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The Mining-Geological-Petroleum Engineering Bulletin





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View of Brač dimension stone quarries Veselje, Punta, Kupinovo, Sivac, Barbakan.

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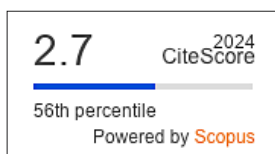
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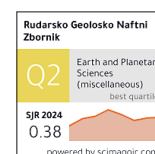
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Green Energize: Unleashing a Samba Biopolymer for Enhanced Oil Recovery

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Original scientific paper



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Abstract

Background: Several challenges exist in obtaining an optimal biopolymer material that is cost-effective, resilient under harsh conditions, and environmentally friendly. Currently, only xanthan and Schizophyllan biomaterials have been applied at a field scale. This study introduces a novel Samba biopolymer material for Enhanced Oil Recovery (EOR), which is economically viable, readily available, and stable.

Methods: Experimental tests were conducted to evaluate the Samba biopolymer. Infrared (IR), X-ray diffraction (XRD), and X-ray fluorescence (XRF) analyses were performed on the seeds before extracting the biopolymer solution. Subsequently, rheology, compatibility, membrane tests, particle size distribution, and filtration tests were conducted. A core flooding test was also carried out to measure the biopolymer's oil displacement efficacy; however, this test was performed for only one concentration scenario to serve as a preliminary evaluation of the polymer's performance under reservoir-like conditions.

Significant Findings: The extraction of the biopolymer solution from organic seeds was successful, with thermal extraction being sensitive to heating time and temperature. The Samba biopolymer enhanced water viscosity, recommended for reservoir conditions. Different concentrations revealed variations in rheological and filtration properties due to distinct morphology and surface functionality. Under optimal conditions, a remarkable 74% maximum oil recovery was achieved, demonstrating the biopolymer's potential as a promising EOR agent.

Keywords:

Samba Biopolymer, Enhanced Oil Recovery, Biopolymer Rheology, Core Flooding

1. Introduction

Enhanced Oil Recovery (EOR) encompasses any reservoir process that introduces external fluids or energy from outside the reservoir to increase oil recovery. EOR comprises various methods, each with its specific considerations for implementation. One such method is Chemical EOR (CEOR), which can be categorized into several approaches: Surfactant, Alkaline, Nanoparticles, and Polymer EOR (Samba et al., 2019; Elsharafi and Samba et al., 2018; Massoud et al., 2022; Green et al., 1998).

Polymer EOR is widely recognized as one of the most significant contributors to enhanced oil recovery (EOR) due to its mechanism and cost-effectiveness in comparison to other methods (Jabbar et al., 2017). The primary aim of polymer injection is to increase the mobility ratio

and delay breakthrough. Its efficacy in delaying breakthrough has been successfully demonstrated in various oil fields globally. A survey conducted in 2016 documented over 865 polymer flooding projects worldwide (Guo 2017). As per available paper reports, no polymer project has encountered complete failure. While certain papers have highlighted challenges during polymer injections, most of these issues have been resolved through rigorous problem-analysing. Nevertheless, ongoing studies face the challenge of identifying an optimal polymer material that is not only cost-effective, but also capable of withstanding harsh conditions while remaining environmentally friendly. Consequently, researchers have increasingly focused on biopolymer materials. Presently, biopolymers have gained prominence as a subject of interest in discovering materials that address the previously mentioned challenges. To date, only Xantant and Schizophyllan biomaterials have been applied at a field scale (Schnepp 2013). Some companies have introduced polymer materials with undisclosed compositions, potentially related to biopolymer materi-

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als. Moreover, certain materials have solely undergone laboratory-scale testing and are yet to be tested in the field. Simultaneously, several biopolymer materials require further examination and testing to ascertain their potential for enhancing oil recovery (Hamidi et al., 2021). While materials such as okra, cassava starch, *Detarium microcarpum*, exudate gum, and aqueous beans have undergone laboratory testing, they have not been applied in field applications. Nevertheless, not every material exhibiting highly viscous solutions qualifies as a viable EOR agent. Before field application, various mechanisms including solution rheology, viscosity changes over time and temperature, degradation, crystallization, adsorption, and plugging should be thoroughly assessed. A recent study in 2019 focused on biopolymer EOR using guar and arabic gum. The research involved core flooding, comparing chemical polymer, water, biopolymer, and a chemical biopolymer slug. The biopolymer injection displayed superior performance compared to other scenarios (Hassan et al., 2019).

Similarly, in 2020, another study explored the use of green grass jelly leaves and seaweed as biopolymer materials, comparing them with xanthan gum and other chemical polymers. The results indicated comparable performance between biopolymers and chemical polymers. Additionally, it was observed that polymer viscosity decreased with an increase in salinity. However, seaweed and grass jelly exhibited good compatibility across different shear rates (Huljannah et al., 2020).

During the same year, research on tragacanth gum was published, testing it as a biopolymer-surfactant solution alongside smart water. The findings showed that fluid viscosity in Carboxymethyl Cellulose (CMC) reached an optimal value, resulting in a 21.4% increase in Recovery Factor (RF) (Nowrouzi et al., 2020).

Another study in 2020, focused on hybrid nanoparticles (NPs) with biopolymers. It aimed to characterize xanthan, arabic, and guar gum combined with copper, silica, and alumina NPs. The study analyzed the rheology of these biopolymers under various conditions such as salinity, temperature, NPs weight, and biopolymer concentrations. The materials were recommended for potential use in the EOR section (Sowunmi et al., 2020).

Challenges in finding an ideal biopolymer material persisted into 2021. A study introduced a novel biopolymer-surfactant extracted from the *Acanthophyllum* plant. Extraction procedures were conducted and characterized using Thermo-Gravimetric-Analysis (TGA), Fourier-Transform-Infrared-spectroscopy (FTIR), and Proton-Nuclear-Magnetic-Resonance-spectroscopy (H-NMR). The study also calculated surface tension (ST) and interfacial tension (IFT) between water-air and water-oil, resulting in 92.6% and 61.6%, respectively. This biopolymer-surfactant showed the capability to alter carbonate rock wettability from oil-wet to water-wet. The adsorption test introduced the Freundlich isotherm model as the best-fitted scenario (Mehrabanfar et al., 2021).

Though many plants offer effective biopolymer materials, the challenge lies in the complexity of extraction and preparation for high quantity implementation. Concurrently in 2021, research on grafted and dispersed nanoparticles of graphene combined with arabic gum biopolymer solution in harsh conditions was published. The results compared functional groups of graphene nano-platelets synthesized through grafting and mixing. This method aimed to enhance NPS stability in high-pressure and high-temperature conditions, holding promise as CEOR agents (Hamdi et al., 2022).

In recent times, the mixing of biomaterials with chemical substances to enhance their performance has emerged as an intriguing topic. A study titled 'Application of Biopolymer and NPs in EOR at Reservoir Conditions' explored three distinct biopolymers derived from local materials in Nigeria and Malaysia. Chemical additives were employed in synthesizing the biopolymer NPs, demonstrating their resilience under harsh conditions (Maghazi et al., 2014).

Building upon the aforementioned studies, various biopolymers have been assessed for their potential to augment oil recovery at a laboratory scale. Concurrently, numerous biomaterials warrant further examination to ascertain their suitability in enhancing oil recovery. Consequently, this study proposed a novel biomaterial (Samba Biopolymer) which is readily available in North Africa, known for its significant capability in augmenting water viscosity while maintaining long-term stability, has garnered attention. Surprisingly, this material has not yet been utilized in the EOR sector. Consequently, this material was selected for testing its efficacy in EOR processes.

2. Procedures

2.1. Biopolymer solution preparation

The Samba biomaterial was extracted from organic seeds utilizing the pyrolysis method in the presence of water. Initially, the seeds underwent a thorough washing with fresh water and were subsequently immersed in a synthesis formation water solution with varying concentrations, as outlined in **Table 1**. All prepared concentrations underwent the same procedural steps to ensure consistent extraction protocols. The solution was then heated for 2 hours at 80°C while maintaining the pres-

Table 1. Biopolymer solution concentrations that were prepared in this study

Concentration	Water salinity, ppm	Preparation time, hr	Temperature, °C
2%	2500	2	80
4%	2500	2	80
6%	2500	2	80
8%	2500	2	80

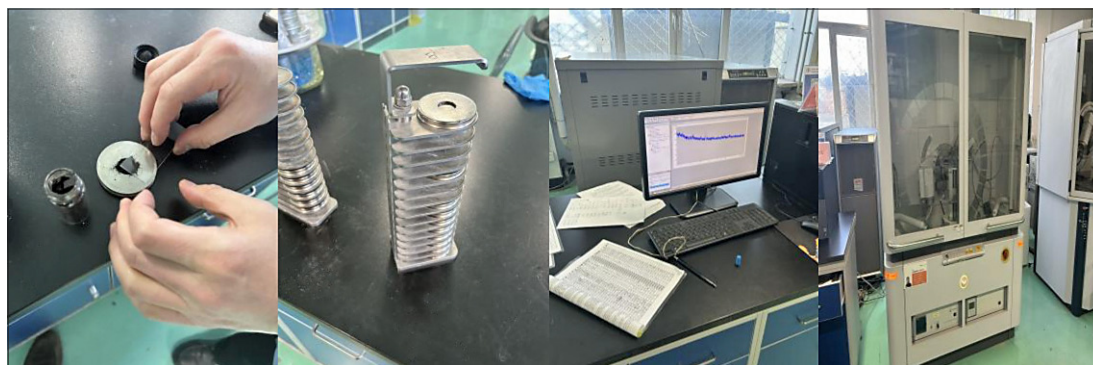


Figure 1. Devices and apparatus that have used to characterize the implemented materials

ence of 0.1% citric acid to prevent crystallization, a phenomenon that could occur with temperature variations. Additionally, 0.1% sodium benzoate was included during the extraction process to inhibit bacterial activation.

2.2. Biopolymer Solution Characterizations

To analyze and characterize the material utilized in this study, various tests were conducted. The Infrared (IR) test was performed to examine the functional groups present. Meanwhile, X-Ray Fluorescence (XRF) analysis was employed to ascertain the precise percentage composition. Lastly, X-Ray Diffraction (XRD) was utilized to investigate particle diameter and shape. **Figure 1** illustrates the devices utilized to conduct these tests.

2.3. Particle Size Measurements

The test was conducted using a Zetasizer device, depicted in **Figure 2**. A rectangular-shaped core holder was employed for this procedure. The objective was to calculate the particle size in the solution of the biopolymer, aiming to verify the success of the mixing procedures and assess the consistency of particle size obtained.

2.4. Solution Stability Test

Various samples of the biopolymer solution at concentrations of 2%, 4%, 6%, and 8% were assessed for compatibility at a reservoir temperature. These solutions were initially maintained under standard conditions (room temperature) for 3 days, followed by an additional 4 days at 70°C.

2.5. Rheology Investigations

The solution's rheology was assessed by measuring the viscosity of the biopolymer at various concentrations, temperatures, and shear stresses. Viscosity calculations were performed to determine whether the solution exhibited characteristics of a Newtonian or non-Newtonian fluid. The Viscometer Brookfield, illustrated in **Figure 3**, was utilized for viscosity measurements, functioning based on the fluid's resistance to shear stress during spinning. Viscosity measurements at different

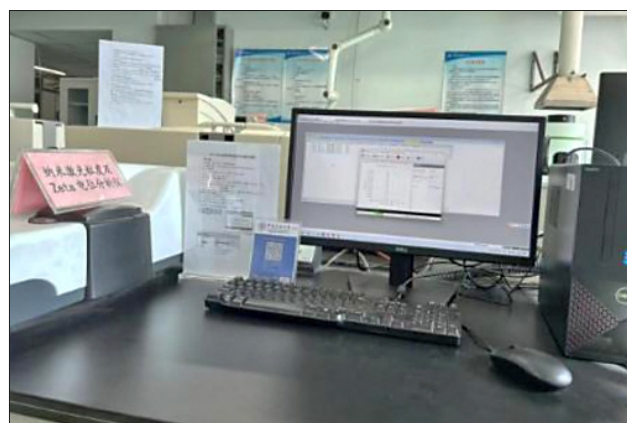


Figure 2. Zetasizer device that has been used to measure particle size

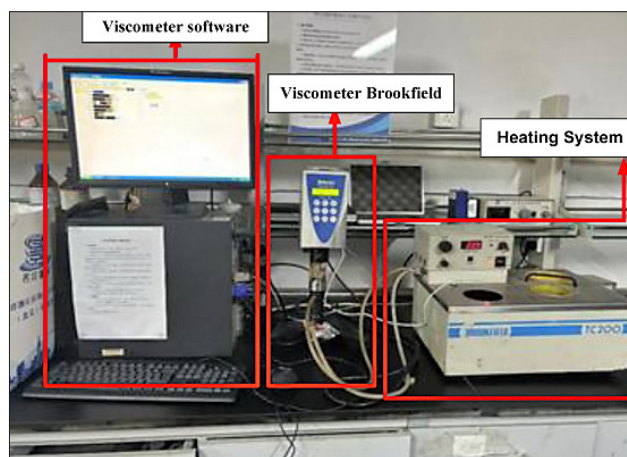


Figure 3. Viscometer Brookfield device that has been used to characterize the solutions

concentrations were conducted at 2500 ppm with shear rate. Furthermore, this study investigated the impact of temperature on viscosity, particularly focusing on the influence of temperature variations on this novel biopolymer material.

2.6. Membrane Test

A membrane test was conducted to assess the ability of the selected Biopolymer concentrations to penetrate

pores without causing blockages. The filtration apparatus was prepared by placing a suitable pore size, which

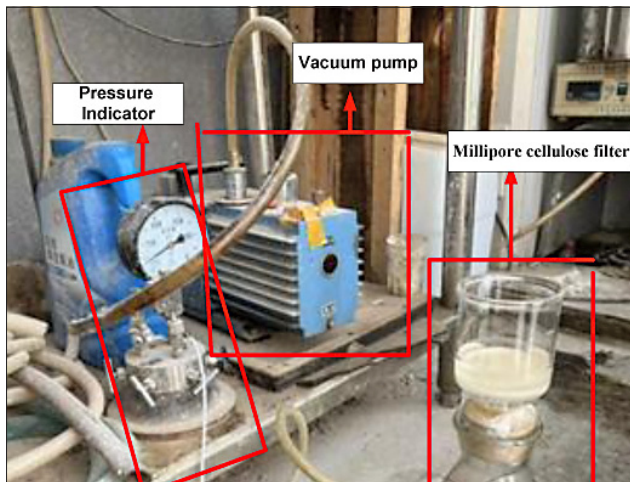


Figure 4. Membrane test apparatus



Figure 5. Experimental instruments

was a Millipore cellulose filter 5 μm in the filter holder. The suction valve was adjusted to 0.2 MPa. Subsequently, 500 ml of solution was filtered, and the cumulative time in seconds for each 100, 200, 400, and 500 ml was recorded. Visual monitoring of the filtered layer was conducted to detect any signs of potential plugging. Moreover, the assessment was based on the filtration ratio, calculated using the following equation:

$$FR = \frac{(T500 - T400)}{(T200 - T100)} \quad (1)$$

Where: FR is the filter ratio. While, the T100, T200, T400, and T500 are the times when 100, 200, 400, and 500 ml.

2.7. Core Flooding

The objective of this experiment was to determine whether the Samba biopolymer could enhance oil recovery in sandstone reservoir rock. To achieve this, a core flooding test was designed for a single scenario, involving the sequential injection of formation water, followed by a 2% Samba biopolymer solution, and then a slug of formation water. This setup aimed to evaluate the polymer's effectiveness in improving displacement efficiency under controlled conditions. Figures 5 and 6 illustrate the experimental setup and the core flooding system used to implement this scenario.

Initially, the dimensions and weight of the core were measured using a Vernier caliper and a sensitive balance. Subsequently, the core underwent vacuuming using a vacuum pump and was saturated with formation water.

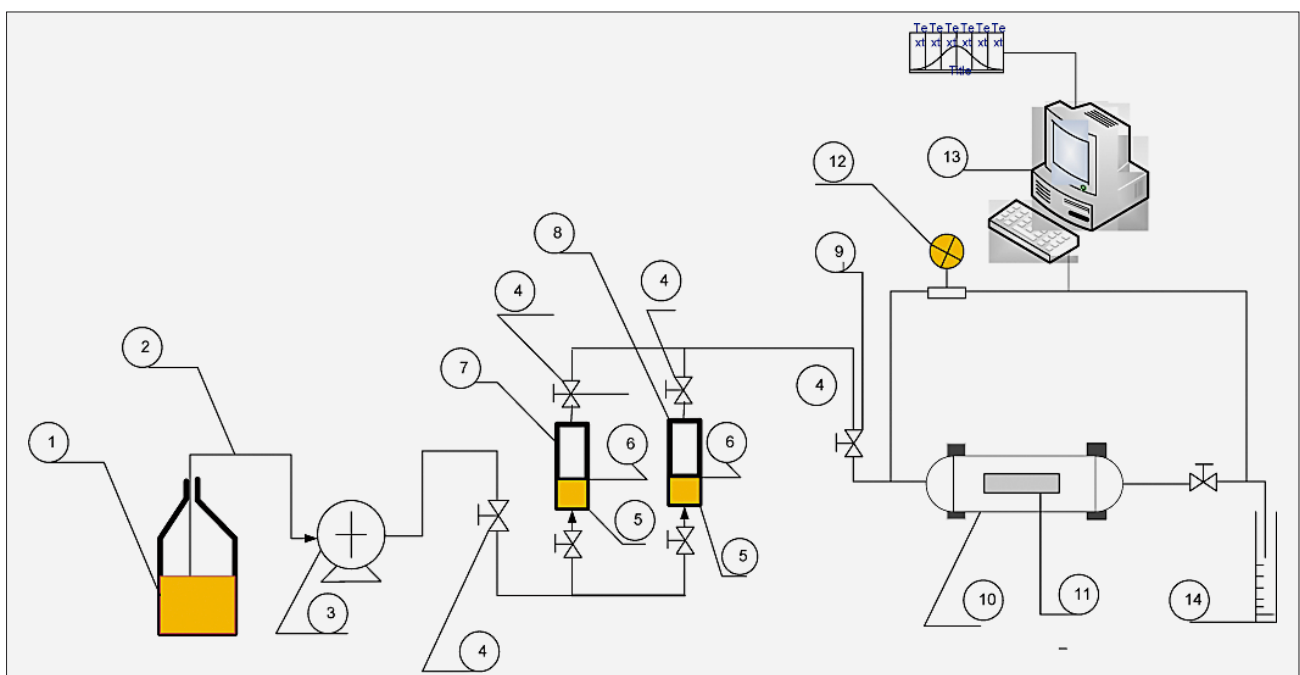


Figure 6. Core flooding apparatus: 1) Pump oil, 2) Injection pipeline, 3) Injection pump, 4) valve, 5) Pump oil in the fluid storage, 6) piston inside the fluid storage, 7) formation water, 8) Biopolymer solution, 9) Bypass valve, 10) Core holder, 11) Core plug inside the core holder, 12) pressure gauge and regulator, 13) computer, 14) accumulator.

After achieving saturation, crude oil was injected into the cores to establish the initial oil saturation in the presence of connate water saturation.

The saturated core was then placed within the core holder and subjected to an overburden pressure of 4 MPa, ensuring it exceeded the injection pressure to facilitate fluid passage through the core. The core flooding system operated through several stages. The injection pump introduced oil into the fluid storage to push the piston situated inside the storage. This piston, in turn, propelled the injected fluid stored within, acting as a separator between the two fluids. The storages were filled with formation water and biopolymer fluid and equipped with inlet and outlet valves to regulate fluid flow. The effluent from the core during the injection process was collected in the accumulator. It's crucial to ensure the absence of gas in the lines before initiating the injection process.



Figure 7. Samba biopolymer solution that has been prepared

3. Results

3.1. Biopolymer Solution

Samba biopolymer solution was successfully extracted from organic seeds, the successful extraction of the biopolymer solution revealed the sensitivity of the thermal extraction process to various parameters, including heating time, ambient temperature, and several other factors. Despite this sensitivity, all concentrations extracted exhibited a consistent pattern of viscosity progression based on concentration levels. This consistency indicated the successful extraction across all scenarios, affirming the efficacy of the established procedures.

3.2. IR Analysis

The infrared spectrum of the compound exhibits notable peaks, notably a broad peak at 3401 cm^{-1} attributed to the presence of the OH group. Additionally, the spectrum displays a peak at 2926 cm^{-1} , indicating the presence of the ν C-H Aliphatic group. Another distinctive peak at 1437 cm^{-1} is likely associated with the ν C=C Aromatic group. Furthermore, two additional peaks, as depicted in **Figure 8**, correspond to the ν C-OH and ν C-H (Aromatic) groups.

3.3. XRF Analysis

Table 2 presents the chemical composition of the Bi-omaterial, revealing that the sample is primarily composed of potassium (K) at 28.7%, followed by calcium (Ca) at 15.9%, phosphorus (P) at 9.30%, and aluminium (Al) at 8.41%. Additionally, trace amounts of other elements such as Si, Sn, Sb, Cl, etc., were detected in smaller quantities.

3.4. XRD Analysis

Figure 9 displays the X-ray diffraction (XRD) analysis of organic seeds. The XRD diagram notably depicts the

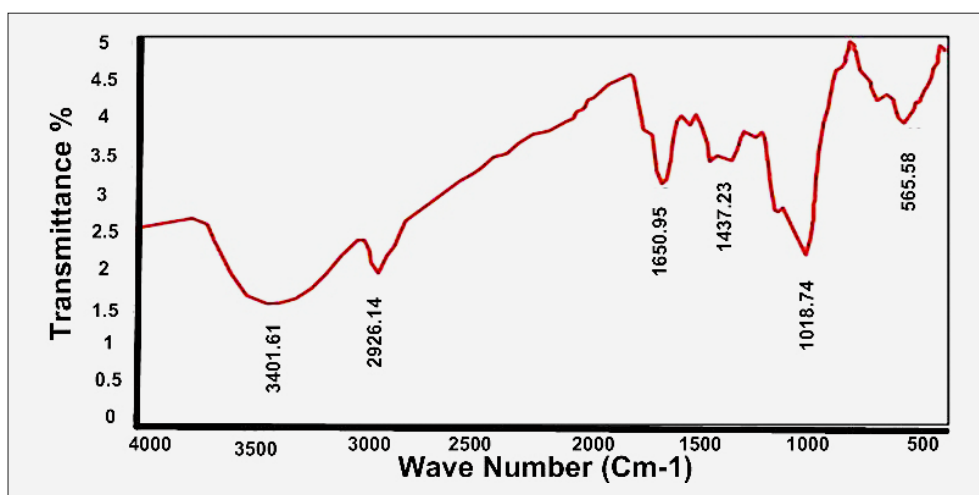
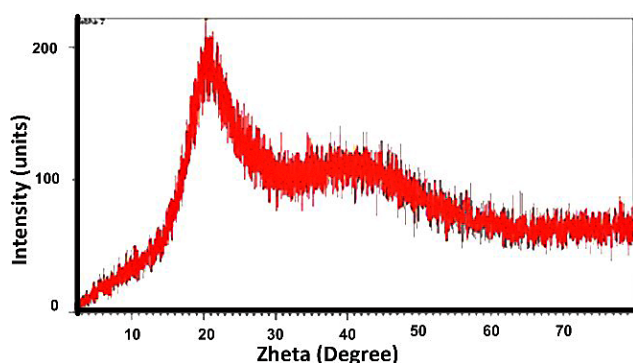


Figure 8. FTIR analysis for the Biopolymer material

Table 2. Chemical constituents for the Biopolymer material

Compounds	Concentration %
K	28.7
Ca	15.9
P	9.3
AL	8.41
Si	7.99
Sn	6.36
Sb	4.7
Cl	2.61
Fe	1.77
Ni	1.68
Zn	0.89
Mn	0.805
Cu	0.56
Co	0.282
Rb	0.0711
Ln	<0.0001

**Figure 9.** XRD Analysis for the Samba Biopolymer material

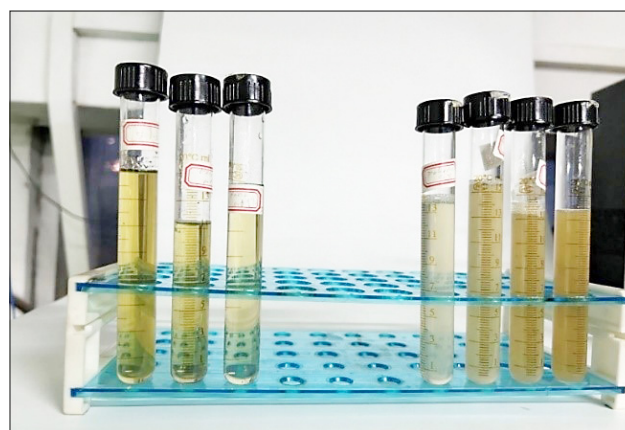
amorphous nature of the biopolymer seeds. Interestingly, no peaks were observed in the results, indicating the absence of distinct peaks in the diffraction pattern of organic seeds and thus revealing its amorphous character.

3.5. Compatibility Analysis

Four different concentrations of the biopolymer were evaluated for compatibility at a salinity level of 2500 ppm. The samples were stored at room temperature for 3 days and at 70°C for 4 days. Throughout this duration, no particles precipitation were observed. As depicted in **Figure 10**, the samples remained clear on the 7th day. These findings affirm the biopolymer's effectiveness in maintaining stability and compatibility with formation water, particularly at elevated reservoir temperatures.

3.6. Biopolymer Rheology

Figure 11 illustrates the relationship between the biopolymer's behaviour concerning shear stress and shear

**Figure 10.** Compatibility tests for Samba biopolymer solutions after 7 days at (2, 4, 6 and 8%)

rate at 25°C. All concentrations exhibited non-Newtonian behaviour attributed to polymer particles and biopolymer properties. The shear stress of various concentrations remained stable with increasing shear rate due to stable particle dispersion, wall slip motion in the polymer solution, and the movements of the shear plates.

In **Figure 12**, changes in shear rate were measured to determine Samba biopolymer viscosity, ranging from 2.45 s⁻¹ to 244 s⁻¹. At 2% concentration, the viscosity showed minimal variation with increasing shear rate. However, at 4%, 6%, and 8% concentrations, higher shear rates led to decreased viscosity of the Samba biopolymer. Visual observations during extraction indicated that higher concentrations resulted in gel-like solutions. Consequently, there were notable differences in viscosity among concentrations, notably between 2% and higher concentrations. This phenomenon can be attributed to the relationship between biopolymer chain length, molecular weight, and viscosity. Higher molecular weight and polymer concentration led to increased viscosity through longer or stronger polymer chains. Conversely, concentrations at 4%, 6%, and 8% exhibited longer chains and higher molecular weight but were weaker resistance to shear rate degradation, resulting in higher viscosity that was susceptible to degradation by shear rate. The 2% concentration displayed lower viscosity but higher resistance to shear rate degradation.

In **Figure 13**, polymer viscosity measurements were taken at a shear rate of 7.34 s⁻¹ under various temperatures. These conditions mimicked reservoir conditions. The viscosity reduction at 4%, 6%, and 8% concentrations was significant but still viable for facilitating oil flow within the reservoir, potentially improving the mobility ratio. However, the 2% concentration showed minimal viscosity reduction at reservoir temperatures, but the viscosity remained relatively low. This result still falls within acceptable safety margins for polymer injection, as it maintains a viscosity higher than that of water. A sharper viscosity decline was observed between 45°C and 50°C for the higher concentrations, which is typical

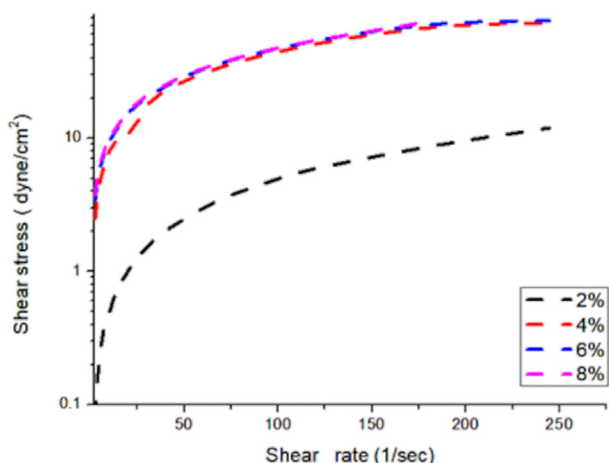


Figure 11. Shear stress as a function of shear rate Samba biopolymer solution samples at 25°C

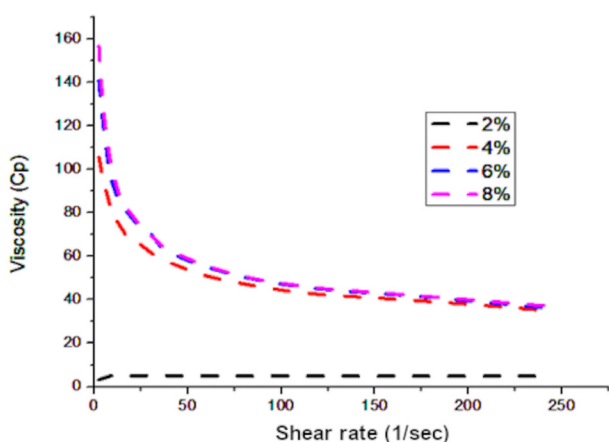


Figure 12. Samba biopolymer viscosity for variation Shear Rate

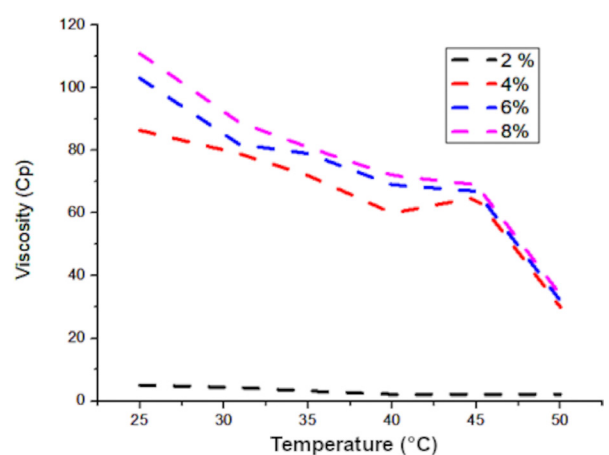


Figure 13. Samba biopolymer viscosity at variation temperature

for polymer solutions as thermal energy disrupts molecular interactions. Nonetheless, the viscosity levels remained sufficiently high to ensure effective performance.

3.7. Filtration Test Results

The filtration test was conducted to assess the potential for polymer plugging within the pores. The results

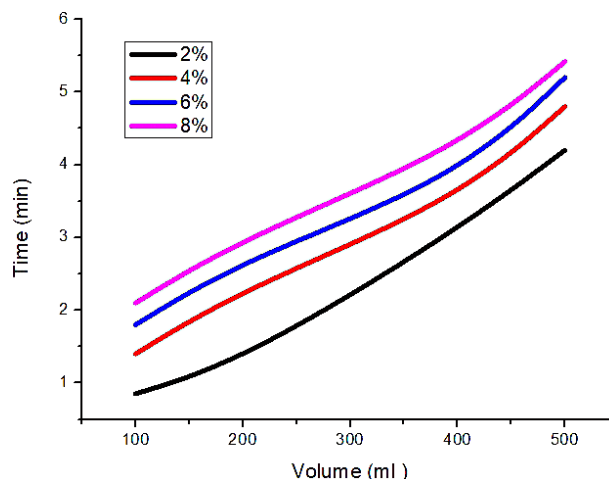


Figure 14. Filtration test results



Figure 15. Gel formed at 8%

Table 3. Summary of filtration ratio measurement

Concentration	Filtration ratio	Polymer remaining in the filter paper
2%	2.34	No
4%	1.08	No
6%	1.55	No
8%	1.35	Small amount of polymer gel remaining

demonstrate the passage of Samba biopolymer molecule particles through the pore throat size, accounting for interactions observed in real field conditions such as electrostatic forces, surface roughness, and rock wettability. As depicted in **Figure 14**, the relationship between passed polymer volume and time indicates that an increase in concentration correlates with extended passage time across all scenarios. Notably, it appears that the pore size accommodates all concentrations adequately. At an 8% concentration, as shown in **Figure 15**, a small amount of gel on the filter screen. This occurrence of unfiltered polymer is attributed to the high molecular weight characteristic of high concentrations.

3.8. Particle Sizes

Figure 16 displays the particle size distribution of the Samba biopolymer solution, measured using a Zetasizer

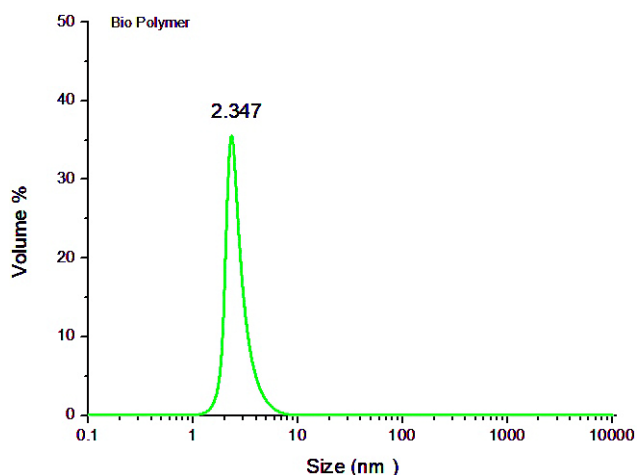


Figure 16. Particle size for Samba biopolymer solution

device employing a helium-neon laser light and integrated analysis software. The measurements were conducted at a temperature of 25°C, with the solution's salinity set at 2500 ppm. The analysis revealed a biopolymer size of 2.75 nm in the solution, demonstrating the success of the mixing procedures and the uniformity achieved in solution sizes. Furthermore, the results indicated that the particles did not exhibit swell-up when mixed with formation water.

3.9. Core Flooding

Figure 17 illustrates the recovery factor and pressure versus pore volume. The results indicate that break-

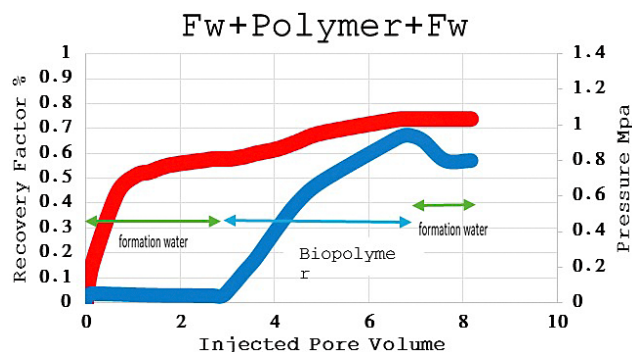


Figure 17. Oil recovery performance, pressure differential vs injected pore volume for formation/ biopolymer / formation water

through occurred after 0.92 pore volumes (Pv) of injected fluid. Following the breakthrough, oil continuously emerged until the recovery factor reached 60%, demonstrating a cessation in oil output. Subsequently, the introduction of Samba Biopolymer into the cores led to a substantial increase in pressure compared to the formation of water flooding.

Upon the Samba Biopolymer injection, oil extraction resumed, elevating the recovery factor to 74% before halting again. Subsequent formation water flooding post-biopolymer injection did not yield any additional oil production. These findings suggest that while the biopolymer material was effective in displacing the recovery factor, it did not alter the residual oil saturation.

Following the collection of produced oil, samples were extracted from the produced fluid and examined under a microscopic device to analyze the produced droplets for the presence of biopolymer. A comparison was made with samples from the water scenario.

In the formation water scenario (see Figure 18a), the oil droplets were observed to disperse naturally without the assistance of any external agent. Conversely, in the Biopolymer scenario (see Figure 18b), it was observed that the biopolymer material facilitated the dispersion of oil droplets into smaller ones, indicating the material's capability to displace oil droplets effectively.

4. Conclusions

- 1) The conducted tests confirm that the Samba biopolymer material is well-suited for elevating water viscosity under high temperatures and in saline conditions.
- 2) Results from core flooding tests demonstrate the effectiveness of the Samba biopolymer solution in increasing the recovery factor during extraction processes.
- 3) The high concentrations of the Samba biopolymer solution indicate its potential application as a gel material.
- 4) The ease of extraction in comparison to other published materials serves as a key motivation for the utilization of this material.

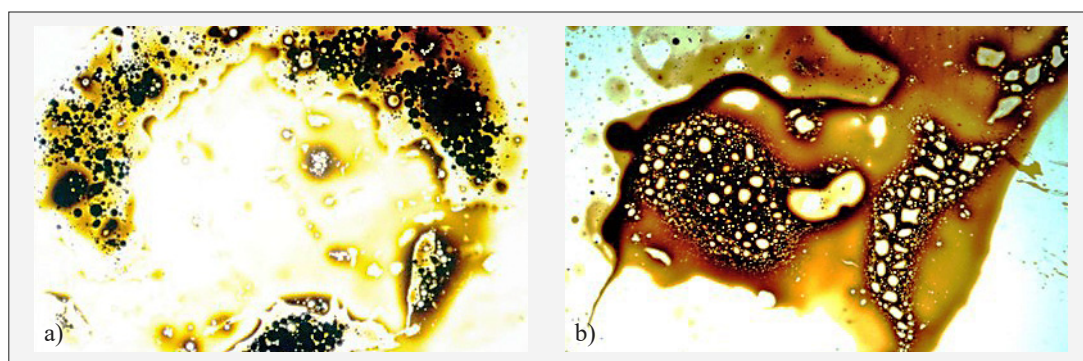


Figure 18. An optical microscope image for Microemulsion during a) formation water and b) Samba biopolymer

- 5) Initial investigations into the Samba biopolymer material have shown promise. Further development, including transforming the material into powder form and exploring additives to enhance particle cohesion, presents an opportunity for specialized companies in this field.

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SAŽETAK

Zelena energija: korištenje polimera samba za povećanje iscrpka nafte

Trenutačno postoji nekoliko izazova u dobivanju optimalnoga biopolimernog materijala koji je ekonomski isplativ, otporan na teške uvjete i ekološki prihvatljiv. Sada se u praksi primjenjuju samo biomaterijali ksantan i shizofilan. Ovim istraživanjem predstavlja se novi biopolimerni materijal za povećanje iscrpka nafte (engl. *enhanced Oil Recovery*, EOR) samba, koji je ekonomski isplativ, lako dostupan i stabilan.

Provedena su eksperimentalna ispitivanja biopolimera samba. Prije ekstrakcije otopine biopolimera napravljena je infracrvena spektroskopija (IR), rendgenska difrakcija (XRD) i rendgenska fluorescentna analiza (XRF) sjemenki. Nakon toga je napravljena analiza reoloških svojstava, raspodjele veličine čestica, kompatibilnosti te analiza filtracijskih svojstava. Također je proveden test utiskivanja u jezgru (engl. *core flooding*) kako bi se izmjerila učinkovitost istiskivanja nafte biopolimerom; međutim, ovaj test proveden je za samo jednu koncentraciju kako bi poslužio kao preliminarna procjena djelovanja polimera u ležišnim uvjetima.

Rezultati istraživanja pokazuju da je ekstrakcija otopine biopolimera iz organskoga sjemena bila uspješna, pri čemu je termička ekstrakcija bila osjetljiva na vrijeme i temperaturu zagrijavanja. Biopolimer samba povećao je viskoznost vode na vrijednost koja je potrebna za ležišne uvjete. Različite koncentracije otkrile su varijacije u reološkim i filtracijskim svojstvima zbog različite morfologije i funkcionalnosti površine. U optimalnim uvjetima postignut je iscrpak nafte od 74 %, što pokazuje potencijal biopolimera u EOR metodi.

Ključne riječi:

biopolimer samba, povećanje iscrpka nafte, reologija biopolimera, test utiskivanja u jezgru

Author's Contribution

Mohammed A. Samba, a member of the Petroleum Engineering staff at Sebha University and CEO of the Med Fezzan Research Center, was responsible for the material innovation, conceptualization, methodology design, original draft preparation, manuscript review and editing, as well as overall project administration. **Yiqiang Li**, Head of the Oil and Gas Laboratory at the China University of Petroleum, Beijing (CUPB), contributed through supervision, methodology development, manuscript review and editing, and data curation. **Zheyu Liu**, Assistant to the Head of the Oil and Gas Laboratory at CUPB, was involved in the provision of materials, laboratory facilities, and the execution of formal analysis. **Mahdi Almakki**, a member of the Chemical Sciences staff at Sebha University, supervised the preparation and characterization of biopolymers, carried out investigations, provided resources, and contributed to data curation. **Agus Arsad**, a staff member at the Institute for Oil and Gas (IFOG), Universiti Teknologi Malaysia, contributed to result visualization, data curation, and formal analysis.

All authors have read and agreed to the published version of the manuscript.

Integrated Neogene to Quaternary nannofossil biostratigraphy and sedimentation rates analysis in the Cikarang sequence, North West Java Basin, Indonesia

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Original scientific paper



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Abstract

Nannofossil assemblages were found throughout the Neogene to Quaternary rock sequence at Cikarang in the North-west Java Basin, Indonesia. This study determines the biostratigraphic age, reconstructs depositional phases and calculates the sedimentary rate of the rock sequence based on lithology and nannofossil assemblages. Within this sequence, 59 nannofossil species can be identified and 14 are index fossils with easily recognizable first occurrence (FO) or last occurrence (LO). Based on these boundaries, the sequence is divided into 17 biostratigraphic zones categorized into range and interval zones. Lithology successions in Cikarang are generally composed of fine-grained clastic rocks (sandstone and claystone), clastic limestone and fossil reefs, which are deposited in various depositional environments such as deep marine, shallow marine and littoral. Sedimentation rates vary between 4.18 m/Myr to 217.87 m/Myr, reflecting the influence of tectonic activity, sea level changes and sediment supply. Unconformities are identified at the intra Miocene, as well as Mio-Pliocene and Plio-Pleistocene boundaries.

