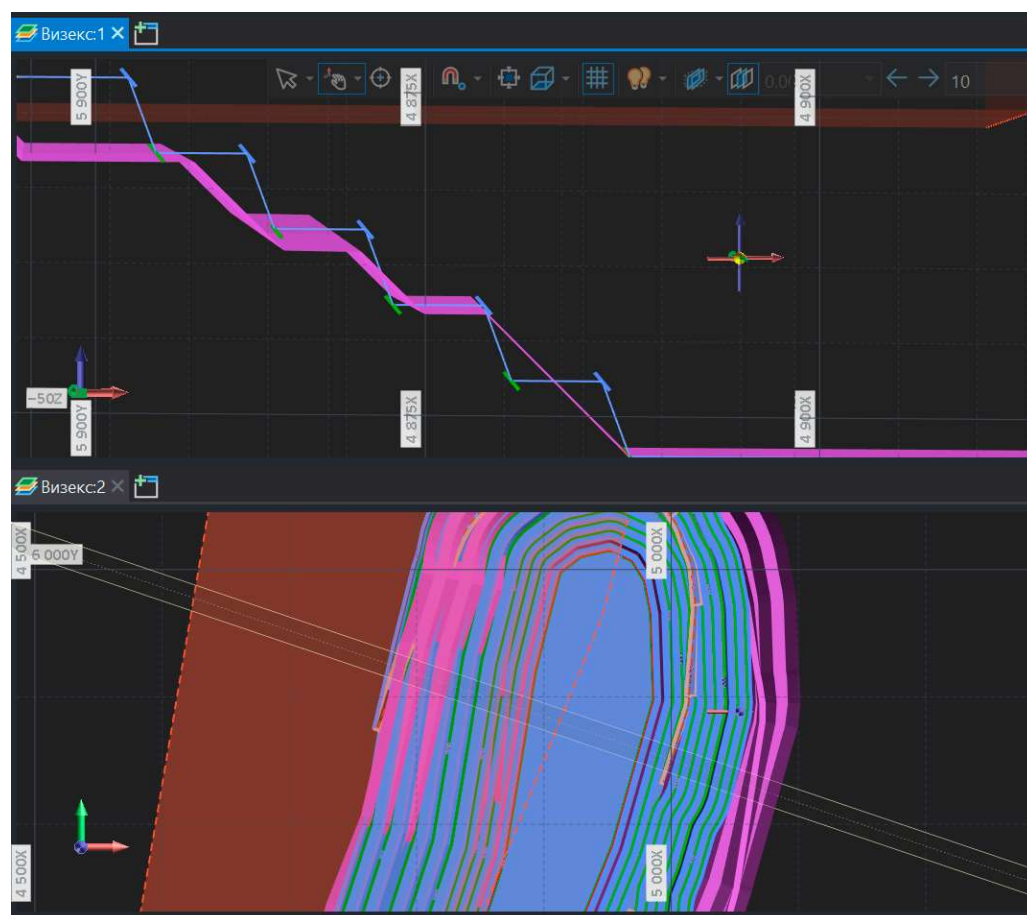


Figure 13. Comparison of the geometric parameters of the pit wall along profile A-A at a slope angle of 35°: the pink line indicates the current design contour, and the blue line shows the recommended optimized contour.

Figure 14 presents geotechnical modeling of profile A–A with a 45° pit-wall slope. The vertical cross-section shows clearly benched geometry, with base elevations marked at 4800Y, 4900Y, 5000Y, and 5100Y, allowing precise positioning of calculation points. The plan-view projection displays multicolored contours (green, blue, violet) representing bench crests and toes, confirming the spatial configuration and geometric proportions of the optimized pit wall. Analysis indicates 30–35° slopes for depths up to 30–35 m due to Quaternary deposits, with improved rock properties below 40 m. Bench modeling shows minimal effect of slope changes on failure, but detailed geomechanical assessment identified three priority sections for factor-of-safety calculations, focusing stabilization efforts where needed.

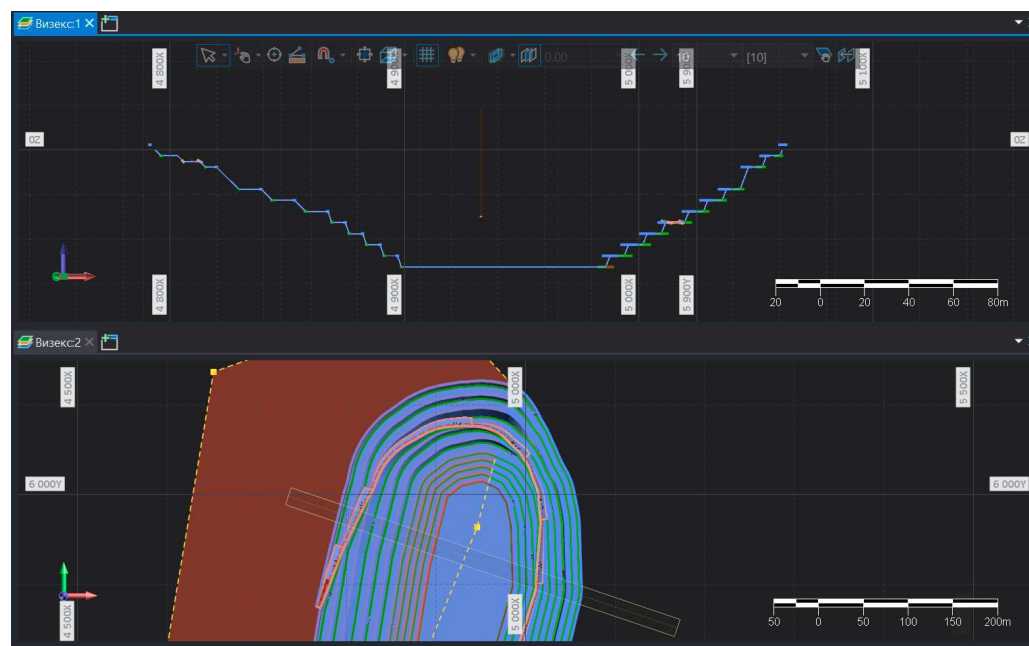


Figure 14. Results of spatial modeling of the optimized open-pit contour along profile A–A with a resulting pit-wall slope angle of 45°: **Top**—Vertical cross-section with elevation marks; **bottom**—plan view of the open pit showing the position of the calculated profile and coordinate reference. Slope angle 45° (A–A).

3.1.3. Geotechnical Analysis of Rock Mass Stability Using Numerical Modeling

The Kundybay deposit is planned for open-pit mining, with separate pits for each ore body, justified by simple engineering–geological conditions and limited initial stripping volumes. According to the State Reserves Commission Protocol No. 1192 (22 May 2012), 49,308 kt of REE ore is recoverable, including 36,008 kt from ore bodies 3 and 4. Mining is designed down to the 250 m horizon, with surface boundaries accounting for wall flattening and platform widths. The Third ore body (strike 920 m, width 50–200 m) lies west of the Fourth ore body (strike 850 m, width 250–500 m). Average rock density is 2.2 t/m³ with 14% moisture. Bench slopes are 30–35°, overall pit-wall angles 32°, bench height 5 m, and platform width 20 m (Tables 4 and 5).

Table 4. Depths of the designed open pits at the Kundybay deposit.

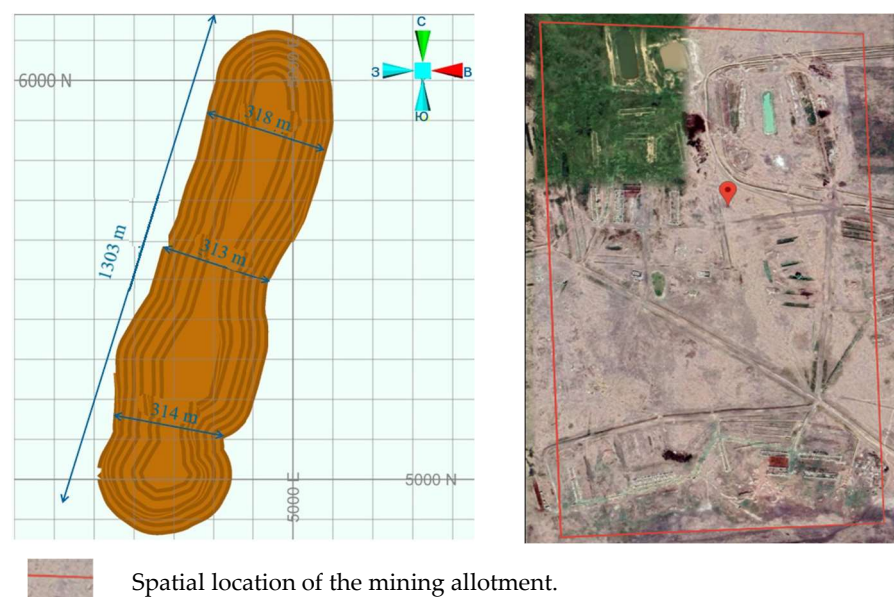
No.	Open Pit Name	Design Pit Depth
1	First ore body (Open pit 1)	20 m
2	Second ore body (Open pit 2)	40 m
3	Third ore body (Open pit 3)	60 m (146 + 100)
4	Fourth ore body (Open pit 4)	80 m (147 + 150)

Table 5. Main open-pit parameters.