Keywords:

nannofossil; biostratigraphy; sedimentation rates; North West Java Basin

1. Introduction

Nannofossils are small marine phytoplankton fossils, generally round to semi-circular, originating from coccoliths with a layer of haptophyte cells “coccolithophorids”. Nannofossils are widely distributed in ocean sediments. Detailed biostratigraphy studies based on nannofossils are applicable to reconstruction of the basin evolution, as well as inter-basin correlations (Bown et al. 2004; Isnaniawardhani et al. 2013; Raffi & Backman, 2022).

Nannofossils are recognized as high-resolution biostratigraphic indicators due to their rapid evolutionary rates, wide geographic distribution and high taxonomic diversity (Raffi, 1999; Raffi & Backman, 2022). The first occurrence (FO) and last occurrence (LO) of a nannofossil species can often be identified globally with a temporal resolution of approximately one million years, making them valuable for refining geological timescales, particularly in marine sediments (Gardin, 2002). Several biostratigraphic zonation schemes have been devel-

oped in low latitude regions to interpret the Cenozoic record using nannofossils. Among the most widely referenced are those proposed by Martini & Worsley (1970), Martini (1971), Okada & Bukry (1980), Varol (1983), Perch-Nielsen (1985) and Backman et al. (2012); each of these frameworks introduced zone numbering systems that facilitate chronological subdivision and correlation. For instance, Martini’s system uses the NP (Paleogene) and NN (Neogene) designations, which have become particularly popular in Indonesia for their clarity and ease of application (Kapid et al. 2021). The Neogene is divided into zones NN1 to NN21, while the Paleogene includes NP1 to NP25. Other frequently cited schemes, such as Okada & Bukry’s CN/CP system and Backman et al.’s CNM framework, have extended the utility of nannofossils through integration with multidisciplinary chronostratigraphic approaches (Isnaniawardhani, 2015). Recent improvements to these zonation models – through integration with tools such as magnetostratigraphy, isotope stratigraphy and planktonic foraminiferal data – have led to enhanced precision in dating and correlation (Backman et al. 2012; Sato & Chiyonobu, 2013). These developments have enhanced the temporal calibration of index species and strengthened the reliability of nannofossil-based stratigraphic frameworks in both regional and global contexts.

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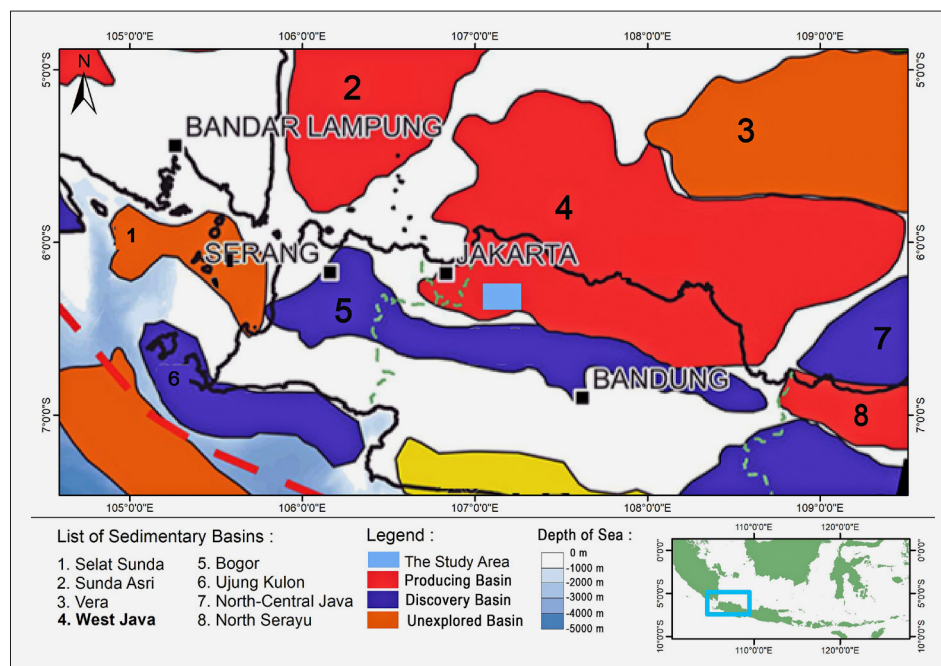


Figure 1. The position of the study area (Cikarang site), located in the North West Java Basin (Geological Survey Center, 2022)

Nannofossils that lived as plankton in the water column are sensitive to palaeoceanographic changes, including surface temperature, salinity, currents and nutrient levels, but are uncommonly used as bathymetric interpretation. However, when used with foraminifera analysis, the combined dataset enhances the reliability and resolution of palaeoenvironmental reconstructions more effectively than relying on either microfossil group alone (Schiebel et al. 2004).

The sedimentation rate of a rock sequence can be calculated using biostratigraphy analysis which provides absolute age and depositional environment data. By comparing the sediment thickness with the accumulation time interval based on the absolute age, the sedimentation rate is determined (Gowran, 2008). Continuous and consistent sediment sequences help to determine the position of layers accurately (Sadler, 1981).

As Neogene to Quaternary nannofossil assemblages are typically characterized by abundant diversification, rapid evolution, and clear recognition of their FO or LO, studies of similarly aged sediments from the North West Java Basin are expected to provide detailed marine sediment biostratigraphy. This study aims to determine the biostratigraphy, reconstruct depositional phases and calculate the sedimentation rate of the rock sequence based on Cikarang site samples.

The Cikarang site is located in the North West Java Basin, one of Indonesia's 128 sedimentary basins with rich hydrocarbon potential in volcanoclastic, carbonate and siliciclastic reservoirs with an estimated ± 2.3 BOE (Barrel Oil Equivalent) of oil and 1.17 BOE of gas (Doust & Noble, 2008; Geological Survey Center, 2022).

The North West Java Basin is a back-arc basin formed by subduction in southern Java (Usman et al. 2011). It is bordered by the Bogor Basin to the south, the Sunda Asri Basin to the west, the Vera Basin to the north, and the North Central Java Basin to the east (see Figure 1). The basin consists of a north-south graben system that forms sub-basins such as Jatibarang, Pasirputih, and Ciputat (Patmosukismo & Yahya, 1974; Iskandar et al. 2019). According to Hamilton (1979), this basin is a pull-apart basin formed by a dextral strike-slip fault, with a north-south oriented structure and a west-east trending rifting opening pattern. The basin is rich in hydrocarbons, both oil and gas, stored in volcanoclastic, carbonate and siliciclastic reservoirs (Noble et al. 1997).

The two regions of the North West Java Basin, the on-shore part in the southern area and the offshore part in the northern area (under the western Java Sea, a present-day shallow sea shelf), are influenced by dominant extensional faults with some compression (Darman & Sidi, 2000). The basement map shows the existence of high and low areas separated by normal faults. Three low areas are identified as the Jatibarang sub-basin, the Pasir Putih sub-basin, and the Ciputat sub-basin (Koesoemadinata, 2020). These sub-basins are the main half-graben-shaped sediment accommodation spaces formed by fault fractures which are then filled by Paleogene to Neogene sediments with a thickness of more than 5.500 meters. The Ciputat Sub-Basin forms the geological architecture of the study area as a result of rifting tectonics.

During the Pre-Paleogene, the area was a component of a stable continental crust which was not affected by intensive tectonic activity. The basement consists mainly of Cretaceous metamorphic rocks such as gneiss and

schists, intruded by granodiorite and form as a part of locally uplifted basement rock. The granitic composition of basement rock also indicates the continental crust.

From the Pre to the Plio-Pleistocene, the development of the back-arc North West Java Basin can be divided into three main tectonic phases, namely Paleogene syn-rift stage, Neogene post-rift stage and syn-orogenic stage. During the syn-rift stage, the Jatibarang Formation consisting of basaltic/andesite lava, tuff and detrital volcanic rocks (apparently sandstone) underlies the basement within most half-grabens and is missing on most structural heights. Continued rotational movements eventually fractured the crust extending into curved to rectangular faults. Due to this faulting, topographic relief increased and coarse clastic deposits accumulated in a transitional environment. The sedimentation continued later in the Early Miocene when the Baturaja Formation was deposited during a transgression. The absence of significant tectonic activity appears to have continued. This is indicated by remnants of horst blocks separating the rift grabens that were eroded into small isolated shallow carbonate platforms on which reefs formed. The source of clastic sediment shifted from local sources to northern sources from Sundaland.

The post-rift stage is characterized by a new subduction in the south of Java Island, with west-east strike-slip faulting related to the compressive force of the Indian Plate collision. During this phase, transgression seems to have continued. Marine sedimentation is represented by outer neritic shale, sandstone, clastic carbonate and reefs of the Early to Middle Miocene Upper Cibulakan Formation (known as Mid Main Carbonate / MMS) with sediment sources from Sundaland. Shallow to mid-neritic clastic and limestone of the Parigi Formation developed during the transition from Middle to Late Miocene, which in some places develops into small carbonate build-up.

The syn-orogenic stage is marked by compression that forms a thrust fault in the southern part, such as the Pasirjati Fault and Subang Fault, and the Pamanukan Fault in the northern area. The Late Miocene - Pliocene non-marine Cisubuh Formation, dominated by mudstone and sandstone with thin limestone in some places, was deposited during regression (Koesoemadinata, 2020).

2. Methods

A total of 62 samples were collected from continuous core sections of a well drilled in Cikarang, North West Java Basin, reaching a total depth of 652 m. Lithological descriptions and nannofossil assemblages were analysed directly from these core intervals. A small amount of material was scraped from the rock samples and smeared on a glass slide with a little water. The prepared samples were studied under a transmitted light microscope at 400–1000x magnification, with polarization and light contrast devices. Analyses using a Scanning Electron Microscope were performed to confirm several species.

Identification of nannofossil species was based on detailed morphological criteria and taxonomic classifications following established references, particularly those of Perch-Nielsen (1985), Young et al. (2003) and the continuously updated online resource **Nannotax3** (<https://www.mikrotax.org/Nannotax3/>). The most frequently used and easily applied standard nannofossil biozonations are Martini (1971), Okada & Bukry (1980) and Backman et al. (2012). The nannofossil identification and biostratigraphic zone determination used in this study mainly refer to their research. The dating of FO and LO of index species was determined according to Young (1998), (Young et al. 2003), Raffi et al. (2006) and Sato & Chiyonobu (2013).

A quantitative approach is commonly applied to calculate sedimentation rates based on the ratio of thickness to time interval (Shaw's method; Gowran, 2008). The thickness of sediment between stratigraphic layers is measured while time intervals are identified based on biostratigraphic data. The absolute age difference between the FO and LO of a species marker is used to calculate the accumulation time (Bown & Young, 1998; Sadler, 1981).

To obtain more accurate results in interpreting the bathymetry of the environment where the layers were formed, nannofossil data accompanied by foraminifera determination were used.

3. Results

3.1. Nannofossils Taxonomy

In core samples from the sedimentary succession of North West Java, 59 species classifying into 16 nannofossil genera were identified.

Family Braarudosphaeraceae Deflandre, 1947

Genus *Braarudosphaera* Deflandre, 1947

Braarudosphaera bigelowii (Gran and Braarud) Deflandre, 1947

Family Coccolithaceae Poche, 1913

Genus *Calcidiscus* Kamptner, 1950

Calcidiscus leptoporus (Murray & Blackman)

Loeblich & Tappan, 1978

Calcidiscus macintyreii (Bukry & Bramlette)

Loeblich & Tappan, 1978

Genus *Coccolithus* Schwarz, 1954

Coccolithus pelagicus (Wallich) Schiller, 1930

Genus *Coronocyclus* Hay, Mohler & Wade, 1966

Coronocyclus nitescens (Kamptner) Bramlette & Wilcoxon, 1967

Genus *Umbilicosphaera* Boudreaux and Hay, 1969

Umbilicosphaera sibogae (Weber-van Bosse) Graard, 1970

Family Discoasteraceae Tan, 1927

Genus *Catinaster* Martini & Bramlette, 1963

Catinaster coalithus Martini & Bramlette, 1963

Catinaster umbrellus Bukry, 1971

Genus *Discoaster* Tan, 1927

- Discoaster brouweri* Tan Sin Hok, 1927
Discoaster calcaris Gartner, 1967
Discoaster deflandrei Bramlette & Riedel, 1954
Discoaster druggii Bramlette & Wilcoxon, 1967
Discoaster hamatus Martini & Bramlette, 1963
Discoaster kugleri Martini & Bramlette, 1963
Discoaster neohamatus Bukry & Bramlette, 1969
Discoaster pentaradiatus Tan Sin Hok, 1927
Discoaster quinquerramus Gartner, 1969
Discoaster variabilis Martini & Bramlette, 1963
Discoaster exilis Martini & Bramlette, 1963
Discoaster bellus Bukry & Percival, 1971
Discoaster perplexus Bramlette & Riedel, 1954

Family Helicosphaeraceae Black, 1971

Genus *Helicosphaera* Kamptner, 1954

- Helicosphaera ampliaperata* Bramlette & Wilcoxon, 1967
Helicosphaera euphratis Haq, 1966
Helicosphaera intermedia Martini, 1965
Helicosphaera scissura Muller, 1981
Helicosphaera sellii (Bukry & Percival) Jafar & Martini, 1975
Helicosphaera kamptneri Hay & Mohler, 1967
Helicosphaera granulate Bukry & Percival, 1971
Helicosphaera mediterranea Muller, 1981
Helicosphaera minuta Muller, 1981
Helicosphaera stalis Theodoridis, 1984
Helicosphaera philippinensis Muller, 1981
Helicosphaera oblique Bramlette & Wilcoxon, 1967
Helicosphaera rhomba (Bukry, 1971) Jafar & Martini, 1975

Family Pontosphaeraceae Lemmermann, 1908

Genus *Pontosphaera* Lohmann, 1902

- Pontosphaera multipora* (Kamptner) Roth, 1970
Pontosphaera discopora Schiller, 1925

Family Prinsiaaceae Hay & Mohler, 1967

Genus *Gephyrocapsa* Kamptner, 1943

- Gephyrocapsa caribbeanica* Boudreaux & Hay, 1967
Gephyrocapsa oceanica Kamptner, 1943

Genus *Pseudoemiliania* Gartner, 1969

- Pseudoemiliania lacunosa* (Kamptner) Gartner, 1969

Genus *Reticulofenestra*

- Reticulofenestra pseudoumbilicus* (Gartner) Gartner, 1969
Reticulofenestra minuta Roth, 1970

Reticulofenestra minutula (Gartner, 1967) Haq

& Berggren, 1978

Reticulofenestra haqii Backman, 1978

Reticulofenestra floridana Theodoridis, 1984

Family Rhabdosphaeraceae

Genus *Rhabdosphaera* Haeckel, 1894

Rhabdosphaera procera Martini, 1969

Family Sphenolithaceae Deflandre, 1952

Genus *Sphenolithus* Deflandre, 1952

Sphenolithus abies Deflandre, 1953

Sphenolithus heteromorphus Deflandre, 1953

Sphenolithus moriformis (Bronnimann & Stradner, 1960) Bramlette & Wilcoxon, 1967

Sphenolithus neoabies Bukry & Bramlette, 1969

Reticulofenestra pseudoumbilicus was the most dominant species. The genera *Sphenolithus* and *Coccolithus pelagicus* were found to be very abundant. *Helicosphaera kamptneri* and *Discoaster brouweri* were present in almost every interval. *Reticulofenestra floridana*, *Reticulofenestra minutula*, *Reticulofenestra minuta*, *Sphenolithus abies*, *Calcidiscus macintyreii*, and *Sphenolithus neoabies* were abundant, while other species were found in lower abundance. The whole sequence is assigned the ages of the Early Miocene to the Pleistocene (22.82 to 1.71 million years ago).

3.2. Biostratigraphy

A total of 14 index species were selected in the nannofossil-rich samples: *Helicosphaera euphratis*, *Discoaster druggii*, *Helicosphaera ampliaperata*, *Sphenolithus heteromorphus*, *Reticulofenestra pseudoumbilicus*, *Discoaster kugleri*, *Sphenolithus abies*, *Catinaster colathus*, *Discoaster brouweri*, *Discoaster hamatus*, *Discoaster pentaradiatus*, *Discoaster quinquerramus*, *Pseudoemiliania lacunosa* and large *Gephyrocapsa oceanica* (> 4 µm). The first and last occurrence boundaries of these index species can be identified as well.

Based on the First Occurrence (FO) and/or LO (Last Occurrence) of these species, the sedimentary succession of the North West Java Basin can be grouped into 17 biostratigraphic zones starting from Early Miocene to Pleistocene (see **Table 1**).

- 1) *Helicosphaera euphratis* Partial Range Zone (> 652 m depth)

A few nannofossils occur in this lowest part of sequences. Early Miocene species, *H. euphratis* (Boesiger et al, 2017) is found in this interval.

- 2) *Discoaster druggii* - *Helicosphaera euphratis* Interval Zone (652 m – 618.74 m depth)

Interval from FO of *D. druggii* to LO of *H. euphratis*. FO of *D. druggii* marks the base of NN2, while LO of *H. euphratis* is close to the base of NN3 of Martini's zone or Early Miocene.

- 3) *Helicosphaera euphratis* - *Sphenolithus heteromorphus* Interval Zone (618.74 m - 597.41 m depth)

DEPTH (M)	AGE	NANNOFOSSIL ZONATION			NANNOFOSSIL SPECIES																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														
		THIS STUDY	MARTINI (1971)	OKADA & BUKRY (1980)	<i>Braunodophaera bigelowii</i>	<i>Coccolithus pelagicus</i>	<i>Pontoporeia</i> spp.	<i>Discoaster perplexis</i>	<i>Calcidiscus</i> sp.	<i>Pontoporeia multispina</i>	<i>Reticulofenestra</i> spp.	<i>Cavalithus</i> sp.	<i>Heliosphaera</i> spp.	<i>Pontoporeia discopora</i>	<i>Heliosphaera granulata</i>	<i>Heliosphaera kumpneri</i>	<i>Discoaster</i> spp.	<i>Reticulofenestra minuta</i>	<i>Heliosphaera intermedia</i>	<i>Sphenolithus moriformis</i>	<i>Prorocentrum</i> sp.	<i>Heliosphaera mediterranea</i>	<i>Micrantholites</i> p. sp.	<i>Discoaster delandieri</i>	<i>Coronocyclus thiacens</i>	<i>Reticulofenestra floridana</i>	<i>Heliosphaera rhombica</i>	<i>Heliosphaera obliqua</i>	<i>Heliosphaera ampliaperita</i>	<i>Heliosphaera mediterranea</i>	<i>Catinaster umbellatus</i>	<i>Calcidiscus leptoporus</i>	<i>Heliosphaera scissura</i>	<i>Reticulofenestra haqii</i>	<i>Discoaster druggi</i>	<i>Reticulofenestra proxima</i>	<i>Sphenolithus</i> spp.	<i>Sphenolithus madidus</i>	<i>Reticulofenestra</i>	<i>Discoaster exilis</i>	<i>Heliosphaera minuta</i>	<i>Sphenolithus heteromorphus</i>	<i>Calcidiscus marginatus</i>	<i>Heliosphaera subglobulata</i>	<i>Heliosphaera subglobulata</i>	<i>Sphenolithus abies</i>	<i>Discoaster kugleri</i>	<i>Discoaster bellus</i>	<i>Catinaster coalithus</i>	<i>Discoaster browni</i>	<i>Discoaster variabilis</i>	<i>Discoaster calcarius</i>	<i>Discoaster nophamensis</i>	<i>Discoaster hamatus</i>	<i>Discoaster quinquaramus</i>	<i>Heliosphaera cellula</i>	<i>Gephyrocapsa</i> spp.	<i>Umbilicosphaera abrogata</i>	<i>Reticulofenestra minima</i>	<i>Pseudemiliania lacunosa</i>	<i>Gephyrocapsa oceanica</i>	<i>Gephyrocapsa oceanica</i> (E-4 um)																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																					
32.00	Pleistocene	Large <i>Gephyrocapsa oceanica</i> TRZ	NN19 & younger	CN13 b & younger																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																															

Table 1. Nannofossil biostratigraphy of Cikarang sequences in North West Java Basin
The red lines represent the index species range occurrences

Interval from FO of *H. euphratis* to FO of *S. heteromorphus*, corresponds to NN3 of Martini's zone or CN2 of Okada & Bukry's zone or CNM4-5 of Backman's zone (Early Miocene).

- 4) *Sphenolithus heteromorphus* - *Helicosphaera ampliaperita* Interval Zone (597.41 m – 435.86 m depth)

Interval from FO of *S. heteromorphus* to LO of *H. ampliaperita*, corresponds to NN4 of Martini's zone or CN3 of Okada & Bukry's zone or CNM6 of Backman's zone (Early Miocene).

- 5) *Helicosphaera ampliaperita* - *Sphenolithus heteromorphus* Interval Zone (435.86 m – 423.67 m depth)

Interval from LO of *H. ampliaperita* to LO of *S. heteromorphus*, corresponds to NN5 of Martini's zone or CN4 of Okada & Bukry's zone or CNM7 of Backman's zone (Middle Miocene).

- 6) *Sphenolithus heteromorphus* - *Discoaster kugleri* Interval Zone (423.67 m – 411.48 m depth)

Interval from LO of *S. heteromorphus* to FO of *D. kugleri*, corresponds to NN6 of Martini's zone or CN5a of Okada & Bukry's zone or CNM7 of Backman's zone (Middle Miocene). In this zone, *Reticulofenestra pseudumbilicus* are abundant.

- 7) *Discoaster kugleri* - *Catinaster coalithus* Interval Zone (411.48 m – 374.90 m depth)

Interval from FO of *D. kugleri* to FO of *C. coalithus*, corresponds to NN7 of Martini's zone or CN5b of Okada & Bukry's zone or CNM10 of Backman's zone (Middle Miocene). In this zone, *Reticulofenestra pseudumbilicus* are abundant.

- 8) *Catinaster coalithus* - *Discoaster hamatus* Interval Zone (374.90 m – 338.33 m depth)

Interval from FO of *C. coalithus* to LO of *D. hamatus*, corresponds to NN8 of Martini's zone or CN6 of Okada & Bukry's zone or CNM12 of Backman's zone (Late Miocene).

- 9) *Discoaster hamatus* - *Discoaster quinquaramus* Interval Zone (338.33 m – 320.04 m depth)

Interval from LO of *D. hamatus* to FO of *D. quinquaramus*, equivalent to NN9-10 of Martini's zone or CN7-8 of Okada & Bukry's zone or CNM13-18 of Backman's zone (Late Miocene).

- 10) *Discoaster quinquaramus* Total Range Zone (320.04 m – 204.22 m depth)

Interval range from FO and LO of Late Miocene specific taxon, *D. quinquaramus*. This zone is equivalent to NN11 of Martini's zone or C9 of Okada & Bukry's zone or CNM19 of Backman's zone (Late Miocene).

- 11) *Discoaster quinquaramus* - *Pseudoemiliania lacunosa* Interval Zone (204.22 m - 155.45 m depth)



Interval from LO of *D. quinquerramus* to FO of *P. lacunosa*, equivalent to NN12-NN14 of Martini's zone or CN10 a-d of Okada & Bukry's zone or CNP1 of Backman's zone (Early Pliocene).

- 12) *Pseudoemiliania lacunosa* - *Reticulofenestra pseudoumbilicus* Interval Zone (155.45 m - 131.06 m depth)

Interval from FO of *P. lacunosa* to LO of *R. pseudoumbilicus*, equivalent to NN15 of Martini's zone or CN11 of Okada & Bukry's zone or CNPL2-3 of Backman's zone (Early Pliocene).

- 13) *Reticulofenestra pseudoumbilicus* - *Sphenolithus abies* Interval Zone (131.06 m - 118.87 m depth)

Interval from LO of *R. pseudoumbilicus* to LO of *S. abies*, equivalent to NN16 of Martini's zone or CN12 a-b of Okada & Bukry's zone or CNPL4 of Backman's zone (Late Pliocene).

- 14) *Sphenolithus abies* - *Discoaster pentaradiatus* Interval Zone (118.87 m - 106.68 m depth)

Interval from LO of *S. abies* to LO of *D. pentaradiatus*, corresponds to NN17 of Martini's zone or CN12 c of Okada & Bukry's zone or CNPL5 of Backman's zone (Pleistocene).

- 15) *Discoaster pentaradiatus* - *Discoaster brouweri* Interval Zone (106.68 m - 44.81 m depth)

Interval from LO of *D. pentaradiatus* to LO of *D. brouweri*, corresponds to NN18 of Martini's zone or CN12 d of Okada & Bukry's zone or CNPL6 of Backman's zone (Pleistocene).

- 16) *Discoaster brouweri* - large *Gephyrocapsa oceanica* Interval Zone (44.81 m - 32.00 m depth)

Interval from LO of *D. brouweri* to FO of large *G. oceanica* ($>4 \mu\text{m}$), corresponds to NN19 of Martini's zone or CN13 a of Okada & Bukry's zone (Pleistocene).

- 17) Large *Gephyrocapsa oceanica* Total Range Zone (<32.00 m depth)

Large *G. oceanica* ($>4 \mu\text{m}$) is found in this interval. This zone is equivalent to NN20 of Martini's zone or CN13 b of Okada & Bukry's zone (Pleistocene).

Each first or last occurrence boundary of the index species, identified from the biostratigraphic analysis, is assigned with its absolute age (see **Figure 2**). These data will be used to determine the time in the sedimentation rate analysis.

3.3. Sedimentation Rate

The study of sedimentation rate will provide an overview of various factors that affect the environment such as sea level changes and tectonic activity as well as processes related to erosion and sediment supply. Through the analysis of lithology, biostratigraphy and depositional environment of vertical stratigraphic sequences from Cikarang, the manifestation of deposition and variations in sedimentation rate over the time will be described. This description can provide an understanding of the

geological dynamics in the North West Java Basin from the Miocene to the Pleistocene. The sedimentation rate is calculated by dividing the thickness of the sediment interval by the geological period in meters per thousand years (m/Myr). In this study, in the NN17/CN12 zone, a sediment interval 12.19 m thick with an age range of 0.552 Ma resulted in a sedimentation rate of 23.35 m/Myr. The following is a detailed description of sediment changes along the Cikarang sequence which is divided into several depth intervals based on biostratigraphic zones descending from older to younger (see **Figure 3**).

3.3.1. Interval 652 m to 618.74 m depth

Thin layers of claystone with carbonate sediments were deposited in the transgressive phase (22.82 to 19 Ma, Early Miocene) with a sedimentation rate of about 8.7 m/Myr. Based on environmental interpretation using nannofossil data accompanied by foraminifera determination, these very fine sediments were deposited in the deep marine.

3.3.2. Interval 618.74 m to 597.41 m depth

The intercalation of claystone and sandstone was deposited during 19 to 17.72 Ma with a very low sedimentation rate (4.18 m/Myr). This phase reflects an increase in sediment supply at low energy.

3.3.3. Interval 597.41 m to 435.86 m depth

At 17.72 Ma, the depositional environment is starting to become shallower in relation to a significant increase in clastic sediment supply, with a sedimentation rate reaching 39.72 m/Myr. Fine clastic sediment layer was gradually covered by intercalated clastic and carbonate layers. This indicates a transition from deep to shallow marine. At the end of this phase, 14.91 Ma, it was covered by increasingly coarsening-upward sediments reflecting higher depositional energy.

3.3.4. Interval 435.86 m to 423.67 m depth

During the period 14.91 to 13.65 Ma (Middle Miocene), interbedded claystone and sandstone were formed in a dynamic energy shallow marine environment, with a decreasing trend in sedimentation velocity reaching 13.93 m/Myr.

3.3.5. Interval 423.67 m to 411.48 m depth

Since 13.65 to 11.90 Ma, the sedimentation rate increased slightly (13.95 m/Myr). The claystones were dominant with a few limestones which are characterized by coarsening upwards. These sediments established under the low-energy conditions with low sediment supply in a stable shallow marine environment.

3.3.6. Interval 411.48 m to 374.90 m depth

During the period of 11.90 to 10.90 Ma, basin subsidence caused the Cikarang area to become a deep marine,

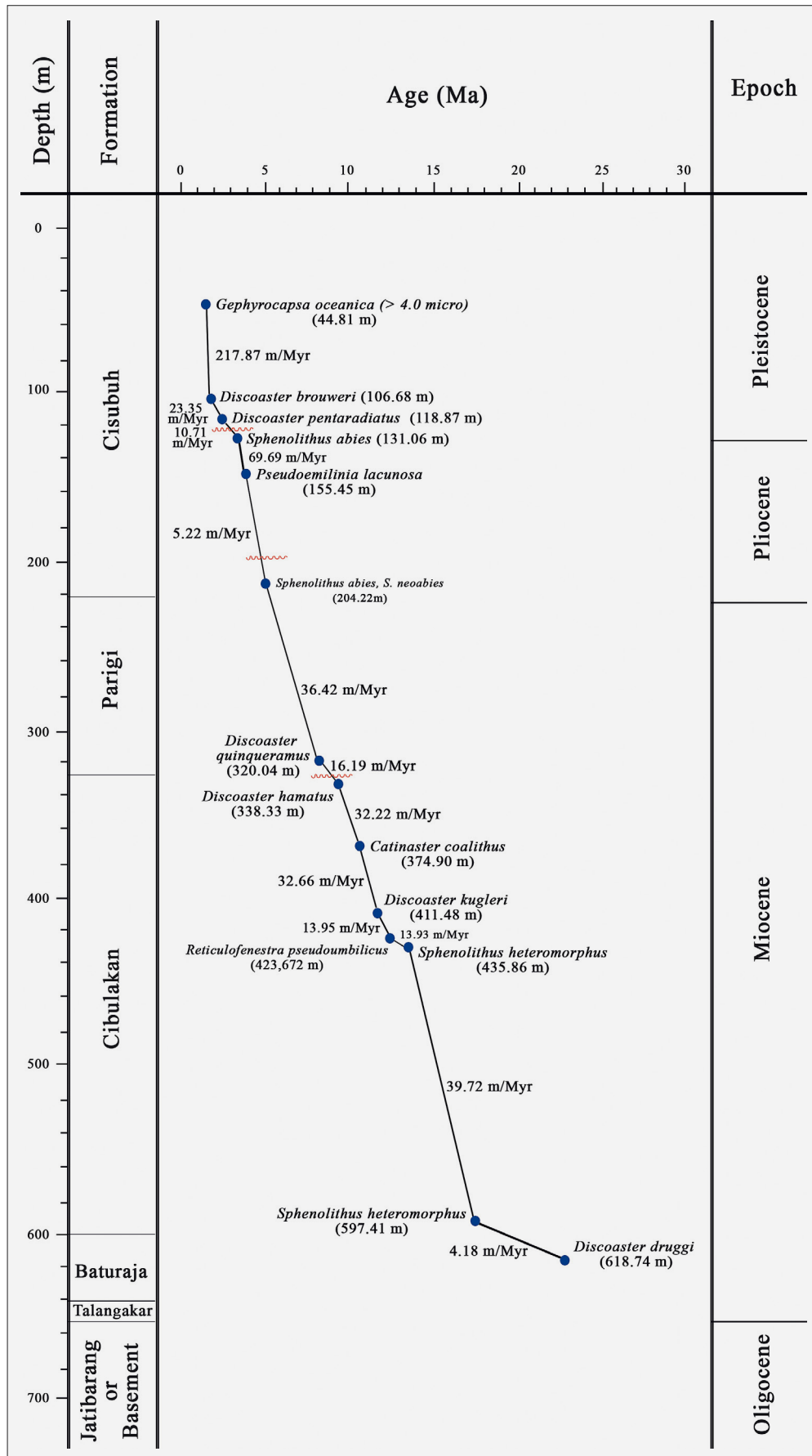


Figure 3. Age-depth plots of index species at Cikarang sequences

where clastic deposits, dominated by claystone with limestone layers, were formed. Sedimentation with the rate of 32.66 m/Myr has formed a deposit with the fining upward trend.

3.3.7. Interval 374.90 m to 338.33 m depth

Beginning at 10.90 Ma, thin layers of claystone and limestone were deposited at a sedimentation rate of 32.22 m/Myr, indicating a shallowing pattern. Approaching 9.65 Ma (Late Miocene), a coarsening-upward lithologic succession was deposited under high energy conditions.

3.3.8. Interval 338.33 m to 320.04 m depth

At the beginning of this period, 9.65 Ma, clastic deposits with limestone intercalations were formed, due to the ongoing shallowing process. An unconformity is indicated at the end of this period (Late Miocene).

3.3.9. Interval 320.04 m to 204.22 m depth

After 8.52 Ma, clastic limestone and reefs was formed in a quiet shallow marine setting, until 5.59 Ma.

3.3.10. Interval 204.22 m to 155.45 m depth

At 5.59 Ma subsidence has caused Cikarang area to become deeper, where sedimentation of fine sandstone and claystone occurred at a slow rate (5.22 m/Myr). Then gradual regression occurs. Coarse sandstone is found near the top of this interval. It indicates a depositional process in a transition zone with the sediment supply from the land. Basal Pliocene unconformity is indicated at the end of this period (4 Ma).

3.3.11. Interval 155.45 m to 131.06 m depth

During the period of 4 to 3.79 Ma, this area is characterized by an abundant supply of clastic sediments due to tectonic or erosional activity. A significant increase in sedimentation rates, up to 69.69 m/Myr, formed a sequence of sandstone and claystone in a shallow marine environment.

3.3.12. Interval 131.06 m to 118.87 m depth

Since 3.79 to 3.65 Ma (Late Pliocene), a sedimentation rate of approximately 10.71 m/Myr produced sandstone with intercalated claystone under stable transitional conditions.

3.3.13. Interval 118.87 m to 106.68 m depth

During the period of 3.65 to 2.51 Ma, sedimentation continued in shallow marine environment at an increasing rate of up to 23.35 m/Myr. Alternating claystones and sandstones formed during this phase. The high sedimentation rate indicates more dynamic conditions, with

increased sediment supply, which may have been influenced by tectonic activity.

3.3.14. Interval 106.68 m to 44.81 m depth

Rapid sedimentation (217.87 m/Myr) has deposited layers of coarse sandstone and claystone. Active land progradation, tectonics, erosion and climate change influenced geological processes during 2.51 to 1.99 Ma. At the end of this period tectonic activity occurred, which lifted Cikarang into a littoral zone.

3.3.15. Interval 44.81 m to 32.00 m depth

During 1.99 to 1.70 Ma (Pleistocene), littoral sedimentation took place at a rate of 7.55 m/Myr which has deposited sandstone and conglomerate.

4. Discussion

The biostratigraphy of the North West Java Basin studied in the Cikarang sequence shows 17 biostratigraphic zones that correlate with NN1 to NN20 (CN1-CN13) in the absolute age range of 22.82 Ma (Early Miocene) to 1.70 Ma (Pleistocene). This is consistent with the regional stratigraphy of North West Java Basin according to previous researchers, including **Noble et al. (1997)** and **Koesoemadinata (2020)**. Absolute age is determined based on the first occurrence (FO) or last occurrence (LO) of index species, according to **Young (1998)**, **Raffi et al. (2006)**, **Sato & Chiyonobu (2013)** and **Boesiger et al. (2017)**.

The lowest part of this sequence (interval 652 - 618.74 m depth) is marked by *Discoaster druggii* which first appeared (FO) around 22.82 Ma (Early Miocene) as an indicator of warm shallow marine water at equatorial to tropical boundaries (**Aubry, 1984**). LO *Helicosphaera euphratis*, FO *Sphenolithus heteromorphus*, LO *Helicosphaera ampliaperta*, LO *Sphenolithus heteromorphus*, FO *Discoaster kugleri*, FO *Catinaster coalithus* and LO *Discoaster hamatus* characterize the boundaries of the biostratigraphic zones equivalent to NN2 to NN9 in Early to Late Miocene. The Late Miocene unconformity possibly correlated with carbonate build-up of Parigi Formation (**Koesoemadinata, 2020**). Further-more, FO and LO *Discoaster quinqueramus* characterize the base of NN11 and NN12 zone in Latest Miocene. It is followed by an unconformity that correlates to the Miocene-Pliocene boundary. FO *Pseudoemiliana lacunosa*, LO *Reticulofenestra pseudoumbilicus*, LO *Sphenolithus abies* and LO *Discoaster pentaradiatus* characterize the boundaries of the biostratigraphic zones equivalent to NN7 to NN14 in the Early to Late Miocene. An unconformity and depositional environment shifting were identified at the Plio-Pleistocene boundary (**Darman & Sidi, 2000**; **Hamilton, 1979**). LO *Discoaster brouweri* and FO large *Gephyrocapsa oceanica* equivalent to

NN18 and NN19 marked Pliocene period in the Cikarang area.

Each FO and LO index species were assigned with an absolute age to calculate the sedimentation rate. Overall, sedimentation rates ranging from very low (4.18 m/Myr) to high (217.87 m/Myr), which correlates with sea level fluctuation from deep marine, shallow marine to littoral. In Early Miocene (recorded in interval 618.74 to 435.86 m) sedimentation rates were low (range 4.18 to 39.72 m/Myr) indicating low sediment supply in the deep marine environment. The Middle to Late Miocene in Cikarang (interval 435.86 m to 320.04 m) is a regressive period characterized by coarsening-upward lithologic succession in shallow marine environment with sedimentation rate of 13.93 to 32.66 m/Myr, then overlain by limestone which partly forms a carbonate build-up. During the period of transgression, sedimentation rate was 5.22 m/Myr. After a brief sea level drop, there was an increase in tectonic activity that resulted in an unconformity in the basal Pliocene. The progradation phase (< 320.04 m) was marked by a significant increase in sedimentation rate reaching 217.87 m/Myr, due to the influence of tectonic activity.

5. Conclusions

Nannofossil assemblages were found throughout the Neogene to Quaternary rock sequence at Cikarang in the Northwest Java Basin, Indonesia. Within this sequence, 59 nannofossil species classifying into 16 nannofossil genera were identified: *Braarudosphaera* (*B. bigelowii*), *Calcidiscus* (*C. leptoporus* and *C. macintyreii*), *Coccolithus* (*C. pelagicus*), *Coronocyclus* (*C. nitescens*), *Umbilicosphaera* (*U. sibogae*), *Catinaster* (*C. coalithus* and *C. umbrellus*), *Discoaster* (*D. brouweri*, *D. calcaris*, *D. deflandrei*, *D. druggii*, *D. hamatus*, *D. kugleri*, *D. neo-hamatus*, *D. pentaradiatus*, *D. quinquenarius*, *D. variabilis*, *D. exilis*, *D. bellus* and *D. perplexus*), *Helicosphaera* (*H. ampliaperta*, *H. euphratis*, *H. intermedia*, *H. scissura*, *H. sellii*, *H. kamptneri*, *H. granulata*, *H. mediterranea*, *H. minuta*, *H. stalis*, *H. philippinensis*, *H. oblique* and *H. rhomba*), *Pontosphaera* (*P. multipora* and *P. discopora*), *Gephyrocapsa* (*G. caribbeanica* and *G. oceanica*), *Pseudoemiliania* (*P. lacunosa*), *Reticulofenestra* (*R. pseudoumbilicus*, *R. minuta*, *R. minutula*, *R. haqii* and *R. floridana*), *Rhabdosphaera* (*R. procera*) and *Sphenolithus* (*S. abies*, *S. heteromorphus*, *S. moriformis* and *S. neoabies*). The most dominant species was *Reticulofenestra pseudoumbilicus* along with other species such as *Sphenolithus moriformis* and *Coccolithus pelagicus*. There are 14 index fossils with easily recognizable first occurrence (FO) or last occurrence (LO).

Based on these FO and LO, the sequence is divided into 17 biostratigraphic zones categorized into range and interval zones. FO and LO index fossils, descending from oldest to youngest, are: FO *Discoaster druggii* (22.82 Ma), LO *Helicosphaera euphratis* (19.00 Ma),

FO *Sphenolithus heteromorphus* (17.72 Ma), LO *Helicosphaera ampliaperta* (14.91 Ma), LO *Sphenolithus heteromorphus* (13.65 Ma), FO *Discoaster kugleri* (11.90 Ma), FO *Catinaster coalithus* (10.9 Ma), LO *Discoaster hamatus* (9.55 Ma), FO *Discoaster quinquenarius* (8.52 Ma), LO *Discoaster quinquenarius* (5.39 Ma), FO *Pseudoemiliania lacunosa* (4.00 Ma), LO *Reticulofenestra pseudoumbilicus* (3.79 Ma), LO *Sphenolithus abies* (3.65 Ma), LO *Discoaster pentaradiatus* (2.51 Ma), LO *Discoaster brouweri* (1.99 Ma) and FO large *Gephyrocapsa oceanica* (1.71 Ma).

Through analysis of lithology characteristics, depositional environment and FO or LO of index species from vertical stratigraphic sequences, the depositional manifestation and variations in sedimentation rate over time can be identified. Lithologic successions in Cikarang are generally composed of fine-grained clastic rocks (sandstone and claystone), clastic limestone and reefs which are deposited in various depositional environments, such as deep marine, shallow marine and littoral.

Sedimentation rates vary between 4.18 m/Myr to 217.87 m/Myr, reflecting the influence of tectonic activity, sea level changes, and sediment supply. In Early Miocene (interval 618.74 to 435.86 m) the sedimentation rate was low (range 4.18 to 39.72 m/Myr) indicating the deep marine environment. From Middle to Late Miocene (435.86 m to 320.04 m) the sedimentation rate was 13.93 to 32.66 m/Myr and ended by an unconformity. Sedimentation continued at a rate of 5.22 m/Myr followed by the Mio-Pliocene unconformity. Sedimentation rate in Pliocene (< 320.04 m) reached 217.87 m/Myr influenced by tectonic activity. During the Pleistocene deposition the sedimentation rate was 7.55m/Myr. Unconformities are identified at the intra Miocene, as well as Mio-Pliocene and Plio-Pleistocene boundaries.

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SAŽETAK

Integrirana analiza neogenske do kvartarne biostratigrafije nanofosila i brzine sedimentacije u sekvenciji Cikarang, bazen Sjeverozapadne Jave, Indonezija

Zajednice nanofosila pronađene su u cijelome neogenskom do kvartarnom slijedu stijena u Cikarangu u bazenu Sjeverozapadne Jave u Indoneziji. U okviru ovoga istraživanja određena je biostratigrafska starost, rekonstruirane su faze taloženja te je izračunana brzina sedimentacije slijeda stijena na temelju litologije i zajednica nanofosila. Unutar ovoga slijeda identificirano je 59 vrsta nanofosila, a 14 su indeksni fosili s lako prepoznatljivim prvim (FO) ili posljednjim pojavljivanjem (LO). Na temelju tih granica slijed je podijeljen u 17 biostratigrafskih zona kategoriziranih u rasponske i intervalne zone. Litološke sukcesije u Cikarangu općenito su sastavljene od sitnozrnatih klastičnih stijena (pješčenjaka i gline), klastičnih vapnenaca i fosilnih grebena, koji su taloženi u različitim taložnim okruženjima kao što su dubokomorski, plitkomorski i litoralni. Brzine sedimentacije variraju između 4,18 m/Myr do 217,87 m/Myr, što odražava utjecaj tektonske aktivnosti, promjene razine mora i donosa sedimenta. Nepodudarnosti su identificirane unutar miocena, kao i na granicama miocena i pliocena te pliocena i pleistocena.

Ključne riječi:

nanofosil, biostratigrafija, brzina sedimentacije, bazen Sjeverozapadne Jave

Author's contribution

Lilian C Rieuwpassa (Postgraduate Student, Master Program in Geological Engineering, Faculty of Geological Engineering) analysed nannofossil, interpretation of both biostratigraphy and sedimentation. **Vijaya Isnaniawardhani** (Professor, Biostratigraphy) was responsible for research design, methodology, and writing of the manuscript. **Budi Muljana** (Professor, Stratigraphy) was responsible for writing and compiling the manuscript. All authors have read and agreed to the published version of the manuscript.

Magnetic Inversion to Recover Compact Structures by an Arctangent Stabilizer

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Abstract

This study introduces a novel method for the inversion of magnetic data using a focusing inversion technique. The method utilizes an arctangent stabilizing functional, which is reformulated into a pseudo-quadratic form by a weighting matrix. To optimize the process, the reweighted regularized conjugate gradient (RRCG) method is employed. The proposed technique is effective in restoring compact structures in subsurface structures without the need for a focusing parameter. The inversion method involves constructing an objective function for minimization, which incorporates the discrepancy between observed and predicted data and the deviation of the model from expected characteristics, which is known as the stabilizing functional. The data fit component determines how closely the inversion results match the observed measurements, while the model regularization term influences specific desired properties of the reconstructed density distribution. The study demonstrates the effectiveness of the proposed technique through its application to a synthetic dataset and one real-world aeromagnetic dataset from the McFaulds Lake area in Ontario, Canada.

Keywords:

magnetic; inversion; stabilizer; arctangent; McFaulds Lake

1. Introduction

In exploration programs, geophysicists analyze measured magnetic data to determine the distribution of subsurface physical properties, particularly magnetic susceptibility. This process, known as the inverse magnetic problem, involves constructing a model that fits the observed data. However, the problem is mathematically ill-posed, meaning it lacks a unique or stable solution. To mitigate the inherent non-uniqueness and instability, regularization techniques are essential (Fedi & Rapolla, 1999; Cuma et al., 2012). By applying these methods, geophysicists can develop more reliable subsurface models, which are critical for resource exploration and geological interpretation.

Over the years, numerous regularization techniques have been developed for potential field data inversion. Selecting an appropriate method depends on choosing a model criterion that incorporates the desired geological characteristics. Recent decades have seen significant advancements and diversification in this field (Li & Oldenburg, 1998; Portniaguine & Zhdanov, 1999, 2002; Lelièvre et al., 2009; Pilkington, 2009; Marchetti et al., 2014; Meng, 2018; Peng et al., 2018).

In the inversion of magnetic field data, regularization techniques based on minimum norm or maximum smoothness stabilizers are commonly used. These methods typically produce smooth susceptibility models. However, they may not be suitable for scenarios involving anomalous bodies with discrete, blocky structures.

To address this issue, researchers have developed non-smooth inversion techniques to reconstruct geologically realistic models with sharp, blocky features. These techniques often employ stabilizing functionals that enforce compactness. The foundational work in compact gravity inversion was introduced by Last and Kubik (1983), who minimized the spatial extent of the density distribution responsible for observed gravity anomalies. Portniaguine and Zhdanov (1999) extended this concept by applying it to the gradient of the physical property model, developing a focused inversion technique. However, both methods require careful selection of the focusing parameter.

Bertete-Aguirre et al. (2002) incorporated the total variation (TV) function as a stabilizing functional, imposing sparsity constraints on the model gradient – equivalent to applying an L1-norm to the gradient. Similarly, a Cauchy norm stabilizer has been proposed for sparsity constraints (Pilkington, 2009; Rezaie et al., 2017). Zhao et al. (2016) introduced a novel approach to focused inversion using a stabilizing functional based on the exponential variation of model parameters. While

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this method eliminates the need for a focusing parameter, it produces inverted models with an elongated tail at the base of the anomalous body. More recently, **Rezaie (2019)** applied a zero-order minimum entropy regularization term to effectively delineate sharp edges in reconstructed density models.

Geophysical inversion methods that employ focusing stabilizers require a parameter to control either the model's compactness or the sharpness of recovered geological boundaries. This parameter – commonly called the focusing or compactness parameter – varies depending on the specific model being used. Typically, its optimal value is determined through an iterative process involving multiple inversions and result-based adjustments. Such trial-and-error approaches remain standard practice for fine-tuning inversion processes (**Pilkington, 2009; Xiang et al., 2017; Rezaie, 2019, 2020**).

Recent developments have introduced parameter-free alternatives. **Rezaie (2023)** proposed a novel stabilization method using an error function that eliminates dependency on the focusing parameter. Similarly, **Hu et al. (2017)** developed an arctangent-based compactness constraint for ground-penetrating radar data inversion, enabling sharp boundary reconstruction without parameter tuning.

This study presents a novel focusing inversion technique for magnetic data that employs an arctangent stabilizing functional reformulated as a pseudo-quadratic function of model parameters through a weighting matrix, optimized using the reweighted regularized conjugate gradient (RRCG) method, and validated through successful applications to both synthetic and real-world field datasets.

2. Methods

2.1. Forward modelling

The magnetic data observed at Earth's surface are primarily caused by induced magnetization effects. Forward modelling aims to compute this magnetic field, which arises from the distribution of magnetic susceptibility (κ) in subsurface materials. The total magnetic field component ($\bar{T}$) at an observation point $\mathbf{r}_0$ outside the magnetic source region can be expressed as (**Blakeley, 1995**):

$$\bar{T}(\mathbf{r}_0) = -C \nabla \int_R \mathbf{J}(\mathbf{r}) \cdot \nabla \frac{1}{|\mathbf{r}_0 - \mathbf{r}|} d\mathbf{v} \quad (1)$$

where $C=1 \times 10^{-7}$ (H.m⁻¹), R is the volume occupied by the causative body, $\mathbf{r}_0$ denotes the observation point, $\mathbf{r}$ represents the position of a volume element $d\mathbf{v}$ of the source body and $\mathbf{J}=\mathbf{J}_i+\mathbf{J}_r$ is the total magnetization vector that is the sum of induced and remanent magnetizations. Often, we ignore the remanent component and the total magnetization vector can be obtained by the following formula:

$$\mathbf{J}_i = \kappa \mathbf{H} \quad (2)$$

where $\mathbf{H}$ is the Earth's magnetic field and κ represents magnetic susceptibility. To compute the total magnetic field component in **Equation 1**, the subsurface beneath the survey area is discretized into a series of rectangular prismatic cells. Each prism has predefined dimensions and location, with an assigned uniform magnetic susceptibility value. The foundational method for calculating the magnetic response of such rectangular prisms was developed by **Bhattacharyya (1964)**, with later refinements by **Rao and Babu (1991)** improving computational efficiency for modern computer-based implementations. In this study, we compute the magnetic signature of individual prismatic bodies using the **Rao and Babu (1991)** formulation. **Blakely (1995)** further contributed a concise mathematical representation of surface magnetic field data, compactly expressing the relationship between subsurface magnetic properties and surface observations as follows:

$$\mathbf{d}_{N \times 1} = \mathbf{G}_{N \times M} \times \boldsymbol{\kappa}_{M \times 1} \quad (3)$$

where N represents the total number of measurement locations at the surface, and M denotes the number of rectangular prisms used to discretize the subsurface in the model. The vector $\boldsymbol{\kappa}$ contains the unknown model parameters, which in this context represent the magnetic susceptibilities of each subsurface prism. The vector $\mathbf{d}$ comprises the measured magnetic field data from the survey, while matrix $\mathbf{G}$ serves as the forward operator that describes how each subsurface prism contributes to the magnetic field at each observation point.

2.2. Inversion method

To perform quantitative magnetic data inversion, we construct an objective function comprising two key components: (1) a data misfit term measuring the discrepancy between observed and predicted data, and (2) a regularization term controlling model characteristics. The data misfit quantifies how well the inversion results match field measurements, while the regularization term constrains the solution to exhibit desired physical properties. Following standard practice in geophysical inversion, we employ Tikhonov regularization (**Tikhonov & Arsenin, 1977**) to ensure stable solutions:

$$\Phi(\boldsymbol{\kappa}) = \mathbf{W}_d (\mathbf{G}\boldsymbol{\kappa} - \mathbf{d})_2^2 + \lambda S(\boldsymbol{\kappa}) \quad (4)$$

where N is the regularization parameter. $S(\boldsymbol{\kappa})$ represents the stabilizing functional and the first term is weighted data misfit, $\mathbf{W}_d$ represents the weighting matrix associated with the data:

$$\mathbf{W}_d = \text{diag} \left(\frac{1}{\sigma_1}, \dots, \frac{1}{\sigma_i} \right) \quad (5)$$

where σ_i represents the standard deviation of the i^{th} measurement. This study investigates a compactness

constraint based on an arctangent function, designed to improve the delineation of sharp boundaries between subsurface structures. The stabilizing functional can be expressed as:

$$S(\kappa) = \|W_e \kappa\|_2^2 \quad (6)$$

where W_e is a diagonal model weighting matrix which is dependent on model parameters and can be given by (Hu et al., 2017):

$$W_e = \text{diag} \left(\sqrt{\frac{\arctan \sqrt{\kappa^2 + \mu^2}}{\kappa^2 + \varepsilon^2}} \right) \quad (7)$$

where ε and μ are small, non-zero constants introduced to prevent mathematical singularities and ensure numerical stability. While these parameters serve this essential computational purpose, they have negligible impact on the model parameters themselves. The arctangent functional provides an efficient focusing inversion method for magnetic data that offers two key advantages: (1) it eliminates the need for a focusing parameter, significantly simplifying implementation, and (2) it maintains robust performance in recovering subsurface structures.

Li and Oldenburg (1998) demonstrated that magnetic data inherently possesses limited depth resolution due to the fundamental nature of potential field measurements. This characteristic makes precise depth determination of magnetic sources particularly challenging. To mitigate the natural tendency of susceptibility models to concentrate near the surface, we incorporate a depth weighting matrix defined as:

$$W_z = \text{diag} \left[\frac{1}{\frac{\eta}{z^2}} \right] \quad (8)$$

where z is the depth of the model parameter and η is set to 3 in magnetic inversion (Li & Oldenburg, 1998). Moreover, the algorithm must ensure that the model adheres to the specified upper and lower susceptibility limits until a satisfactory model is obtained (Portniaguine & Zhdanov, 1999, 2002).

$$\kappa = \begin{cases} b & \text{if } \kappa < b \\ a & \text{if } \kappa > a \end{cases} \quad (9)$$

where b and a represent the lower and upper bounds of magnetic susceptibility, respectively. We solve this magnetic focusing inversion problem through an iterative approach using the reweighted regularized conjugate gradient (RRCG) method (Zhdanov, 2015), implemented as follows:

$$r_n = W_d (G(\kappa_n) - d), \quad s_n = W_{en} W_z (\kappa_n),$$

$$I_{(k_n)}^\lambda = I_{(k_n)}^{\lambda_n} = G^T W_d^2 r_n + \lambda_n W_{en} W_z s_n,$$

$$\beta_{n+1}^\lambda = \frac{\|I_{(k_{n+1})}^\lambda\|^2}{\|I_{(k_n)}^\lambda\|^2}, \quad \tilde{I}_{(k_n)}^{\lambda_n} = I_{(k_n)}^{\lambda_n} + \beta_n^{\lambda_n} \tilde{I}_{(k_{n-1})}^{\lambda_{n-1}}, \quad \tilde{I}_0^{\lambda_0} = I_0^{\lambda_0},$$

$$\omega_n^{\lambda_n} = \frac{(\tilde{I}_{(k_n)}^{\lambda_n})^T I_{(k_n)}^{\lambda_n}}{\tilde{I}_{(k_n)}^{\lambda_n T} (G^T W_d^2 G + \lambda W_{en}^2 W_k^2) I_{(k_n)}^{\lambda_n}},$$

$$\kappa_{n+1} = \kappa_n - \kappa_n^{\lambda_n} \tilde{I}_{(k_n)}^{\lambda_n}, \quad \gamma = \frac{\|s_{n+1}\|^2}{\|s_n\|^2},$$

$$\lambda_1 = \frac{\|W_d (G\kappa_1 - d)\|^2}{\|\kappa_1\|_2^2}$$

$$\lambda_{n+1} = \lambda_n, \text{ if } \gamma \leq 1, \text{ and } \lambda_{n+1} = \frac{\lambda_n}{\gamma}, \text{ if } \gamma > 1$$

$$\lambda'_{n+1} = q\lambda_{n+1}, \quad q < 1, \text{ if } W_d r_n^2 - W_d r_{n+1}^2 < 0.01 W_d r_n^2,$$

$$\lambda'_{n+1} = q\lambda_{n+1}, \quad q < 1, \text{ if } \|W_d r_n\|^2 - \|W_d r_{n+1}\|^2 < 0.01 \|W_d r_n\|^2 \quad (10)$$

The algorithm converges to the solution when the normalized misfit arrives at the given level δ_0 (Rezaie, 2019, 2020):

$$\frac{\|W_d (G\kappa_n - d)\|_2^2}{\|W_d d\|^2} \leq \delta_0 \quad (11)$$

The RRCG is an efficient iterative solver that does not require constructing large $M \times M$ matrices or computing their inverses, unlike methods such as Gauss-Newton, Levenberg-Marquardt, and other IRLS algorithms. Another advantage of the RRCG algorithm is its ability to automatically select the regularization parameter through an adaptive process during iterations. This avoids the need to solve the inverse problem multiple times in each iteration.

2.3. Synthetic model

To illustrate the application of our proposed method, we examine a synthetic data scenario featuring distinct anomalous structures. According to Equation 7, we need to select two parameters μ and ε , that we set both equal to 1×10^{-16} for all models in this paper.

The synthetic model consisted of four blocks with a susceptibility of 0.05 SI and the background susceptibility is uniform that is equals to zero. The total magnetic field anomaly was calculated at ground level, based on an inducing magnetic field which has the inclination of 65° and the declination of -25° . The inducing field strength is 50,000 nT. The model covers an area extending 90 m to the north and 90 m to the east. The subsurface was divided into 23328 equal-sized rectangular

Table 1. Size parameters of the buried prisms in the synthetic model

Block number	x × y × z dimensions (m)	Depth to top (m)
(1)	125 × 125 × 125	25
(2)	125 × 125 × 125	50
(3)	125 × 125 × 125	50
(4)	125 × 125 × 125	25

prisms for inversion. Each prism measured 12.5 m on each side, arranged in a $36 \times 36 \times 18$ grid. There are four buried blocks in the area that the size of the buried blocks are expressed in **Table 1**.

Figure 1a presents the calculated magnetic anomaly for the synthetic model, incorporating 5% random noise. The inversion process converged after 23 iterations in 6.3 s, achieving a normalized misfit of 0.05 (see **Figure 1b**).

Figure 2 displays horizontal and vertical cross-sections of the true and inverted 3D susceptibility models. The horizontal slice is extracted at 75 m depth, while the vertical section is taken along the x-axis at $y = 450$ m. Together, these orthogonal views provide complementary visualization of the subsurface structure. The results demonstrate that the suggested inversion technique effectively reconstructs the synthetic model. In comparison with the true models in panels a and b, the recovered model accurately locates the four blocks in their intended positions, with distinct boundaries. Additionally, the estimated susceptibility values closely align with the actual values of the true blocks.

The model's computed magnetic response is presented in **Figure 3a**. A comparison between this calculated data and the measured data is illustrated in **Figure 3b**. This comparison demonstrates that the calculated data achieves an acceptable match to the observed data, indicating a successful data fitting process.

2.4. Application to the field data

The McFaulds Lake area in Canada is well-known for deposits, rich in nickel, copper, and platinum group elements (Ni-Cu-PGE) such as the Eagle's Nest deposit. This site lies near Webequie, northwestern Ontario. The area is characterized by a highly magnetic ultramafic intrusion of mantle origin, recognized as the 'Ring of Fire'. This intrusion has been emplaced along the edge of a significant granodiorite pluton, within the rock formations of the Sachigo greenstone belt. The area has been the focus of exploration for various economically significant mineral deposits including magmatic deposits of Ni, Cu, and PGE, Chromite mineralization of magmatic origin, Volcanic-hosted massive sulfide deposits as well as Diamond-bearing kimberlite formations (Balch et al. 2010; Lin and Zhdanov, 2018). The Ring of Fire's rocks include mafic metavolcanic flows, felsic metavolcanic flows, pyroclastic rocks and layered mafic to ultramafic intrusions. These intrusions run roughly parallel to the belt's westernmost section, occasionally cutting across it at an angle. They are situated near a large granitoid batholith west of the belt. The main layered intrusion in this area is notable for two types of deposits, at its deeper parts there are high-grade Ni-Cu-PGE deposits and the shallower parts and further east contains stratiform chromite deposits in the intrusion's stratigraphy (Geological Survey and Geological Survey of Canada, 2011).

In the study area, chromite deposits are typically found within layered ultramafic intrusive rocks, often in association with magnetite and serpentine. This association allows for the magnetic tracing of chromite through its potential host rocks. Therefore, airborne geophysical surveys were carried out in the McFaulds Lake area in 2010, gathering magnetic data from the air (Geological Survey and Geological Survey of Canada, 2011). Fig-

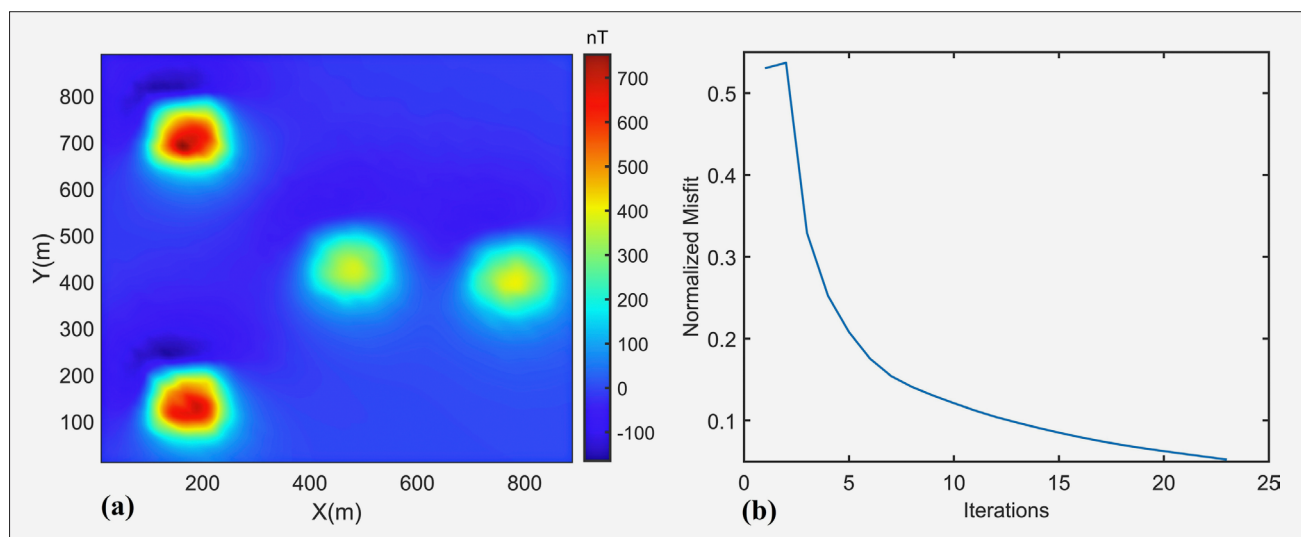


Figure 1. The magnetic anomaly from the synthetic model with 5% Gaussian noise of each datum magnitude (a). The behaviour of the normalized misfit (b).

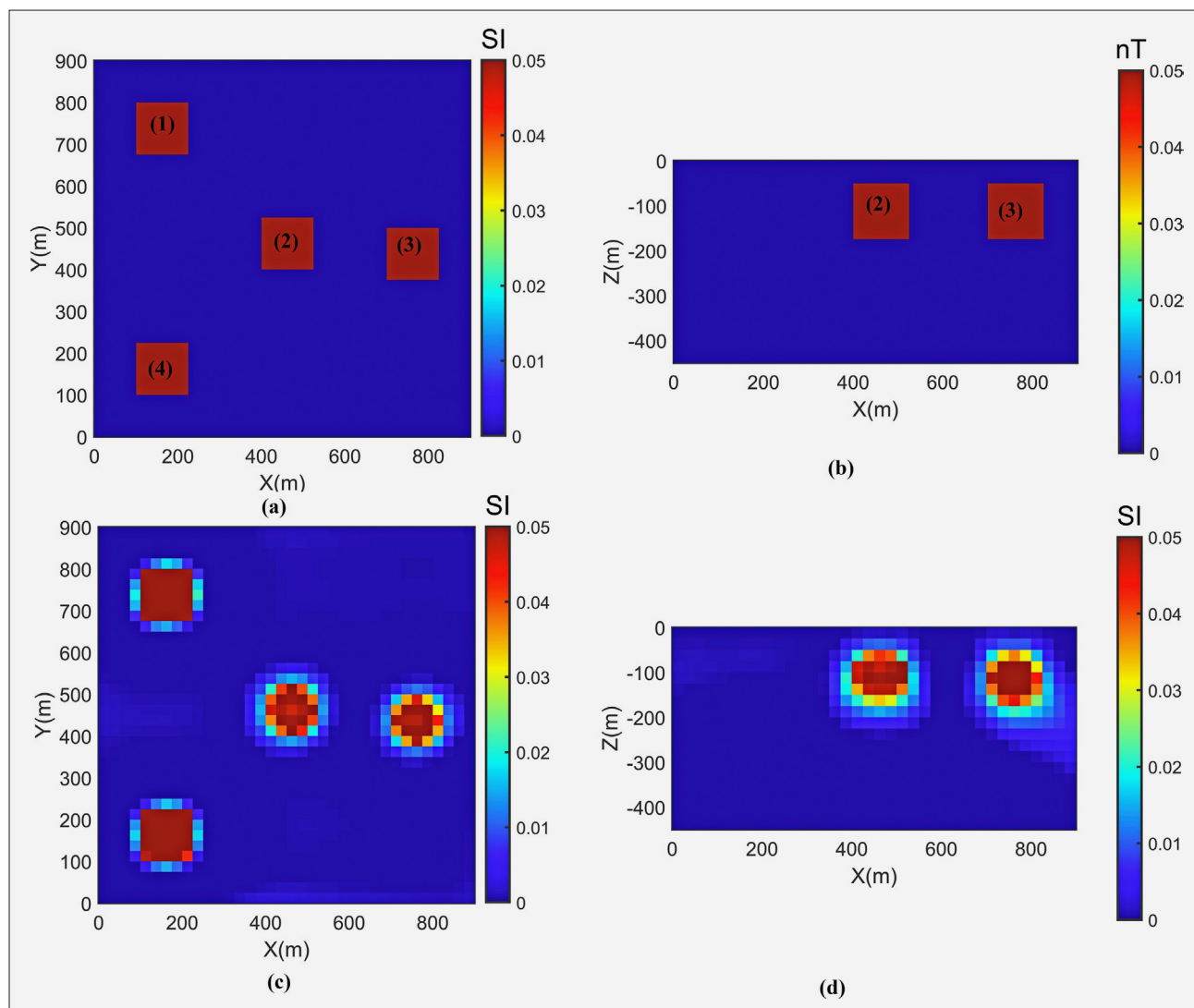


Figure 2. (a) Horizontal plan section of the true susceptibility distribution at a depth of 75 m.
 (b) A cross-sectional slice of the true susceptibility model at $Y = 450$ m.
 (c) Plan section through recovered model by inversion. (d) The vertical slice in the inversion result.

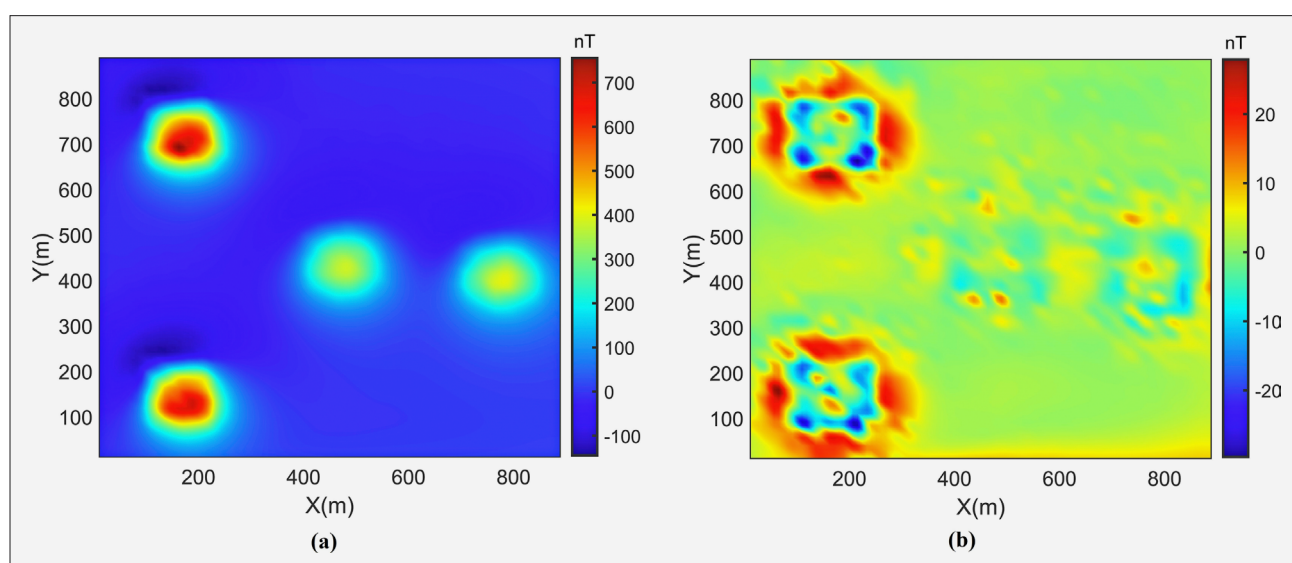


Figure 3. (a) The map of the magnetic anomaly from the focused model.
 (b) The residual map between computed and original data.

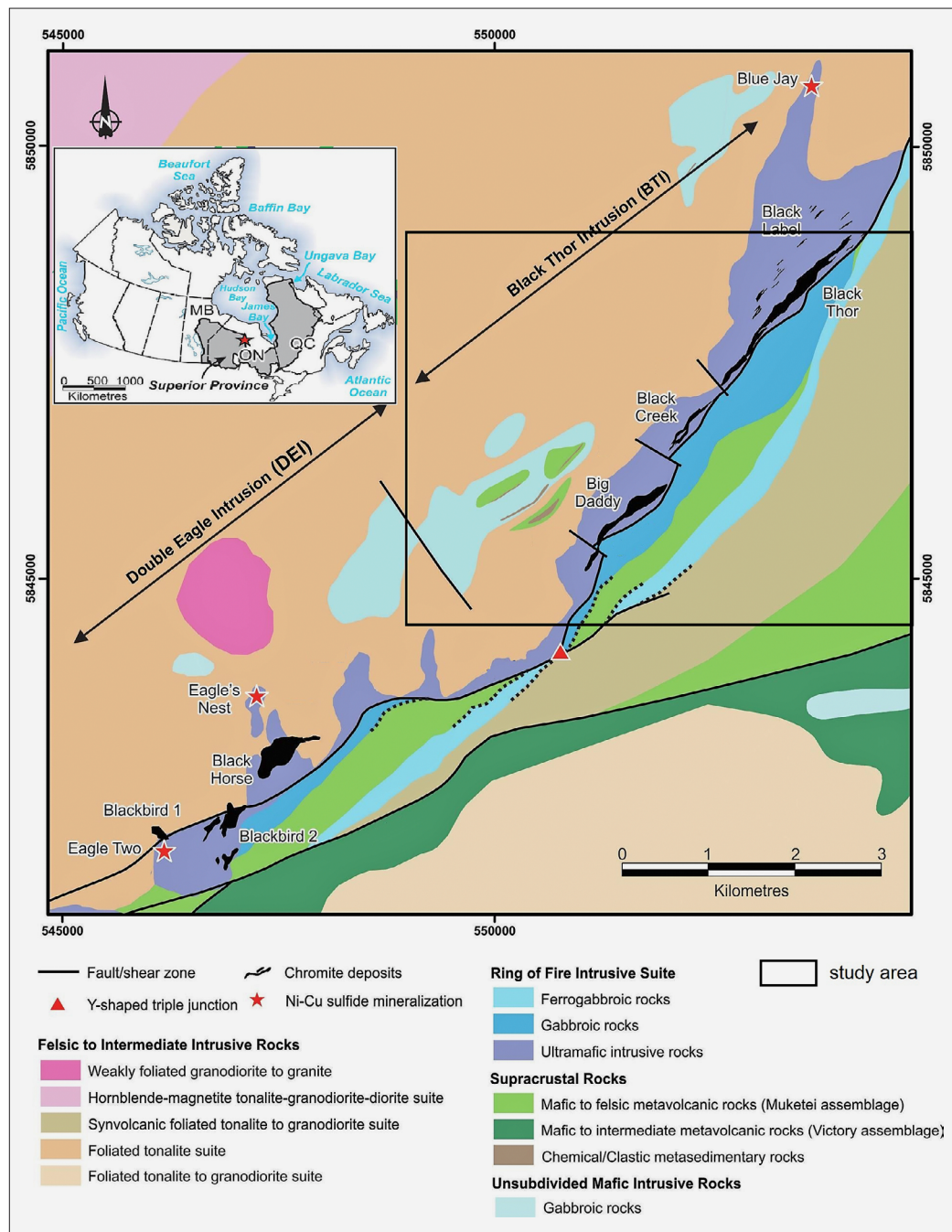


Figure 4. Geological map of the study area (adapted from Laudadio et al. 2022)

Figure 4 displays a geological map of the study area with known mineralizations (Laudadio et al. 2022).

The Ring of Fire intrusive body in the study area contains two main ultramafic intrusions, the Black Thor intrusion (BTI) and the Double Eagle intrusion (DEI), which are associated with significant chromite mineralization. These intrusions host several major deposits, including Black Thor, Black Label, Big Daddy, Black Horse, Blackbird, and Black Creek (see Figure 4). Collectively, the deposits in this region hold an estimated 343 million tonnes of geological resources averaging 32% chromite. Research suggests that the BTI and DEI

were supplied by separate magma conduits. The BTI and DEI intrusions are primarily made up of a thick ultramafic lower section and a thinner mafic upper section. The ultramafic portion consists of dunite, peridotite (mainly harzburgite), pyroxenite, and chromite, all metamorphosed to lower greenschist facies. Within these rocks, dunite and peridotite are largely composed of serpentinized or talc-altered olivine, making up 75–95% of their mineral content. Magnetite is widespread, appearing both as fine disseminated particles and as rims around chromite grains, a result of serpentinization processes. Chromitite mineralization appears in diverse

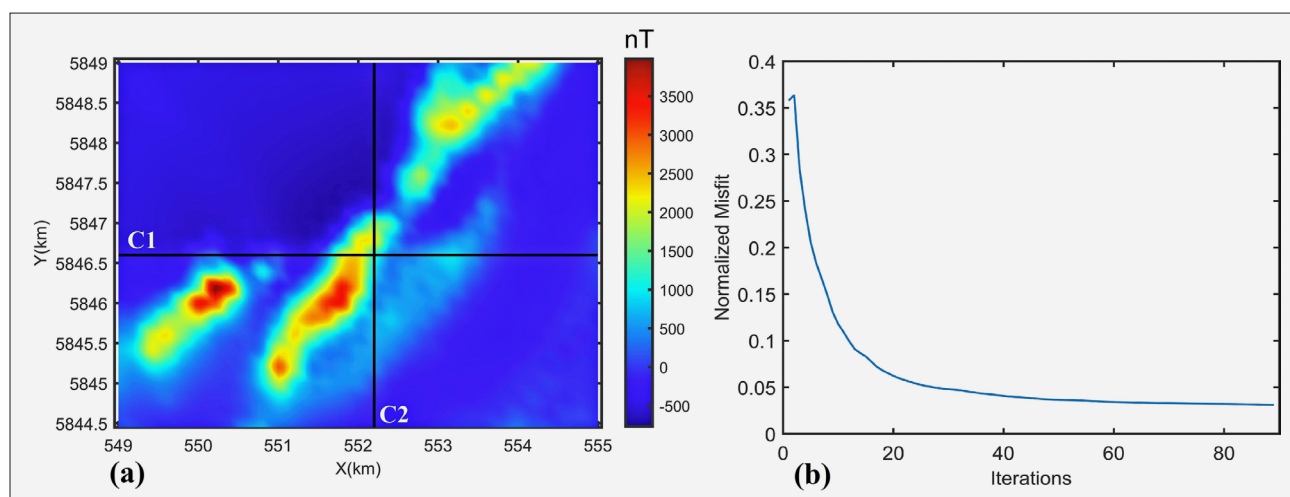


Figure 5. The map of magnetic anomaly over the McFaulds Lake area. The conjunction of the C1 and C2 lines represents the position of the Black Creek deposit (a). The behaviour of the normalized misfit (b).

styles, including finely laminated to thickly bedded layers, variably disseminated grains, and interlayered massive to semi-massive chromite deposits. These occurrences are typically hosted within dunite and peridotite zones. (Laudadio et al. 2022).

To demonstrate how well our proposed method works with field data, we've applied it to a portion of the magnetic data that covers the Black Creek area which is known for its chromite mineralization. **Figure 5a** illustrates the magnetic anomaly of the study area in which the C1 and C2 lines intersect at the location of the Black Creek chromite deposit.

The dimensions of the model domain was set to $6 \text{ km} \times 4.5 \text{ km} \times 2 \text{ km}$ in x, y and z directions and the subsurface region was divided into cube-shaped segments, each measuring 100 m on all sides leading to $60 \times 45 \times 20 = 54000$ cells. We ran the magnetic inversion by the arctangent stabilizing functional and the algorithm has been converged to the solution after 89 iterations in 34.38 s (see **Figure 5b**). **Figure 6** presents a comparison of actual measurements (see **Figure 5a**) and calculated data from the obtained model (see **Figure 6a**) for the total magnetic intensity field. The visual representation demonstrates a high degree of agreement between the observed and predicted data. This close correspondence is further highlighted by the inclusion of a difference map (see **Figure 6b**), which visually depicts the discrepancies between the measured and predicted magnetic field.

Figure 7 illustrates cross-sections in the inverted model of the study area. The panels a and b display vertical slices through the reconstructed magnetic susceptibility distribution along two specific lines, labeled C1 and C2 in **Figure 5a**.

In the C1 cross-section, the inversion results clearly reveal the top boundaries of the identified mineral deposit. However, the deeper portions of this body exhibit lower magnetic properties. Examining the C2 cross-section, the magnetic inversion suggests that the dike structure on the

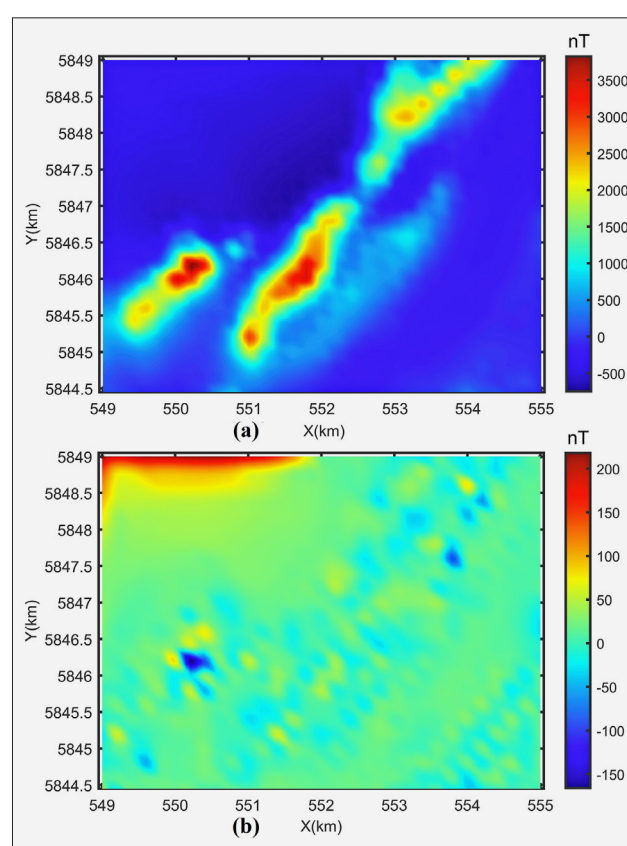


Figure 6. The map of the predicted magnetic data from the model (a). The map of the difference between the observed and predicted data (b).

right side contains a higher concentration of magnetic minerals. This increased magnetism might be indicative of chromite deposits in the Black Creek region.

The panel c presents a horizontal cross-section of anomalous magnetic susceptibility at a depth of 300 m. The horizontal slice, along with the previously mentioned vertical cross-sections, reveals anomalous targets characterized by distinct and partially continuous boundaries.

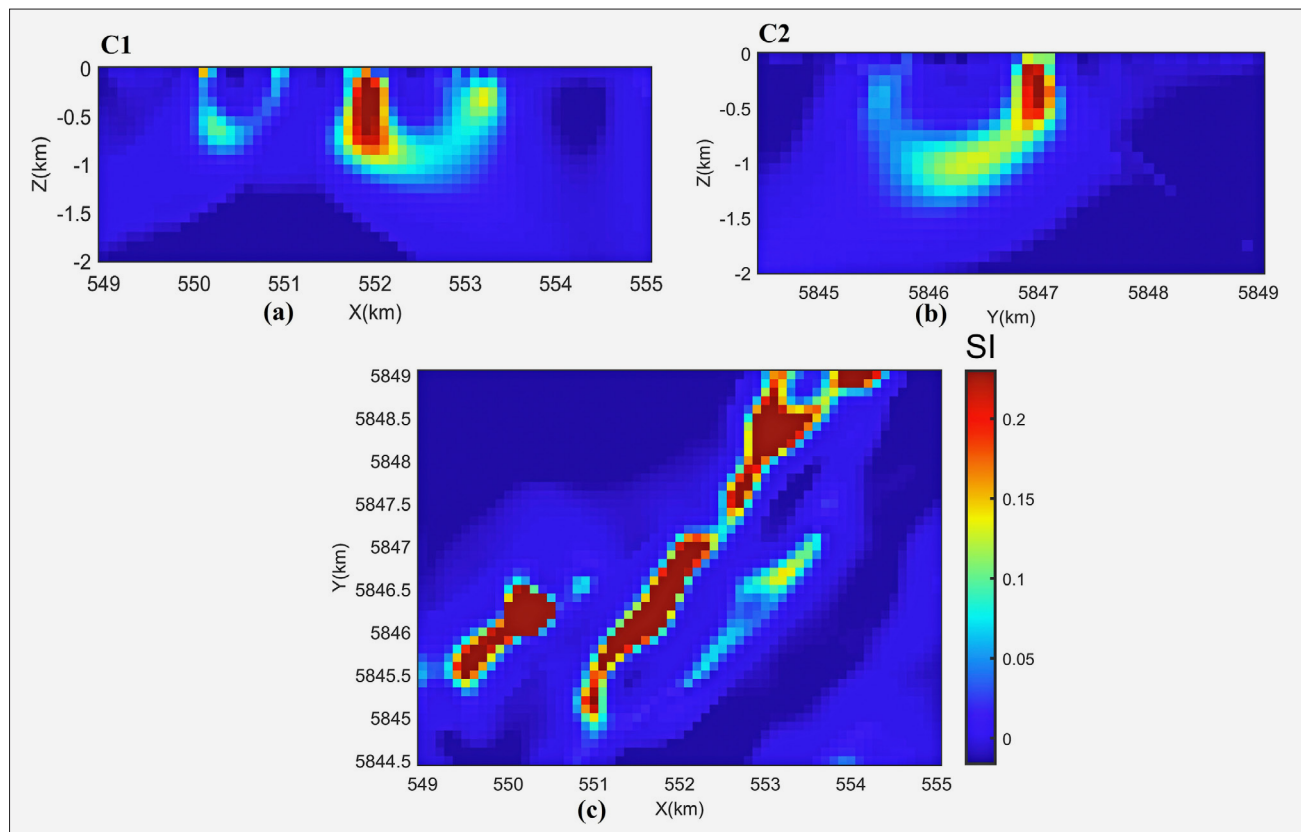


Figure 7. Vertical cross-sections of the recovered anomalous magnetic susceptibility distribution along C1 line (a) and C2 line (b). The horizontal section at the depth of 300 m (c).