No.	Parameter	Unit	Value
1	Slope angle of working benches/non-working benches	deg	30–35/32
2	Operating losses	%	6
3	Dilution	%	6
4	Ore bulk density	t/m ³	2.2
5	Average stripping ratio	m ³ /t	1.6
6	Swell factor	-	1.15
7	Mine life to exhaust industrial reserves	years	15

3.1.4. Justification of the Modeling Calculation Scheme and Geotechnical Analysis of Open-Pit Slope Stability

For the geotechnical analysis, three transverse sections were selected to examine the steepest and highest slopes, considering the presence of weaker zones affected by faulting. The cross-sections were generated using Datamine (version 1.13.202.0, Datamine Software Limited, London, UK), a mine-planning software package. The main parameters of the 3D plan-view projection of the Kundybay open pit and the spatial location of the mining lease area are shown in Figure 15.

**Figure 15.** Left—Main parameters of the 3D plan-view projection of the “Kundybay” open pit.

Pit-wall stability was evaluated using the limit-equilibrium method (Slide2) and finite-element method (RS2), optimizing slope geometry for a factor of safety of 1.3. Calculations accounted for hydrostatic pressure and free-drainage conditions; no significant water inflows are expected, with precipitation managed by drainage ditches. With an average rock density of 2.2 t/m³ and 14% moisture, the deposit is classified as simple mining conditions (Development Group I, Type II). Cross-sections A–A, B–B, and V–V were established to assess pit and haulage ramp stability (Figures 16 and 17, Table 6).

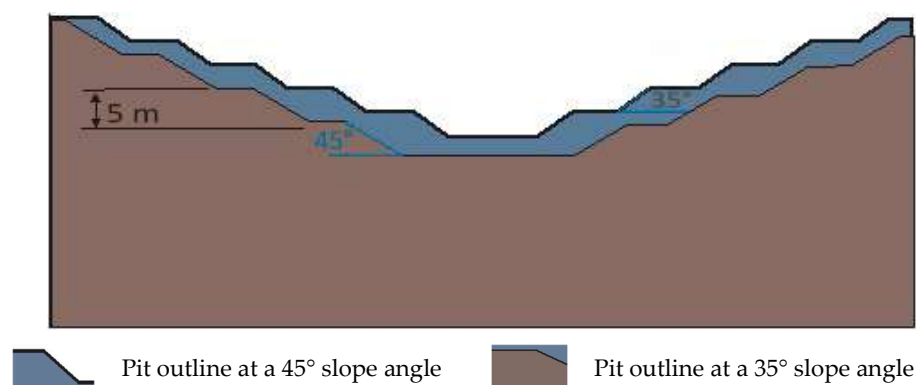


Figure 16. Investigated open-pit contours.

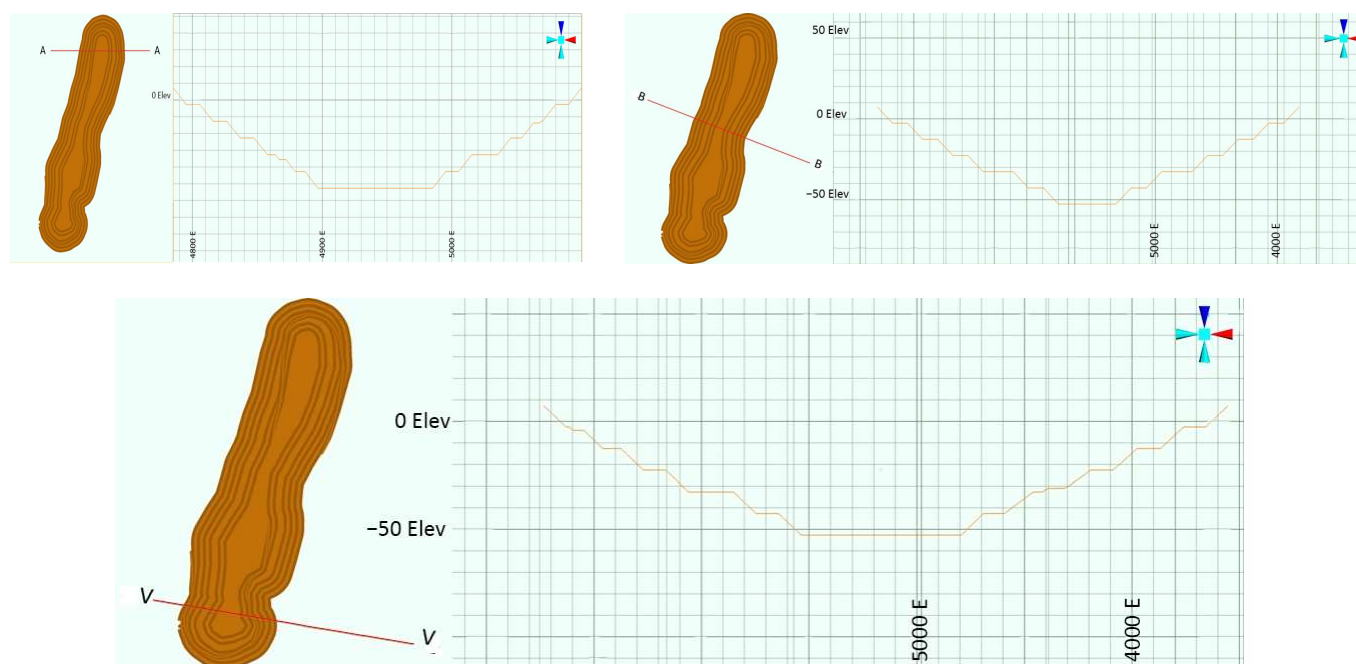


Figure 17. Graphical location of the cross-sections in plan view and in section.

Table 6. Coordinates of cross-section points.

Cross-Section	Start Point x	Start Point y	End Point x	End Point y
A–A	4814.074	5998.667	5100.724	5950.538
B–B	4708.971	5653.275	5000.925	5597.362
V–V	4554.839	5334.448	4929.802	5301.567

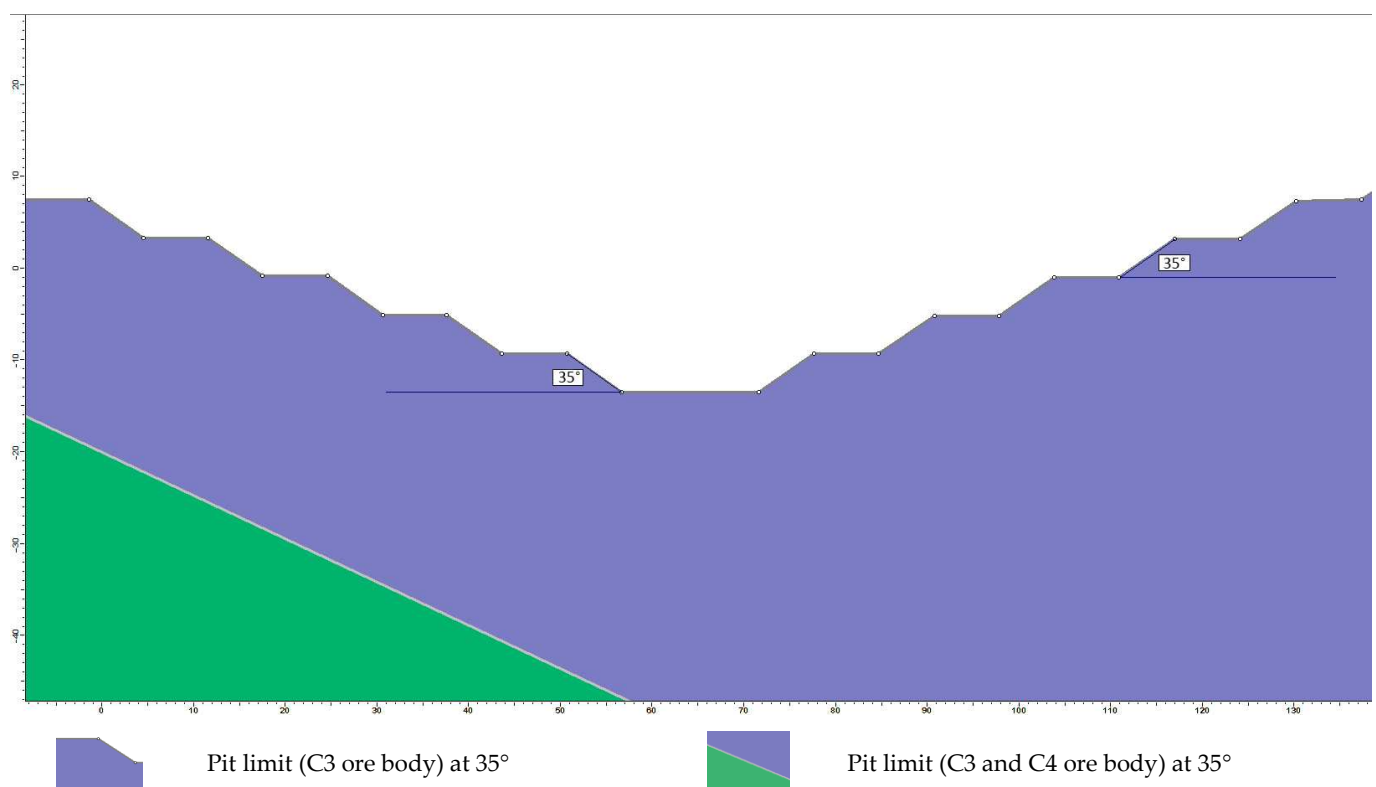
3.1.5. Geotechnical Structural Domains and Calculations in Slide2

For detailed slope optimization and FoS calculation, Slide2 was applied to specific structural–geotechnical sectors with elevated deformation risk. In weathered gneiss and amphibolite zones, critical circular–cylindrical slip surfaces were identified, justifying slope angles of 45–55° without large-scale rock extrusion. For the western wall, pore-water pressures in lacustrine deposits were considered to design berms ensuring FoS = 1.30. In the geologically heterogeneous eastern wall, non-circular Janbu analysis addressed marginal FoS values (0.990–1.256). Incorporating the anthropogenically weakened Zone D (up to 100 m depth) and upper weathered layers (15–20 m) with conservative strength parameters allowed translation of geological data into engineering design while maintaining stability (Table 7).