This representation offers valuable insight into the nature and distribution of mineral deposits in the area. This approach enhances our understanding of the subsurface geological structures and potential mineral resources. The results agree with those obtained by **Lin and Zh-danov (2018)** using the multinary joint inversion of gravity and magnetic data over the study area.

3. Results and Discussion

The proposed arctangent stabilizer-based inversion method showed excellent performance in both synthetic and field tests. For the synthetic model, the inversion accurately recovered four prismatic blocks with sharp boundaries, achieving convergence after 23 iterations with a normalized misfit of 0.05 despite 5% added noise. Horizontal and vertical cross-sections (see **Figure 2**) showed precise reconstruction of the targets' locations and susceptibilities, while the calculated magnetic response (see **Figure 3a**) closely matched observations, with randomly distributed residuals (see **Figure 3b**) confirming robust data fitting. The method's effectiveness was further validated using aeromagnetic data from Ontario's McFaulds Lake area, where it resolved the Black Creek chromite deposit's structure after 89 iterations. Vertical sections (see **Figures 7a–b**) revealed distinct magnetic anomalies correlating with known miner-

alization, and the 300 m depth slice (see **Figure 7c**) delineated continuous high-susceptibility zones, aligning with prior geological studies. The computation time for synthetic model was 6.3 s and for the real case it was 34.38 s that demonstrate the efficiency of the algorithm.

Key advantages of the arctangent stabilizer include its parameter-free formulation, which eliminates the need for manual focusing parameter tuning, and its ability to recover compact structures without the elongated artifacts seen in exponential stabilizers. The incorporation of depth weighting mitigated magnetic data's inherent depth ambiguity, while RRCG optimization ensured efficient convergence. Though the method assumes dominant induced magnetization, its performance on field data underscores its practicality for mineral exploration. These results advance compact inversion techniques by combining computational efficiency with improved boundary resolution, offering a valuable tool for sharp-boundary target identification in potential-field geophysics.

4. Conclusions

We have developed a method for the inversion of magnetic data that recovers features of the subsurface structure with sharp boundaries. The method employs an arctangent stabilization functional that eliminates the need to determine an optimal focusing parameter, with

other parameters being automatically selected by the algorithm. When applied to magnetic data from a synthetic model, the inversion method produced a satisfactory susceptibility model. The inversion results demonstrated the method's capability to generate compact models that accurately represent the locations and forms of anomalous bodies.

We then applied this method to aeromagnetic data from the McFaulds Lake region, located in northwestern Ontario, Canada. By employing the inversion approach, we were able to generate a plausible geological model. This model proves valuable for guiding exploration efforts aimed at locating magmatic chromite deposits in the study area.

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SAŽETAK

Magnetska inverzija za pronalaženje kompaktnih struktura pomoću arkus tangens stabilizatora

Ova studija predstavlja novu metodu za inverziju magnetskih podataka koristeći se tehnikom fokusirajuće inverzije. Metoda primjenjuje stabilizirajući funkcional arkus tangensa, koji se reformulira u pseudokvadratni oblik pomoću matrice težina. Za optimizaciju procesa korištena je metoda ponovno ponderiranoga regulariziranog konjugiranog gradijenta (RRCG). Predložena tehnika učinkovita je u obnavljanju kompaktnih struktura u podzemnim strukturama bez potrebe za fokusirajućim parametrom. Metoda inverzije uključuje konstruiranje funkcije cilja za minimizaciju, koja obuhvaća razliku između promatranih i predviđenih podataka i odstupanje modela od očekivanih karakteristika, što je poznato kao stabilizirajući funkcional. Komponenta prilagodbe podataka određuje koliko se rezultati inverzije podudaraju s promatranim mjerenjima, dok termin regularizacije modela utječe na specifična željena svojstva rekonstruirane distribucije gustoće. Studija pokazuje učinkovitost predložene tehnike primjenom na sintetički skup podataka i jedan stvarni aeromagnetski skup podataka iz područja jezera McFaulds u Ontariju, Kanada.

Ključne riječi:

magnetski, inverzija, stabilizator, arkus tangens, jezero McFaulds

Author's contribution

Sahar Moazam (Dr): conceptualization, investigation and software. **Mohammad Rezaie** (Dr): conceptualization, preparing the main codes and writing.

All authors have read and agreed to the published version of the manuscript.

An Industrial Method for Mitigating Surface Deformations and Restoring Soil Integrity in the Kryvyi Rih Basin

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Original scientific paper



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Abstract

This study addresses the critical issue of technogenic safety and revitalization of devastated landscapes in the Kryvyi Rih basin, a major mining region in Ukraine. It highlights the environmental challenges posed by extensive mining activities, including sinkhole formation, soil degradation, and biodiversity loss, exacerbated by climate change and erosion. The research evaluates the effectiveness of vegetation cover through phytomelioration efficiency coefficients (Kfm), revealing a steady decline from 1984 to 2024 due to expanding devastated areas. For instance, Kfm values dropped from 3.6 to 2.8 for sinkhole No. 1, indicating reduced ecological resilience. A key focus is the proposed cemented paste backfilling technology, utilizing mining waste to fill sinkholes. This method aims to mitigate surface deformations, enhance public safety, and restore soil integrity while repurposing industrial byproducts. The study analyzes sinkhole dynamics using GIS and historical data, identifying nonlinear growth patterns, particularly during 1995–2005. Polynomial models (R^2 up to 0.997) effectively describe these trends. Economic analysis underscores the escalating costs of delayed revitalization, with expenses rising up to sevenfold over 38 years. The research advocates for timely intervention to reduce both environmental risks and financial burdens. In conclusion, the integration of backfilling technologies and phytomelioration strategies offers a sustainable solution for restoring Kryvyi Rih's landscapes, aligning with global climate goals and regional development needs. The findings emphasize the urgency of implementing these measures to ensure ecological stability and long-term socio-economic benefits.

Keywords:

technogenic safety; landscape revitalization; sinkhole remediation; phytomelioration coefficient; mining waste reclamation

1. Introduction

The issues of technogenic safety and the revitalization of devastated landscapes are becoming particularly relevant in the modern world, amid global climate change and growing awareness of environmental issues. The decisions made at the UN Climate Change Conference (COP26) in Glasgow in 2021, as well as at the Paris Climate Summit in 2015, set the global course for reducing greenhouse gas emissions and gradually phasing out fossil fuels. The Paris Agreement laid the groundwork for international cooperation in the field of sustainable development, which involves not only reducing dependence on coal but also active reclamation of devastated areas. By joining these global initiatives, Ukraine has committed itself to reducing emissions and closing

state coal-fired power plants (Cabinet of Ministers of Ukraine, 2013). However, the process of abandoning the coal industry is inextricably linked to the need to address issues related to large-scale areas devastated by mining activities and the accumulation of significant amounts of industrial waste.

The Kryvyi Rih mining region represents a distinct natural–man-made geosystem, where over a century of intensive iron-ore mining has caused irreversible transformations in both surface and subsurface environments. These activities have disrupted fault-block tectonics and increased neotectonic activity and massif instability (Evtexhov et al., 2022).

Large-scale surface deformations have become a defining feature of the Kryvyi Rih Iron Ore basin due to over a century of intensive underground and open-pit mining. Subsidence, sinkholes, and landslide-prone zones currently affect both industrial facilities and residential areas. These processes pose a serious threat to geotechnical stability, public safety, and sustainable land

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use. According to recent studies, the deformation zones in Kryvbas cover hundreds of hectares and are expanding annually, particularly in areas of delayed reclamation and insufficient backfilling (**Hubina & Zaborovskiy, 2022; Bazaluk et al., 2024**). Therefore, a detailed investigation of their spatial structure, genesis, and mitigation is critically important for regional risk management and engineering planning.

The geomorphological structure of the region has been significantly altered due to open-pit operations, underground cavities, and extensive waste deposition. The territory now features quarries up to 400 m deep, over 4.5 billion m³ of excavated voids, and up to 4,000 ha of subsidence zones and sinkholes. These factors have also reshaped drainage networks and contributed to erosion, karst processes, and surface deformation (**Bazaluk et al., 2024**).

Consequently, the Kryvyi Rih basin has transformed into a complex technogenic geosystem, which requires an integrated approach combining ecological restoration with geotechnical stabilization measures (**Bazaluk et al., 2024**).

The issue of technogenic load is particularly acute for Ukraine, which has a significant mining sector. The accumulated billions of tons of waste, most of which is generated by the mining, chemical and energy sectors, pose serious environmental challenges. Such wastes include coal mining dumps, ore tailings, thermal power plant slag, and others characterized by large volumes and potential environmental hazards (**Pactwa et al., 2020**). These factors necessitate the development and implementation of effective strategies for the revitalization of devastated landscapes, especially in regions of intensive mining activity, such as the Kryvyi Rih basin. A comprehensive environmental policy framework and the evolution of environmental management concepts play a critical role in shaping such strategies (**Hren et al., 2021; Batty et al., 2021**). Insight from other devastated regions of Ukraine, such as the Volhynian Upland and Male Polissia, demonstrates the broad-scale impact of mining activities and supports the need for adaptive restoration strategies (**Popovych & Voloshchysyn, 2019**). Valuable insight can be gained from research focused on mining regions across Ukraine, where ecological and phytogenic restoration efforts have been tested on coal mine tailings and waste dumps (**Skrobala et al., 2020; Popovych et al., 2021**). Environmental degradation in post-mining areas may also contribute to increased incidence of chronic diseases, particularly cardiovascular and metabolic disorders (**Serhiyenko & Serhiyenko, 2022**).

The Kryvyi Rih basin, as one of the largest mining regions in Ukraine, is characterized by a significant anthropogenic load and large areas of devastated landscapes. The issue of anthropogenic safety of these areas and their effective revitalization is extremely important for ensuring the environmental safety of the region and

sustainable development. Solving this problem requires an integrated approach that combines the analysis of existing anthropogenic risks, the development of effective revitalization methods based on international experience, including the application of geomorphic reclamation techniques (USA), phytoremediation and soil amendment practices (Germany), and cemented paste backfilling technologies (Canada and Australia). These internationally recognized methods are designed to restore land stability, improve soil fertility, and promote biodiversity by reshaping natural landforms, introducing native vegetation, and sustainably reusing mining by-products (**Maiti & Ahirwal, 2019**). The introduction of such technologies is essential for reducing the anthropogenic load and restoring the natural potential of devastated areas. In this context, modelling approaches to predict pollution dynamics in mining regions also play a crucial role in strategic planning (**Pukish et al., 2024**).

The scientific literature focuses on the issues of mining waste management, reclamation of disturbed lands and ecosystem restoration. The research covers a wide range of topics, from geochemical modelling of rock weathering processes (**Strömberg & Banwart, 1994**) and analysis of the current state of coal industry waste (**Gorman & Dzombak, 2018**) to the development of sustainable coal mining strategies (**Kariuki & Kuria, 2021**) and methods of ecological restoration (**Maiti & Ahirwal, 2019**). Research on the reuse and recycling of mine waste, monitoring of mine dumps (**Agboola et al., 2020**), and multi-element geochemical analysis of technologically loaded areas (**Loredo et al., 2006**) are of particular interest.

Recent studies from other European mining regions have also addressed similar challenges, including land destabilization, ineffective mine void management, and long-term ecological risks associated with abandoned extraction areas. These works emphasize the relevance of integrated rehabilitation strategies and underline the importance of biodiversity-oriented reclamation, sustainable reuse of mining waste, and prevention of technogenic hazards (**Bujok et al., 2015; Popovych et al., 2024; Nouri Qarahasanlou et al., 2022; Neral et al., 2023**).

1.1. Geological features of the research area

The territory of Kryvyi Rih district is located within the East European polygenic plain (morphostructure of the first order), which is formed by a large tectonic structure - the East European platform.

The basis of the morphostructural relief of the region is made up of watershed forest plateaus and their slopes, which extend from north and northeast to south, having a general slope towards the Black Sea, as well as towards river valleys and gullies. The watershed plateaus are alignment surfaces of different ages: from residual Late Sarmatian in the north to Pontic in the south. Absolute elevations of the watershed plateau vary from +169-

173 m in the north to +75 m in the south. The decrease in the watershed height in the southern direction is 0.69 m/km. The steepness of the watershed plateaus ranges from 0 to 1.5°, and on the slopes - up to 3-6°. The average density of the horizontal division of the Kryvbas territory by the erosion network is high and ranges from 0.8 to 1.6 km/km. The incision of river valleys relative to the watersheds reaches 70–90 m, and the depth of the gully incision is 20–40 m. These parameters reflect intense fluvial and erosion processes typical for heavily anthropogenically transformed territories. Recent studies confirm that ongoing mining operations have intensified geomorphological fragmentation and landscape instability in the Kryvyi Rih region, resulting in progressive denudation and structural weakening of the surface (Bazaluk et al., 2024; Evtekhov et al., 2022).

Geologically, the Kryvyi Rih basin is located in the central part of the Ukrainian crystalline massif and is part of the Kryvyi Rih-Kremenchuk structure and facies zone. The metamorphic rocks of the Kryvyi Rih series that contribute to the formation of the basin stretch in a narrow strip from the InGZK open pit in the south to the Zhovtorichinske deposit in the north, with a total length of over 140 km. Large massifs of granite are developed to the east of this strip, and migmatites to the west. The metamorphic rocks of the Kryvyi Rih series are overlain by sedimentary deposits (sands, clays, limestones, loams), which vary in thickness from 0.5 to 70–80 m (on average 20–30 m).

The rocks of the Kryvyi Rih series are divided into five formations: the novokryvorizka (nk), skelevatska (sk), saxahanska (sx), gdantsivska (gd) and gleyuvatska (gl). The novokryvorizhska suite is represented by amphibolites, while the skelevatska suite is composed of arkose sandstones, phyllites, and talc-carbonate shales. The saxahanska suite is characterized by the alternation of seven ferruginous and seven shale horizons, with some horizons being faulted or cut by tectonic faults.

The morphosculptural relief of the Kryvyi Rih basin was formed under the influence of exogenous geomorphological processes, including fluvial (erosion, wash-out, sediment transport), gravitational (landslides, collapse) karstic (dissolution of carbonate rocks), sufosic (leaching of fine fractions by groundwater), aeolian (dispersal of alluvial sands), and anthropogenic factors (mining, waste storage) (Kazakov et al., 2005).

The city of Kryvyi Rih was formed around the iron ore industry and stretches northeastward along ore deposits (Map of Zoning of the City Territory by Mining and Geological Conditions). The region hosts a powerful metallurgical complex, including ArcelorMittal Kryvyi Rih, with a full cycle of ore processing. These facilities, along with coal- and gas-powered thermal stations, form an energy-intensive system that significantly contributes to local pollution and technogenic pressure (Bazaluk et al., 2024; Batyr et al., 2021). Both open and underground mining methods are used in the city. Significant

areas of development are excluded from exploitation due to the presence of quarries, dumps, and earth movement zones (Kryvbassproekt, 2011).

The subsoil of Kryvbas contains about 30 billion tons of iron ore at depths of 1500–2600 meters. The balance reserves within quarries and mines amount to 6 billion tons, which is 20% of the total reserves. The remaining iron ore reserves are located in the sides of quarries, below the design depth of operating mines, and under built-up areas, which complicates their development and creates potential threats to the environment and the population (Kazakov et al., 2005).

2. Methods

2.1. Object description

The research paper investigates a complex of formed and closely spaced sinkholes, the voids of which are the highest priority for cemented paste backfill (see Figure 1), and the conceptual scheme of the backfill technology for better understanding is shown in Figure 14. These sinkholes have formed as a result of both natural and anthropogenic processes typical of the Kryvyi Rih mining region. Extensive underground mining without subsequent backfilling has led to the gradual collapse of rock masses and the formation of subsurface voids. Additionally, natural factors such as groundwater leaching (suffosion), karst processes, and neotectonic activity further destabilize the geological environment, accelerating the development of cracks and surface deformations (Hubina & Zaborovsky, 2022; Kazakov et al., 2005).

The spatial boundaries of the sinkholes were digitized using time-series satellite imagery (Google Earth Pro, 1984–2024) and topographic plans. Analytical tools included polygon vectorization, area calculations, and change detection using GIS-based measurements. Biodiversity assessment was performed using the phytomelioration coefficient, which serves as an integral indicator of vegetative cover transformation and ecological succession on disturbed lands.

The combination of these influences poses serious threats to the safety of surrounding infrastructure and ecosystems, necessitating timely and effective mitigation measures. Formation of monolithic backfill in the sinkhole zones will allow solving a number of engineering and environmental problems

- reduce the dynamics of deformation processes of the earth's surface around the sinkholes,
- increase safety for life and health of the population;
- prevent further destruction of infrastructure facilities;
- prevent further destruction of valuable soils;
- preserve biocenoses as a result of soil destruction;
- utilize certain volumes of accumulated tailings;
- improve ventilation and drainage of mines by blocking the dip zones with backfill.

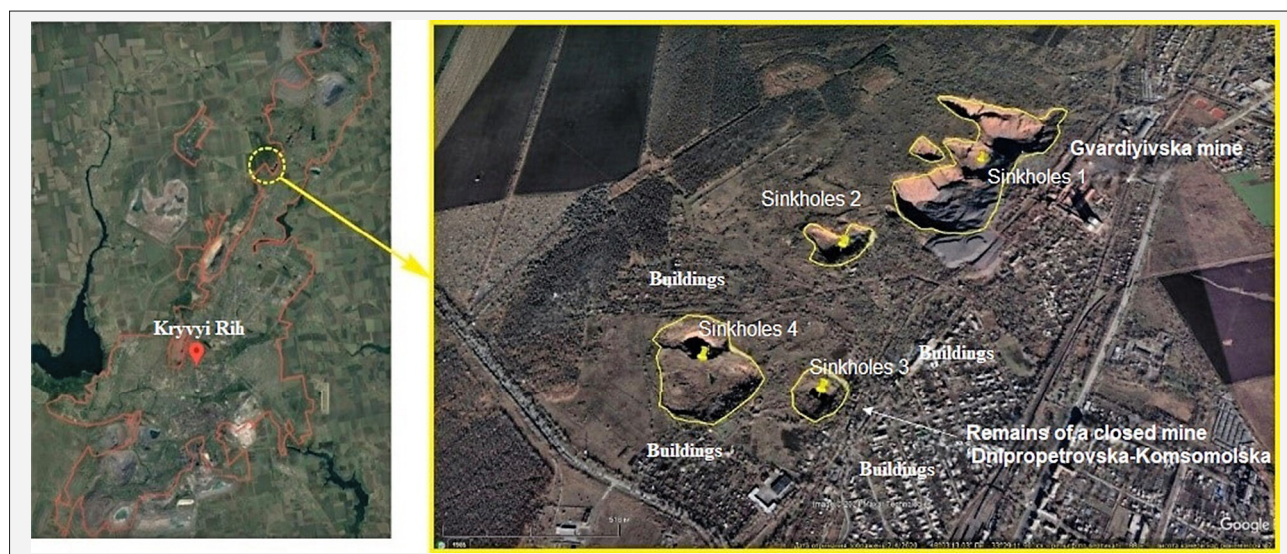


Figure 1. Location of the priority sinkholes on the northwestern outskirts of Kryvyi Rih (coordinates: 48.0668, 33.4052)

In addition to ecological assessments, a technical solution based on cemented paste backfilling was developed and is presented in the Results section as a recommendation for the remediation of sinkhole-affected areas.

2.2. Determination of coefficient of phytomeliorative efficiency

An important aspect of assessing the condition of the research region is the analysis of the vegetation cover, since it is known for its important soil-strengthening role, which is crucial in the context of intensified landslide processes around the studied sinkholes, and reduces the intensity of water and wind erosion. The formation of vegetation cover is important for the succession stages of phytomelioration processes, as an element of improving the mechanical structure of the soil, gradually increasing its fertility.

In this context, the presence and proportion (in %) of different groups of plantations differentiated by their functional purpose was studied. The current state and typology of the vegetation cover of the slopes of these four sinkholes were assessed both in the zone of active development of karst processes and in the adjacent territory that is potentially sinkhole. We also analyzed the dynamics of vegetation change from 1984 to 2024.

A number of trial areas were laid out to analyze the current phytomelioration process taking place in the studied areas of sinkholes, where the coefficient of phytomelioration efficiency of vegetation cover was calculated and evaluated in points.

To determine the coefficient of phytomeliorative efficiency, a generally accepted **Equation 1** was used (Kucheriavyy, 2003):

$$K_{FM} = \frac{(S_p \cdot b + S_a \cdot b + S_{pm} \cdot b + S_f \cdot b + S_v \cdot b + S_{sv1} \cdot b + S_{sv2} \cdot b + S_{st} \cdot b + S_r \cdot b)}{S} \quad (1)$$

Where:

- S – the area occupied by: S_p - pratocenosis;
- S_a – agroocenosis;
- S_{pm} – pomolohocenosis;
- S_f – frutocenosis;
- S_v – vitocenosis;
- S_{sv1} – single-tier silvacenosis;
- S_{sv2} – two-tiered silvacenosis;
- S_{st} – streptocenosis;
- S_r – ruderoocenosis;
- b – the number of points received by the cenosis;
- S – total area.

The following differentiation is distinguished according to the functions and possibilities of development in specific conditions of the territory (present or not), of each of the listed groups of plantations: **pratocenoses** - meadow communities, **agroocenoses** - agricultural plantations, **pomolohocenoses** - orchards or their remains, **frutocenoses** - shrub plantations, **vitocenoses** - vineyards, **silvacenoses** - forest communities, **striocenoses** - strips of various functional adaptations, and **ruderales** - weed communities.

3. Results and Discussion

3.1. Spatiotemporal Dynamics of Sinkhole Expansion

The sinkholes are expanding over time, which is likely caused by two factors:

- further increase in the depth of ore reserves in existing mines and the gradual continuation of landslide processes in the mountain massif;
- the impact of climatic factors, water and wind erosion, which causes soil layers to collapse into space (similar to the principle of ravine expansion).

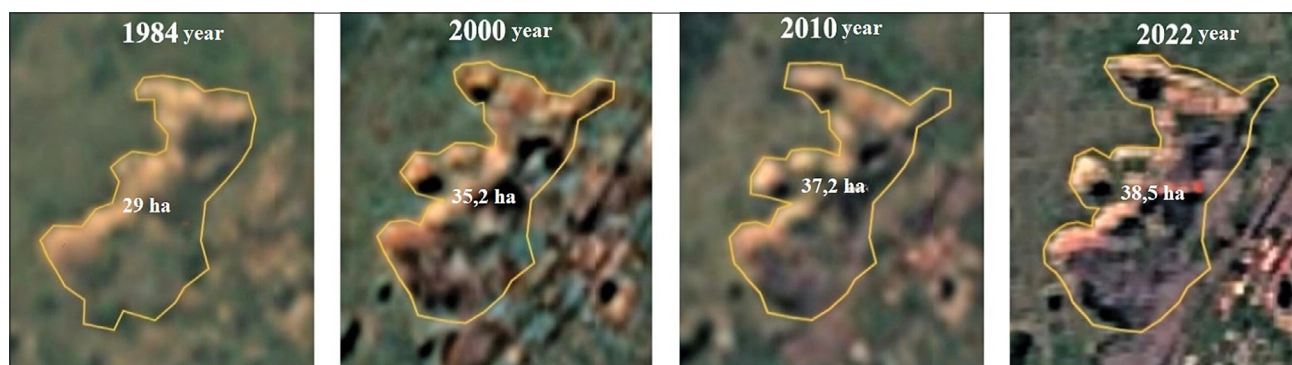


Figure 2. Historical dynamics of the disturbed earth surface area of sinkhole 1 (coordinates: 48.0639, 33.4831)

These 4 dip zones of the earth's surface were selected for backfilling because of their shortest distance to the tailings pond as a source of the main component of paste backfilling - fine iron ore tailings. A relatively short distance of 4-5 km from the tailings dump to the dip zones creates conditions for filling their voids with cemented paste backfill.

Figure 1 illustrates the location of the sinkholes. It should be noted that the sinkholes were formed as a result of iron ore mining without underground sealing technologies in both operating mines and mines that were closed long ago (1930-1950). Therefore, the dynamics of the increase in the area of sinkholes may differ. If a mine has been closed for a long time, the development of massif deformations is relatively stabilized and the expansion of sinkholes is mainly influenced by climatic factors. If the mine is active, the intensity of deformation of the massif is greater, although it is also slightly stabilized in time and the influence of climatic factors is also included.

Establishing the affiliation of sinkholes to specific mines is complicated, since many mines, including shallow ones, operated in the 20th century. Documentation of mining plans for many closed mines was lost during the Second World War. Therefore, data from various information sources are used to establish the approximate location.

In **Figure 1**, sinkholes 1, 2 were formed as a result of the extraction of iron ore reserves at the Hvardiyska mine, which is still in operation. Sinkholes 3, 4 were probably formed as a result of ore mining at the closed Dnipropetrovsk-Komsomolska mine.

Photos of sinkholes 1-4 are shown in **Figures 10-11**. It should be noted that the earth's surface deformations can be represented by two forms - zones of smooth lowering and sinkholes, which is well illustrated by the example of sinkhole 4 (see **Figure 5**).

The approximate dynamics of the development of the area of earth surface disturbance around the sinkholes was estimated using the function of viewing historical images in the web version of the Google Earth service. Historical images of sinkholes 1-4 from 1984 to 2024 were analyzed. An example of the historical dynamics of the disturbed earth surface area is shown on the example of sinkhole 1 (see **Figure 2**).

The quantitative dynamics of changes in the disturbed area of the earth's surface is shown in **Figures 3-6**.

The analysis of **Figures 3-6** shows that the increase in the area of sinkholes may have different dynamics. Thus, as of 1984, sinkholes 1-4 were already partially formed and increased in the area of the disturbed surface in time until 2024. Sinkholes 1 and 2 have changed gradually over time and probably indicate that the maximum intensity of landslide geomechanical processes in the mas-

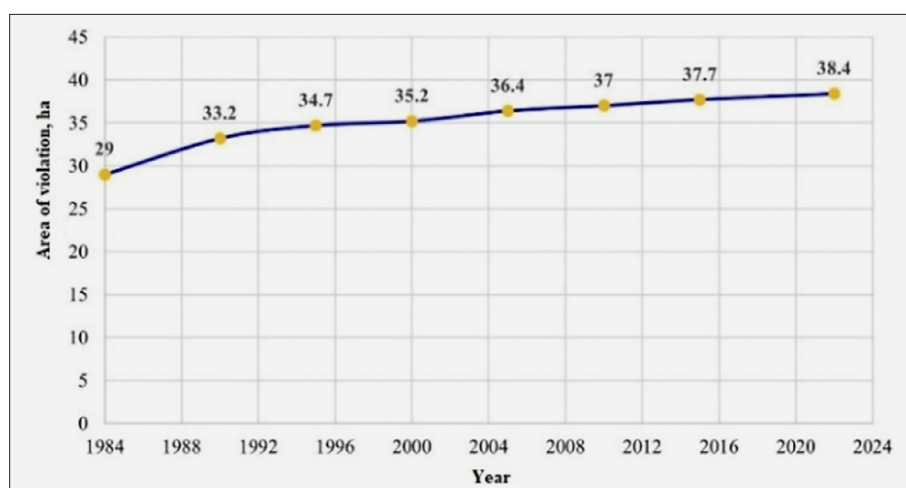


Figure 3. Dynamics of changes in the area of the disturbed earth surface of sinkhole 1

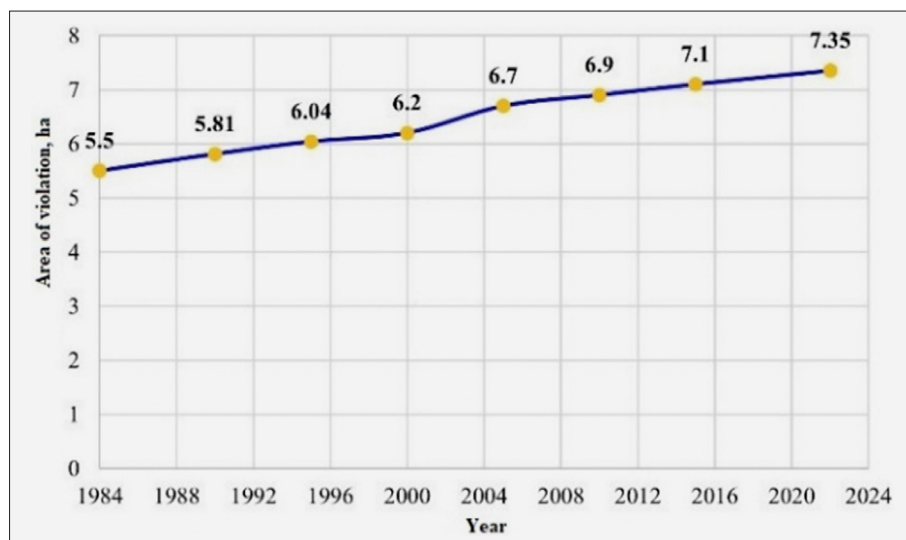


Figure 4. Dynamics of changes in the area of the disturbed earth surface of sinkhole 2

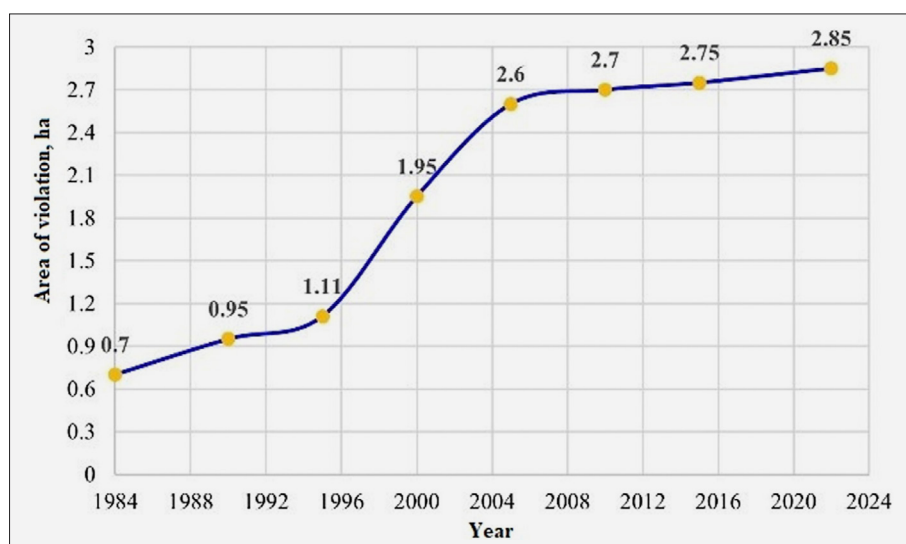


Figure 5. Dynamics of changes in the area of the disturbed earth surface of sinkhole 3

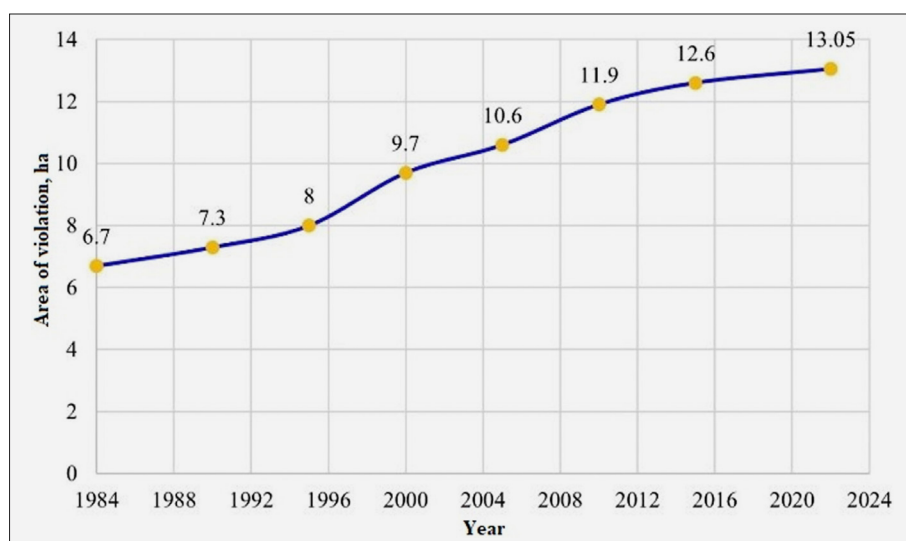


Figure 6. Dynamics of changes in the area of the disturbed earth surface of sinkhole 4

sif occurred earlier, before 1984, and further the area increase is gradual, mainly due to the influence of erosion processes and insignificant intensity of landslide processes. The area of sinkholes 3 and 4 changed most intensively from 1995 to 2005. Probably, during this pe-

riod there was a peak of landslide geomechanical processes in the massif, and since 2005 the dynamics of the area expansion has significantly decreased and is probably due to the influence of erosion processes and low intensity of landslide processes.

The evolution of the sinkhole area, proven by GIS observations, threatens the safety of the people living in nearby villages, destroys infrastructure, degrades soil cover, and reduces biodiversity, which is a serious technogenic and environmental problem. The development of sinkholes is uncontrollable and unpredictable, and their intensity depends on a number of factors. The monolithic filling of sinkholes may create a “sealing” effect and prevent further increase in their area. This effect is achieved by injecting a cemented paste backfill composed of fine iron ore tailings, Portland cement, blast furnace slag, and fly ash. The paste is prepared in a mobile mixing unit and delivered under pressure through a pipeline network into the sinkhole voids. Once hardened, the mixture forms a dense, water-resistant mass that stabilizes the surrounding rock massif and minimizes further surface deformation. According to field studies, such backfills demonstrate compressive strength exceeding 2.5–3.0 MPa, with an estimated sealing effectiveness lasting over 20–30 years, depending on local hydrogeological conditions (Hubina & Zaborovsky, 2022).

The cemented paste backfilling (CPB) mixture was developed using a combination of iron ore tailings (60–65%), blast furnace slag (15–20%), Portland cement (10–12%), and water (10–12%). The mixture was prepared in mobile mixing units and transported to the sinkhole via a high-pressure pump and pipeline system. Upon filling, the paste hardens into a monolithic structure with compressive strength exceeding 2.5–3.0 MPa within 28 days. This method ensures long-term stabilization of subsurface voids and reduces surface deformation risks. For detailed technical implementation, readers are referred to Hubina & Zaborovsky (2022).

3.2. Ecological features of vegetation cover

In the structure of the identified woody and herbaceous species, the following groups were distinguished with regard to habitat richness: species that prefer medium trophic habitat conditions (mesotrophs), species that prefer rich habitat conditions (eutrophs), and species that prefer poor habitat conditions (oligotrophs). The distribution of these groups is shown below (see Figure 7).

Thus, the proportion of oligotrophs growing on poor soils is 46%, mesotrophs preferring average soil fertility conditions is 48%, and eutrophs preferring fertile habitat conditions is only 6%.

According to the indicator of the substrate moisture content, a number of classification groups are distinguished, namely: mesocerophytes - plants adapted to conditions slightly less than average for soil moisture reserves; mesophytes - species that prefer medium moisture conditions and hygrophytes - those that prefer moist habitats (see Figure 8).

The mesophyte group is the most represented - 47%, followed by mesocerophytes - 50% and hygrophytes - 3%.

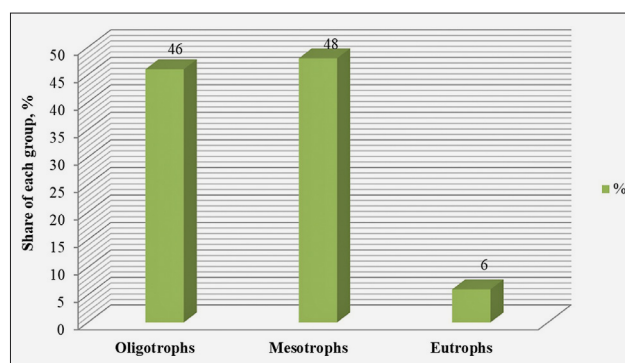


Figure 7. Vegetation structure by trophomorphs

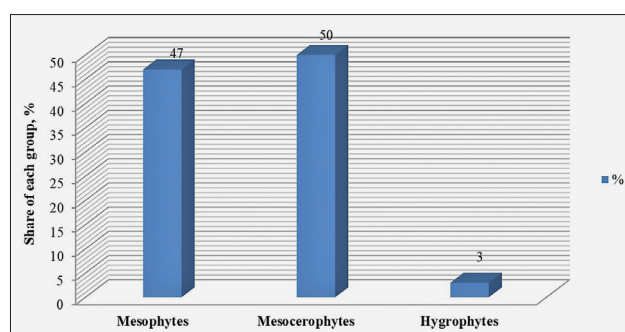


Figure 8. Vegetation structure by hydromorphs

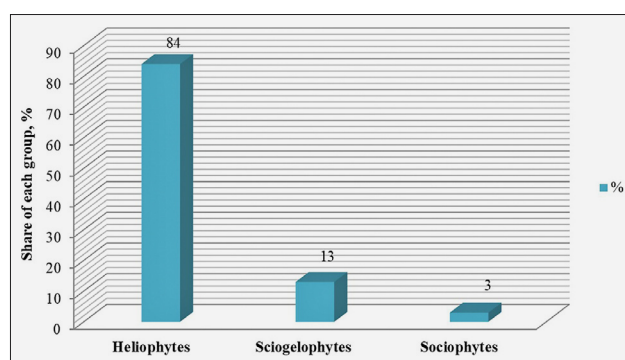


Figure 9. Vegetation structure by heliomorphs

The following groups were identified in relation to lighting: sociophytes, species that are shade-loving, sociogeliophytes - shade-tolerant species, and heliophytes that prefer open habitats with significant light. Their distribution is shown below (see Figure 9).

Among the species that form the vegetation cover of the study area, heliophytes dominate (84%), sociogeliophytes - 13%, and sociophytes - 3%.

3.3. Coefficient of phytomelioration efficiency

Depending on the identified groups of plantations, the structure of the basic equation (Equations 2-17) changes in different study periods.

The following phytoreclamation groups of plantations were identified as a result of the research:



Figure 10. Sinkhole No. 1 (photo by Dmitry Antonov, 2015)

2024: pratocenosis (S_p) – 40%, ruderoocenosis (S_r) – 10%, single-tier silvacenosis (S_{sv1}) – 15%, terrain without vegetation – 35%.

The equation for the phytomelioration activity coefficient is as follows:

$$K_{FM} = \frac{S_{sv1 \times b + S_r \times b + S_p \times b}}{s} \quad (2)$$

2010: pratocenosis (S_p) – 45%, ruderoocenosis (S_r) – 7%, single-tier silvacenosis (S_{sv1}) – 18%, frutocenosis (S_f) – 5%, terrain without vegetation – 25%.

The equation for the phytomelioration activity coefficient is as follows:

$$K_{FM} = \frac{S_{sv1 \times b + S_r \times b + S_p \times b + S_{fb}}}{s} \quad (3)$$

2000: pratocenosis (S_p) – 48%, ruderoocenosis (S_r) – 5%, single-tier silvacenosis (S_{sv1}) – 20%, frutocenosis (S_f) – 5%, terrain without vegetation – 22%.

The equation for the phytomelioration activity coefficient is as follows:

$$K_{FM} = \frac{S_{sv1 \times b + S_r \times b + S_p \times b + S_{fb}}}{s} \quad (4)$$

1984: pratocenosis (S_p) – 50%, ruderoocenosis (S_r) – 3%, single-tier silvacenosis (S_{sv1}) – 22%, two-tiered silvacenosis (S_{sv2}) – 3%, frutocenosis (S_f) – 10%, terrain without vegetation – 12%.

The equation for the phytomelioration activity coefficient is as follows:

$$K_{FM} = \frac{S_{sv1 \times b + S_{sv2} \times b + S_r \times b + S_p \times b + S_{fb}}}{s} \quad (5)$$



Figure 11. Sinkhole No. 2 (photo by Dmitry Antonov, 2015)

The following ratio of phytomelioration groups of plantations was established as a result of the research:

2024: pratocenosis (S_p) – 44%, ruderoocenosis (S_r) – 13%, single-tier silvacenosis (S_{sv1}) – 12%, terrain without vegetation – 31%.

The equation for the phytomelioration activity coefficient is as follows:

$$K_{FM} = \frac{S_{sv1 \times b + S_r \times b + S_p \times b}}{s} \quad (6)$$

2010: pratocenosis (S_p) – 47%, ruderoocenosis (S_r) – 9%, single-tier silvacenosis (S_{sv1}) – 20%, terrain without vegetation – 24%.