Table 7. Design physical and mechanical properties of soils and rocks.

Geotechnical Domain	Density, γ (g/cm ³)	Cohesion, c (kPa)	Internal Friction Angle, ϕ (°)	Deformation Modulus, E (MPa)	Deformation Modulus, E (MPa)
Quaternary deposits	2.03	55	18	48.0	0.34
Miocene clays	2.02	58	15	100.5	0.34
Weathering-crust products	2.10	115	22	48.9	0.32

The geotechnical stability of Kundybay pit walls was assessed using three representative transverse sections (A–A, B–B, V–V) featuring the greatest slope heights and potentially weak zones. Cohesion values of 55–58 kPa were adopted for Quaternary deposits and Miocene clays, while weathering-crust materials had 115 kPa at 2.10 g/cm³, reflecting lithological heterogeneity. A quadrilateral finite-element mesh with local refinement in expected deformation zones was applied, with full fixation at the base and restricted lateral displacements. Slide2 was used for limit-equilibrium analysis (GLE/Morgenstern–Price) with the Cuckoo Search algorithm to identify critical slip surfaces. An anthropogenic disturbance zone (D) up to 100 m depth simulated blasting effects. Two pit geometries were compared: Variant 1—Conservative 35° slope (Figure 18); Variant 2—Optimized 45° slope (Figure 19).

**Figure 18.** Variant 1. Geometric and parametric model of the design pit contour (slope angle 35°).

Stability modeling was performed in two stages: first, wireframe models were generated for 35° and 45° slopes; second, geotechnical domains were parameterized for rock mass plasticity. Variant 1 (35°) showed excessive stability (FoS = 1.40–1.55), increasing stripping volumes unnecessarily. Variant 2 (45°) maintained western-wall stability, while eastern-wall analysis (Janbu method) revealed local risk zones with FoS = 0.990–1.256. Table 8 quantifies these results, highlighting the need for targeted bench adjustments to optimize slope angles within the regulatory FoS range (1.1–1.3).

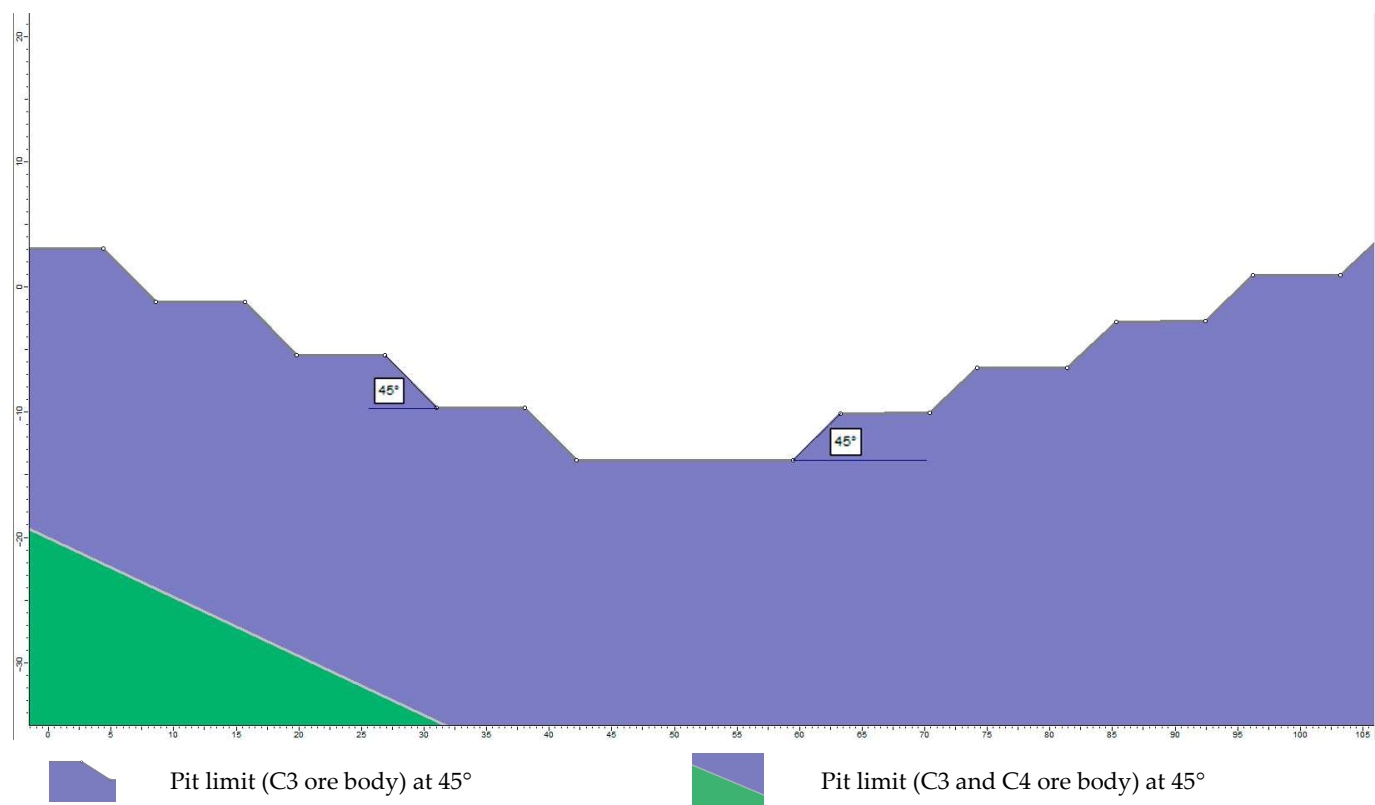


Figure 19. Variant 2. Geometric and parametric model of the design pit contour (slope angle 45°).

Table 8. Summary results of the stability modeling.

Modeling Parameter	Variant 1 (Design Case)	Variant 2 (Design Case)
Pit-wall slope angle	35°	45°
FoS (western pit wall)	1.40–1.55	1.30
FoS (eastern pit wall)	>1.30	0.990–1.256
Recommendation	Excessive stability margin	Optimal, subject to local refinement

Transitioning to Variant 2 (45°) achieved an optimal balance of safety and economic efficiency. For the western wall, despite water-saturated lacustrine deposits, FoS remained 1.30, meeting safety requirements. On the eastern wall, Janbu analysis identified local benches with FoS = 0.990–1.256, requiring targeted berm or bench adjustments. Overall, Variant 2 improves profitability while maintaining controllable geomechanical risk.

3.2. Assessment of the Beneficiation Amenability of Rare Earth Ores Based on Their Mineralogical, Physicochemical Properties

The transition from geomechanical justification of pit-wall parameters to the technological development cycle of the Kundybay deposit requires ensuring the representativeness of the ore sample for subsequent analyses. Given the high clay content and heterogeneity of the rock mass, the ore preparation methodology was designed to preserve the natural characteristics of the material during mechanical disintegration. The initial stage (Step 1) involved receipt of 220 kg of rare earth ore (−80 + 0.0 mm), which was air-dried to prevent fine-particle agglomeration [13–15].

Technological sample preparation included repeated homogenization using the cone-and-quartering method, followed by staged reduction from 110 kg to 55 kg for sieve and sedimentation analyses. The ore was crushed and ground to −2.5 mm, providing a

representative basis for compositional analysis, including determination of REE occurrence forms using chemical and microstructural methods [16–18].

At the final stage, portions of 42.25 kg and 20.625 kg were allocated for desliming (removal of -0.045 mm fraction) and assessment of gravity beneficiation using heavy-liquid separation. This methodology ensures a consistent transition from macro-scale pit-stability investigations to microstructural and technological characterization, forming the basis for producing a marketable rare earth concentrate [19,20].

The beneficiation-testing methodology (Figure 20) was developed to address the poor amenability of weathering-crust ores to conventional processing. Step 4—ultrasonic desliming using the UAGD unit—effectively removed the fine -0.045 mm fraction, which negatively impacts gravity separation. Following the complete technological sequence (Step 5), a rare earth concentrate with an average Σ REE grade of 948.89 g/t was obtained at 45.66% overall recovery, demonstrating the practical effectiveness of the proposed flowsheet.

Integrated elemental and mineralogical studies confirm that Kundybay ores are of the ion-adsorption type within weathering crusts. Σ REE values in the samples range from 307.78 to 320.45 g/t, reflecting both natural heterogeneity and analytical variability. The highest-grade sample (320.45 g/t) was selected for detailed elemental profiling. Cerium dominates (155.765 g/t), with notable amounts of lanthanum (48.0 g/t), praseodymium (41.8 g/t), neodymium (26.09 g/t), and yttrium (14.12 g/t); the full distribution is shown in Table 9).