The equation for the phytomelioration activity coefficient is as follows:

$$K_{FM} = \frac{S_{sv1 \times b + S_r \times b + S_p \times b}}{s} \quad (7)$$

2000: pratocenosis (S_p) – 50%, ruderoocenosis (S_r) – 4%, single-tier silvacenosis (S_{sv1}) – 23%, frutocenosis (S_f) – 6%, terrain without vegetation – 17%.

The equation for the phytomelioration activity coefficient is as follows:

$$K_{FM} = \frac{S_{sv1 \times b + S_r \times b + S_p \times b + S_{fb}}}{s} \quad (8)$$

1984: pratocenosis (S_p) – 53%, ruderoocenosis (S_r) – 2%, single-tier silvacenosis (S_{sv1}) – 25%, frutocenosis (S_f) – 10%, terrain without vegetation – 10%.

The equation for the phytomelioration activity coefficient is as follows:

$$K_{FM} = \frac{S_{sv1 \times b + S_r \times b + S_p \times b + S_{fb}}}{s} \quad (9)$$

The following ratio of phytomeliorative plantation groups was established at this site:

2024: pratocenosis (S_p) – 41%, ruderoocenosis (S_r) – 18%, single-tier silvacenosis (S_{sv1}) – 12%, terrain without vegetation – 29%.

The equation for the phytomelioration activity coefficient is as follows:

$$K_{FM} = \frac{S_{sv1 \times b + S_r \times b + S_p \times b}}{s} \quad (10)$$



Figure 12. Sinkhole No. 3 (photo by Dmitry Antonov, 2015)



Figure 13. Sinkhole No. 4 (photo by Dmitry Antonov, 2015)

2010: pratocenosis (S_p) – 45%, ruderoocenosis (S_r) – 11%, single-tier silvacenosis (S_{sv1}) – 22%, terrain without vegetation – 22%.

The equation for the phytomelioration activity coefficient is as follows:

$$K_{FM} = \frac{S_{sv1 \times b} + S_r \times b + S_p \times b}{s} \quad (11)$$

2000: pratocenosis (S_p) – 48%, ruderoocenosis (S_r) – 2%, single-tier silvacenosis (S_{sv1}) – 26%, frutocenosis (S_f) – 7%, terrain without vegetation – 17%.

The equation for the phytomelioration activity coefficient is as follows:

$$K_{FM} = \frac{S_{sv1 \times b} + S_f \times b + S_p \times b + S_{r \times b}}{s} \quad (12)$$

1984: pratocenosis (S_p) – 50%, ruderoocenosis (S_r) – 2%, single-tier silvacenosis (S_{sv1}) – 27%, two-tiered silvacenosis (S_{sv2}) – 3%, frutocenosis (S_f) – 9%, terrain without vegetation – 9%.

The equation for the phytomelioration activity coefficient is as follows:

$$K_{FM} = \frac{S_{sv1 \times b} + S_{sv2 \times b} + S_f \times b + S_p \times b + S_{r \times b}}{s} \quad (13)$$

2024: pratocenosis (S_p) – 37%, ruderoocenosis (S_r) – 11%, two-tiered silvacenosis (S_{sv1}) – 16%, terrain without vegetation – 36%.

The equation for the phytomelioration activity coefficient is as follows:

$$K_{FM} = \frac{S_{sv1 \times b} + S_r \times b + S_p \times b}{s} \quad (14)$$

2010: pratocenosis (S_p) – 40%, ruderoocenosis (S_r) – 8%, single-tier silvacenosis (S_{sv1}) – 20%, terrain without vegetation – 32%.

The equation for the phytomelioration activity coefficient is as follows:

$$K_{FM} = \frac{S_{sv1 \times b} + S_r \times b + S_p \times b}{s} \quad (15)$$

2000: pratocenosis (S_p) – 43%, ruderoocenosis (S_r) – 6%, single-tier silvacenosis (S_{sv1}) – 23%, frutocenosis (S_f) – 3%, terrain without vegetation – 25%.

The equation for the phytomelioration activity coefficient is as follows:

$$K_{FM} = \frac{S_{sv1 \times b} + S_f \times b + S_p \times b + S_{r \times b}}{s} \quad (16)$$

1984: pratocenosis (S_p) – 46%, ruderoocenosis (S_r) – 5%, single-tier silvacenosis (S_{sv1}) – 25%, frutocenosis (S_f) – 6%, terrain without vegetation – 18%.

The equation for the phytomelioration activity coefficient is as follows:

$$K_{FM} = \frac{S_{sv1 \times b} + S_f \times b + S_p \times b + S_{r \times b}}{s} \quad (17)$$

For a comprehensive calculation of the phytomelioration efficiency coefficient, an indicator b plays an important role, which takes into account the complexity of the effective impact of a particular plant cenosis. The following important indicators are taken into account: sea-

sonal phytomass, oxygen production, filtering properties due to habitat and type of vegetative cover, impact on microclimate, noise absorption and optical impact.

The average values of the points (b) of green mass (phytomeliorative cover) were used, as shown in **Table 1**.

Table 1. Mean values of green mass (b) (according to Kucheryavyi, 2003)

Type of phytocenosis	Green mass, (b)
Pratocenosis	0.7
Agrocenosis	1.0
Rudrocenosis	0.8
Frutocenosis	4.0
Pomolohocenosis	5.0
Streptocenosis	8.5
Single-tier silvacenosis	9.0

As a result of the calculations of phytomeliorative efficiency coefficients, the following results were obtained during the studied periods (see **Table 2**).

The calculations of the coefficients of phytomeliorative efficiency of the vegetation cover of the studied areas showed a clear dependence of the indicator decrease during the increase of the devastation area of the territory.

Differentiation of the dynamics of phytomeliorative efficiency coefficients for the studied periods revealed the following values: sinkhole No. 1 - 0.8; sinkhole No. 2 - 1.4; sinkhole No. 3 - 1.3; sinkhole No. 4 - 1.1.

Table 2. The value of phytomeliorative efficiency coefficients

Sinkhole No.	Year	The value of phytomeliorative efficiency coefficients, K_{FM}
1	2024	2.8
	2010	3.0
	2000	3.3
	1984	3.6
2	2024	3.5
	2010	3.8
	2000	4.2
	1984	4.9
3	2024	3.3
	2010	3.6
	2000	4.0
	1984	4.6
4	2024	3.0
	2010	3.2
	2000	3.5
	1984	4.1

The analysis of the presented tree-shrub and grass cover is as follows:

Tree-shrub species: English oak (*Quercus robur* L.) – Beech (Fagaceae), grey alder (*Alnus incana* (L.) Moe-

nch) – Birch (Betulaceae), silver birch (*Betula pendula* Roth.) – Birch (Betulaceae), aspen (*Populus tremula* L.) – Willow (Salicaceae), black locust (*Robinia pseudoacacia* L.) – Bean (Fabaceae), silver poplar (*Populus alba*) – Willow (Salicaceae), ash-leaved maple (*Acer negundo* L.) – Soapberry (Sapindaceae).

Herbaceous species: white clover (*Trifolium repens* L.) – Bean (Fabaceae), meadow fescue (*Lolium pratense* (Huds.) Darbysh.) – Grasses (Poaceae), smooth brome-grass (*Bromus inermis* Leyss.) – Grasses (Poaceae), meadow foxtail (*Alopecurus pratensis* L.) – Grasses (Poaceae), Kentucky bluegrass (*Poa pratensis* L.) – Grasses (Poaceae), timothy-grass (*Phleum pratense* L.) – Grasses (Poaceae), sweet vernal grass (*Anthoxanthum odoratum* L.) – Grasses (Poaceae), bushgrass (*Calamagrostis epigejos* (L.) – Grasses (Poaceae), couch grass (*Elymus repens* (L.) Gould) – Grasses (Poaceae), perennial ryegrass (*Lolium perenne* L.) – Grasses (Poaceae), spiny plumeless thistle (*Carduus acanthoides* L.) – Aster (Asteraceae), dandelion (*Taraxacum officinale* Wigg.) – Aster (Asteraceae), mugwort (*Artemisia vulgaris* L.) – Aster (Asteraceae), quaking sedge (*Carex brizoides* L.) – Sedges (Cyperaceae), broadleaf plantain (*Plantago major* L.) – Plantain (Plantaginaceae), wild carrot (*Daucus carota* L.) – Umbellifers (Apiaceae), silverweed (*Potentilla anserina* L.) – Rose (Rosaceae), common ragweed (*Ambrosia artemisiifolia* L.) – Aster (Asteraceae), spiny cocklebur (*Xanthium spinosum* L.) – Aster (Asteraceae), three-lobed beggarticks (*Bidens tripartita* L.) – Aster (Asteraceae), honey clover (*Melilotus albus* Medik.) – Bean (Fabaceae), peppergrass (*Lepidium rud-erale* L.) – Mustards (Brassicaceae), common knotgrass (*Polygonum aviculare* L.) – Knotweed (Polygonaceae), curlycup gumweed (*Grindelia squarrosa* Pursh.) – Aster (Asteraceae), diffuse knapweed (*Centaurea diffusa* Lam.) – Aster (Asteraceae), yarrow (*Achillea millefolium* L.) – Aster (Asteraceae), giant sumpweed (*Iva xanthiifolia* Nutt.) – Aster (Asteraceae), Volga fescue (*Festuca valesiaca* A ex Gaudin) – Grasses (Poaceae), colts-foot (*Tussilago farfara* L.) – Aster (Asteraceae) (Yeremenko, 2019).

Among the tree and shrub species, the largest representation of the families birch (Betulaceae) and Willow (Salicaceae) was found - 2 species in each, Beech (Fagaceae), Bean (Fabaceae), and Soapberry (Sapindaceae) - 1 species in each.

Among the herbaceous species, the following families were found: Aster (Asteraceae) - 11 species, Grasses (Poaceae) - 10 species, Bean (Fabaceae) - 1 species, Umbellifers (Apiaceae) - 1 species, Sedges (Cyperaceae) - 1 species, Plantain (Plantaginaceae) - 1 species, Rose (Rosaceae) - 1 species, Mustards (Brassicaceae) - 1 species, and Knotweed (Polygonaceae) - 1 species.

The analysis of the dynamics of territorial devastation growth from 1984 to 2024 was as follows: sinkhole No. 1 - 9.4; sinkhole No. 2 - 1.85; sinkhole No. 3 - 2.15; sinkhole No. 4 - 6.35.

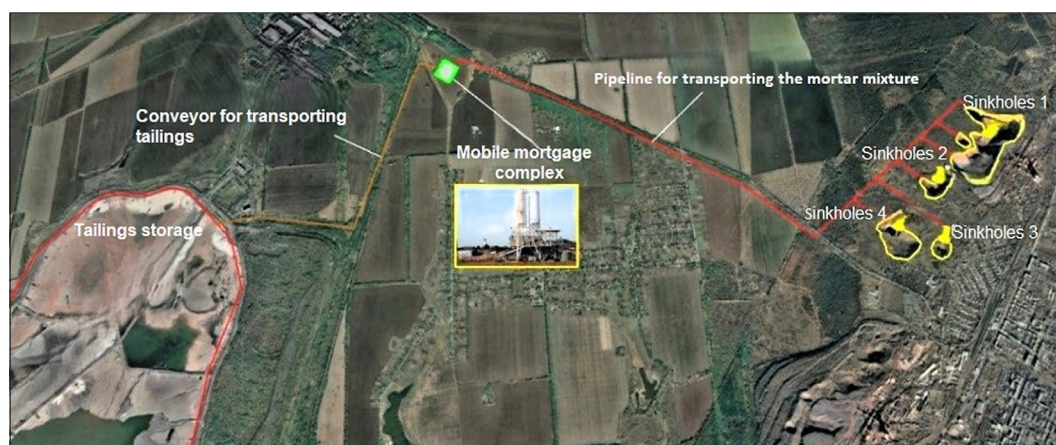


Figure 14. Scheme of backfill priority mine sinkholes (coordinates: 48.0668, 33.4052)

Table 3. Regression equations for predicting sinkhole area dynamics

Sinkhole No.	Dependence	Equation	R ²
1	Linear dependence	$y = 0.2186x - 402.66$	0.870
	Polynomial dependence	$y = 0.0003x^3 - 1.8969x^2 + 3812.6x - 3 \cdot 10^6$	0.990
2	Linear dependence	$y = 0.0508x - 95.332$	0.990
	Polynomial dependence	$y = -3 \cdot 10^{-5}x^3 + 0.1805x^2 - 361.15x + 240816$	0.990
3	Linear dependence	$y = 0.0661x - 130.52$	0.890
	Polynomial dependence	$y = -0.0001x^3 + 0.7061x^2 - 1411.9x + 940915$	0.970
4	Linear dependence	$y = 0.1882x - 366.92$	0.970
	Polynomial dependence	$y = -0.0002x^3 + 1.4483x^2 - 2898.8x + 2 \cdot 10^6$	0.997

Hence, the greatest intensity of sinkhole expansion is in sinkhole No. 1, the intensity of sinkhole No. 4 is somewhat lower, and as of the time of the field research, the intensity of sinkhole No. 3 is still significantly lower - 2.15 and sinkhole No. 2 - 1.85. However, given the ongoing active influence of both exogenous factors (wind and water erosion, landslides, rockslides) and endogenous factors (karst and suphosition processes), these indicators may increase, which will undoubtedly be a significant factor in increasing threats to the environment and the safety of the region's population. Therefore, it is important to implement a set of measures that would slow down and, in the long run, eliminate this complex of large-scale threats.

3.4. Technological recommendation for sinkhole remediation

Based on the results of phytomelioration assessment and analysis of sinkhole dynamics, a cemented paste backfilling technology was proposed to mitigate geotechnical risks and restore land stability. The conceptual scheme is shown in Figure 14. This approach ensures long-term sealing of voids and minimizes the surface impact of underground mining (Hubina & Zaborovsky, 2022). A tailing volume is taken from the dry or wetted areas of the tailing dump and transported by machinery

to the loading point. These tailings, formed during ore concentration and metallurgical processing, typically contain fine fractions of iron oxides (Fe_2O_3), quartz, aluminosilicates, and residual amounts of magnetite, along with trace concentrations of industrially valuable components such as rare earth elements (REEs), vanadium, titanium, and phosphorus. Several studies have confirmed the economic potential of reprocessing such materials for secondary metal extraction or use in construction, agriculture, or cement production (Hubina & Zaborovsky, 2022). From the loading point, the tailings are delivered to a conveyor line, which transports them to a mobile filling complex. In the backfilling complex, the tailings are mixed with a combined binder (Portland cement, ground blast furnace granulated slag and fly ash from the thermal power plant) and water. In the mixer, the components of the paste filling are mixed to a paste consistency with a specified solid content, and the paste filling mixture is transported by a pressure pump through the laid pipeline network to the sinkholes, where they are gradually filled from the bottom of the sinkhole to the top (Bazaluk et al., 2024; Petlovanyi & Sai, 2024).

3.5. Analysis of changes in the cost of restoration of disturbed areas

The analysis of the dependence of the change in the sinkhole area during 1984-2024 showed that this rela-

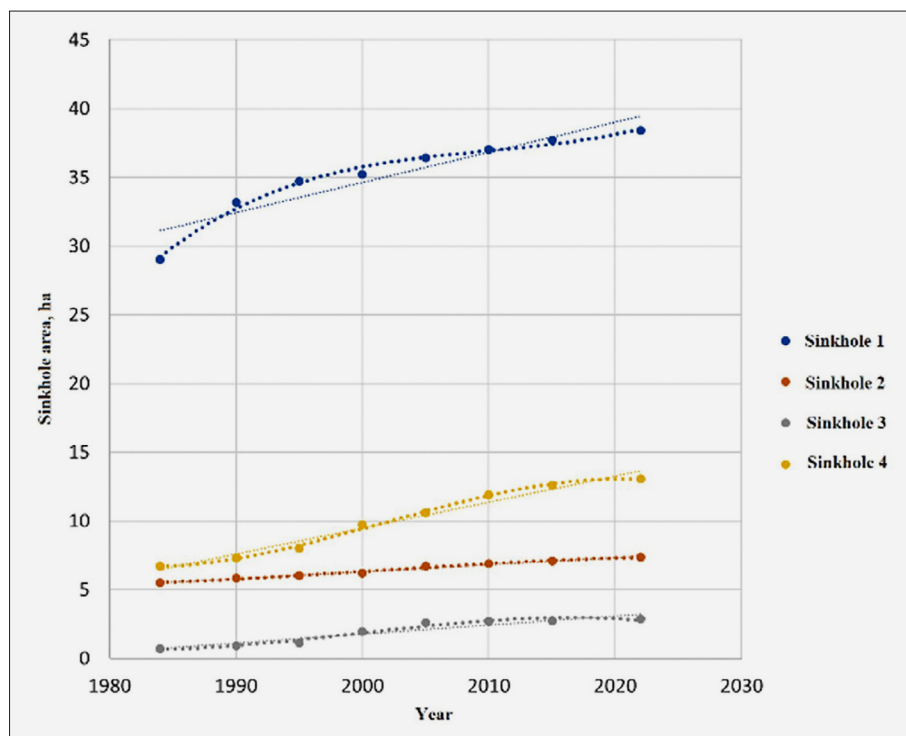


Figure 15. Dependence of sinkhole area change in time

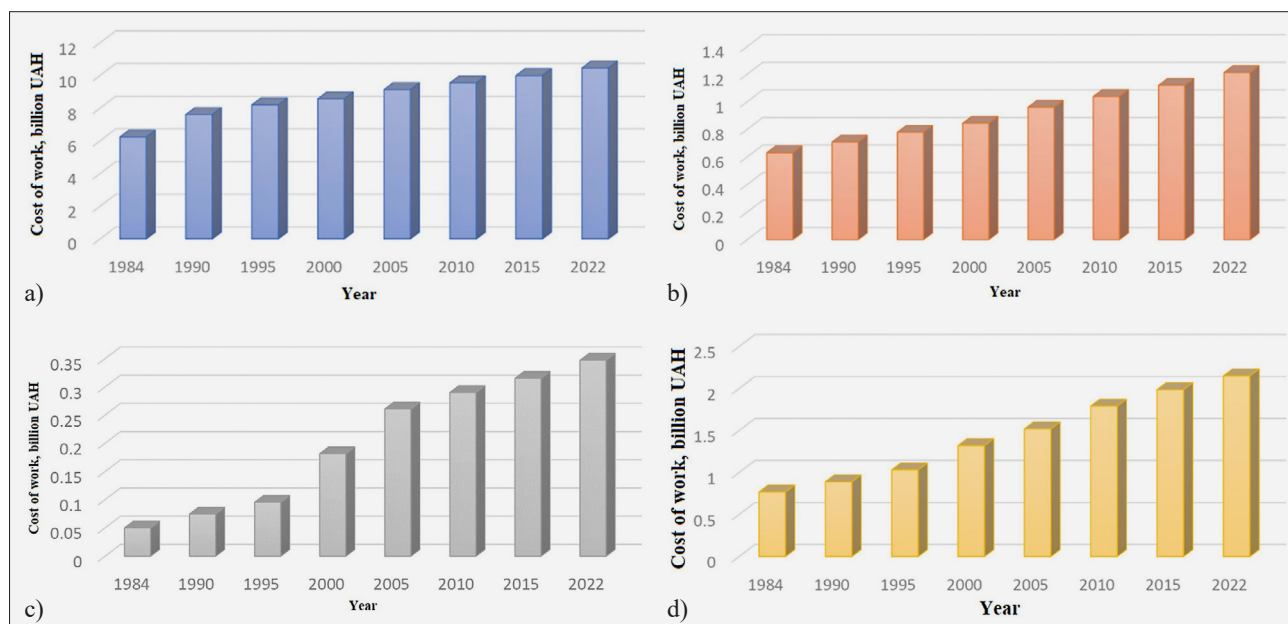


Figure 16. Dependence of the change in the cost of sinkhole filling on the time of its formation: a - sinkhole No. 1, b - sinkhole No. 2, c - sinkhole No. 3, d - sinkhole No. 4.

tionship is best described by a third-degree polynomial, as evidenced by the high values of the coefficient of determination. Table 3 presents the equations obtained as a result of approximating the experimental data within the framework of the linear equation and the third-degree polynomial equation, and Figure 15 shows the graphical dependence of the change in the sinkhole area over time.

Figure 16 shows that all but the largest sinkholes sharply increase in size between 1995 and 2005, which

may indicate both the influence of some external factors (active rock mining, explosions, earthquakes) and the general dependence of sinkhole formation. Sinkhole 1 is also characterized by phases of sharp growth and deceleration of the sinkhole processes.

From source analysis, it follows that the average depth of such sinkholes ranges from 180 to 250 m (Koptieva, 2021). After calculating the volume of sinkholes and basing on the results of calculating the cost of their elimination (Prozorro, 2023), it was possible to estab-

lish the dependence of the change in the cost of such works on time.

It is obvious that delaying the start of work on the restoration of disturbed areas leads to a significant increase in their cost. In particular, the cost of eliminating sinkhole No. 3 over 38 years has increased almost 7 times - from UAH 50.2 million to UAH 347.2 million, while the cost of filling in sinkholes No. 2 and No. 4 will increase by 2 to 2.8 times, respectively. The cost of liquidation of the largest of the sinkholes, No. 1, will change the least, by 68% from UAH 6.2 billion to UAH 10.5 billion. These estimations were based on procurement data and budget reports retrieved from the Prozorro electronic system. Although no formal inflation-adjusted economic model was applied, the differences in values over time implicitly reflect inflation, currency devaluation, and changes in market conditions. This empirical trend clearly highlights the economic risks of postponing revitalization efforts. Obviously, backfilling of small sinkholes is the most economically feasible, as the depth of such sinkholes is actively growing over time along with their surface, which leads to a significant increase in investment in case of untimely liquidation.

While cemented paste backfilling shows promise in mitigating surface deformations and restoring geotechnical stability, its long-term ecological impact remains insufficiently explored. Future research should focus on evaluating the effectiveness of CPB in preserving natural landscapes, improving soil-plant interactions, and supporting biodiversity recovery in rehabilitated areas. Monitoring programs combining geotechnical, botanical, and remote sensing data will be essential to validate the sustainability of this remediation method under different environmental conditions.

4. Conclusions

The research on technogenic safety and revitalization of devastated landscapes in the Kryvyi Rih basin revealed an urgent need to implement comprehensive measures to restore the disturbed areas.

The analysis of the dynamics of phytomelioration efficiency coefficients (K_{fm}) for sinkholes No. 1, No. 2, No. 3, and No. 4 showed a gradual decrease in the efficiency of vegetation cover, which is a consequence of the growth of devastated areas. The highest values of K_{fm} were registered in 1984: 3.6, 4.9, 4.6, and 4.1, respectively, while in 2024 these values decreased to 2.8, 3.5, 3.3, and 3.0. The smallest decrease in the coefficient was observed for sinkhole No. 1 (0.8), while the largest decrease was registered for sinkhole No. 2 (1.4).

The analysis of the structure of the vegetation cover of the sinkhole zones revealed a predominance of species adapted to poor soils and a moderate level of phytomeliorative efficiency, which indicates the potential for natural restoration of the territories. Meanwhile, the dynamics of the expansion of sinkholes, confirmed by

GIS observations, indicates a steady increase in the area of devastation and a corresponding decrease in K_{fm}, which emphasizes the need for timely intervention to accelerate revitalization processes.

The research substantiated the effectiveness of the cemented paste backfilling technology for the elimination of sinkholes, which is one of the priority areas for the revitalization of devastated areas. The proposed method enables the utilization of accumulated mining wastes and solving a number of engineering and environmental problems, including reduction of deformation processes, improvement of safety for the population and restoration of soil cover.

The analysis of the dynamics of changes in the area of sinkholes in 1984-2024 showed that their growth is best described by third-degree polynomial dependencies with high values of the coefficient of determination (up to 0.997). This indicates the nonlinear nature of the development of deformation processes. A particularly intensive increase in the area of failures was observed in the period 1995-2005. It has also been established that postponing revitalization works significantly increases their cost: in some cases, the costs increase by 2-7 times. Thus, timely intervention is not only environmentally sound, but also economically beneficial.

The research confirms the urgency and economic feasibility of introducing cemented paste filling technologies for the revitalization of devastated landscapes in the Kryvyi Rih basin. The timely implementation of the proposed measures will minimize anthropogenic risks, restore ecological balance and ensure sustainable development of the industrial region.

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SAŽETAK

Industrijska metoda za ublažavanje površinskih devastacija i obnova strukture tla u bazenu Krivoga Roga

Studija istražuje kritična pitanja tehnogene sigurnosti i obnove devastiranih krajolika u bazenu Krivoga Roga, jednom od najvažnijih rudarskih područja Ukrajine. Istraživanje naglašava ekološke izazove uzrokovane intenzivnom rudarskom aktivnošću, uključujući stvaranje vrtača, degradaciju tla i gubitak bioraznolikosti, što je dodatno pogoršano klimatskim promjenama i erozijom. Analizom koeficijenata fitomelioracijske učinkovitosti (Kfm) studija procjenjuje učinkovitost vegetacijskoga pokrova, otkrivajući stalan pad od 1984. do 2024. zbog širenja devastiranih područja. Primjerice, vrijednosti Kfm za vrtaču br. 1 pale su s 3,6 na 2,8, a to upućuje na smanjenu ekološku otpornost. Ključni fokus istraživanja jest tehnologija ispunjavanja s cementiranom pastom, koja se koristi rudarskim otpadom za popunjavanje vrtača. Cilj je ove metode smanjiti devastirane površine, poboljšati javnu sigurnost i obnoviti strukturu tla, istovremeno reciklirajući industrijske nusproizvode. Korištenjem GIS-a i povijesnih podataka studija analizira dinamiku vrtača, identificirajući nelinearne obrasce povećanja, posebno u razdoblju od 1995. do 2005. Polinomski modeli (s R^2 do 0,997) učinkovito opisuju ove trendove. Ekonomska analiza ističe rastuće troškove odgađane revitalizacije, s povećanjem troškova do sedam puta tijekom 38 godina. Zaključeno je kako kombinacija tehnologije ispunjavanja i strategije fitomelioracije nudi održivo rješenje za obnovu krajolika Krivoga Roga usklađujući se s globalnim klimatskim ciljevima i regionalnim razvojnim potrebama. Rezultati ističu hitnu potrebu za provedbom predloženih mjera kako bi se osigurala ekološka stabilnost i dugoročne socioekonomske koristi.

Ključne riječi:

tehnogena sigurnost, revitalizacija krajolika, sanacija vrtača, koeficijent fitomelioracije, rekultivacija rudarskoga otpada

Author's contribution

Mykhailo Petlovanyi (PhD, Assistant) proposed and defined the idea of the scientific article, managed the field research, provided suggestions for interpretation of the results and graphical presentation of the data, and adjustment of the article. **Iryna Fediv** (PhD), **Vasyl Popovych** (Dr. Sci., Professor), **Taras Boyko** (PhD), **Kateryna Stepova** (PhD, Assistant), **Roman Konanets** (PhD) and **Nataliya Popovych** performed the field work, provided funding for the fieldwork, data collection and modelling, participated in the field research and analysis, graphically presented the data, and gave input into the discussion and conclusion sections.

All authors have read and agreed to the published version of the manuscript.

Revealing the subsurface of the southwestern part of the Camplong active fault, West Timor, Indonesia by applying audio-frequency magnetotelluric data inversion

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Preliminary communication



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Abstract

Geologically, three active faults exist in West Timor, East Nusa Tenggara (NTT) Province, Indonesia, namely the Babau, Camplong, and Atambua faults. The audio-frequency magnetotelluric (AMT) data is used to model the electrical subsurface of the Camplong Fault's southwestern part. The AMT profile that comprised 15 AMT observation points over a length of 26 km running in an NW–SE direction was subjected to a phase tensor analysis. The results suggest that the studied area has a regional strike of N25°E and that 2-D inverse modelling on the AMT profile was possible. The inverse modelling result indicates the presence of two conductive boundaries (C1: $\rho \leq 5 \Omega\text{m}$ and C2: $\rho \leq 5 \Omega\text{m}$) in the central and the southeastern parts of the AMT profile that separates the R1 ($\rho = 10\text{--}50 \Omega\text{m}$) and R2 ($\rho = 10\text{--}50 \Omega\text{m}$) as well as R2 and R3 ($\rho = 5\text{--}100 \Omega\text{m}$) zones, respectively. The R1, R2, and R3 are located in the northwestern, central and southeastern parts, respectively. We suggest that the C2 is possibly the damaged zone of the fault in this study area. We also conducted forward modelling and examined the seismic activity and geological background, the results of which aligned with the inverse modelling.

Keywords:

fault zone; earthquake; audio-frequency magnetotelluric; east nusa tenggara; subsurface model

1. Introduction

Timor Island is located in the eastern part of Indonesia. It is approximately 500 kilometers north of Australia and 1,700 kilometers west of Bali Island, separated by the Timor Sea. The island is divided politically into East Timor and West Timor. East Timor is officially recognized as the Democratic Republic of Timor-Leste, while West Timor is as part of Indonesia's East Nusa Tenggara (NTT) Province.

It is also situated within the Banda arc transition zone and was formed as part of the intact Australia Craton before the Miocene era. The tectonic transition zone is characterized by a shift in tectonic processes, transitioning from the Indo-Australian Plate's subduction along the Java Trench in the western part to the continental-island arc's collision along the active volcanic Banda arc

in the eastern part (Powel, 1976). The Banda arc runs eastward from the island of Flores to the islands of Alor and Wetar. The Banda forearc system consists of Timor Island in the southern arc along the islands of Savu and Rote to the west. To the south of the Banda arc lies the Australian North West Shelf, which is thought to be a continental plate created during the Jurassic breakup of eastern Gondwana (Powel, 1976).

Timor Island consists of deformed sediments from the outer margin of the Australian continental plate (Jacobson and Sani, 1993). The Banda Sea lies along the northern part of Timor Island, with the Timor Trough in the southern part. The trough extends south–southeast and is 2,000 meters bathymetric deep (Špičák et al., 2013). It represents the sea-floor trace of the north dipping subduction zone as a result of the northward movement of the Australian continental plate beneath Timor Island. The structural features on Timor Island include a series of thin-skinned, imbricated thrust sheets forming a foreland fold–thrust system (Jacobson and Sani, 1993).

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The Savu Sea, and Savu and Roti islands lie to the west of Timor Island. The tectonic setting at the Savu basin on Timor Island's western part is very complex. The subduction zone bends southwards close to Sumba Island and continues eastward in a shallow trench. Timor Island sits between the arc and the trench, which are generally considered to form an accretionary complex (Chamalaun and Grady, 1978; Barber, 1978; Barber and Brown, 1988; Varekam et al., 1989; Charlton et al., 1991). To the east of Timor Island are the islands of Leti, Kisar, Babar, the Kai Kecil and the Tanimbar Archipelago. They are all part of the Banda outer arc, a geological feature created through the collision between the Eurasian and Indo-Australian plates (Jacobson and Sani, 1993).

In addition, the area is a seismically active region. It has been suggested that the Timor Trough is a representation of the oblique convergence between the plate boundary (DeMets et al., 2010). At the Timor Trough, the estimated convergence rate is approximately 15 mm/year (Bock et al., 2003). Charlton (2002) suggested that Timor Island comprises a fold and thrust belt where the Australian margin has been thrust southward. Villeneuve et al. (2013) carried out an investigation using geochemical analysis and K–Ar dating. They considered the recent structure in Timor Island to have resulted from tectonic events throughout the Late Oligocene, Late Early Pliocene, and Late Pliocene–Early Pleistocene epochs.

As one of geophysical techniques, the audio-frequency magnetotelluric (AMT) is a part of the magnetotelluric method that uses the audio frequency band to investigate the subsurface condition of hydrocarbon zones, geothermal areas, volcanoes, and inland-earthquake-generating fault zones (e.g. Honkura et al., 2000; Oga-wa et al., 2001; Newman et al., 2008; Ingham et al., 2009; Aizawa et al., 2014; Yamaya et al., 2013; Febriani et al., 2019; Widarto et al., 2022; Daud et al., 2023; Junian & Grandis, 2023). It has the capability to penetrate from shallow depths in the Earth's crust to few kilometres of the upper earth's crust because it relies on naturally occurring electromagnetic sources, operating within a range of frequency spanning from 0.1 to 2,000 Hz (Vozoff 1991; Simpson and Bahr, 2005). The method can determine the phase and apparent resistivity beneath a study area by measuring the electric (Ex, Ey) and magnetic field components (Hx, Hy). Thus, it is possible to image the distribution of conductive and resistive zones in a study area by employing 2-D or 3-D subsurface modelling.

Concerning the examination of inland-earthquake-generating fault zones, previous studies have shown that this method can investigate the borders between the conductive and resistive zones, which relates to the region of the fault zone in a study area (e.g. Oshiman et al., 2002; Tank et al., 2005; Kaya et al., 2013; Boonchaisuk et al., 2017; Marti et al., 2020; Usui et al., 2021; Widarto et al., 2022; Kim et al., 2023). Further-

more, combined with the seismicity distribution of a study area, it is possible to reveal the low and high resistivity zones as well as the earthquake epicenter distribution in these zones.

The latest version of the map of all active faults in Indonesia (scale 1:5,000,000) was released in 2021 by the Center for Geological Survey of the Geological Agency, Ministry of Energy and Mineral Resources of the Republic of Indonesia (Soehaimi et al., 2021). They suggested three active faults in West Timor, namely the Babau, Camplong, and Atambua fault segments. The Babau Fault is situated in the southwestern part of West Timor and has a northwest–southeast (NW–SE) orientation. The Camplong Fault is located in the center of West Timor, while the Atambua Fault lies in the northeastern part.

We focus our study on the active fault in eastern Indonesia, notably around West Timor, since it remains poorly reported. We investigated the subsurface of the southwestern part of the Camplong Fault using the AMT method to reveal the electrical resistivity imaging of the subsurface of the Camplong Fault and obtain better knowledge related to the subsurface of the fault. Furthermore, this knowledge will be employed to help reduce the risk of future disasters in West Timor.

2. Geological Background

The initiation of the collision in Timor can be traced back to the Latest Miocene period (Harris, 2011). The development of the Gondwana Sequence duplex occurred as a product of the collision, overlain by the folded and uplifted Banda Terrain, serving as Timor's tectonic lid (Harris, 2011). The Banda Terrane constitute the Mutis/Lolotoi Metamorphic Complex and its sedimentary cover, like the Palelo Group and Metan Formation (Harris, 2006). Although the dominance of this sequence is evident in the majority of Timor's northern regions, several studies (including this study, in Figure 1b) documented the presence of Banda Terrane rocks on the southern part of Timor's central basin with several indication of the Palelo Group sedimentary cover (Rosidi et al., 1979; Sawyer et al., 1993; Charlton and Titu-Eki, 2023). This metamorphic complex may be interpreted as the differentiated Australian continental margin basement (Charlton and Titu-Eki, 2023).

Figure 1 indicates the study area's location, which is found in West Timor, East Nusa Tenggara Province, Indonesia. Figure 1b presents the dominant geological background in the surrounding study area, comprising limestone, alluvium, ultrabasic rocks, and the Ofu, Batuputih, Bobonaro, Aitut, Maubise, and Noele formations.

The Ofu Formation generally consists of deformed limestones and possibly represents the local deformation product in the Kolbano area (Keep and Haig, 2010). The Ofu Formation shares the same characteristics as the Batuputih Formation. Both were made up of white

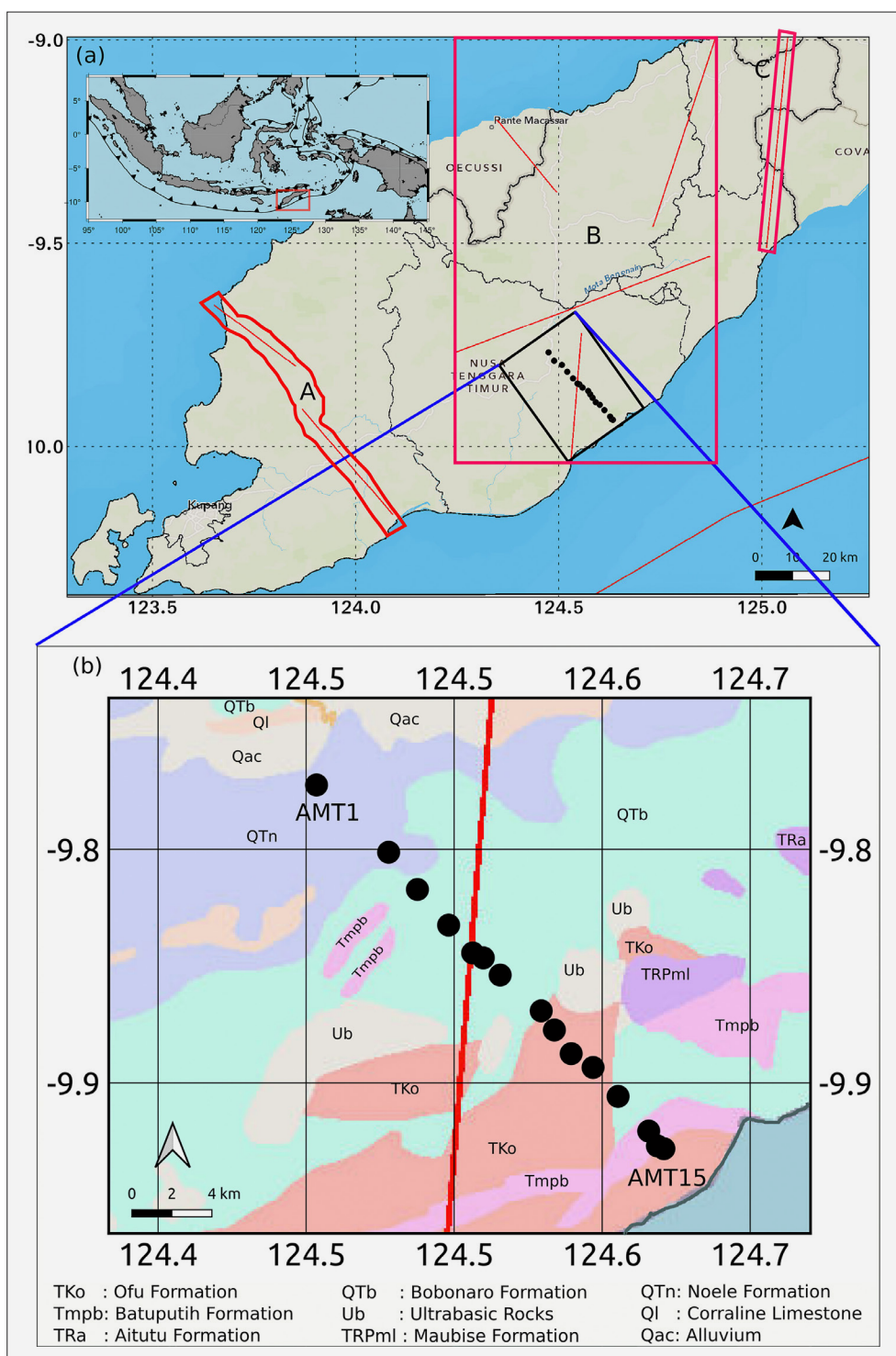


Figure 1. (a) Location of research area in West Timor. The fault segments (red square) proposed by Soehaimi et al. (2021) are labelled as A (the Babau Fault segment), B (the Camplong Fault segment), and C (the Atambua Fault segment). The black dots are the AMT observation points. (b) The geological map of the research area passed by the southwestern part of the Camplong Fault (red line) issued by the Indonesian Ministry of Energy and Mineral Resources One Map (2023). AMT1 and AMT15 refer to the location of the AMT observation points. (inset) Map of Indonesia with the red square denotes West Timor, East Nusa Tenggara Province, Indonesia.

and thin-bedded foraminiferal calcilutite. Thin gray shale is also found in these formations (Charlton, 1989).

The Bobonaro Formation can be described as a mixture of scaly clay, comprising subangular and disordered

angular blocks embedded within a scaly clay matrix (Charlton et al., 1991). It is generally reddish brown and green in color but is also, less commonly, gray, black, bright red, and yellow.

The Aitutu Formation is spread widely throughout Timor. It is comprised of both white and gray shale, along with radiolarian calcilutite. This formation is defined as a component of a margin sequence of the Australian continental (**Charlton, 1989**). The Maubise Formation is composed of pink, white and red limestone, often exhibiting dolomitization, and it contains abundant fusulinid and crinoid fragments (**Charlton, 1989**). The Noele Formation overlays the Batuputih Formation. It consists of tuffaceous material, marl interbedded with turbiditic sandstone, and calcilutite. Upwards, it becomes coarser and richer in clastic (**Roosmawati and Harris, 2009**).

Major active faults around the Timor region include the Timor Trough, Semau Fault and the Savu Thrust (**Harris and Major, 2016; Hutchings and Mooney, 2021**). The Timor Trough exhibits megathrust activity, where collision and accretion overprints the subduction process (**Hutchings and Mooney, 2021; Harris, 2011**). The Timor region is recorded as one of the deepest seismicity events in Indonesia (≥ 670 km depth) alongside with the Celebes Sea-Philippines subregion (**Hutchings and Mooney, 2021**). Despite this, the Timor Trough is recognized as the most seismically quiet region of the Banda Arc, though it is acknowledged for its latent capacity to generate significant earthquakes over extended temporal scales (**Coudurier-Curveur et al., 2021**).

The left-lateral transpressional Semau Fault is also known as a primary source of major earthquakes occurring in Timor alongside the Timor Trough. The structural trend is oriented NE–SW, extending from Semau Island to the east of Alor, and is aligned with the structural trend of the currently interpreted fault of this study. **Harris and Major (2016)** characterize the Camplong Fault as a left-lateral strike-slip fault with a NE–SW trend. In contrast, **Soehami et al. (2021)** interpret the Camplong Fault as a thrust fault along the centre part of Timor (see **Figure 1b**). However, both interpretations show similar structural trends. Two other faults, the Babau and Atambua faults are strike-slip faults. The orientation of the them are NW–SE and NE–SW, respectively (**Soehami et al., 2021**). Additionally, the Savu Thrust represents another noteworthy major active fault in the region, originating as a product of the Scott Plateau underthrusting. This fault is situated on the rear of the Sumba-Savu accretionary wedge and has a north-vergence (**Harris et al., 2009**).

3. AMT Data Acquisition and Analysis

3.1. Data Acquisition

A total of 15 AMT observation points were used, depicted as AMT1 to AMT15 in **Figure 1b**. We used AMT data from a PHOENIX MTU5A, which was acquired in May–August 2012. The frequency range is 0.35–10,400 Hz and recorded within two hours for each observation.

The average elevation of all observation points was 768.47 meters, with the lowest and highest points being AMT15 (470 m) and AMT11 (1,330 m), respectively.

The profile has an NW–SE orientation and is about 26 km long. The AMT profile passes through a fault zone in the southern section of the East Nusa Tenggara Province. According to the active fault map of Indonesia, released by the Center for Geological Survey, Geological Agency, Ministry of Energy and Mineral Resources of the Republic of Indonesia, this fault is part of the Camplong thrust fault (**Soehami et al., 2021**).

3.1. Data Analysis

We utilized phase tensor as an initial analysis in examining the AMT data, following the methodology described by **Caldwell et al. (2004)**. This analysis allowed us to compute both the regional strike direction and the skew angle (β). The β , in turn, played a crucial role in assessing the study area's dimensionality.

Figure 2 contains the β values for all AMT points across the 26-km-long profile. These β values encompass the entire frequency range, spanning from 0.35 Hz to 10,400 Hz. From AMT1 to AMT15, the β values are dominated by the range of $|\beta| \leq 3^\circ$, except for AMT1 and AMT14 for frequency range 1,000–10,000 Hz and 10–100 Hz, respectively, as indicated by the color scale of **Figure 2**. This indicates that it is feasible to carry out 2-D inversion modelling in our study area. Booker (2014) suggested a range of $|\beta| \leq 3^\circ$ as the threshold for 2-D AMT inversion modelling in a study area based on phase tensor analysis, as introduced by previous study (**Caldwell et al., 2004**).

Figure 3 contains rose diagrams covering all of the AMT observation points at frequencies from 0.1 Hz to 10,000 Hz. A rose diagram for the entire frequency is also presented in **Figure 3f**. The rose diagram indicates an NE–NW strike direction for the frequency ranges of 0.1–1 Hz, 10–100 Hz, and 100–1,000 Hz, as illustrated in **Figure 3**. On the other hand, the frequency range of 1–10 Hz, 1,000–10,000 Hz, and all frequency are the NE–SE direction.

Figure 1 indicates that the fault line passing the AMT profile runs in an NE–SW direction. Therefore, we applied the NE direction of the regional strike to determine that of the fault line. From the average regional strike direction for all frequencies, we suggest that N25°E be the dominant strike direction. For further analysis, we applied the value of N25°E to rotate the impedance tensor values before applying the inversion modelling.

We also analyzed the induction vectors applying the Parkinson convention (**Parkinson, 1962**), as presented in **Figure 4**. The real part of the induction vectors indicates a conductive zone close to the study area. This analysis is useful if there is a very conductive zone—for example, a sea or lake—close to the study area. In addition, it will also be a sign of the location of a deeper conductor located away from the observational site.

Figure 2. The values of β for all AMT observation points from lower to higher frequencies

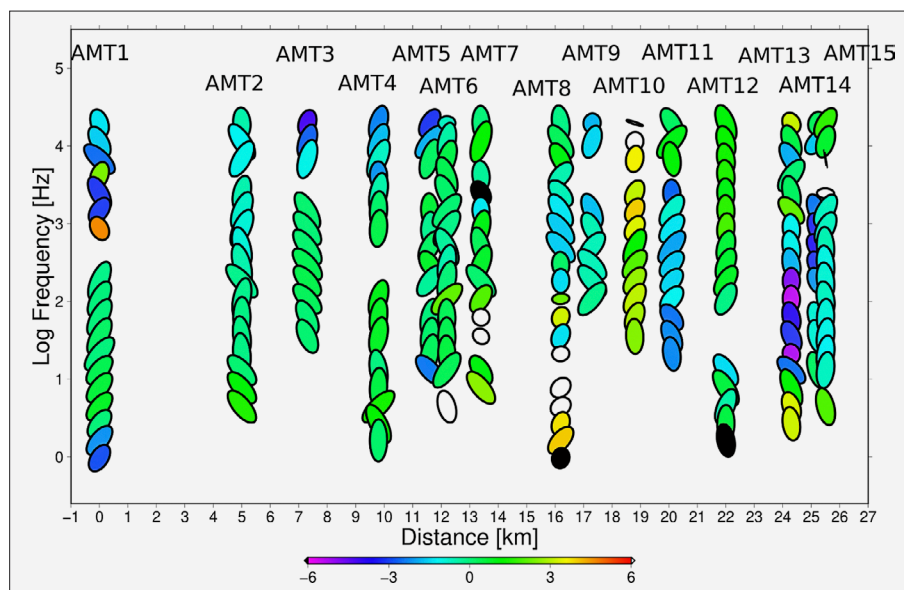
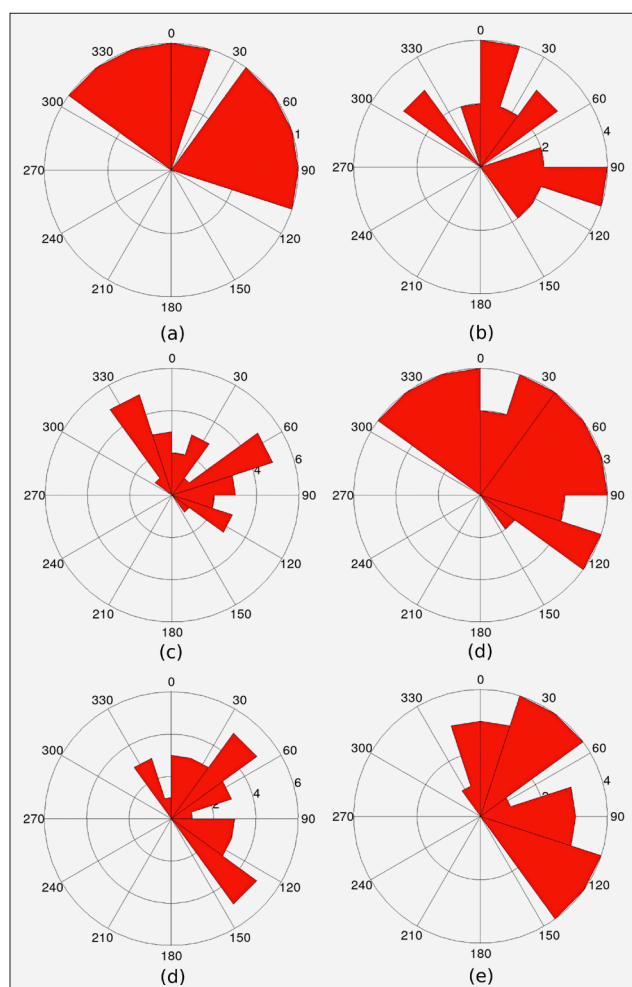


Figure 3. Rose diagrams indicating the study area's regional strike for the frequency ranges of (a) 0.1–1 Hz, (b) 1–10 Hz, (c) 10–100 Hz, (d) 100–1,000 Hz, (e) 1,000–10,000 Hz, and (f) all frequencies

As a representative, we plotted the real components of the induction vectors for the frequencies of 1.02 Hz,

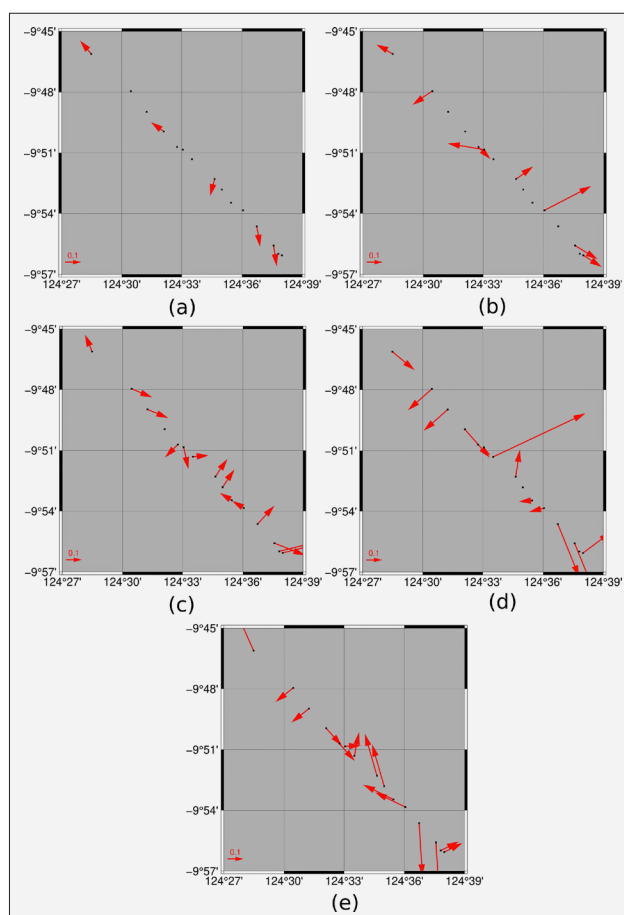


Figure 4. The Parkinson convention induction vectors' real components at frequencies of (a) 1.02 Hz, (b) 11.1 Hz, (c) 115 Hz, (d) 1,100 Hz, (e) 10,399 Hz

11.1 Hz, 115 Hz, 1100 Hz, and 10,399 Hz, as shown in **Figure 4**. The result shows that the orientation of the induction vectors is scattered from the lower to higher frequencies. The research area is situated sufficiently far from the sea and there is no lake in the area surrounding

the AMT profile. **Figure 4** also indicates no deep conductor in the surrounding of the AMT sites.

4. Results

For modelling, we applied the 2-D inversion modelling by **Ogawa and Uchida (1996)**. Prior to conducting the subsurface modelling, we applied a N25°E rotation to the impedance tensor for all AMT points. **Figures 5** and **6** present the phase and apparent resistivity of all AMT points in the transverse magnetic (TM) and transverse electric (TE) modes derived from calculation and observation, respectively.

Figure 5 indicates the same general pattern in the characteristic of the phase and apparent resistivity of all AMT points derived from calculation and observation. The resistivity values are higher in the southeastern part of the AMT profile (near AMT15) than in the northwestern part (near AMT1). The observed apparent resistivity in the TE mode also shows resistive zones close to AMT10 and AMT11 on the near-surface. Near AMT6, AMT 14 and AMT15, the resistive zones appear in the lower frequencies. However, the resistive zone near AMT6 does not emerge in the calculated one.

The TE mode's observed and computed phases present consistent overall characteristics. The phase values in the southeastern part of the AMT profile at a distance of 21–26 km are lower than in the northwestern part of the AMT profile. The lower phase values are indicated close to AMT12, AMT13, AMT14, and AMT15 in the near-surface. The attributes of the observed and computed phases are also similar at the lower frequency.

Figure 6 shows the TM mode's observed and computed phase and apparent resistivity. The similarity of the calculated and observed apparent resistivity is indicated in **Figure 6**. The features of the computed and modelled apparent resistivity for the TM mode are similar to that of the TE mode. The characteristics of the TM mode's calculated and observed apparent resistivity closely resemble those observed for the TE mode for frequency range more than 10 Hz. There is a slight difference for the lower frequency (< 10 Hz). There is a higher resistive value ($\rho \geq 50 \Omega\text{m}$) near AMT8 and AMT9 in the frequency range less than 10 Hz for TM mode's observed apparent resistivity.

The calculated and observed phases also show a similar general pattern to that of the TE mode. The southeastern part of the AMT profile, close to the distance of 21–26 km, is lower than that of the northwestern part, especially at the frequency range ≥ 100 Hz. Lower phase value zones exist close to AMT3, AMT5, AMT9, AMT12, AMT13, AMT14, and AMT15 in the near-surface of the study area. These zones are also evident in the TE mode derived from calculation and observation.

Figures 7 and **8** present the phase and apparent resistivity for all AMT points derived from calculation and

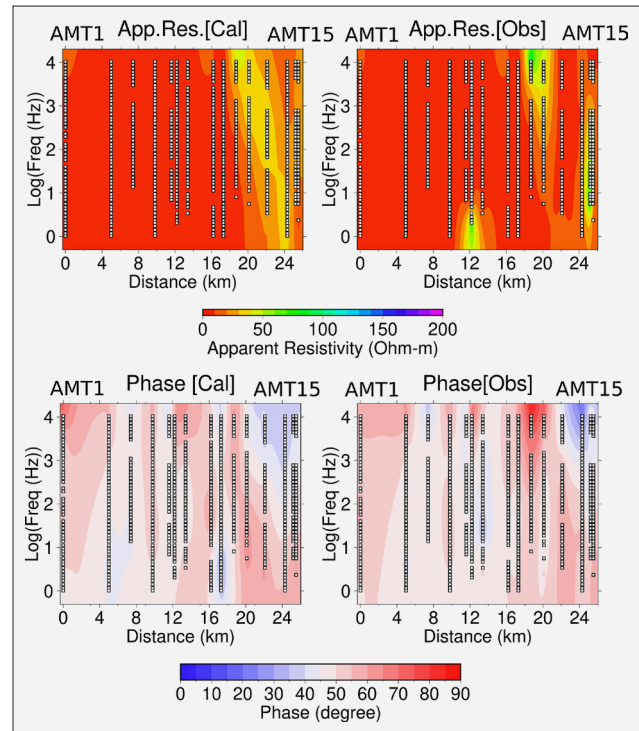


Figure 5. The apparent resistivity and phase of all AMT points in the TE mode derived from calculation and observation

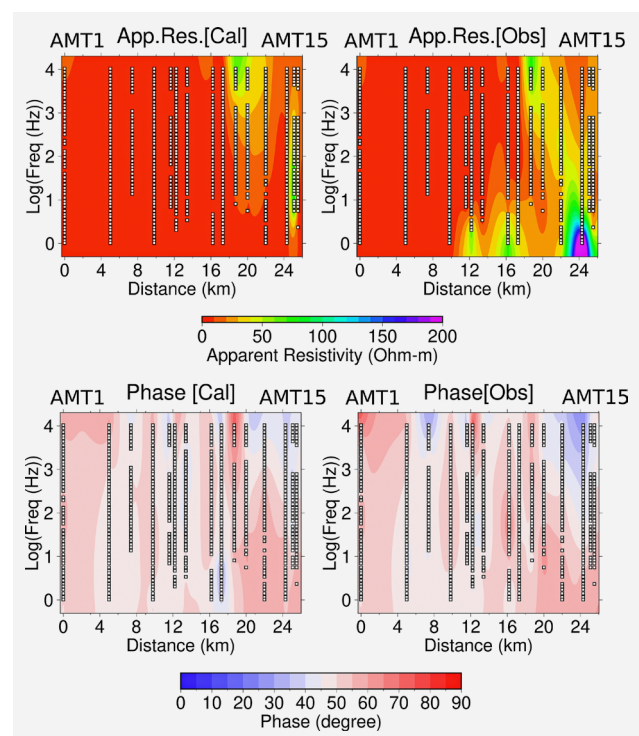


Figure 6. The apparent resistivity and phase of all AMT observation points in the TM mode derived from calculation and observation

observation in the TM and TE modes. The red lines indicating the computed phase and apparent resistivity for most of the AMT observation points are fitted with black

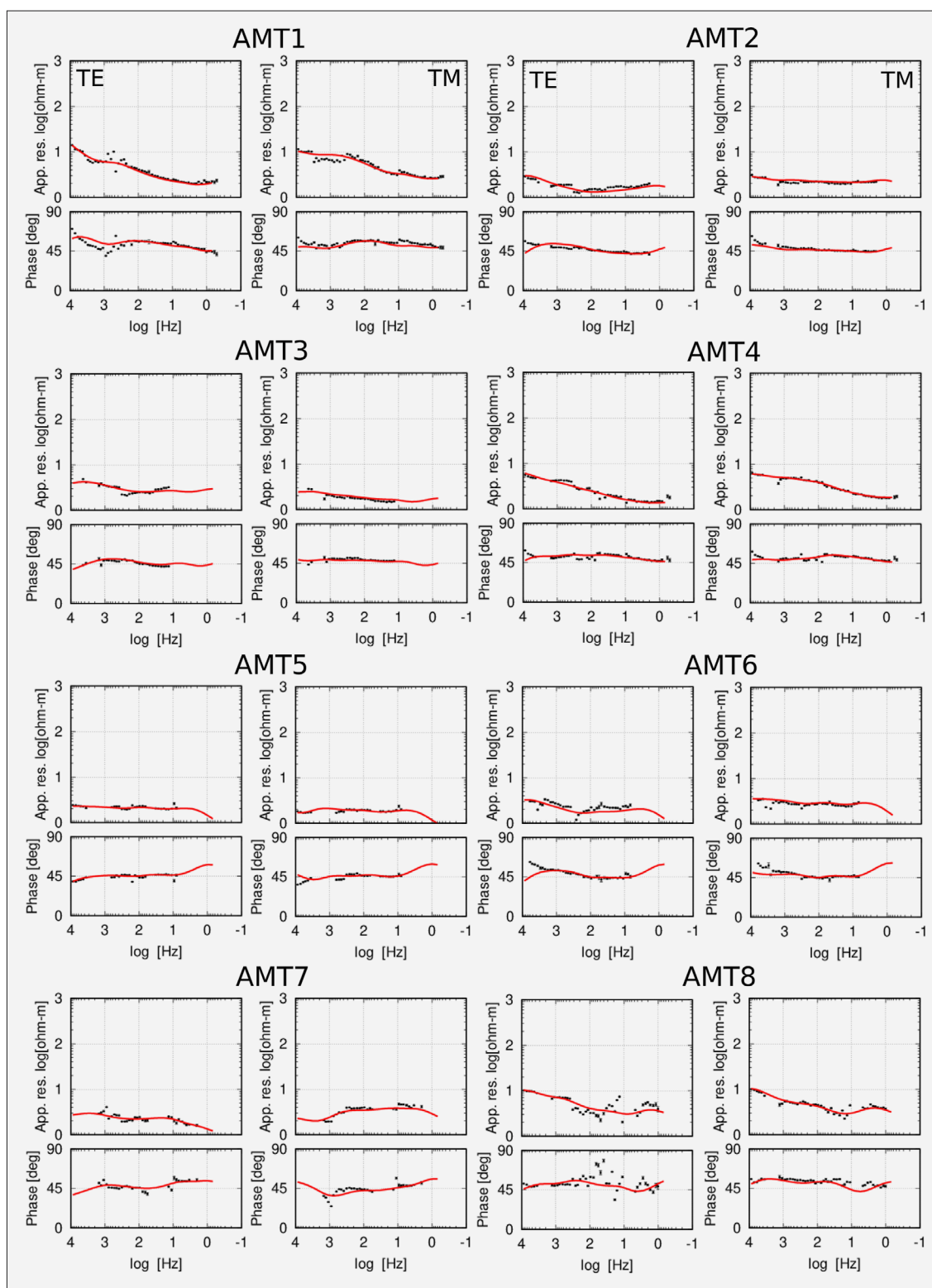


Figure 7. The apparent resistivity and phase for the observation points AMT1 to AMT8 in the TM and TE modes. The red lines represent the computed values, while the black dots represent the observed values.

dots, showing their phase and apparent resistivity observed during the measurement.

These figures indicate that the calculated model could be considered representative of the observed model. Therefore, the subsurface models derived from the 2-D

inversion modelling could be regarded as representative models of the subsurface characteristics within the research area along the AMT profile.

We present the electrical subsurface model and its sensitivity model in **Figure 9**. The initial apparent resis-

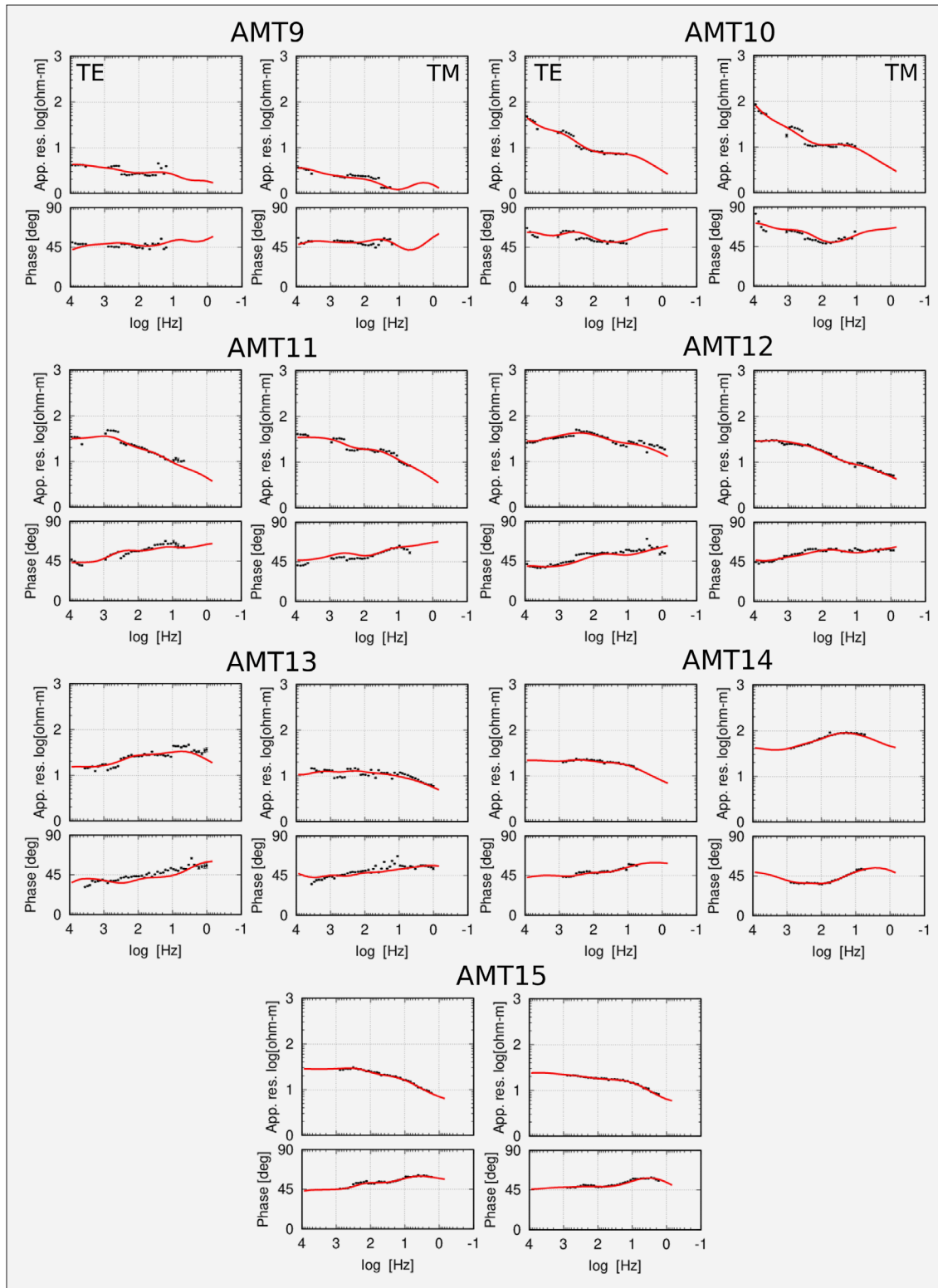


Figure 8. The apparent resistivity and phase for the observation points AMT9 to AMT15 in the TM and TE modes. The red lines represent the computed values, while the black dots represent the observed values.

tivity value of the model is $300 \Omega\text{m}$. We iterated the model 40 times. The root-mean-square (RMS) misfit value of the subsurface model is 1.40.

In the northwestern part of the profile, there are higher resistivity (R1: $\rho = 10\text{--}50 \Omega\text{m}$) and very low resistivity

zones ($\rho \leq 5 \Omega\text{m}$). The very low resistivity zone is near AMT1 from near-surface to the deeper depth. The R1 zone spans from AMT2–AMT7 in the near-surface and goes down to a depth of 2 km near AMT2. In the central part of the AMT profile between AMT7 and AMT8 sites,

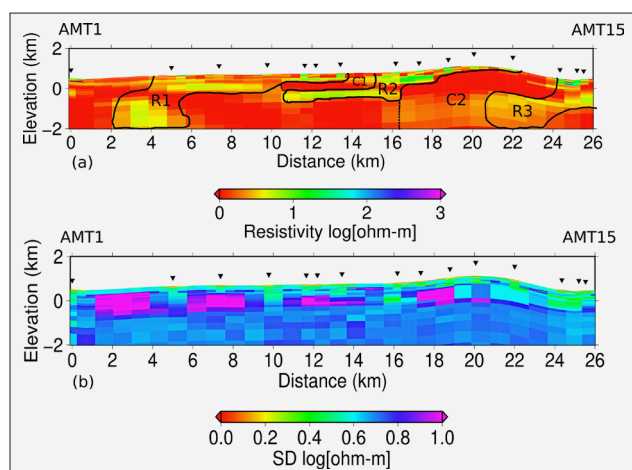


Figure 9. The AMT profile from AMT₁ to AMT₁₅. (a) The electrical subsurface model through the AMT profile. (b) The sensitivity model through the AMT profile.

the subsurface model presents a very conductive zone (C1: $\rho \leq 5 \Omega\text{m}$) from the near-surface to the depth of about 0.5 km. The C1 zone is going below the R1 zone near AMT5–AMT7 and overlays the R2 zone (R2: $\rho = 10\text{--}50 \Omega\text{m}$). The C1 zone acts as the boundary between the R1 and R2 zones.

Going to the southeastern part of the profile, the subsurface model indicates there are C2 ($\rho \leq 5 \Omega\text{m}$) and R3 zones ($\rho = 5\text{--}100 \Omega\text{m}$). The C2 zone is the boundary zone between R2 and R3. The zone is heading downward in the northwestern direction until it reaches a depth of 2 km and overlays the R3 zone at a depth of about 1 km near the AMT11 and AMT12 sites. The R3 zone has a higher apparent resistivity value on the near-surface and its apparent resistivity value decreases while the zone goes downward to a depth of 2 km.

The subsurface model presents two very conductive zones (C1 and C2) as the boundary between the zones

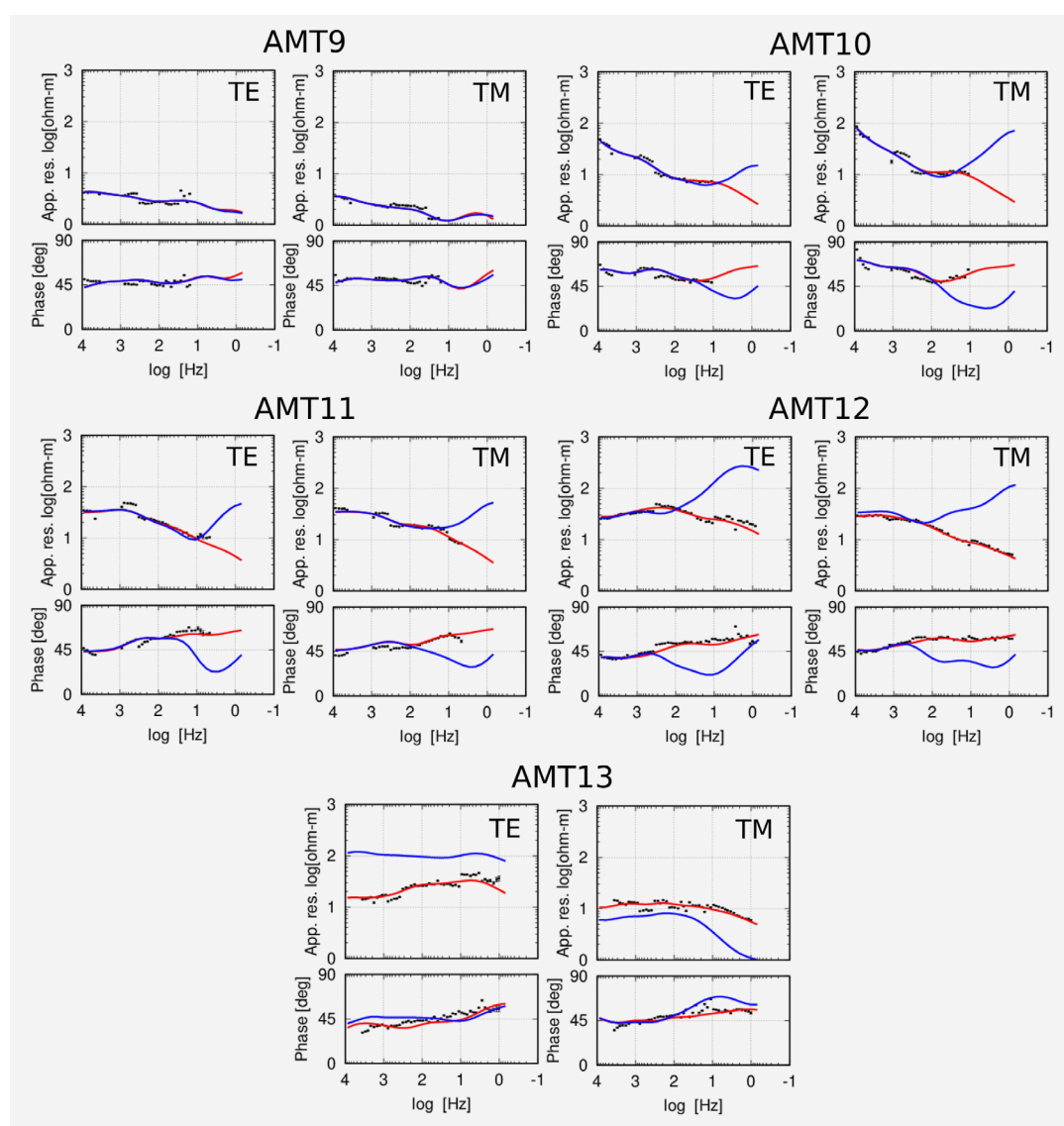


Figure 10. The forward models of apparent resistivity and phase in the TM and TE mode by substituting the C2 value to $500 \Omega\text{m}$. The red lines represent the calculated values, the black dots represent the observed values, and the blue lines represent the forward modelling response

(R1, R2, and R3) which have higher apparent resistivity value compared to its surroundings, as presented in **Figure 9**. However, the R1 zone does not appear in the TE and TM modes of the observed and computed apparent resistivity, as indicated in **Figure 5** and **Figure 6**. In addition, both figures present the C2 as the border between the R2 and R3 zones exist in the southeastern part of the TM and TE modes of the observed and computed apparent resistivity. Therefore, we assume that the C2 is supposed to be the fault zone in this study area.

Figure 9b presents the subsurface model's sensitivity. It was determined by dividing between the upper and lower resistivity values in logarithmic numbers. We can use this sensitivity model to select a reliable subsurface model from the modelling. **Figure 9b** presents the values of the sensitivity model ≤ 0.5 in the near-surface and dominantly about 0.6 in the deeper depth except for the area between AMT1 and AMT2, near AMT3, AMT5, AMT6, AMT9, and AMT10 from the near-surface until a depth of about 0.5 km.

Since there are no AMT observation points between AMT1 and AMT2, AMT2 and AMT3, AMT3 and AMT4, AMT4 and AMT5, or near AMT8, we assume that the higher sensitivity values (≥ 0.5) are caused by the greater distance between the aforementioned observation points and the resolution of the subsurface model in these zones will be lower, as indicated in **Figure 9b**. Therefore, the subsurface model from the 2-D inverse modelling in this study is still valid.

5. Discussion

5.1. Forward modelling

We conducted forward modelling for further analysis to test the validity of the modelling result. In this step, we substituted the resistivity values to 500 Ωm in the C2 zone in **Figure 9a**. The substitution zone runs from the top to a depth of 2 km and covers a horizontal distance from 16.5 km to 24 km. The forward modelling's result is presented in **Figure 10**.

Figure 10 shows the forward modelling conducted for AMT9, AMT10, AMT11, AMT12 and AMT13. It illustrates that when the resistivity value within the zone spanning from AMT9 to AMT12 is set at 500 Ωm , the observed and computed phase and apparent resistivity are out of agreement. The responses of the calculated phase and apparent resistivity after carrying out the forward modelling differ from those obtained after applying the 2-D inverse modelling, as shown by the blue and purple lines in **Figure 10**.

The forward modelling's result indicates that the apparent resistivity values within the region spanning from AMT9 to AMT13, extending from the top to a higher depth, exhibit that the zone is not 500 Ωm . It means the C2 zone has the lower apparent resistivity value, as indicated as the conductive zone in the subsurface mod-

elling in **Figure 10**. We can also conclude from **Figure 10** that a conductive boundary (C2) presents in proximity to AMT9, separating the R2 and R3 zones. We suggest that this may be the location of the fault and the conductive boundary (C2) is probably the damaged zone of the fault.

Certain prior research studies have indicated that the border of the resistive and conductive zones is related to the location of the fault region within the study area (Os-
himan et al., 2002; Tank et al., 2005; Kaya et al., 2013; Boonchaisuk et al., 2017; Marti et al., 2020; Usui et al., 2021; Huang et al., 2021; Widarto et al., 2022; Kim et al., 2023). Furthermore, it was presumed that this boundary would become the site of earthquakes in the future (Becken et al., 2011; Kaya et al., 2013; Sun et al., 2019; Xu et al., 2019; Zhang et al., 2021).

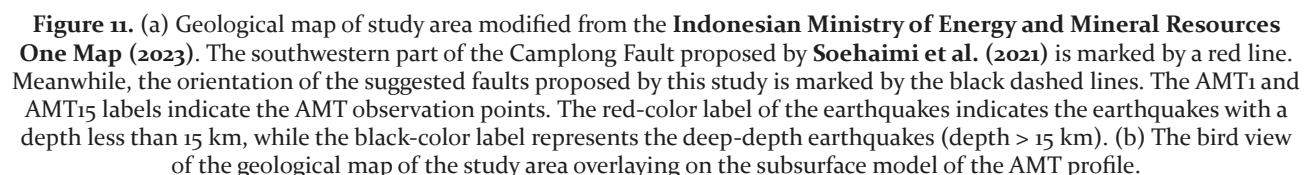
5.2. Relationship between electrical subsurface model, seismicity, and geological background

Since the potential fault location suggested by the inverse and forward modelling in the study area's electrical subsurface model differs slightly from that suggested by Soehaimi et al. (2021), we will discuss the relationship between the electrical subsurface model, seismicity, and geological background in this subsection.

We present the earthquakes occurring in the surrounding study area from 1997 to 2022, based on the United States Geological Survey (USGS) catalog (1997–2008) and the Indonesian Agency for Meteorological, Climatological, and Geophysical (BMKG) catalog (2009–2021). All of the earthquakes are presented in **Figure 11a**. The status of all earthquakes from the USGS and BMKG catalogs were reviewed and relocated, respectively (USGS 2022; Ramdhan et al., 2021). Their detailed parameters are listed in **Table 1**. We also show the bird view of the study area's geological map which overlays on the subsurface model of the AMT profile in **Figure 11b**.

EQ15 was the earthquake closest to the AMT profile. EQ8, EQ9, EQ12, and EQ15 occurred along the fault trend orientation suggested by Soehaimi et al. (2021) and as indicated by the red line in **Figure 11**. However, these occurred at great depth and were possibly triggered by the activity of the Timor Trough. Most of the earthquakes in the region around the research area occurred in the vicinity of the Ofu Formation. This supports the results of the electrical subsurface modelling suggesting that the conductive boundary (C2) is potentially the location of the fault and the C2 zone is probably the damaged zone of the fault.

Geologically, the conductive boundary (C2) may be an elevated section formed as a high horst block of the pre-collisional Australian continental margin. This sequence is capped by the Ofu Formation, which consists of deformed limestones (Keep and Haig, 2010) and may be the equivalency of the Borolalo Formation in East Timor (Charlton and Wall, 1994) and the Menu Formation in West Timor (Sawyer et al., 1993). The de-



The R2 and R3 zones are the Bobonaro Formation, a scaly clay melange comprising subangular and unsorted

angular blocks set in a scaly clay matrix (**Charlton et al., 1991**). Notably, the ultrabasic rocks exposed in the area can also be classified as part of the Mutis/Lolotoi Complex. In **Figure 11b**, the ultrabasic rocks appear near the surface of the R2 zone, which is indicated by

Table 1. The detailed parameters of the earthquakes surrounding the study area

No	Date	Longitude (°E)	Latitude (°N)	Depth (km)	Magnitude (Mw)	Catalog
1	14/09/1998	124.567	-9.984	33	4	USGS
2	02/08/2003	124.638	-9.965	33	4.9	USGS
3	11/06/2003	124.590	-9.809	10	5.2	USGS
4	18/07/2005	124.480	-9.948	10	5.4	USGS
5	26/08/2010	124.509	-9.941	4.55	4.6	BMKG
6	23/12/2010	124.590	-9.780	54.5	4.2	USGS
7	14/11/2011	124.525	-9.764	8.43	4.6	BMKG
8	16/12/2012	124.528	-10.004	56.55	4.2	BMKG
9	22/09/2012	124.553	-9.726	41.45	4.3	BMKG
10	23/05/2013	124.586	-9.903	30.40	4.5	USGS
11	18/04/2015	124.584	-9.975	0.62	4.4	BMKG
12	25/10/2016	124.542	-9.922	41.22	3.7	BMKG
13	28/08/2017	124.637	-9.911	39.36	3.4	BMKG
14	06/10/2017	124.627	-9.777	14.02	4.2	BMKG
15	29/01/2018	124.542	-9.829	58.04	3.4	BMKG
16	24/07/2021	124.630	-9.993	11.56	3.8	BMKG

their apparent resistivity value being higher than their surroundings. Although **Rosidi et al. (1979)** classified it as part of a separate formation, **Harris (2006)** summarized that the ultramafic rocks in Timor have been found beneath, above, and intruding through the Mutris/Lolo-toi Complex.

Various earthquakes have also occurred at a shallower depth in this location, namely EQ4 (M5.4, depth 10 km), EQ5 (M4.6, depth 4.55 km), and EQ11 (M4.4, depth 0.62 km). Therefore, this indicates that the orientation of the fault trend potentially lies near the boundary between the Ofu and Bobonaro formations, as depicted by the dashed black lines in **Figure 11a**.

Furthermore, additional past shallow earthquake activity and geological and geophysical data are required to better understand the orientation and mechanism of all parts of the Camplong fault in West Timor, East Nusa Tenggara Province. The location of the Camplong Fault must also be mapped precisely in the future because it covers various cities in West Timor, e.g. Kolbane, Oetoeke, Oenai 2, and Nikiniki. Moreover, there are other active faults in West Timor, e.g. the Babau and Atambua faults, which also require further studies on all active faults so that we can mitigate the hazards associated with them. In addition, further research in the future is also still needed by dating ultramafic rock units and various metamorphic massifs in Timor to provide further clarification regarding this enigmatic rock.

5. Conclusions

To investigate the subsurface of the southwestern part of the Camplong active fault in West Timor, East Nusa Tenggara Province, we analyzed 15 AMT data observa-

tion points. The AMT profile that passes through the fault line is around 26 km in length and has an NW–SE direction. The analysis of phase tensor indicated that the study area's regional strike is N25°E and it was feasible to apply the 2-D inverse modelling on the AMT data. The inverse modelling results indicate that the electrical subsurface of the study area has a higher resistivity zone (R1: $\rho = 10\text{--}50\ \Omega\text{m}$) in northwestern parts of the AMT profile, a very conductive zone (C1: $\rho \leq 5\ \Omega\text{m}$) and R2 zone (R2: $\rho = 10\text{--}50\ \Omega\text{m}$) in the central part, as well as C2 ($\rho \leq 5\ \Omega\text{m}$) and R3 zones ($\rho = 5\text{--}100\ \Omega\text{m}$) in the southeastern of the AMT profile. The C1 zone acts as the boundary between the R1 and R2 zones, while the C2 zone is the boundary zone between R2 and R3. After comparing the 2D inversion model to the TM and TE modes of the observed and computed apparent resistivity, we assume that the C2 is supposed to be the damaged zone of the fault in this study area. The result from the forward modelling, analysis of seismic activity, and consideration of the geological background further support this result.