Table 9. Elemental composition of total REEs in the initial ore according to chemical analysis.

Element	Content (g/t)	Share in Σ REE (%)	Element	Content (g/t)	Share in Σ REE (%)
Ce (Cerium)	155.765	48.61	Dy (Dysprosium)	9.175	2.86
La (Lanthanum)	48.000	14.98	Gd (Gadolinium)	6.800	2.12
Pr (Praseodymium)	41.800	13.04	Tm (Thulium)	6.524	2.04
Nd (Neodymium)	26.090	8.14	Er (Erbium)	3.930	1.23
Y (Yttrium)	14.120	4.41	Sm (Samarium)	3.890	1.21
Yb (Ytterbium)	2.780	0.87	Eu (Europium)	0.874	0.27
Ho (Holmium)	1.030	0.32	Tb (Terbium)	0.722	0.23
Lu (Lutetium)	0.600	0.19	Σ REE	320.45	100.00

The elemental profile is dominated by the cerium group, with particularly high Ce (155.77 g/t), La (48.0 g/t), and Pr (41.8 g/t), alongside significant Nd and Y contents. Granulometric analysis of ore crushed to -2.5 mm showed that 70.65% of total REEs are concentrated in the ultrafine fractions (-0.02 mm). Although these fractions represent only 32.65% of the mass, their average REE grade reaches 667 g/t, justifying preliminary desliming.

XRD and IR spectroscopy indicate the mineral matrix consists mainly of illite (42.5%), quartz (30.6%), and kaolinite (21.2%), with associated phases including feldspars (oligoclase, anorthite, albite), calcite, and muscovite. Ore phases comprise goethite (2.5%), hematite, ilmenite (1.7%), and rutile. Chemical analysis confirms a silicate nature, with SiO_2 51.97%, Al_2O_3 24.7%, Fe_2O_3 3.29%, and minor K, Ca, and Ti oxides.

SEM and electron microprobe analysis show major elements (Al, Si, K, Fe) in oxide and aluminosilicate phases, while most REEs are dispersed, typical of ion-adsorption on clay surfaces. Element maps reveal La and Ce microlocalized in iron oxide particles, and WDS confirms microinclusions of Tb, Er, Ho, Tm, plus isolated grains of native platinum and Zn, Pb, Cu sulfides.

Analysis of the -0.045 mm fraction confirmed trace concentrations of nearly all lanthanides (Pr, Sm, Eu, Tb, Dy, Ho, Nd, Yb). The high dispersion of REEs and their close

association with clays necessitate a combined flowsheet involving deep disintegration, ultrasonic desliming, and subsequent gravity recovery of heavy mineral concentrates.

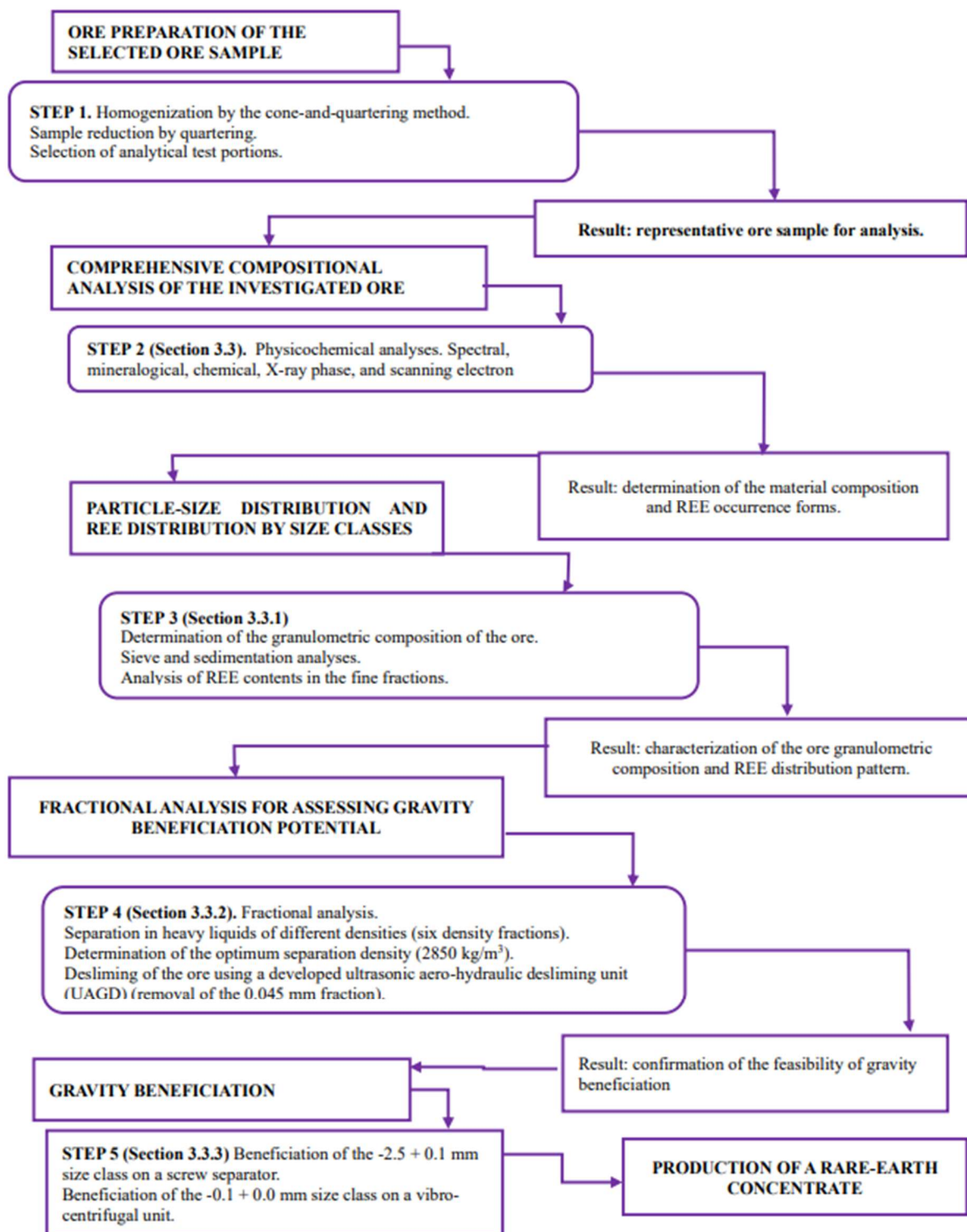


Figure 20. Methodology for assessing the beneficiation amenability of rare earth ores.

Preparation of the Initial Weathering-Crust Ore Sample

A 220 kg rare earth ore sample from the Kundybay deposit with an initial particle size of $-80 + 0.0$ mm was received for investigation. Before sample preparation, the material was dried to an air-dry state. The dried ore was then mixed, reduced, crushed, and ground in order to obtain representative portions for the following analyses and tests: sieve

analysis, sedimentation analysis, mineralogical analysis, fractional analysis, and gravity beneficiation testing. The sample preparation scheme for the initial 80–0.0 mm material intended for sieve and sedimentation analyses is shown in Figure 21.

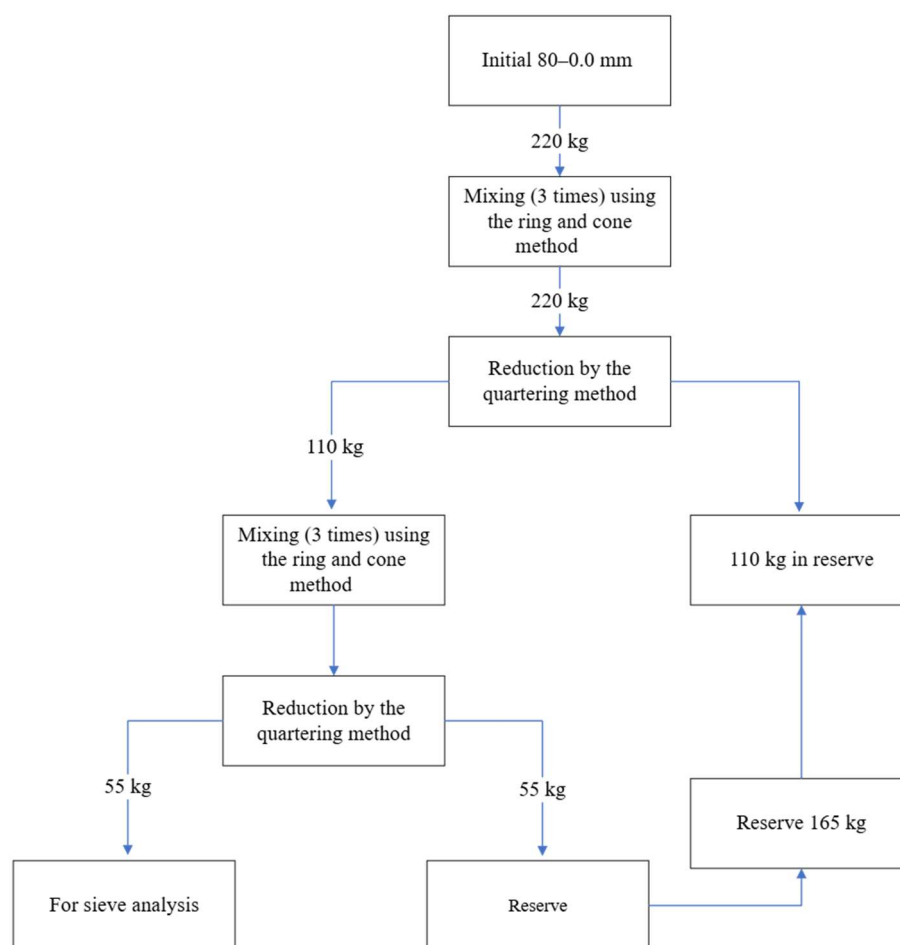


Figure 21. Sample preparation scheme for the initial 80–0.0 mm material for sieve and sedimentation analyses.

The initial ore sample ($-80 + 0.0$ mm) was homogenized three times using the cone-and-quartering method. It was then split into two 110 kg portions, one retained as a reserve. The second portion was further homogenized and reduced to two 55 kg portions, with one reserved and the other used for sieve and sedimentation analyses, yielding a total reserve of 165 kg. Sieve analysis showed low REE content in fractions coarser than 2.5 mm, making independent beneficiation impractical. Consequently, the remaining sample was crushed and ground to -2.5 mm (Figure 22).

The remaining 165 kg ore sample was crushed to -2.5 mm and homogenized. It was quartered into two 82.5 kg portions; one was further reduced to two 41.25 kg sub-samples—one for fractional analysis, the other for gravity beneficiation. The second 82.5 kg portion was reduced to two 42.5 kg portions—one for mineralogical and XRD analyses, the other further divided into two 20.625 kg portions, one for sieve and sedimentation analyses and the other retained as a reserve.

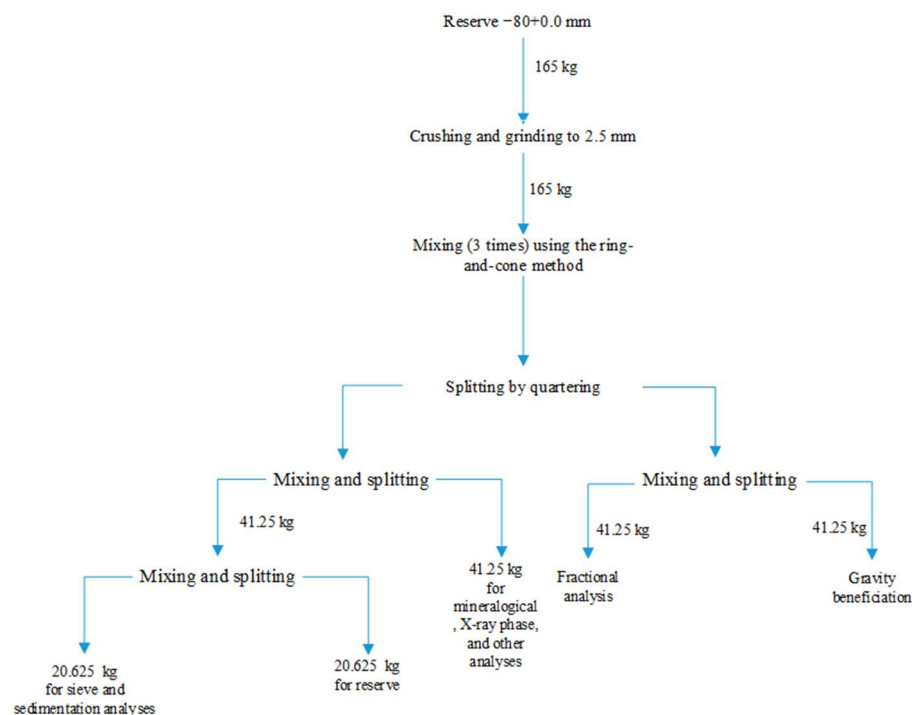


Figure 22. Sample preparation scheme for the initial ore after crushing and grinding to 2.5 mm.

3.3. Comprehensive Analysis of Composition and REE Occurrence Forms

To characterize the material composition of the Kundybay rare earth ore and its processing products, modern physicochemical methods were applied. Qualitative atomic-emission analysis was performed using a DFS-13 spectrograph (LOMO, St. Petersburg, Russia), and elemental composition was quantitatively determined. Mineral phases were identified using a MIN-8 petrographic microscope (LOMO, St. Petersburg, Russia) in transmitted light and an inverted Leica microscope (Leica Microsystems, Wetzlar, Germany) in reflected light. X-ray diffraction (D8 Advance, Bruker AXS GmbH, Karlsruhe, Germany) and FTIR spectroscopy (Avatar 370, Thermo Nicolet, Madison, WI, USA) refined crystal-structure identification, while SEM verified microparticle morphology and local chemical composition. All the aforementioned equipment is located in the Research Laboratory of Geomechanics and Geotechnologies and the Laboratory for Ore Beneficiability Research at Satbayev University.

Results confirmed that the Kundybay mineralization is of the ion-adsorption type within weathering crusts, with REEs adsorbed on clay surfaces (kaolinite, montmorillonite) and associated with supergene iron and titanium oxides (goethite, leucoxene). Scandium is included in Σ REE, behaving similarly to heavy yttrium-group lanthanides and concentrating in high-density fractions during gravity beneficiation. Valuable components are primarily in fine slimes, both as ion-exchange and microinclusion forms, necessitating preliminary desliming to concentrate REEs for efficient gravity separation of heavy minerals.

3.3.1. Relationship Between Particle Size Distribution and REE Distribution by Size Class

To assess particle size distribution and the distribution of rare earth elements (REEs) among fractions, a detailed sieve analysis was performed for the initial ore ($-80 + 0$ mm) and the crushed 2.5 mm sample. Wet sieving with intensive washing was applied to disintegrate clay aggregates, while particles finer than 0.05 mm were classified by sedimentation [21,22].

The initial ore showed highly uneven REE distribution: coarse fractions ($-80 + 2.5$ mm) had low Σ REE (73.43 g/t) and a minor yield (11.29%), contributing only 2.56% of the total

metal balance, with the lowest content (22.05 g/t) in the coarsest 80 + 40 mm class. In contrast, fine fractions contained most REEs: the 0.02 + 0.01 mm and 0.01 + 0.05 mm classes reached 609.98 g/t and 821.60 g/t, respectively, and, with a combined yield of 31.49%, accounted for 68.23% of Σ REE recovery. The finest slime fraction (<5 μ m) had the maximum grade (890.64 g/t) despite its low yield (1.14%). The weighted-average Σ REE content of the initial sample was 308.18 g/t.

These findings justified enlarged laboratory-scale tests using a combined gravity beneficiation flowsheet, with results summarized in Table 10.

Table 10. Optimal technological parameters of enlarged laboratory beneficiation tests for ore of 2.5 mm particle size.

Product	Yield (%)	Σ REE Grade (g/t)	Recovery (%)
Concentrate, 2.5–0.1 mm class	3.76	640.68	7.83
Concentrate, 0.1–0.0 mm class	11.05	1053.76	37.83
Total concentrate (2.5–0.0 mm)	14.81	948.89	45.66
Middlings (combined 2.5–0.1 mm class)	17.55	107.93	6.15
Tailings–middlings, 0.1–0.0 mm class	35.20	378.53	43.29
Total middlings (including tailings–middlings)	52.75	208.50	49.44
Tailings, 2.5–0.1 mm class	32.44	46.44	4.90
Feed ore	100.00	307.78	100.00

Analysis of the intermediate products showed that the combined middlings—including sand (−2.5 + 0.1 mm) and fine tailings (−0.1 + 0.0 mm)—had a total yield of 52.75% at an average Σ REE grade of 208.5 g/t. With 49.44% of the metal recovered in this fraction, additional concentration (cleaner) stages are required to increase the valuable-component grade.

Gravity tailings from the sand fraction (−2.5 + 0.1 mm) had a low Σ REE grade (46.44 g/t) and minor metal losses (4.90%), qualifying them as final discard. Overall, the total discard mass amounted to 85.19% at 146.79 g/t, confirming the high selectivity of the proposed flowsheet.

3.3.2. Investigation of the Gravity Beneficiation Potential of the Studied Ore

To assess the gravity beneficiation potential of the ore, fractional analysis was performed for the −2.5 + 0.315 mm, −0.315 + 0.1 mm, and −0.1 + 0.0 mm size classes using heavy liquid M-45 (separation density up to 2950 kg/m³). The weighted-average Σ REE content was 307.7–307.8 g/t. The main share of REEs was concentrated in the fine −0.1 + 0.0 mm fraction, which accounted for 48.81% of the mass and 81.12% of total recovery at a grade of 511.44 g/t.

For the −2.5 + 0.315 mm and −0.315 + 0.1 mm classes, the optimum cut density was 2850 kg/m³. Heavy fractions yielded 3.35% at 719.09 g/t (concentration ratio 6.34), while light fractions were low in REEs (69.62 g/t). A middling product could be isolated in the −2.5 + 0.315 mm class, whereas in the −0.315 + 0.1 mm class, light and intermediate fractions were not clearly separable. Fractional composition of the finest −0.1 + 0.0 mm class under dynamic centrifugation is shown in Table 11.

Table 11. Fractional composition of the 0.10–0.00 mm size class.