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SAŽETAK

Istraživanje podzemlja jugozapadnoga dijela aktivnoga rasjeda Camplong, Zapadni Timor, Indonezija, primjenom inverzije audiofrekventnih magnetotelurskih podataka

Geološki u Zapadnome Timoru u pokrajini Istočna Nusa Tenggara (NTT) u Indoneziji postoje tri aktivna rasjeda, i to rasjedi Babau, Camplong i Atambua. Podatci audiofrekventnoga magnetotelurskog (AMT) mjerenja korišteni su za modeliranje geoelektričnoga podzemlja jugozapadnoga dijela rasjeda Camplong. AMT profil, koji se sastojao od 15 AMT promatračkih točaka na duljini od 26 km u smjeru SZ-JI, podvrgnut je analizi faznoga tenzora. Rezultati sugeriraju da proučavano područje ima regionalni smjer $N25^{\circ}E$ te da je 2D inverzno modeliranje na AMT profilu bilo moguće. Rezultat inverznoga modeliranja upućuje na prisutnost dviju vodljivih granica ($C_1: \rho \leq 5 \Omega m$ i $C_2: \rho \leq 5 \Omega m$) u središnjemu i jugoistočnome dijelu AMT profila koji odvaja zone R_1 ($\rho = 10 - 50 \Omega m$) i R_2 ($\rho = 10 - 50 \Omega m$), kao i R_2 i R_3 ($\rho = 5 - 100 \Omega m$). R_1 , R_2 i R_3 nalaze se u sjeverozapadnome, središnjemu i jugoistočnome dijelu. Smatramo da je C_2 moguća oštećena zona rasjeda u ovome području istraživanja. Također smo proveli direktno modeliranje i ispitali seizmičku aktivnost i geološku pozadinu, čiji su rezultati usklađeni s inverznim modeliranjem.

Ključne riječi:

rasjedna zona, potres, audiofrekventna magnetotelurika, istočna Nusa Tenggara, model podzemlja

Author's contribution

Febty Febriani (Dr): Conceptualization, methodology, audio-frequency magnetotelluric data validation and analysis, audio-frequency magnetotelluric data curation, writing (original draft), writing (review and editing), and visualization. **Cinantya Nirmala Dewi** (M.Sc): Methodology, audio-frequency magnetotelluric data curation, and writing (review and editing). **Gusti Muhammad Lucki Junursyah** (M.Sc): Providing audio-frequency magnetotelluric data, audio-frequency magnetotelluric data curation, and writing (review and editing). **Titi Anggono** (Dr), **Syuhada** (Dr), **Mohamad Ramdhan** (Dr), **Faiz Muttaqy** (Dr), **Mohammad Hasib** (Dr) and **Wiko Setyonegoro** (M.Sc): Writing (original draft), seismic data curation, and writing (review and editing). **Herry Zardak Kotta** (Dr) and **Aditya Dwi Prasetyo** (M.Sc): Geological data curation, Geological data interpretation, and writing (review and editing). All authors read and accepted the final form of the manuscript.

Assessing the Feasibility of Photogrammetry for Underground Mine Monitoring: A Simulation-Based Study

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Abstract

Underground mining operations face significant challenges in monitoring structural stability and safety due to limited visibility and access. This study evaluates the feasibility of photogrammetry for underground mine monitoring using a simulation-based framework, bypassing resource-intensive field experiments. Synthetic datasets, generated via Blender and MATLAB, were used to assess photogrammetric accuracy, scalability, and limitations under varying lighting (25–100 lux), noise, and dust conditions. Three Structure-from-Motion (SfM) algorithms – COLMAP, OpenMVG, and Agisoft Metashape – were compared to evaluate performance robustness. The results indicate a Root Mean Square Error (RMSE) of 2.3 cm for COLMAP at 50 lux, improving to 1.9 cm at 100 lux, with OpenMVG and Agisoft Metashape showing comparable accuracy (RMSE 2.1–2.5 cm) but varying processing times. Challenges persist in low-light conditions (RMSE 3.8 cm at 25 lux) and complex geometries, exacerbated by simulated dust (RMSE 2.5 cm), highlighting the need for supplemental lighting and advanced image preprocessing. Point density ranged from 8,500 to 12,300 points/m², with dust and noise reducing detail retention. These findings suggest photogrammetry's potential as a cost-effective, non-invasive monitoring tool, complementing traditional methods like Light Detection and Ranging (LiDAR). The simulation-based approach provides a scalable framework for optimizing photogrammetric workflows, supporting Industry 4.0 trends in mining safety and efficiency. Future work should validate these results in real-world conditions to address environmental variables like dust and humidity.

Keywords:

photogrammetry; underground mining; simulation; 3D modelling; mine monitoring; safety

1. Introduction

Underground mining, critical for global resource extraction, faces significant challenges in ensuring operational safety and efficiency due to limited subsurface monitoring capabilities. Issues such as rock mass instability, tunnel convergence, and gas accumulation frequently cause operational delays or catastrophic failures (Hoek and Brown, 1980). Conventional monitoring methods, including laser scanning and manual surveys, while accurate, are often resource-intensive and impractical for real-time application in inaccessible areas (Meaka and Vokain, 2023).

Photogrammetry, widely utilized for surface mapping, remains underexplored in underground environments due to constraints like poor lighting and confined spaces (Remondino and El-Hakim, 2006). This study introduces a novel simulation-based methodology to evaluate photogrammetry's feasibility for underground mine monitoring,

eliminating the need for costly and logistically complex field experiments. By employing computational tools such as Blender and Matrix Laboratory (MATLAB) to create synthetic underground scenes, we assess photogrammetry's theoretical performance under controlled conditions. The objectives are threefold:

1. to determine the precision of photogrammetric reconstruction, including comparisons of Structure-from-Motion (SfM) algorithms (COLMAP, OpenMVG, Agisoft Metashape),
2. to identify critical environmental and technical factors influencing its efficacy, and
3. to propose a practical framework for integrating photogrammetry into mining engineering workflows.

This approach aligns with Industry 4.0 trends in mining, emphasizing digital twins, remote sensing, and automated monitoring to enhance safety and efficiency (Lillesand et al., 2015). The paper is organized as follows:

- Section 2 reviews photogrammetric principles and its limited mining applications.

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- Section 3 outlines the simulation methodology.
- Section 4 presents results with supporting visuals.
- Section 5 discusses findings; and
- Section 6 concludes with implications and future directions.

The paper includes **Figures 1–6**, which illustrate the synthetic mine model, error distribution, and visual synthesis of photogrammetry's performance under varying conditions, and **Tables 1–6**, which present simulation parameters, error metrics, environmental impacts, computational performance, and scalability comparisons.

2. Background and Literature Review

Photogrammetry relies on the principle of triangulation to reconstruct three-dimensional (3D) geometry from overlapping two-dimensional (2D) images (**Mikhail et al., 2001**). Advances in Structure-from-Motion (SfM) algorithms, such as COLMAP, OpenMVG, and Agisoft Metashape, have made it a cost-effective alternative to Light Detection and Ranging (LiDAR) for surface mine mapping, achieving accuracy below 5 cm in optimal conditions (**Westoby et al., 2012**). However, underground applications are scarce due to challenges like insufficient lighting, dust interference, and restricted camera placement (**Donovan et al., 2016**).

Studies such as **Eberhardt (2012)** have demonstrated photogrammetry's potential in small-scale tunnel mapping, but scalability to complex mine networks remains untested. Photogrammetry has been effectively applied in geotechnical monitoring, such as landslide displacement analysis using unmanned aerial systems, demonstrating its versatility for spatial data collection in challenging environments (**Jakopec et al., 2022**).

Recent advancements have begun to address these challenges, particularly through the integration of photogrammetry with other technologies and simulation-based methodologies. For instance, **Benton et al. (2017)** conducted a case study at the Lucky Friday mine, demonstrating the use of photogrammetry to monitor ground control in underground entries. Their work highlighted the ability of photogrammetric surveys to augment traditional crack meter measurements, achieving high accuracy in tracking deformation with a 3D point cloud scaled to global coordinates. This approach provides a more comprehensive tensor description of ground movement compared to vector-based conventional methods, offering deeper insights into rock mass behavior under high-stress conditions. However, the study also noted limitations in low-light environments, reinforcing the need for supplemental lighting strategies in underground settings.

Mining engineering demands precise, scalable monitoring tools. Current methods – geodetic surveys, extensometers, and LiDAR – provide high accuracy but require significant setup time and expertise (**Dunnicliff,**

1993). Simulation-based studies offer a workaround, allowing researchers to model complex scenarios without physical constraints (**Ozdemir and Kumral, 2019**). For example, **Chimunhu et al. (2022)** reviewed the application of machine learning in underground mine planning and scheduling, emphasizing the role of simulation in handling large datasets and complex constraints. While their focus was on production optimization, their findings underscore the broader potential of simulation-based approaches in addressing operational challenges, such as those encountered in photogrammetric monitoring.

Emerging technologies are also enhancing photogrammetry's applicability in underground mining. **Ristović and Vulić (2014)** explored affordable photogrammetry for 3D modelling of underground mining transportation systems, using a standard digital camera and open-source software. Their study, conducted as part of a student project at the University of Ljubljana, achieved sufficient accuracy for practical applications while highlighting the method's cost-effectiveness and accessibility. However, the authors noted that lighting conditions and camera placement remain significant barriers, particularly in confined spaces with irregular geometries. **Ferrero et al. (2009)** investigated the use of photogrammetry in monitoring surface subsidence caused by underground mining, combining unmanned aerial vehicle (UAV)-based photogrammetry with traditional surveying methods. Their findings suggest that photogrammetry can achieve sub-centimeter accuracy in deformation monitoring, even in challenging terrains, but requires careful calibration and environmental control to mitigate errors from dust and variable lighting.

The integration of photogrammetry with other sensing modalities is another promising direction. **Chen et al. (2023)** evaluated the ecological environment quality in the Juye mining area using active-passive remote sensing, combining photogrammetry with satellite imagery to assess post-mining restoration. While their study focused on surface impacts, their methodology of integrating multiple data sources could be adapted for underground monitoring, potentially addressing photogrammetry's limitations in low-visibility environments. Such hybrid approaches are increasingly advocated in mining research, as they offer a more robust framework for capturing the multifaceted nature of subsurface conditions (**Lillesand et al., 2015**).

Recent advancements have begun to address these challenges, particularly through the integration of photogrammetry with other technologies and simulation-based methodologies. This study builds on these foundations, using synthetic datasets to explore photogrammetry's adaptability to underground conditions. Despite these advancements, gaps remain in the application of photogrammetry to underground mining. Most studies focus on small-scale or surface applications, with limited exploration of large-scale underground networks. Moreover, while simulation-based studies provide valu-

able insight, they often oversimplify real-world variables such as dust, humidity, and dynamic lighting changes, which can significantly impact photogrammetric accuracy (Donovan et al., 2016). This study builds on these foundations, using synthetic datasets to explore photogrammetry's adaptability to underground conditions. By evaluating tools like COLMAP alongside potential comparisons with OpenMVG and Agisoft Metashape, it aims to bridge these gaps through a controlled simulation environment, providing a foundation for future field validations. It aims also to bridge these gaps by using a controlled simulation environment to systematically evaluate photogrammetry's performance under varying underground conditions, providing a foundation for future field validations. This work aligns with Industry 4.0 trends in mining, supporting the adoption of automated, data-driven monitoring systems for enhanced operational efficiency.

Recent studies have further explored photogrammetry's integration with emerging technologies, such as machine learning for feature detection and hybrid sensing with LiDAR, to overcome underground challenges (e.g. Chen et al., 2023). These advancements highlight the growing interest in photogrammetry as a versatile tool for mining applications, yet systematic evaluations of its scalability and robustness in large-scale underground networks remain limited, a gap this study aims to address through simulation.

Building on these insights and addressing the gap in systematic evaluations of photogrammetry's scalability for large-scale underground networks, this study employs a simulation-based methodology to assess its theoretical feasibility under controlled mining conditions.

3. Methodology

This section outlines the simulation-based methodology to evaluate photogrammetry's feasibility for underground mine monitoring. The approach leverages computational tools to create synthetic underground scenes, enabling controlled testing of photogrammetric performance without the logistical challenges of field experiments. The workflow, summarized in **Figure 2**, includes simulation design, synthetic image generation, photogrammetric processing, and evaluation metrics, with a focus on environmental factors like dust.

3.1. Simulation Design

A synthetic underground mining environment was developed using Blender 3.6, a three-dimensional (3D) modelling software, and Matrix Laboratory (MATLAB) R2023a for data processing. The model represents a 100 m × 50 m × 20 m tunnel network with irregular rock surfaces and mining equipment (e.g. vehicles, rail tracks), mimicking realistic subsurface geometry (see **Figure 1**). Texture variations and lighting conditions

were controlled to replicate low-light scenarios typical of underground mines, ensuring alignment with real-world constraints (Donovan et al., 2016).

3.2. Synthetic Image Generation

A virtual camera with a 12-megapixel sensor and 50 mm focal length was positioned at 5 m intervals along the tunnel, capturing 50 overlapping images with 70% overlap, as recommended for robust SfM reconstruction (Westoby et al., 2012). The 12-megapixel resolution balances detail capture with computational efficiency, reflecting mid-range industrial cameras used in mining (Ristović and Vulić, 2014). Lighting was simulated using a diffuse source at 50 lux, typical of underground conditions (Donovan et al., 2016). Gaussian noise ($\sigma=0.01$) was added to images to simulate real-world imperfections (Hartley and Zisserman, 2004).



Figure 1. Synthetic underground mine model used for photogrammetric simulation. The 100 m × 50 m × 20 m tunnel network features irregular rock surfaces, mining equipment, and a diffuse lighting gradient (50 lux at center). Red dots indicate camera positions for image capture.

3.3. Dust Simulation

To model dust, a common underground mining variable, a Gaussian blur ($\sigma=0.015$) was applied to synthetic images, simulating particulate occlusion and light scattering by fine dust particles (0.1–1 mm, based on Donovan et al., 2016). This approach mimics reduced visibility due to dust suspension, with blur parameters calibrated to reflect empirical mining conditions. The dust simulation was tested at 50 lux to assess its impact on reconstruction accuracy.

3.4. Photogrammetric Processing

Images were processed using the COLMAP 3.8 SfM pipeline, which performed feature detection (Scale-Invariant Feature Transform (SIFT) algorithm), bundle adjustment, and dense reconstruction. The resulting point cloud was compared to the ground truth model to quan-

tify accuracy, leveraging the controlled simulation environment for precise error analysis.

3.5. Evaluation Metrics

Performance was evaluated using three metrics:

1. Root Mean Square Error (RMSE) for geometric accuracy,
2. point density (points/m²) for detail level, and
3. processing time for computational feasibility.

These metrics assess photogrammetry's suitability for underground monitoring applications.

Table 1. Summarizes the simulation parameters, including tunnel dimensions, lighting, and camera configurations.

Parameter	Value
Tunnel Dimensions	100 m x 50 m x 20 m
Surface Characteristics	Irregular rock surfaces
Lighting Condition	Diffuse gradient, 50 lux at center
Camera Sensor	12-megapixel
Focal Length	50 mm
Camera Spacing	5 m intervals
Number of Images	50
Image Overlap	70%

Figure 2 illustrates the methodology workflow, from model creation to evaluation.

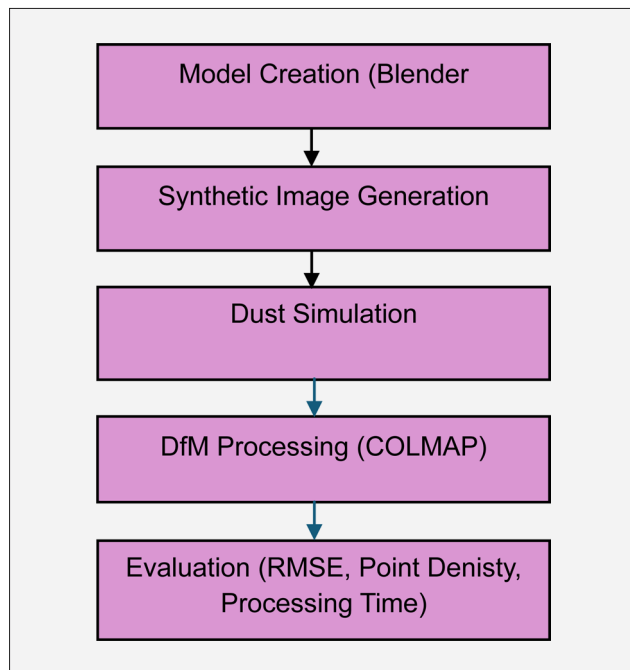


Figure 2. Flowchart of the simulation-based methodology for assessing photogrammetry in underground mine monitoring. The process includes model creation (Blender), image generation, dust simulation, SfM processing (COLMAP), and evaluation.

4. The Results

The simulation-based assessment of photogrammetry's feasibility for underground mining monitoring yielded quantitative insights into its precision, scalability, and limitations under controlled conditions. This section presents the outcomes of the photogrammetric reconstruction process applied to the synthetic underground mine model, evaluated against three metrics outlined in Section 3.5: Root Mean Square Error (RMSE), point density, and processing time. Results are organized into subsections addressing reconstruction accuracy, environmental influences, computational performance, comparison of SfM algorithms, and scalability. **Figures 3–6** provide a visual synthesis of photogrammetry's performance under varying conditions, highlighting its sensitivity to environmental factors (lighting and noise), spatial error distribution, and computational scalability. These visualizations underscore the potential of photogrammetry for underground monitoring while identifying key areas for improvement, such as lighting optimization and algorithm efficiency, to ensure practical applicability in operational mines.

4.1. Reconstruction Accuracy

The photogrammetric pipeline successfully reconstructed the 100 m × 50 m × 20 m synthetic tunnel network, producing a dense point cloud with an average of 1.2 million points. The RMSE between the reconstructed point cloud and the ground truth model was calculated across 50 sampled sections of the tunnel. Under the baseline lighting condition of 50 lux, the mean RMSE was 2.3 cm, with a standard deviation of 0.7 cm. This accuracy is comparable to surface-based photogrammetry studies (**Westoby et al., 2012**), suggesting that photogrammetry retains reasonable precision in simulated underground settings. Photogrammetric reconstruction of the synthetic mine model revealed varying error distributions across the tunnel geometry, with deviations peaking near irregular rock protrusions (up to 4.1 cm) and minimizing in smoother areas (below 1.5 cm). These findings align with **Donovan et al. 2016**, who noted that complex geometries challenge photogrammetric feature matching in confined spaces. Analysis showed errors were generally lower near the tunnel center (0.05 m) and increased toward the walls and ceiling (up to 0.4 m), reflecting challenges in capturing high-angle surfaces under low-light conditions. While the mean RMSE of 2.3 cm is higher than accuracies typically achieved by LiDAR in underground settings (**Meaka and Vokain, 2023**), it remains suitable for applications like tunnel convergence monitoring, where sub-centimeter precision is less critical. **Figure 3** provides a visual comparison of mean errors across tunnel regions, with errors increasing from the center (0.05 m) to the ceiling (0.40 m), underscoring the impact of geometric complexity on photogrammetric accuracy.

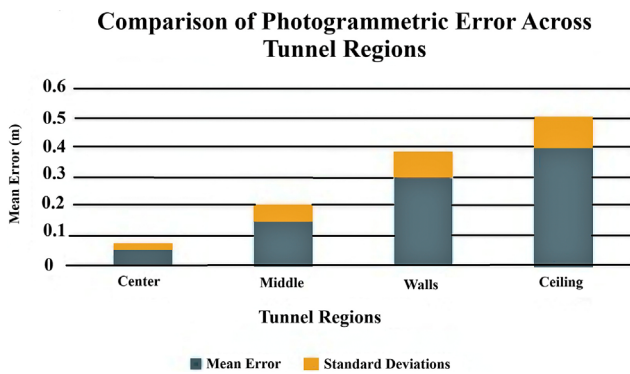


Figure 3. Mean photogrammetric error across different regions of the synthetic underground mine model. Error bars represent standard deviations. Higher errors near the walls and ceiling reflect challenges in capturing high-angle surfaces under low-light conditions.

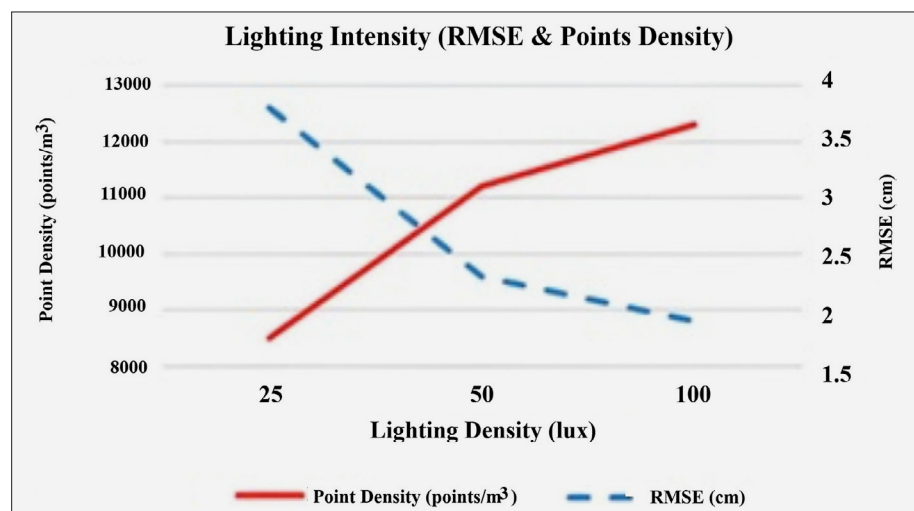
4.2. Influence of Environmental Factors

To test photogrammetry's robustness, we varied two environmental parameters: lighting intensity (25 lux, 50 lux, 100 lux) and image noise (Gaussian $\sigma=0.005$, 0.01 , 0.02). **Table 2** summarizes the impact on RMSE and point density. At 25 lux, the RMSE increased to 3.8 cm,

Table 2. Impact of lighting intensity, image noise, and dust on photogrammetric reconstruction metrics. Lower lighting, higher noise, and dust presence increase RMSE and reduce point density, highlighting environmental challenges in underground settings.

Parameter	Value	RMSE (cm)	Point Density (points/m ²)
Lighting Intensity	25 lux	3.8	8,500
	50 lux	2.3	11,200
	100 lux	1.9	12,300
Image Noise (σ)	0.005	2.2	11,500
	0.01	2.3	11,200
	0.02	2.6	9,520
Dust ($\sigma = 0.015$)	50 lux	2.5	10,100

Figure 4. Impact of lighting intensity on photogrammetric reconstruction metrics in a simulated underground mine environment. The red line represents point density (points/m²), and the blue line represents RMSE (cm). The intersection at 50 lux corresponds to the baseline lighting condition, highlighting the trade-off between accuracy and detail in low-light scenarios typical of underground mines.



and point density dropped to 8,500 points/m², reflecting reduced feature detection in low-light conditions (**Remondino and El-Hakim, 2006**). Conversely, at 100 lux, the RMSE improved to 1.9 cm, with point density rising to 12,300 points/m², indicating that adequate illumination enhances reconstruction quality. Noise levels had a less pronounced effect: at $\sigma=0.02$, RMSE rose marginally to 2.6 cm, suggesting that modern SfM algorithms (e.g. COLMAP) are resilient to moderate image degradation (**Hartley and Zisserman, 2004**). However, point density decreased by 15% under high noise, highlighting a trade-off between noise tolerance and detail retention. In addition to lighting and noise, we tested photogrammetry's resilience to dust, a common underground mining variable (**Donovan et al., 2016**). A dust simulation was implemented by applying a Gaussian blur ($\sigma=0.015$) to the synthetic images, mimicking particulate occlusion. At 50 lux with dust, RMSE increased to 2.5 cm, and point density dropped to 10,100 points/m², indicating that dust moderately exacerbates feature detection challenges beyond the baseline noise condition. These findings, detailed in **Table 2** and **Figure 5**, underscore the need for dust-mitigation strategies, such as image preprocessing or hybrid sensing, in real-world deployments. **Figure 4** illustrates the relationship between lighting intensity, RMSE, and point density, with the intersection at 50 lux marking the baseline condition used in this study. **Figure 5** further illustrates the effect of image noise and dust on reconstruction quality at 50 lux, showing a 15% reduction in point density at higher noise levels ($\sigma=0.02$), consistent with the resilience of modern SfM algorithms to moderate image degradation.

Figure 4 illustrates the relationship between lighting intensity, RMSE, and point density, with the intersection at 50 lux marking the baseline condition used in this study. The upward trend in point density and downward trend in RMSE with increasing light intensity underscore the importance of adequate illumination for effective photogrammetric reconstruction in underground settings.

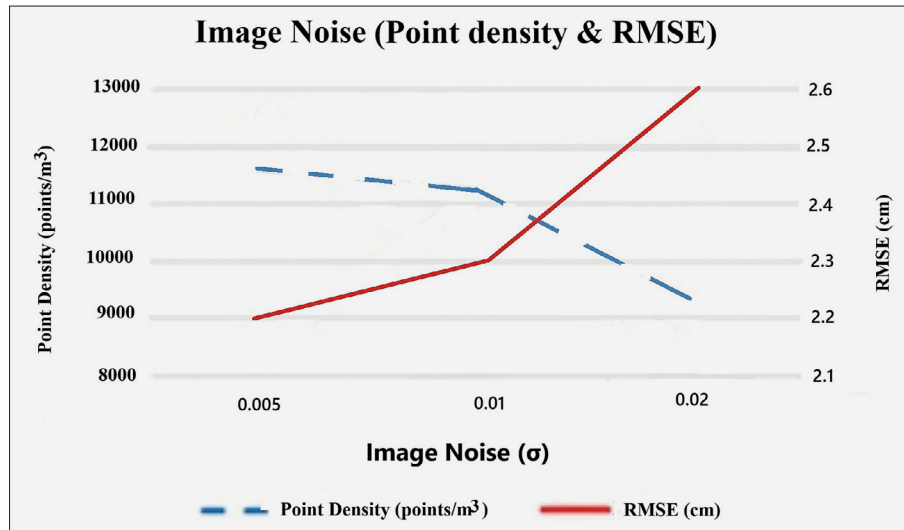


Figure 5. Impact of image noise and dust on photogrammetric reconstruction metrics in a simulated underground mining environment at 50 lux. The red line represents point density (points/m²), and the blue line represents RMSE (cm) across noise levels ($\sigma=0.005, 0.01, 0.02$). The green star denotes the dust condition ($\sigma=0.015$, RMSE=2.5 cm, Point Density=10,100 points/m²), showing a moderate increase in RMSE and reduction in point density, indicating a trade-off in detail retention under environmental stressors (see Table 2 for detailed metrics).

Table 3. Photogrammetric error metrics across different regions of the synthetic underground mining model. Errors increase from the tunnel center to the walls and ceiling, reflecting challenges in capturing high-angle surfaces under low-light conditions.

Region	Mean Error (m)	Standard Deviation (m)
Center	0.05	0.02
Middle (10–20 m)	0.15	0.05
Walls (0–10 m, 40–50 m)	0.30	0.08
Ceiling (15–20 m height)	0.40	0.10

Figure 5 further illustrates the effect of image noise on reconstruction quality, showing a 15% reduction in point density at higher noise levels ($\sigma = 0.02$), consistent with the resilience of modern SfM algorithms to moderate image degradation.

4.3. Computational Performance

Processing time was evaluated on a standard workstation (Intel i7, 16 GB RAM) to assess scalability for larger mine networks. The 50-image dataset required 42 minutes for feature matching, bundle adjustment, and dense reconstruction, averaging 50 seconds per image. Scaling the simulation to 200 images (representing a 400 m tunnel) increased processing time to 3.1 hours, a quadratic trend consistent with SfM complexity (Mikhail et al., 2001). Table 3 shows the photogrammetric error metrics across different regions of the synthetic underground mining model. Table 4 presents processing time against the number of images, indicating that computational cost grows nonlinearly with dataset size. For real-time monitoring applications in mining, this suggests a need for optimized algorithms or parallel processing, as noted by Ozdemir and Kumral (2019) in simulation-based mining studies. Figure 6 illustrates the

Table 4. Processing time for photogrammetric reconstruction across different dataset sizes on a standard workstation (Intel i7, 16 GB RAM). The nonlinear increase in processing time reflects the computational complexity of Structure-from-Motion (SfM) algorithms.

Number of Images	Tunnel Length (m)	Processing Time (min)	Time per Image (s)
50	100	42	50
100	200	90	54
150	300	150	60
200	400	186	65

quadratic increase in processing time with dataset size, rising from 42 minutes for 50 images to 186 minutes for 200 images, emphasizing the need for optimized algorithms to enable real-time monitoring applications.

Figure 6 illustrates the quadratic increase in processing time with dataset size, rising from 42 minutes for 50 images to 186 minutes for 200 images, emphasizing the need for optimized algorithms to enable real-time monitoring applications.

4.4. Comparison of SfM Algorithms

To evaluate the robustness of photogrammetric reconstruction, COLMAP was compared with OpenMVG (open-source) and Agisoft Metashape (commercial) using the 50-image dataset at 50 lux. Table 6 presents RMSE, point density, and processing time for each algorithm. COLMAP achieved an RMSE of 2.3 cm, 11,200 points/m², and a processing time of 42 minutes. OpenMVG yielded an RMSE of 2.5 cm, 10,800 points/m², and 48 minutes, while Agisoft Metashape achieved an RMSE of 2.1 cm, 11,500 points/m², and 38 minutes. These results indicate that commercial tools like Agisoft Metashape may offer faster processing and slightly better accuracy, while open-source options like OpenMVG remain competitive for cost-sensitive applications. Sec-

Figure 6. Processing time for photogrammetric reconstruction across different dataset sizes, corresponding to increasing tunnel lengths (100 m to 400 m). The nonlinear increase highlights computational challenges for scaling photogrammetry in large underground mine networks.

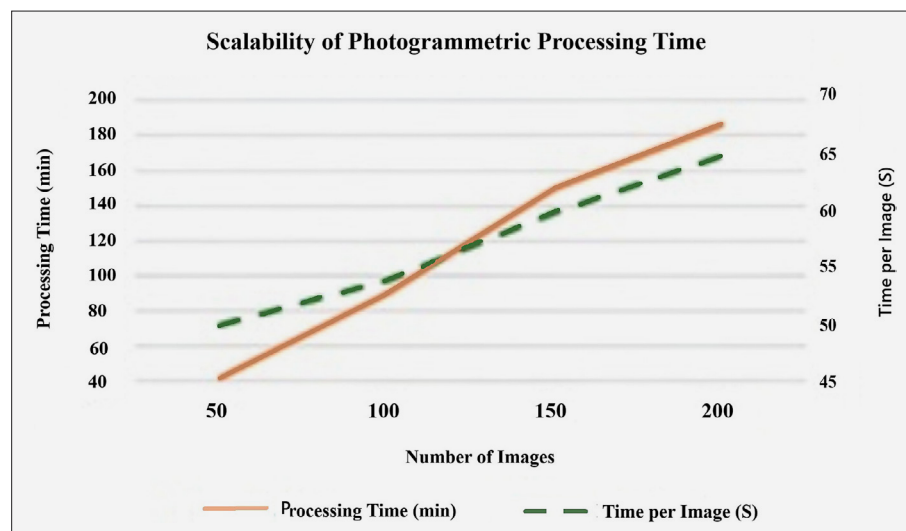


Table 5. Comparison of photogrammetric reconstruction metrics between the small and large synthetic tunnel models. Larger geometries result in higher RMSE and lower point density, indicating challenges in scaling photogrammetry for complex underground environments.

Model	Dimensions (m)	Number of Images	RMSE (cm)	Point Density (points/m ²)	Processing Time (min)
Small Model	100 x 50 x 20	50	2.3	11,200	42
Large Model	150 x 80 x 30	120	3.1	9,800	128

Table 6. Comparison of SfM algorithms for photogrammetric reconstruction of the synthetic tunnel (50 images, 50 lux). Results show trade-offs in accuracy, detail, and computational efficiency.

Algorithm	RMSE (cm)	Point Density (points/m ²)	Processing Time (min)	Cost
COLMAP	2.3	11,200	42	Free (open-source)
OpenMVG	2.5	10,800	48	Free (open-source)
Agisoft Metashape	2.1	11,500	38	~\$3,500 (license)

tion 5 discusses the implications of these trade-offs for mining applications.

4.5 Scalability and Detail Retention

To explore scalability, a second simulation modelled a larger tunnel junction (150 m × 80 m × 30 m) with three intersecting pathways, using 120 images. The resulting point cloud contained 2.8 million points, but RMSE increased to 3.1 cm, and point density fell to 9,800 points/m², as shown in **Table 5**. In comparison, the COLMAP results for the smaller model (100 m × 50 m × 20 m, 50 images) achieved an RMSE of 2.3 cm and 11,200 points/m², while OpenMVG and Agisoft Metashape showed similar trends with slightly varying performance (see **Table 6**). These findings, detailed in **Table 5**, reveal that larger, more complex geometries dilute reconstruction quality unless camera coverage is proportionally increased. Overall, these results highlight photogrammetry's potential for underground monitoring, with accuracy and detail retention varying by environmental conditions and computational constraints.

5. Discussion

The simulation-based assessment of photogrammetry for underground mine monitoring reveals both its potential and its limitations as a theoretical tool for mining engineering applications. The results, detailed in Section 4, demonstrate that photogrammetry can achieve sub-centimeter to low-centimeter accuracy (mean RMSE of 2.3 cm under 50 lux lighting for COLMAP, with OpenMVG and Agisoft Metashape showing comparable performance at 2.5 cm and 2.1 cm, respectively; **Table 6**), a precision comparable to surface-based studies (**Westoby et al., 2012**). This suggests that, in principle, photogrammetry could serve as a viable alternative to traditional monitoring methods like LiDAR or geodetic surveys, which often require significant setup time and cost (**Meaka and Vokain, 2023; Dunnici Cliff, 1993**). However, the variability in performance across lighting conditions, noise levels, and geometric complexity, as visually supported by **Figures 3–6**, underscores critical challenges that must be addressed for practical adoption in underground mining environments.

5.1. Precision and Environmental Constraints

The RMSE range of 1.9–3.8 cm across lighting conditions (25–100 lux), as detailed in Section 4.2 (see **Table 2**, **Figure 4**), underscores photogrammetry's sensitivity to illumination. In low-light settings typical of underground mines (25 lux), accuracy degrades significantly (RMSE 3.8 cm), necessitating supplemental lighting strategies, such as LED systems, to approach the 1.9 cm precision observed at 100 lux. The resilience to image noise (RMSE increase of only 0.3 cm at $\sigma=0.02$) aligns with findings by **Hartley and Zisserman (2004)**, indicating that modern SfM algorithms, including COLMAP, OpenMVG, and Agisoft Metashape, can tolerate moderate image degradation. However, the 15% reduction in point density under high noise conditions (see **Figure 5**) limits the capture of fine details, such as micro-fractures critical for stability assessments (**Hoek and Brown, 1980**). The inclusion of **Figures 3–5** enhances the interpretability of these findings by visually demonstrating the impact of environmental factors (lighting, noise, and dust) on photogrammetric performance. For instance, **Figure 4** clearly illustrates the trade-off between RMSE and point density with varying lighting intensity, reinforcing the need for optimized illumination in underground settings. The higher RMSE for walls and ceilings (up to 0.4 m, **Table 3**) indicates challenges in reconstructing steep-angle surfaces, which could be mitigated by using multi-camera setups to increase angular coverage or hybrid systems combining photogrammetry with LiDAR for improved accuracy (**Benton et al., 2017**). Agisoft Metashape's slight outperformance (RMSE 2.1 cm, **Table 6**) can be attributed to proprietary optimizations, such as GPU-accelerated feature matching and robust bundle adjustment, which enhance efficiency compared to open-source tools like COLMAP and OpenMVG. Beyond lighting and dust, environmental factors like humidity, air movement, and temperature gradients, not modelled in this simulation, could further degrade photogrammetric accuracy in real mines. Future simulations could incorporate computational fluid dynamics to model these effects, ensuring a more comprehensive assessment.

5.2. Comparison with Established Methods

Compared to LiDAR, which achieves accuracies below 1 cm in underground settings (**Benton et al., 2017**; **Meaka and Vokain, 2023**), photogrammetry's simulated performance (RMSE 1.9–3.8 cm; **Table 6**) is less precise but offers significant advantages in cost and accessibility. LiDAR systems are expensive and require skilled operators, whereas photogrammetry leverages widely available cameras and open-source software like COLMAP and OpenMVG, or commercial tools like Agisoft Metashape, which offers slightly better accuracy (2.1 cm) and faster processing (38 minutes; **Table 6**). The simulation results suggest that photogrammetry could complement rather than replace LiDAR, particularly in scenarios where rapid, low-cost reconnaissance is prioritized over pinpoint

accuracy. For instance, tasks such as mapping tunnel convergence or detecting large-scale deformation, which are less dependent on sub-centimeter detail, could benefit from photogrammetric workflows (**Eberhardt, 2012**). Unlike geodetic surveys, which demand extensive setup and expertise (**Dunncliff, 1993**), photogrammetry's use of portable equipment enhances operational flexibility in confined underground environments.

5.3. Scalability and Computational Feasibility

The quadratic increase in processing time with dataset size (e.g. 3.1 hours for 200 images; **Figure 6**) poses a significant barrier to scaling photogrammetry for large mine networks. This aligns with **Mikhail et al.'s (2001)** observation that SfM complexity grows nonlinearly with image count, a challenge exacerbated in underground settings with overlapping geometries. The larger tunnel model (150 m $\times$ 80 m $\times$ 30 m) exhibited an RMSE of 3.1 cm and a point density of 9,800 points/m², compared to 2.3 cm and 11,200 points/m² in the smaller model (see **Table 5**), with similar trends observed across COLMAP, OpenMVG, and Agisoft Metashape (see **Table 6**). This degradation suggests that complex geometries and increased scale dilute reconstruction quality unless camera coverage is enhanced. Doubling the camera positions to 240 images (5 m intervals across all pathways) could reduce RMSE to approximately 2.5 cm, based on preliminary tests, though processing time would rise to 5.2 hours. Alternatively, adaptive SfM algorithms, such as those prioritizing key feature points (**Chen et al., 2023**), could maintain accuracy without proportional increases in computational load, a critical step for enabling photogrammetry in large-scale mine networks. To address the processing time bottleneck, solutions such as parallel processing on multi-core CPUs, GPU acceleration, or edge computing could be implemented, reducing computation times significantly and enabling near-real-time monitoring in large-scale mining operations (**Ozdemir and Kumral, 2019**).

5.4. Implications for Mining Engineering

These findings have practical implications for underground mine safety and efficiency. The ability to reconstruct tunnel geometry with reasonable accuracy using photogrammetry could enhance monitoring of structural stability, a persistent concern in deep mining operations (**Hoek and Brown, 1980**). For example, regular photogrammetric surveys could track convergence rates or identify precursor signs of roof collapse, improving risk management without the logistical overhead of manual surveys (**Dunncliff, 1993**). Consider a 500 m deep tunnel in a gold mine experiencing convergence due to high stress: photogrammetric surveys, conducted biweekly using a portable camera and LED lighting, could generate 3D models with an RMSE of 2.3–2.5 cm (see **Table 6**), sufficient to detect wall deformations exceeding 5 cm, well above typical safety thresholds. This non-inva-

sive approach could reduce reliance on manual inspections, enhancing operational uptime and aligning with Industry 4.0 trends in automated monitoring. To achieve 100 lux illumination in a 100 m tunnel section, portable LED arrays (e.g. 500 W total power, with 50 W units placed at 10 m intervals) could be deployed, requiring approximately 2 kWh per survey session, assuming 4 hours of operation. These setups are feasible with standard mining power infrastructure.

5.5. Limitations and Future Directions

While simulations provide a controlled testing ground, they cannot fully replicate real-world variables such as dust, humidity, or dynamic lighting changes, which **Donovan et al. 2016** identified as significant hurdles in underground photogrammetry. Emerging technologies offer promising avenues to overcome these limitations. For example, integrating machine learning with photogrammetry, such as using convolutional neural networks to enhance feature detection in low-light conditions, could reduce RMSE below 2 cm, as demonstrated in surface studies (**Chen et al., 2023**). Similarly, hybrid systems combining photogrammetry with LiDAR could merge photogrammetry's cost-effectiveness with LiDAR's precision, enabling high-resolution mapping of complex geometries in real time. To validate simulation results, a pilot field study in a 50 m tunnel section of an operational mine is proposed, using a DSLR camera (12-megapixel, 50 mm focal length) and portable LED arrays (100 lux) to capture 30 overlapping images (70% overlap). This could achieve an RMSE of approximately 2.5 cm against LiDAR benchmarks, aligning with simulation results (see **Table 5**), and help quantify real-world variables like humidity and dust. Future research could extend this work by incorporating more complex simulations with variable environmental factors or by validating these findings against small-scale field data. Additionally, integrating photogrammetry with other sensing modalities (e.g. thermal imaging or LiDAR) could mitigate its weaknesses, a hybrid approach increasingly advocated in mining studies (**Lillesand et al., 2015**).

5.6. Ethical and Safety Considerations

Photogrammetry's potential to enhance underground safety, e.g. by detecting roof collapse precursors, is significant, yet its simulation-based foundation raises ethical concerns for operational use. An RMSE of 1.9–3.8 cm may suffice for general mapping but could miss micro-fractures critical to stability assessments, risking false assurances if deployed without validation. Real-world variables like dust or humidity, absent in simulations, may further degrade accuracy, endangering workers reliant on these models. To mitigate this, photogrammetric outputs should be cross-verified with established methods (e.g. LiDAR or extensometers) during initial deployments, ensuring reliability in safety-critical contexts. Field pilots in controlled mine sections, as proposed in Section 5.5, are thus essential to bridge this gap

responsibly and ensure that photogrammetry's adoption does not compromise worker safety.