Size Class, mm	Fraction Density, kg/m ³	Yield, % of Class	Yield, % of Ore	Σ REE Grade, g/t	Recovery, % of Class	Recovery, % of Ore
0.10–0.00	<2850	73.96	36.10	369.090	53.37	43.296
0.10–0.00	>2850	26.04	12.71	915.792	46.63	37.825
0.10–0.00	Total	100.0	48.81	511.450	100.0	81.121

The fractional composition of the $-0.10 + 0.00$ mm class showed that at a separation density of 2850 kg/m^3 , REEs are mainly concentrated in the $>2850 \text{ kg/m}^3$ fraction. Elevated REE contents in the $<2850 \text{ kg/m}^3$ fraction are due to the high proportion of very fine, slimy material, which is difficult to separate even under centrifugation.

The analysis indicates that gravity beneficiation is effective for coarser fractions (>0.10 mm), but the high slime content ($>30\%$) necessitates preliminary desliming. This was performed using an ultrasonic aerohydraulic desliming (UAGD) unit developed at Satbayev University, capable of removing up to 90% of fine clayey slimes (Figure 23).

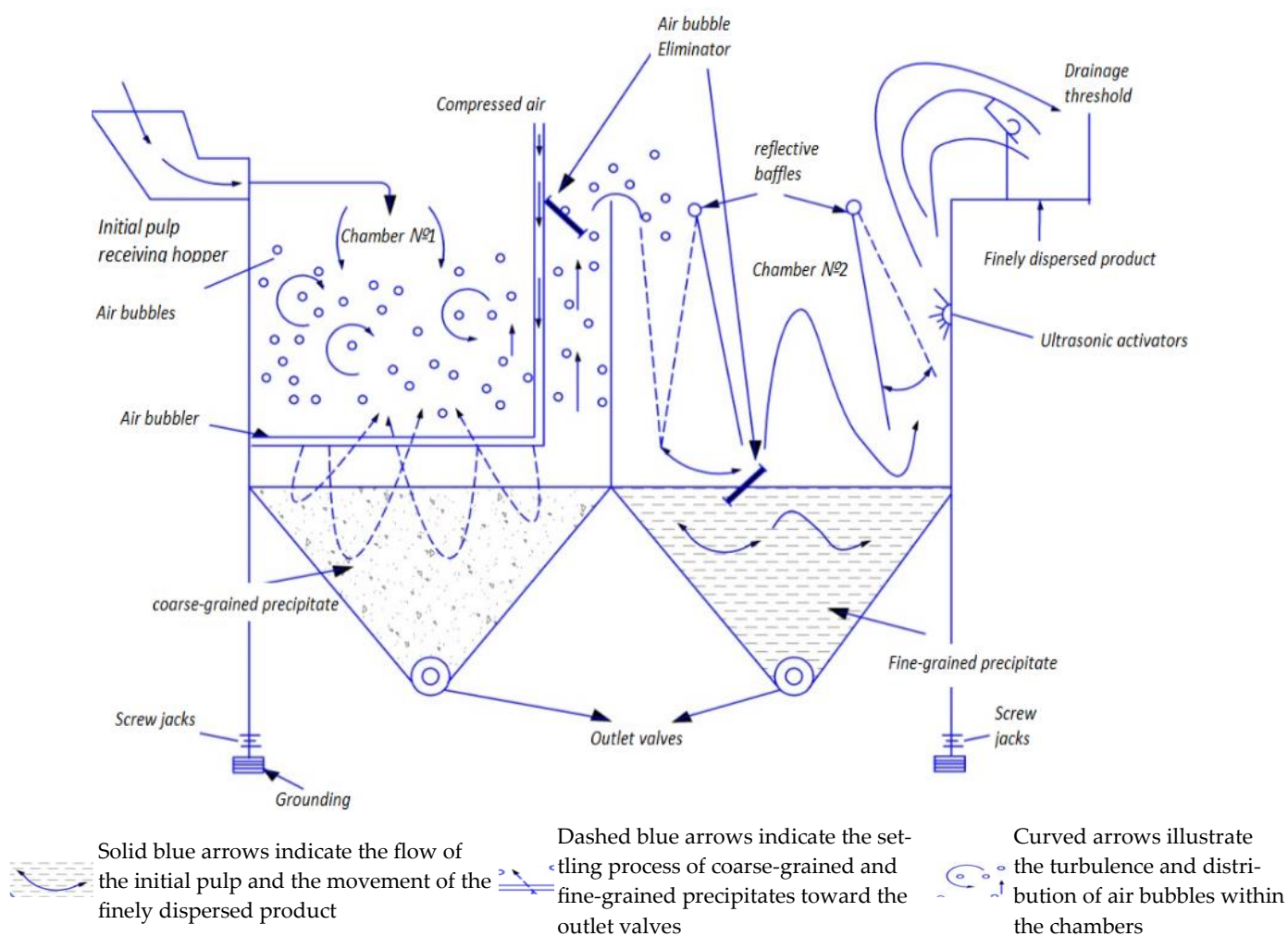


Figure 23. Schematic diagram of the ultrasonic aerohydrodynamic desliming unit.

Preliminary studies showed that the required ore size for the enlarged laboratory tests was 2.5 mm. Therefore, the initial ore of size $-80 + 0.0$ mm was crushed and ground to 2.5 mm. The resulting $-2.5 + 0.0$ mm material was then subjected to desliming in the UAGD in order to separate the $-0.1 + 0.0$ mm slimy fraction. The two resulting size classes, $-2.5 + 0.1$ mm and $-0.1 + 0.0$ mm, were subsequently directed to gravity beneficiation tests.

Before the enlarged laboratory beneficiation tests, the ore crushed to 2.5 mm was deslimed at the $-0.1 + 0.0$ mm size class. The results of the desliming operation are presented in Table 12

Table 12. Desliming results for ore crushed to 2.5 mm.

Size Class, mm	Yield, %	Σ REE Grade, g/t	Σ REE Recovery, %
−2.5 + 0.1	53.75	108.09	18.88
−0.1 + 0.0	41.25	534.02	81.12
Ore (total)	100	307.78	100

3.3.3. Gravity Beneficiation

Enlarged laboratory tests employed a specialized processing setup combining conventional and innovative gravity separation methods. The coarse fraction (−2.5 + 0.1 mm) was beneficiated on a spiral separator, while fine-dispersed REEs in the −0.1 + 0.0 mm fraction were recovered using a vibro-centrifugal bowl separator developed by the authors [23,24]. Operations were conducted at a liquid-to-solid ratio of 3:1, with concentrate cleaning in the vibro-centrifugal bowl at 500 rpm.

For the −2.5 + 0.1 mm fraction, separation into concentrate, two middlings and tailings were achieved. The concentrate yield was 3.76% of the feed ore (7.00% of the class mass) with a Σ REE grade of 640.68 g/t and recovery of 41.47% of the class potential, demonstrating high selectivity. Middlings 1 and 2 totaled 17.55% of the ore with an average Σ REE grade of 107.93 g/t. The final tailings, 32.44% of the ore, contained minimal REEs (46.44 g/t). The established conditions for the vibro-centrifugal bowl separator for the −0.1 + 0.0 mm fraction provide the basis for completing the full beneficiation flowsheet at the Kundybay deposit (Figures 24 and 25).

**Figure 24.** Cascade of vibro-centrifugal bowl separators, top view (VCB).

To implement gravity beneficiation under laboratory conditions, a set of specialized equipment was employed to ensure highly selective density-based separation, which is critical for fine-dispersed rare earth ores with subtle differences in physical properties. A key unit in the flowsheet is the vibro-centrifugal bowl separator (VCB), an improved analog of centrifugal hydroconcentrators (Kazakhstan patent No. 25645). The VCB eliminates the need for additional fluidizing water, instead maintaining an active mineral bed via superimposed vibrations at 3000–6000 oscillations/min. This intensification allows concentration ratios of 100–200 $\times$, even with small sample masses. The unit efficiently recovers heavy fractions across a wide particle size range, from 95% for >0.1 mm to 50% for 0.01–0.05 mm,

with a throughput of 40–100 kg/h, low specific energy consumption (0.75–1.1 kW), and minimal water usage (2 L/min), making it suitable for both primary concentration and cleaner stages.



Figure 25. Cascade of vibro-bowl apparatuses, top view.

For continuous beneficiation of fine fractions, a VSP-type spiral separator with a 250 mm diameter was used. Separation relies on the combined effects of gravity, centrifugal forces, and transverse flow circulation in the curved trough. High-density particles migrate to the low-velocity inner-wall zone, while light minerals are carried to the periphery. The spiral pitch is adjustable between 94 and 137 mm, allowing optimization of inclination and maximization of phase separation. A recirculation system stabilizes process parameters, with controlled water addition enabling pulp density adjustments [25–27].

Laboratory tests on the $-0.1 + 0.0$ mm size class produced a concentrate yield of 11.05% of the ore (23.89% of the class) with Σ REE grade 1053.76 g/t and 37.83% recovery from the ore (46.63% from the class). Tailings accounted for 35.2% of the ore (76.11% of the class) with Σ REE grade 378.53 g/t and 43.29% recovery, indicating that these tailings should be considered a middling product rather than final waste.

Overall, beneficiation of the $-2.5 + 0.0$ mm ore produced a gravity concentrate yield of 14.81% at 948.89 g/t Σ REE and 45.66% recovery. The combined middlings from $-2.5 + 0.1$ mm middlings and $-0.1 + 0.0$ mm tailings totaled 52.75% yield, 208.5 g/t Σ REE, and 49.44% recovery. The final tailings from the $-2.5 + 0.1$ mm class represented 32.44% of the ore, 46.44 g/t Σ REE, and 4.90% recovery. In international practice, this gravity concentrate would typically proceed to hydrometallurgical processing to further enhance the total rare earth metal content.

3.4. Techno-Economic Justification for Optimizing Open-Pit Wall Parameters as a Function of the Overall Slope Angle

When the slope angle is increased to 45° , the stability factor decreases in certain sectors; however, local correction of individual slopes or the application of engineering measures, such as berm construction, drainage, or slope support, remains possible. From the standpoint of stability, a 35° slope angle is optimal, although it requires a larger volume of stripping. A 45° slope angle may be adopted only where rock mass properties are improved, but it offers a favorable effect on economic efficiency by reducing stripping volumes and associated costs.

Figure 26 presents a comparative analysis of stripping volume versus pit-wall slope angle. The horizontal axis shows slope angles from 30° to 55° , while the vertical axis represents stripping mass in million tonnes. The main curve (blue) demonstrates a clear inverse relationship: as slope angle increases, stripping volume decreases. At 30° , the

stripping volume peaks at 206 Mt, whereas at 55°, it drops to 120 Mt, consistent with the dotted trend line.

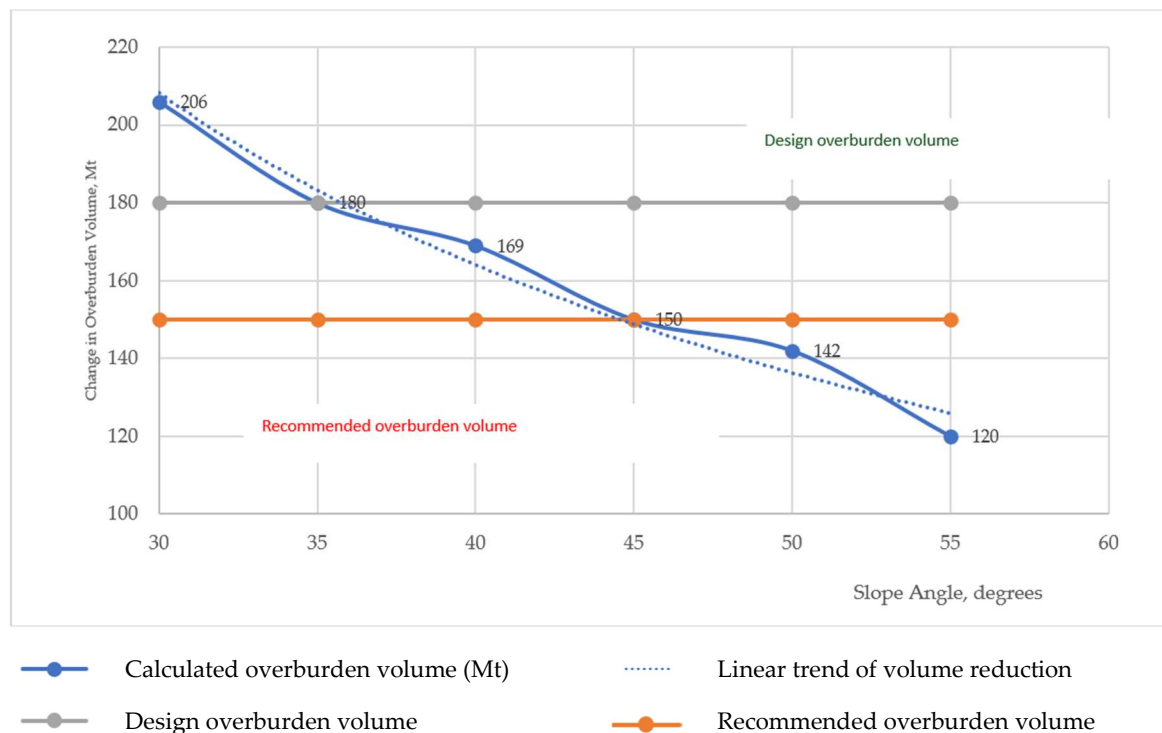


Figure 26. Dependence of stripping volume on pit-wall slope angle, with identification of the design and recommended target values.

Two reference lines highlight target indicators. The green line at 180 Mt intersects the curve at 35°, corresponding to the design stripping volume. The red line at 150 Mt intersects at 45°, indicating the slope angle needed to achieve the recommended technical and economic targets.

This visualization quantitatively demonstrates the economic effect of pit-wall optimization. Increasing the slope from 35° to 45° reduces displaced rock by 30 Mt, significantly lowering transportation and dumping costs. The analysis underscores the value of modern slope-stabilization methods, as each additional degree of steepening within this range improves mine-development efficiency.

Figure 27 illustrates the impact of bench slope angle on the pit-wall factor of safety (FoS) along three critical profiles: A–A, B–B, and V–V. The graph shows a nonlinear decrease in stability as the slope angle rises from 30° to 55°. Profile A–A (blue line) maintains the highest stability, with FoS declining from 1.85 to 0.90, while profile V–V (green line) is the most critical, reaching 0.75 at 55°.

At the design slope of 35°, FoS values for all profiles remain safely above unity (1.40–1.55). Increasing the slope to the recommended 45° lowers FoS to the acceptable range of 1.09–1.15. Further steepening to 50–55° drops FoS below 1.0, signaling a high risk of slope failure and deformation.

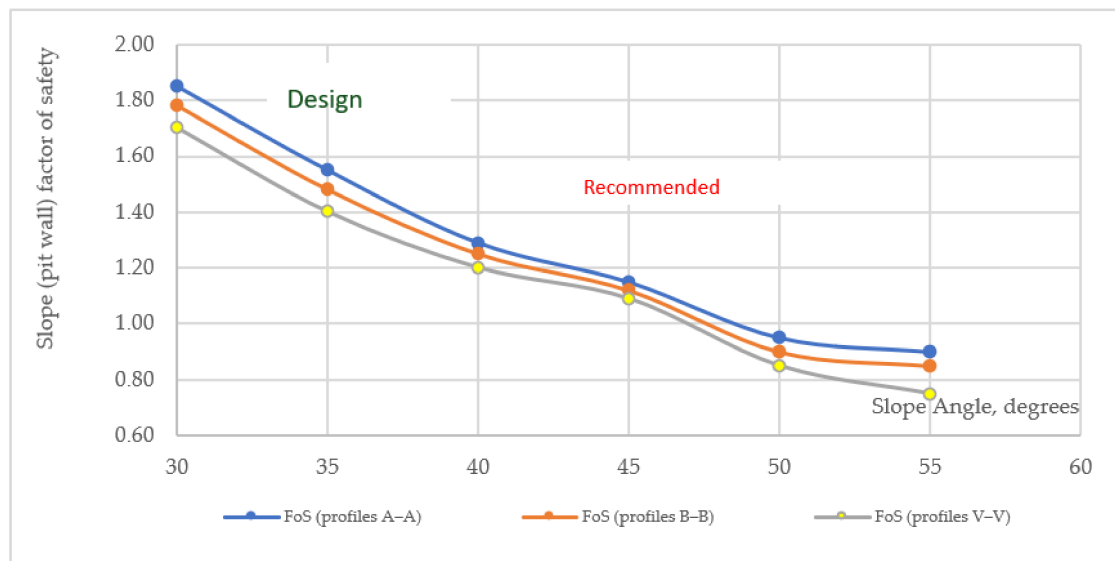


Figure 27. Comparative analysis of the influence of bench slope angle.

Geometric Concept and Mathematical Relationship

The proposed solution is based on representing the open pit as an inverted truncated cone, in which the excavation volume (V) is a function of the pit-wall slope angle (α) under constant technological parameters, namely the pit depth (H) and the bottom radius (r). The mathematical relationship is expressed through the surface radius: $R = r + H \cdot \cot(\alpha)$.

As shown in Figure 28, an increase in slope angle leads to a decrease in the cotangent value, which directly reduces the area of the upper base of the truncated cone and, consequently, the total volume of excavated rock mass, calculated by the following equation:

$$V = \frac{1}{3} \pi \cdot H \left(R^2 + Rr + r^2 \right), m^3 \quad (1)$$

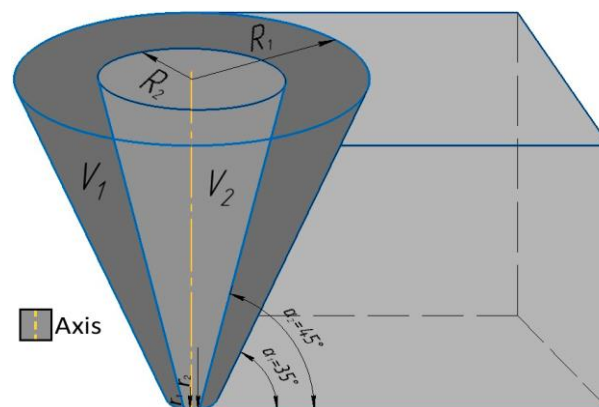


Figure 28. Geometric model for optimizing stripping volumes as a function of pit-wall slope angle. V —Total excavation volume (stripping material), represented as the volume of a truncated cone; V_1 —initial stripping volume at the design pit-wall slope angle of 45° ; V_2 —recommended stripping volume at the increased pit-wall slope angle of 35° ; H —design mining depth of the open pit; r —bottom radius of the open pit, determined by the ore-body outline (constant value); R_1 —upper radius at a slope angle of 45° ; R_2 —upper radius at a slope angle of 35° .

A comparison of the calculation variants V_1 and V_2 shown in Figure 29 demonstrates that the transition from the design slope angle of ($\cot \alpha = 1.43$) ($\cot \alpha = 1.43$) ($\cot \alpha = 1.43$) to the optimized slope angle of 45° ($\cot \alpha = 1.00$) ($\cot \alpha = 1.00$)

($\cot\alpha = 1.00$) makes it possible to significantly modify the contour geometry. The change in excavation volume is calculated by comparing two states of the open pit:

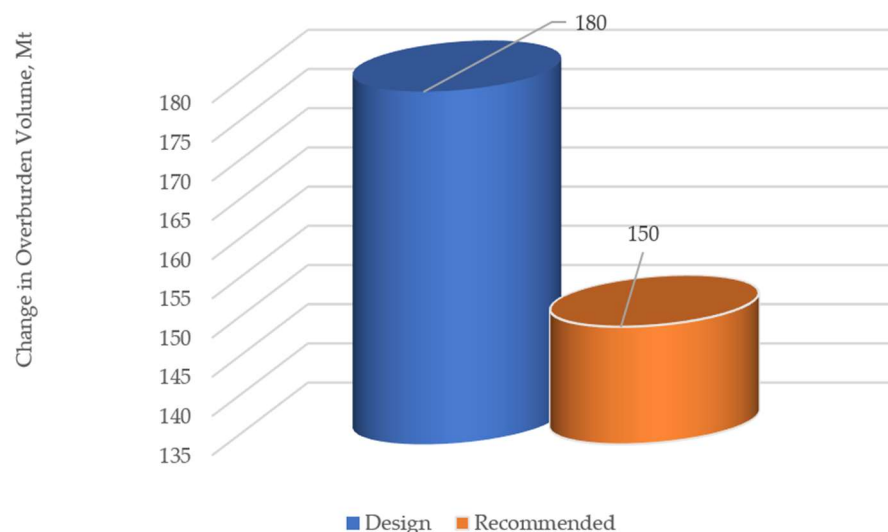


Figure 29. Economic effect of the integrated investigation of rare earth elements at the Kundybay deposit.

Excavation volume at the design slope angle of 35° :

$$V = \frac{1}{3} \pi \cdot H (R^2 + Rr + r^2) = 180 \text{ Mt} \quad (2)$$

Excavation volume at the design slope angle of 45° :

$$V = \frac{1}{3} \pi \cdot H (R^2 + Rr + r^2) = 150 \text{ Mt} \quad (3)$$

The resulting reduction in stripping volume is determined as follows:

$$\Delta V = V_1 - V_2 = 180 - 150 = 30 \text{ Mt} \quad (4)$$

As a result, increasing the slope angle by only 10° provides an economic benefit of 16.7%. Geomechanical verification and accurate determination of the optimum are therefore critical conditions for achieving a balance between economic efficiency and operational safety.

The scientific significance of this visualization lies in identifying an optimal balance between pit-wall steepness and stability so as to minimize stripping volume while maintaining industrial safety (Table 13).

The comparative analysis of the profiles shows that the transition to the recommended slope angle of 45° represents a limit-state condition that requires continuous monitoring, since the factor of safety approaches unity, particularly along profile V–V. Thus, Figure 29 provides the basis for selecting the geometric parameters of the open pit, clearly demonstrating that the economic benefit of steeper slopes is constrained by the physical and mechanical properties of the rock mass and by the corresponding stability requirements.

The study quantitatively demonstrates the economic benefits of optimizing pit-wall geometry, primarily through a reduction in operating costs. Transitioning from the conservative 35° slope to a substantiated $45\text{--}55^\circ$ range lowers the stripping volume from 180 Mt to 150 Mt by minimizing waste-rock excavation while maintaining acceptable FoS values along all critical profiles.

Table 13. Comparative analysis of stripping volume and associated economic effect.

Slope Angle (α), Degrees (X-Axis)	Total Overburden Mass (m), Thousand Tonnes (Y-Axis)	Note (Economic Effect)
30	195.0	Increased stripping volumes (shallower slope angle).
35	180.0	Baseline value. Overburden mass at a safe slope angle required in the upper weak zone.
40	170.5	Reduced volume compared with 35°.
45	162.1	Maximum reduction. Overburden mass saved by adopting 45° in competent rock zone.
50	150.0	Substantial reduction (however, typically geomechanically unacceptable).

This increase in slope steepness is supported by refined physical and mechanical properties of the lithological domains. For the thickest weathering-crust unit, cohesion averaged 1.15×10^5 Pa and density 2.10 g/cm^3 . Numerical modeling with Slide2 and RS2 indicated that the design case ($\text{FoS} = 1.40\text{--}1.55$) has an excessive stability margin, causing an unjustified increase in the stripping ratio, whereas the recommended slope range optimizes costs while keeping FoS at 1.27.

The economic effect, equivalent to 16.7% of the initial stripping volume, corresponds to a 30 Mt reduction in moved rock, accounting for drilling, excavation, and transport costs. Beyond profitability, adopting 45–55° slopes reduces the land required for waste dumps, offering additional environmental benefits. Figure 29 shows that each degree of pit-wall steepening within this range significantly decreases stripping costs while maintaining FoS above the critical threshold, making this geomechanical justification algorithm essential for improving the competitiveness of Kundybay deposit development.

4. Conclusions

Despite the achieved performance indicators, the authors recognize several limitations that should be considered when scaling up the proposed solutions. First, because of the difficulty of selecting representative horizons within the weathering crust of the Kundybay deposit, some of the design physical and mechanical parameters were verified using data from analogous deposits with similar lithological structures, namely the Tokhtarov and Komarov deposits. Although the correlation of properties was statistically supported, refinement of the strength parameters during the pilot-scale mining stage may lead to adjustment of local slope angles. Second, the beneficiation results presented here were obtained under laboratory conditions. Finally, a degree of uncertainty remains regarding the hydrogeological regime. The Slide2 modeling was performed for conditions of maximum saturation; however, the dynamics of pore-pressure variation in the clayey weathering-crust products under deep dewatering require long-term monitoring (Figures 2 and 3). Future studies will therefore be directed toward refining the filtration properties of the rock mass in order to minimize the risk of local deformations during the spring and autumn periods.

The integrated investigation of the Kundybay deposit made it possible to scientifically substantiate the transition from excessively conservative design solutions to rational geometric parameters of the open-pit space. Geomechanical verification carried out using an integrated 3D model in Micromine and limit-equilibrium analysis in Slide2 showed that the initial design factor of safety (FoS) in the range of 1.40–1.55 reflects an excessive stability

margin. Refinement of the calculation schemes with allowance for the actual rock mass structure and nonlinear strength criteria made it possible to optimize the pit-wall slope angles to 45–55°. This provided a direct reduction in stripping volume by 30 Mt (from 180 Mt to 150 Mt), corresponding to an overall economic benefit of 16.7% relative to the initial cost level (Figure 22).

Particular attention was devoted to the analysis of the influence of the spatial configuration of mine workings on the overall stability of the system. It was established that optimization of slope geometry and adherence to a rational mining sequence make it possible to effectively redistribute stresses within the near-wall rock mass. This approach minimizes zones of plastic deformation and reduces risks associated with the high water sensitivity of the clay-rich weathering-crust rocks (Figure 28). As a result, even with steeper pit walls, the FoS for the critical profiles remains within the range of 1.09–1.15. These values indicate a limit-state condition and therefore require local slope adjustment and continuous monitoring; nevertheless, they confirm the technical feasibility of the proposed geometry under controlled geomechanical conditions.

In parallel with the geomechanical justification, an innovative technological flowsheet for the processing of difficult-to-beneficiate ores was developed. The application of ultrasonic aerohydraulic desliming ensured deep disintegration of mineral aggregates and removal of slime coatings from grain surfaces, thereby creating favorable conditions for effective gravity separation in a vibro-centrifugal field. The tests confirmed the possibility of obtaining a marketable concentrate with an average Σ REE grade of 948.89 g/t at an overall recovery of 45.66%. The synergy between digital modeling and novel processing equipment thus establishes a scientific and practical basis for the efficient and economically viable development of rare earth deposits under complex mining and geological conditions.

Author Contributions: Conceptualization, R.Z., T.A. and M.S.; methodology, T.A., R.Z. and M.S.; software, R.Z., D.-M.S., N.A. and N.K.; validation, R.Z., T.A. and D.-M.S.; formal analysis, T.A. and D.-M.S.; investigation, T.A. and R.Z.; resources, T.A., R.Z. and D.-M.S.; data curation, T.A. and R.Z.; writing—original draft preparation, T.A., R.Z., D.-M.S. and M.S.; writing—review and editing, T.A., R.Z., D.-M.S., N.A. and M.S.; visualization, T.A. and N.K., supervision, R.Z., T.A., M.S. and N.A.; project administration, R.Z., T.A. and M.S.; funding acquisition, T.A. All authors have read and agreed to the published version of the manuscript.

Funding: This article is based on the results of research conducted under Project AP23488914, “Development of technology for quantitative assessment of finely dispersed gold in natural and man-made objects and assessment of the prospects for its detection in the territory of Kazakhstan”, implemented within the framework of grant funding for 2024–2026. The project leader is Candidate of Technical Sciences, Shautenov M.R. The research was funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan.

Data Availability Statement: All data generated and/or analyzed during this study are available in open access and can be accessed without restrictions.

Conflicts of Interest: Author Nikita Kadukhin was employed by the company MICROMINE Central Asia. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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