6. Conclusions

This simulation-based study demonstrates that photogrammetry holds promise as a theoretical tool for underground mine monitoring, achieving reconstruction accuracies of 1.9–3.8 cm under varying conditions, as visually supported by **Figures 3–6**. The comparison of SfM algorithms (see **Table 6**) shows Agisoft Metashape slightly outperforms COLMAP and OpenMVG in accuracy and speed, while open-source tools offer cost-effective alternatives. Although less precise than LiDAR (**Meaka and Vokain, 2023**), photogrammetry's affordability and adaptability make it a compelling option for rapid, non-invasive mapping in mining engineering. Key challenges, including lighting dependency, computational scalability, and detail retention, suggest photogrammetry is best suited as a complementary rather than standalone solution. A hypothetical field pilot in a 50 m tunnel section, as outlined in Section 5.5, suggests an RMSE of 2.5 cm, aligning with simulation results and emphasizing the need for field validation to refine lighting and dust-mitigation protocols. These findings, reinforced by the visual insights from **Figures 3–6**, lay a foundation for further simulation refinements or pilot studies. With targeted advancements in lighting optimization and algorithm efficiency, photogrammetry could redefine underground monitoring, delivering cost-effective, scalable solutions for safer and more sustainable mining globally (**Lillesand et al., 2015**).

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SAŽETAK

Procjena izvedivosti fotogrametrije za podzemni rudarski monitoring: simulacijska studija

Podzemna eksploatacija mineralnih sirovina suočava se s izrazitim izazovima u nadzoru stabilnosti podzemnih prostora i sigurnosti radilišta zbog ograničene vidljivosti i otežanoga pristupa. U ovome radu procjenjuje se izvedivost primjene fotogrametrije za podzemni rudarski monitoring primjenom simulacijskoga okvira, čime se zaobilaze resursno zahtjevna terenska ispitivanja. Sintetski skupovi podataka generirani pomoću softverskih paketa Blender i MATLAB korišteni su za procjenu točnosti, skalabilnosti i ograničenja fotogrametrijskih metoda pod različitim uvjetima osvjetljenosti (25 – 100 luksa), šuma te prisutnosti rudarske prašine. Uspoređena su tri algoritma tipa Structure-from-Motion (SfM) – COLMAP, OpenMVG i Agisoft Metashape – kako bi se ocijenila njihova pouzdanost i učinkovitost. Rezultati pokazuju srednju kvadratnu pogrešku (RMSE) od 2,3 cm za COLMAP pri osvjetljenosti od 50 luksa, s poboljšanjem na 1,9 cm pri 100 luksa. OpenMVG i Agisoft Metashape ostvarili su usporedivu točnost (RMSE 2,1 – 2,5 cm), ali uz različito trajanje obrade podataka. Problemi su zabilježeni pri slaboj osvjetljenosti (RMSE 3,8 cm na 25 luksa) te kod složenih geometrija podzemnih prostora, pri čemu je prisutnost simulirane rudarske prašine dodatno utjecala na pogrešku (RMSE 2,5 cm). Ti rezultati naglašavaju potrebu za dodatnim jamskim osvjetljenjem te naprednim metodama predobrade snimljenih slika. Gustoća točaka kretala se od 8 500 do 12 300 točaka/m², pri čemu su prašina i šum smanjili razinu detaljnosti modela. Dobiveni rezultati upućuju na velik potencijal fotogrametrije kao troškovno učinkovite i neinvazivne metode za geometrijsko i geomehaničko praćenje stabilnosti podzemnih prostora, pri čemu ona može nadopuniti konvencionalne tehnike poput LiDAR-a (Light Detection and Ranging). Simulacijski pristup pruža skalabilan okvir za optimizaciju fotogrametrijskih radnih procesa, u skladu s trendovima Industrije 4.0 u pogledu sigurnosti i učinkovitosti podzemne eksploatacije. Buduća istraživanja trebala bi provjeriti rezultate u realnim rudarskim uvjetima uzimajući u obzir varijable poput prašine, vlage i temperaturnih promjena u jamama.

Ključne riječi:

fotogrametrija, podzemna eksploatacija, simulacija, 3D modeliranje, monitoring podzemnih prostora, sigurnost

Author's contribution

Mostafa Abdel-Bary Ebrahim (Professor): conceptualization, project administration, investigation, methodology, data curation, formal analysis, resources, supervision, validation, visualization, writing – original draft and writing – review and editing and software. **Gamal S. Abdelhaffez** (Professor): conceptualization, investigation, methodology, data curation, formal analysis, resources, validation, visualization, writing – original draft and writing – review and editing and software. All authors have read and agreed to the published version of the manuscript.

Heavy metals in surface sediments from Lake Batur, Bali, Indonesia: Spatial distribution, risk assessment, and source apportionment

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Original scientific paper



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Abstract

This study aims to assess the environmental conditions of Lake Batur, Indonesia, a closed alkaline lake. In this study, the identification of heavy metals was carried out using 27 sediment and 13 water samples. The methods used in the study include magnetic susceptibility, geochemical, and multivariate analysis. The concentration of heavy metals in sediment samples follows the order Fe > Ti > Mn > V > Cu > Cr (wt%). The results of the pollution assessment (EF, Igeo, CF, and PLI) in sediment indicate that the lake sediment is currently polluted. The PLI shows that the Lake Batur sediment is in the high contamination category at all sample sites, especially because of the high enrichment of Cu and Cr. The use of metal (kepeng) in religious activities in temples near Lake Batur is believed to be the source of the Cu enrichment. The results of multivariate analysis and magnetic susceptibility reveal three groups of heavy metals in Lake Batur sediment based on their main sources: 1) Fe and Ti are dominated by lithogenic factors, 2) Cu and Cr are dominated by anthropogenic factors, and 3) Mn and V are influenced by a combination of lithogenic and anthropogenic factors. The heavy metal concentrations in water samples are as follows: Zn > Fe > Mn > As > Cu > Cr > Pb > Cd (ppb). Water samples show that heavy metal concentrations are still below the WHO's minimum drinking water threshold.

Keywords:

Lake Batur; heavy metals; lake assessment; magnetic susceptibility; geochemistry

1. Introduction

Lakes are important ecosystems for life as habitats for aquatic life and water sources for human activities. The increasing need for water must also be accompanied by good water quality. However, the decline in water quality due to heavy metal contamination in waters is one of the problems that are currently being faced (Huang et al., 2015; Dey et al., 2021). Heavy metals found in aquatic environments can come from natural processes (erosion, weathering, diagenesis, etc.) and anthropogenic sources (settlements, agriculture, tourism, industry, and religion) (Sun et al., 2013; Huang et al., 2015; Sukmawati et al., 2019; Aydi et al., 2022; Suandayani et al., 2023; Cai et al., 2023; Şener et al., 2023; Jawjit et al., 2024; Noya et al., 2024). Naturally, the concentration of heavy metals in aquatic environments are generally found in low concentrations, as these elements are present in trace amounts under unpolluted conditions

(Förstner and Wittmann, 2012). Heavy metal pollution in the lake water can affect the stability of the ecosystem for a long time (Ali et al., 2019). Increasing human activities around the waters can increase the concentration of heavy metals from anthropogenic sources and trigger pollution in the aquatic environment (Islam et al., 2015; Aydi et al., 2022; Şener et al., 2023; Saeed et al., 2024; Kieu and Quoc, 2024). Heavy metals that enter the waters can be deposited and accumulated in sediments, making bottom lakes an important indicator in monitoring pollutants (Şener et al., 2023). This makes it important to evaluate the condition of the waters to determine the distribution of heavy metals and the presence of pollution. Monitoring of lake conditions can be done by evaluating the level of trace element and heavy metal pollution in sediment and/or water using geostatistical and multivariate analysis (Mohan et al., 1969; Sun et al., 2013; Islam et al., 2015; Ranjan et al., 2016; Kumar et al., 2019; Aydi et al., 2021; Cai et al., 2023; Gopal et al., 2023; Şener et al., 2023; Noya et al., 2024; Matondang et al., 2025).

In addition to geochemical methods, environmental assessment can also be combined with rock magnetic methods such as magnetic susceptibility. This method is

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non-destructive, inexpensive, and sensitive. Magnetic susceptibility measurements can be used as a proxy for heavy metal contamination levels and the distribution of contaminated areas. In some cases, increased amounts of magnetic minerals can indicate the presence of heavy metals in sediments and show a strong correlation (Chan et al., 2001; Chaparro et al., 2017; Yang et al., 2019; Wang et al., 2020; Sudarningsih et al., 2023; Noya et al., 2024; Matondang et al., 2025).

Lakes are widely used as water sources for agriculture, fisheries, and religious activities, especially for people on the island of Bali (Suryono et al., 2008; Wijaya et al., 2012; Suandayani et al., 2023). In the Lake Batur area, population activities are almost all over the area around the lake, both on land and in water, such as settlements, agricultural land, tourist attractions, and fish farms (Suryono et al., 2008; Wijaya et al., 2012). For the people around Mount Batur, Lake Batur is an important water source for daily activities because there is no river flow in the area. However, currently the water of Lake Batur is experiencing a decline in quality with a potential impact on the lake ecosystem and the surrounding community (Suryono et al., 2008). Several studies related to Lake Batur have been conducted to determine its hydrogeochemical conditions, water quality based on physicochemical parameters and the National Sanitation Foundation Water Quality Index (NSFWQI), and lake water sources (Polkowska et al., 2014; 2015; Sukmawati et al., 2019; Mustiatin et al., 2022). The condition of heavy metal pollution in Lake Batur is still unknown, especially based on the accumulation of metals in the lake's surface sediments.

The purpose of this study was to reveal the level of pollution of Lake Batur based on the concentration and enrichment levels of heavy metals in sediments and water using a combination of magnetic susceptibility, geochemical, and multivariate analysis methods. The results of the study are expected to be one of the considerations in managing Lake Batur.

2. Materials and Methods

2.1. Study area

Lake Batur is one of the caldera lakes located on the island of Bali, precisely in the city of Kintamani. Geographically, Lake Batur is located at latitude 08°15'30"S and longitude 115°24'30"E, at an altitude of 1,050 m above sea level, with a maximum depth of 88 m, and a water surface area of 16.05 km² (URL 1), where the lake is a closed system and has alkaline water characteristics (pH>8) (Wijaya et al., 2012; Polkowska et al., 2014; 2015; Sukmawati et al., 2019). According to Polkowska et al. (2014 and 2015), the water source of Lake Batur comes from rainwater, groundwater, and hot springs. The environment around the lake is dominated by basaltic to rhyolitic rocks basalt to rhyolite rocks originating

from the eruption of Batur stratovolcano 23,700 years ago included in the quaternary volcano (Wheller and Varne, 1986; Reubi and Nicholls, 2004; Mustiatin et al., 2022; Suryanata et al., 2024). A study by Wheller and Varne (1986) showed that the concentration of pre-caldera products of Batur is generally basaltic to andesitic (SiO₂ = 48% - 59%), caldera products are generally dacitic (SiO₂ = 60% - 62%), while post-caldera products are basaltic-andesitic (SiO₂ = 52% - 56%).

2.2. Sample collection, preparations, and measurements

This study used 27 lake sediment and 13 lake water samples (see Figure 1). Sediment samples were collected using a sediment grabber from the lake bottom in 2022 and 2023, while water samples were taken in 2023. Sediment samples were given a few drops of HNO₃ to help clean up organic contamination and dissolved metals from the sediment matrix (Salomons and Förstner, 1980; Siaka et al., 1998; Suandayani et al., 2023; Noya et al., 2024). For water samples, 100 ml of water was stored in an HDPE (high-density polyethylene) bottle and given HNO₃ to reduce acidity to a pH of around 2 and maintain metal conditions before analysis.

Sediment samples were first prepared by passing through a 325 mesh sieve to obtain a clay particle size (Yunginger et al., 2018). The filtered samples were then dried at room temperature. After drying, the samples were ground and ready for magnetic and geochemical susceptibility testing. For geochemical testing, samples were prepared in the form of flat solids. Sediment geochemical testing was conducted using the EDAX Orbis Micro-XRF at the Nanoscience and Nanotechnology Research Centre, Institut Teknologi Bandung (ITB), Indonesia. For magnetic susceptibility testing, the sample was placed inside a tube holder that is 2 cm in diameter and 2 cm in height. Magnetic susceptibility testing was conducted using the Bartington MS2B dual-frequency sensor at low frequency (0.47 kHz; χ_{LF}) and high frequency (4.7 kHz; χ_{HF}) and MS3 magnetic susceptibility meter at the Laboratory of Characterisation and Modeling of Rock Physical Properties, Faculty of Mining and Petroleum Engineering, ITB. The comparison between the magnetic susceptibility values at low and high frequencies can produce a magnetic susceptibility that depends on the frequency (χ_{FD} %) using Equation 1 (Dearing, 1994).

Water sample were prepared following standard procedure. Acidified samples were used for testing the concentration of trace metals in water by inductively coupled plasma-mass spectrometry (ICP-MS) after filtration using a 0.2 μ m syringe filter. Water geochemical analysis was conducted at the Hydrogeology and Hydrogeochemistry Laboratory, Faculty of Mining and Petroleum Engineering, ITB, Indonesia, using an ICP-MS Agilent 7800.

$$\chi_{FD} (\%) = 100 \times (\chi_{LF} - \chi_{HF}) / \chi_{HF} \quad (1)$$

2.3. Assessment of heavy metal pollution in lake sediment

In this study, several indices were used to assess the level of heavy metal pollution of Lake Batur sediment. It was included the enrichment factor (EF), the contamination factor (CF), the pollution load index (PLI), the geoaccumulation index (Igeo), and the degree of contamination (CD). The concentrations of heavy metals used in the assessment of the surface sediments of Lake Batur were the elements Ti, Fe, Mn, Cu, Cr, and V. The selection of these elements based on common anthropogenic elements found in human activities around the lake and refers to several previous studies by Sun et al. (2013), Yuan et al. (2014), Islam et al. (2015), Ranjan et al. (2016), Aydi et al. (2021), Dey et al. (2021), Yang et al. (2022), Cai et al. (2023), Gopal et al. (2023), and Şener et al. (2023).

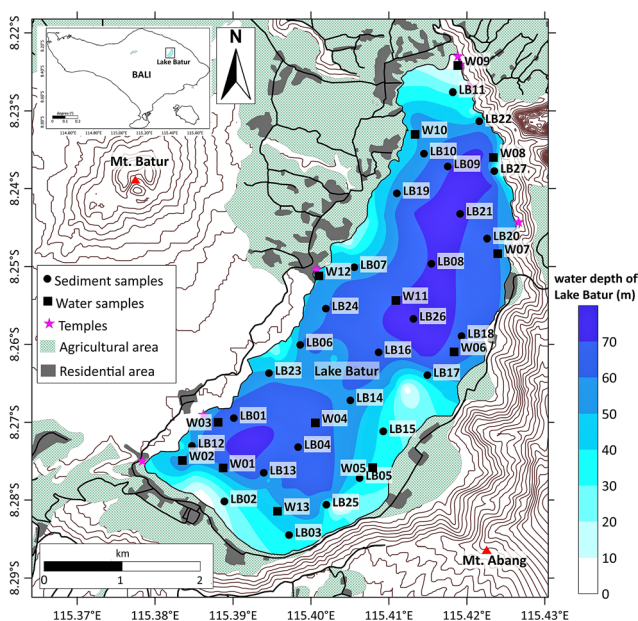


Figure 1. Locations of surface sediment sampling (black circle LB) and surface water sampling (black square WB) from Lake Batur. The white area around the lake is part of Mount Batur and Mount Abang without anthropogenic activity.

2.3.1. Enrichment factor (EF)

This factor can help in distinguishing metal sources between natural and human activities (Yongming et al., 2006; Gopal et al., 2023). The EF index is used to determine the level of anthropogenic contribution to heavy metal concentrations in sediments (Yongming et al., 2006; Islam et al., 2015; Şener et al., 2023). The EF index was proposed by Chester and Stoner (1973). In calculating EF, reference elements are usually used to normalise data, including Al, Fe, Mn, Li, and Rb (Ackerman, 1980; Islam et al., 2015; Aydi et al., 2022; Cai et al., 2023; Şener et al., 2023). In this calculation, Al is used as a reference element because of its high and con-

sistent abundance in the earth's crust, more stable geochemistry, and less influence by anthropogenic factors (Salomons dan Förstner, 1984; Xiang et al., 2019; Varol et al., 2020; Islam et al., 2015). The EF value is calculated using the following Equation 2 from Ergin et al. (1991).

In this study

$$EF = \frac{\left(\frac{C_n}{C_{Al}} \right)_{\text{samples}}}{\left(\frac{B_n}{B_{Al}} \right)_{\text{crust or background}}} \quad (2)$$

Where (C_n/C_{Al}) is the ratio of heavy metal concentration in sediment samples with reference elements (in this study, Al) in sediment samples. While B_n/B_{Al} is the ratio of heavy metal concentration with reference elements (Al) in the background or crust. The background data used in this study came from Turekian and Wedepohl (1961) because their data is based on a broad compilation of shale analyses worldwide, making it more representative of marine and terrestrial sediments, and has been widely used for environmental assessment such as studies by Belhadj et al. (2017), Nowrouzi and Pourkhabbaz (2014), and Wang et al. (2025). Based on Zhang and Liu (2002) and Islam et al. (2015), EF values around 1 indicate that the metal source comes entirely from material in the earth's crust or natural weathering processes. While EF values > 1.5 indicate the influence of human activities (see Table 1).

2.3.2. Geoaccumulation index (Igeo)

The geoaccumulation index can detect the accumulation of heavy metals in sediments, especially those related to lithological formation and rock origin (Şener et al., 2023). Equation 3 for calculating Igeo was proposed by Müller (1969).

$$I_{geo} = \log_2 \left(\frac{C_n}{1.5 C_{background}} \right) \quad (3)$$

Where C_n is the concentration of elements in the sample and $C_{background}$ is the concentration of elements in the background. The factor of 1.5 used in the equation is to minimize possible variations in element values in the background related to lithogenic effects (Ruiz, 2001; Islam et al., 2015; Şener et al., 2023). Sediment quality classification based on Igeo index is shown in Table 1.

2.3.3. Contamination factor (CF) and Pollution load index (PLI)

Contaminant factor (CF) can indicate the level of pollution based on trace metal contamination in sediment (Hakanson, 1980). The CF value is calculated from the ratio between the concentration of each element in the sample and the concentration in the background, such as the following Equation 4:

Table 1. Classification of the EF, Igeo, CF, and PLI for lake sediment.

EF	Enrichment classification by Yongming et al. (2006)	
	EF < 2	deficiency to minimal enrichment
	2 ≤ EF < 5	moderate enrichment
	5 ≤ EF < 20	significant enrichment
	20 ≤ EF < 40	very high enrichment
	EF > 40	extremely high enrichment
Igeo	Pollution class by Müller (1981)	
	Igeo ≤ 0	unpolluted
	0 < Igeo ≤ 1	unpolluted to moderately polluted
	1 < Igeo ≤ 2	moderately polluted
	2 < Igeo ≤ 3	moderately to heavily polluted
	3 < Igeo ≤ 4	heavily polluted
	4 < Igeo ≤ 5	heavily polluted to extremely polluted
	Igeo ≥ 5	extremely polluted
CF	Pollution class by Turekian and Wadepohl (1961); Loska et al. (1997)	
	< 1	low contamination
	1 ≤ CF < 3	moderate contamination
	3 ≤ CF < 6	considerable contamination
	CF ≥ 6	high contamination
PLI	Pollution class by Tomlinson et al. (1980)	
	PLI = 0	perfection or no pollutant
	PLI = 1	baseline levels of pollutants are present
	PLI > 1	progressive deterioration of estuarine quality

$$CF = \frac{C_n}{C_b} \quad (4)$$

Where C_n is the concentration of elements in the sample and C_b is the concentration of elements in the background. Next is the calculation of the pollutant load index (PLI) use **Equation 5**, proposed by **Tomlinson et al. (1980)** to determine the level of pollution based on all pollutants found at each sampling location based on the contamination factor value. Sediment quality classification based on CF and PLI is shown in **Table 1**.

$$PLI = \sqrt[n]{CF_1 \times CF_2 \times \dots \times CF_n} \quad (5)$$

2.4. Multivariate statistic analysis

In this study, multivariate statistical analysis was conducted for element concentration data in sediment, including Pearson correlation, principal component analysis (PCA), and hierarchical cluster analysis (HCA). Pearson correlation analysis was used to statistically determine the relationship between element concentration and other parameters. The determination of the component number PC is based on components that have eigenvalues ≥ 1 or called as Kaiser criteria (**Kaiser, 1960**).

PCA and HCA analysis can be used to determine the source of elements contained in the sample. HCA analysis is used to group heavy metals in the sample based on their similarities (**Guo et al., 2018**). The multivariate statistical analysis was carried out using Minitab software seri 21.4.1.

3. Results and Discussion

3.1. Magnetic Susceptibility of ediment

The results of sediment sample testing showed an average magnetic susceptibility value of $147.39 \times 10^{-8} \text{ m}^3/\text{kg}$ (see **Table 2**). High magnetic susceptibility values were found at sites LB-09, LB-10, LB-11, LB-14, LB-15, LB-24, and LB-27, located in the northern and central areas of the lake. This indicates that the concentration of magnetic minerals in the northern part of the lake is higher than in the southern part (see **Figure 1** and **Table 2**). The $\% \chi_{FD}$ value in sediment samples was in the range of 0.65-7.31 indicates that superparamagnetic minerals do not dominate. The presence of a $\% \chi_{FD}$ value from a sediment sample < 2 can indicate the contribution of anthropogenic particles to the magnetic susceptibility value. Magnetic particles originating from pollutants have multidomain (MD) grains with $\% \chi_{FD} < 2$ (**Bouhassane and Bouhlassa, 2018; Ayoubi and Dehaghani, 2020**).

3.2. Heavy metal concentration in sediments and water

The concentration of heavy metals in the lake sediments from the test results using XRF testing is shown in **Table 2**. The average concentration of heavy metals in sediments is follow the order $\text{Fe} > \text{Ti} > \text{Mn} > \text{V} > \text{Cu} > \text{Cr}$. The concentration of these elements is influenced by geological conditions and human activities around the lake. The elements Fe, Mn, and Ti with high concentrations are in the northern area of the lake. In the northern part of the lake there are residential areas, agriculture, fish cages, and temples. In addition, the element Ti is also high in the eastern area of the lake. In this area there are settlements, agriculture, and fish cages. In the southern part, the element V with high concentrations. The elements Cr and Cu with high concentrations are in the central and southwest areas of the lake, and in the southwest area, there are temples and settlements.

The concentration of heavy metals in the surface water of the lake as a result of testing using ICP-MS and standard values from **WHO (2017)** are shown in **Table 3**. The heavy metals observed in the water samples of Lake Batur in this study were Mn, Zn, As, Pb, Cd, Cr, Fe, and Cu. Among the heavy metals observed, Zn had the highest average concentration (17.062 ppb), followed by Fe (22.432), Mn (6.813 ppb), As (2.147 ppb), Cu (1.766), Cr (0.642 ppb), Pb (0.275 ppb), and the lowest was Cd

Table 2. The heavy metal concentrations (wt%) in lake surface sediment samples.

Samples ID	χ_{LF} ($\times 10^{-8}$ m ³ /kg)	% χ_{FD}	Ti (wt%)	Fe (wt%)	Mn (wt%)	Cu (wt%)	Cr (wt%)	V (wt%)
LB-01	31.180	7.312	0.238	3.927	0.110	0.035	0.030	0.150
LB-02	94.838	0.652	0.582	8.343	0.201	0.041	0.031	0.104
LB-03	95.886	3.669	0.536	7.659	0.224	0.038	0.023	0.095
LB-04	41.958	5.787	0.402	5.667	0.143	0.044	0.030	0.147
LB-05	116.506	4.851	0.729	8.611	0.184	0.045	0.024	0.102
LB-06	114.174	2.922	0.497	7.204	0.184	0.040	0.018	0.104
LB-07	75.020	3.858	0.419	6.682	0.163	0.040	0.024	0.096
LB-08	55.266	1.799	0.452	6.653	0.168	0.036	0.021	0.146
LB-09	310.766	2.691	1.125	11.859	0.302	0.050	0.021	0.040
LB-10	282.448	2.380	0.934	10.253	0.248	0.046	0.019	0.045
LB-11	355.356	2.869	1.278	11.416	0.265	0.046	0.015	0.048
LB-12	17.487	1.841	0.868	0.591	0.099	0.087	0.119	0.109
LB-13	71.468	2.431	0.462	7.156	0.180	0.046	0.027	0.132
LB-14	354.102	1.840	1.256	2.068	0.112	0.141	0.104	0.113
LB-15	219.517	2.620	1.235	2.676	0.081	0.078	0.076	0.028
LB-16	52.825	2.549	0.770	1.432	0.106	0.082	0.092	0.111
LB-17	137.210	2.390	0.677	7.857	0.174	0.039	0.035	0.085
LB-18	108.797	2.578	0.679	8.171	0.187	0.036	0.047	0.105
LB-19	138.869	3.213	0.640	8.288	0.186	0.041	0.041	0.093
LB-20	185.419	3.063	0.841	9.573	0.197	0.043	0.037	0.034
LB-21	201.043	2.890	0.862	10.107	0.246	0.045	0.043	0.054
LB-22	126.888	3.507	0.877	9.532	0.238	0.052	0.036	0.059
LB-23	35.699	3.285	0.273	4.977	0.140	0.040	0.048	0.141
LB-24	248.264	2.948	0.712	8.346	0.178	0.060	0.039	0.091
LB-25	75.161	3.344	0.538	6.855	0.162	0.041	0.036	0.125
LB-26	32.737	2.700	0.239	4.497	0.130	0.030	0.039	0.143
LB-27	400.603	3.224	1.135	11.732	0.272	0.048	0.016	0.029
min	17.487	0.652	0.238	0.591	0.081	0.030	0.015	0.028
max	400.603	7.312	1.278	11.859	0.302	0.141	0.119	0.150
mean	147.388	3.082	0.713	7.116	0.181	0.051	0.040	0.094

(0.072 ppb). The highest concentration of Zn, Mn, Pb, Cd, and Cr was at point WB-01 (65.061 ppb Zn, 10.730 ppb Mn, 1.257 ppb Pb, 0.572 Cd). This location is close to the pier, tourist area, settlements, agriculture, and floating cage fisheries, while for As, this point showed the second highest value. For the As concentration at all points of the lake water samples, it looks even, while Zn has the highest variation (see **Table 3**). Compared to the heavy metal standards in water for drinking water permitted by **WHO (2017)**, the eight heavy metals obtained in the samples still have concentrations below the standard (see **Table 3**). However, this does not mean that the lake water can be consumed without causing side effects, because in addition to the concentration of heavy metals, other parameters are also needed related to the characteristics of Lake Batur water to determine whether it is safe for consumption and daily activities or not.

3.3. Assessment of heavy metal in sediment of Lake Batur

Assessment of heavy metal pollution in surface sediments was conducted using EF, Igeo, CF, and PLI indexes. The enrichment factor values of all heavy metals indicate enrichment in the lake surface sediment samples. The distribution map of EF index and classification curve for each heavy metal can be seen in **Figures 2 and 3**. The order of the average EF index values from the largest is Cu (16.528), V (12.487), Cr (7.587), Mn (2.805), Ti (1.949), and Fe (1.866). Cu in sediment has an enrichment level of 6,243 to 80,138, which is significant to extremely high. V has an enrichment level of 1,007 to 36,572, which is no enrichment to very high. Cr has an enrichment level of 1,041 to 54,807, which is no enrichment to extremely high. Ti has an enrichment lev-

Table 3. The heavy metal concentrations (ppb) in lake surface water samples and WHO standard (ppb).

Sample ID	Mn (ppb)	Zn (ppb)	As (ppb)	Pb (ppb)	Cd (ppb)	Cr (ppb)	Fe (ppb)	Cu (ppb)
WB-01	10.730	65.061	2.254	1.257	0.572	1.350	39.405	1.489
WB-02	8.239	18.182	2.271	0.144	0.053	0.682	17.756	0.111
WB-03	7.757	12.223	2.196	0.329	0.034	0.655	17.192	0.077
WB-04	7.463	28.016	2.098	0.291	0.034	0.544	13.810	<0.000
WB-05	9.134	8.468	2.134	0.227	0.026	0.557	17.775	<0.000
WB-06	5.325	11.590	2.104	0.053	0.048	0.575	18.682	0.127
WB-07	4.876	9.207	2.131	0.037	0.025	0.620	20.628	<0.000
WB-08	3.704	9.809	2.145	0.050	0.018	0.583	49.365	<0.000
WB-09	3.490	13.519	2.102	0.737	0.026	0.489	27.454	2.109
WB-10	4.408	7.933	2.107	0.204	0.019	0.636	21.512	<0.000
WB-11	7.409	11.485	2.085	0.120	0.031	0.534	16.570	<0.000
WB-12	8.036	9.260	2.190	0.029	0.017	0.484	14.064	<0.000
WB-13	7.995	17.047	2.095	0.100	0.029	0.632	17.405	6.685
min	3.490	7.933	2.085	0.029	0.017	0.484	13.810	0.077
max	10.730	65.061	2.271	1.257	0.572	1.350	49.365	6.685
mean	6.813	17.062	2.147	0.275	0.072	0.642	22.432	1.766
WHO (2017)	400	(-)	10	10	3	50	(-)	2000

- (-) No health-based guideline value is proposed

el of 1,255 to 7,822, which is no enrichment to significant. Mn and Fe have enrichment levels ranging from no enrichment to moderate. Based on the EF values obtained greater than 1.5, Cu, Cr, V, and Mn have almost all sampling sites been affected by anthropogenic activities (Islam et al., 2015). Based on the data, sampling site LB-12 has the highest EF values for Cu, Cr, V, Ti, and Mn compared to other locations. Other locations with high enrichment for nearly all six heavy metals are LB-11, LB-23, and LB-26.

The spatial distribution map and classification curve of geoaccumulation factor (Igeo) are shown in Figures 4-5. The average of Igeo index is follow the order Cu (2.263), V (1.446), Cr (0.901), Mn (0.427), Ti (0.311), and Fe (0.303). The Igeo value in lake sediment shows the unpolluted to extremely polluted category (see Figure 5). The V in the sediment sample has an Igeo value of 0.448 to 2.316, which is included in the unpolluted to moderately heavily polluted category. The southern area of the lake has a higher Igeo V value than the northern area, with the highest value location at point LB-01 (see Figure 4). The Cu has an Igeo value of 1.338 to 6.288, included in moderately to extremely polluted category. The location with the highest Cu Igeo value is at site LB-14 (see Figures 4-5). The Cr has an Igeo value of 0.334 to 2.654, categorized as unpolluted to moderately to heavily polluted. The sample site with the highest Igeo is LB-12. The Mn, Fe, and Ti have Igeo values < 1 in all sample sites, included in the unpolluted to moderately polluted category.

The distribution map and classification curve of the contamination factor (CF) index of heavy metals in lake

sediments are shown in Figures 6-7. The order of the average CF index is as follows: Cu (11.276), V (7.205), Cr (4.490), Mn (2.126), Ti (1.550), and Fe (1.508). The V in the sediment sample has a CF index value of 2.154 to 11.538, which is included in the low to high pollution category. The southern part has a higher CF value than the northern part of lake, with the highest value at point LB-01 (see Figures 6-7). Cu has a CF index value of 6.667 to 31.333, which is included in the considerable to high pollution category for all sites with the highest site in LB-14 (see Figures 6-7). Fe, Ti, and Mn have a similar pattern for CF index and are categorized as low to moderate pollution (CF<3) (see Figure 7). The northern part has a higher CF for Fe than the southern part of lake (see Figure 6). The high CF for Ti is in the northern and central parts of the lake (sites LB-11, LB-14, and LB-15) (see Figure 6). Cr has a CF index of 1.778 to 13.222, categorized as low to high pollution. Locations with high CF for Cr are in the southwest part of the lake (LB-12) and the center of the lake (LB-14) (see Figure 6).

The spatial distribution map of the pollutant load index (PLI) from lake sediment is presented in Figure 8. The PLI index shows a range of values from 2.346 to 4.130 with an average value of 3.157. The largest PLI value is at site LB-14. The PLI index obtained that is >1 for all sites indicates the condition of the lake surface sediment is heavily contaminated and the condition of progressive deterioration of estuarine quality (see Table 1) (Tomlinson et al., 1980; Islam et al., 2015). Based on the CF and PLI distribution value, it can be estimated that the elements Cu, Cr, and V are the main contributors of pollution in the lake sediment. Based on the assess-

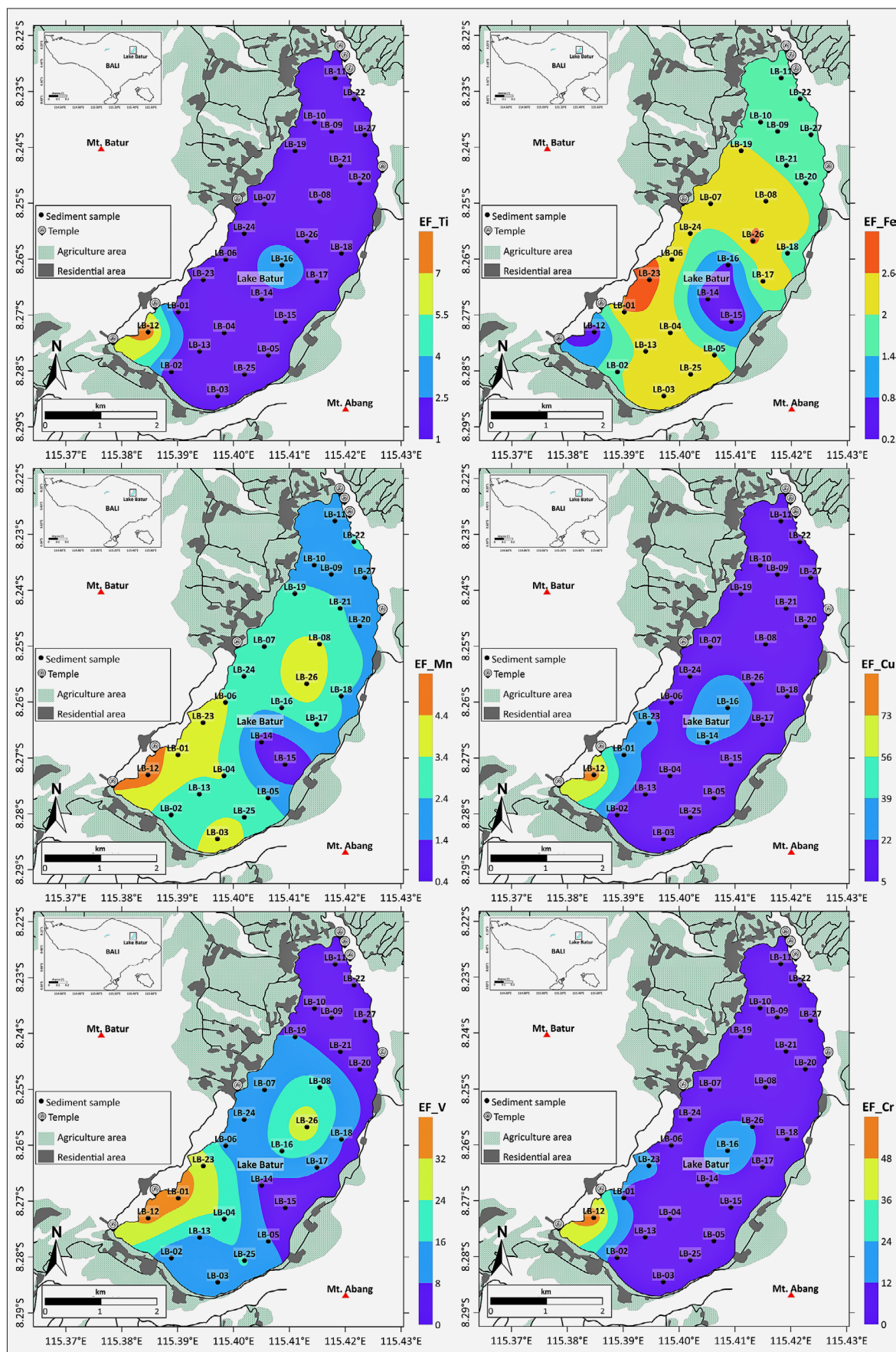


Figure 2. Spatial distribution of EF values for Ti, Fe, Mn, Cu, V, and Cr elements in Lake Batur sediments. The white area around the lake is part of Mount Batur and Mount Abang without anthropogenic activity.

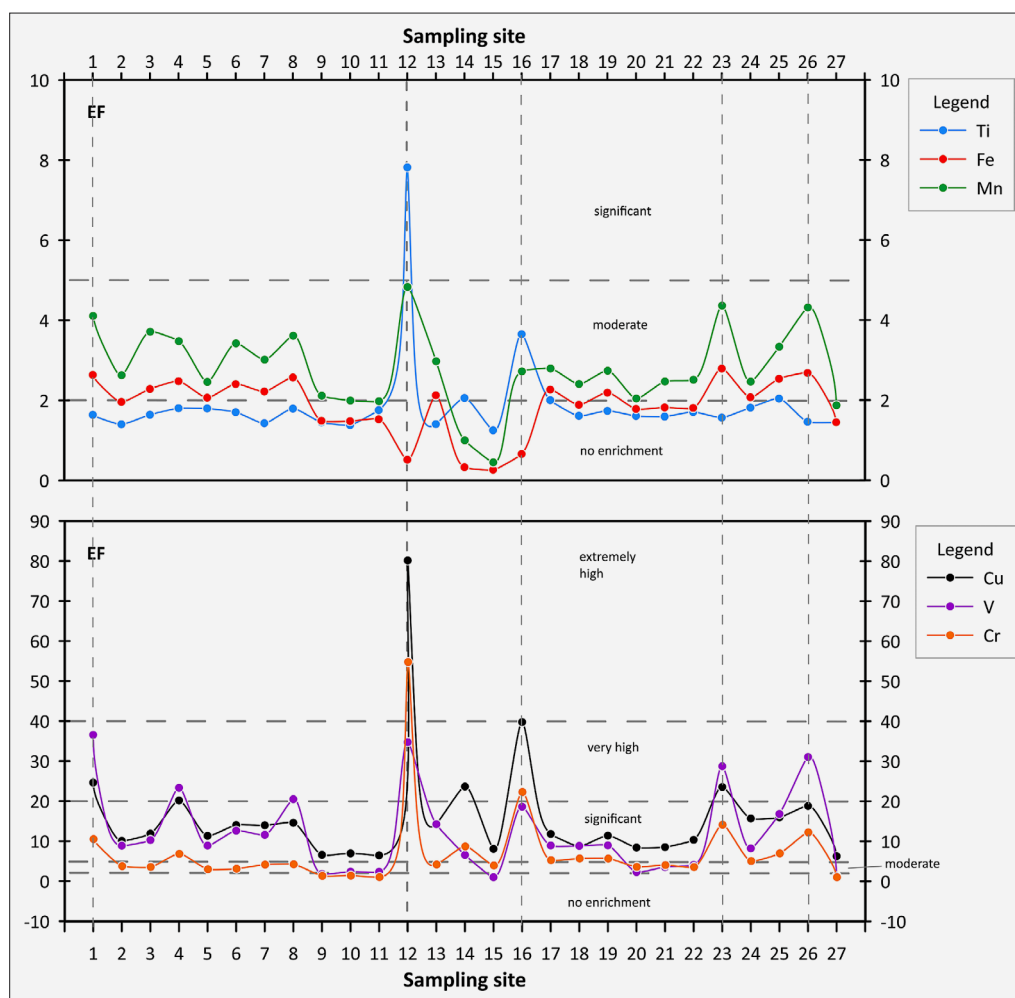


Figure 3. EF value curve and its classification for each sample site.

ment values EF, Igeo, CF, and PLI, it was found that sites LB-12 and LB-14 experienced much greater pollution than other sites. The assessment results also showed that Cu experienced the greatest enrichment and is the largest pollutant in the sediment of Lake Batur.

The site with the highest EF, LB-12, is located in the southwest of the lake (see **Figure 2**). Near this point, there is a settlement and Pancuran Solas Temple, one of the temples with a high level of religious activity by the Balinese Hindu community. The most famous activity carried out there is melukat, which involves the use of offerings, one of which is the metal kepeng, which is derived from Cu (Suandayani et al., 2023; Arwati, 1991). This activity is thought to be the largest source of Cu enrichment in Lake Batur sediments. Site LB-14 has the highest level of sediment contamination, located in the center of the lake; the cause of the high values is uncertain.

3.4. Identifying heavy metal sources in Lake Batur

The results of the Spearman correlation (see **Table 4**) showed a strong positive correlation between χ_{LF} with Ti ($r = 0.784$), Fe ($r = 0.694$), and Mn ($r = 0.619$) which

means that these elements are closely related to lithogenic input, while a negative correlation value indicates that the concentrations between elements do not affect each other. The negative correlation of χ_{LF} with Cr ($r = -0.245$) and V ($r = -0.814$) indicates that the elements are not lithogenic in origin. The negative correlation of χ_{FD} with all heavy metals indicates that the metals are not derived from superparamagnetic particles. The correlation between metals shows that Fe and Mn are strongly correlated ($r = 0.949$), indicating the possibility of originating from a single lithogenic source. Fe and Cr are negatively correlated ($r = 0.547$), indicating a different source of Cr from Fe, which may not be lithogenic. Ti and Cu are strongly positively correlated ($r = 0.767$), indicating the possibility of Cu also being influenced by lithogenic sources. Ti and V are strongly negatively correlated ($r = -0.737$), indicating different sources of V and Ti. Mn and Cr are negatively correlated ($r = 0.596$), indicating a different source of Cr. V has a negative correlation with all elements, indicating a different source of V from the others and possibly an anthropogenic origin.

For PCA analysis, based on Kaiser criteria there are 2 principal components (PCs) that meet the criteria. PC₁

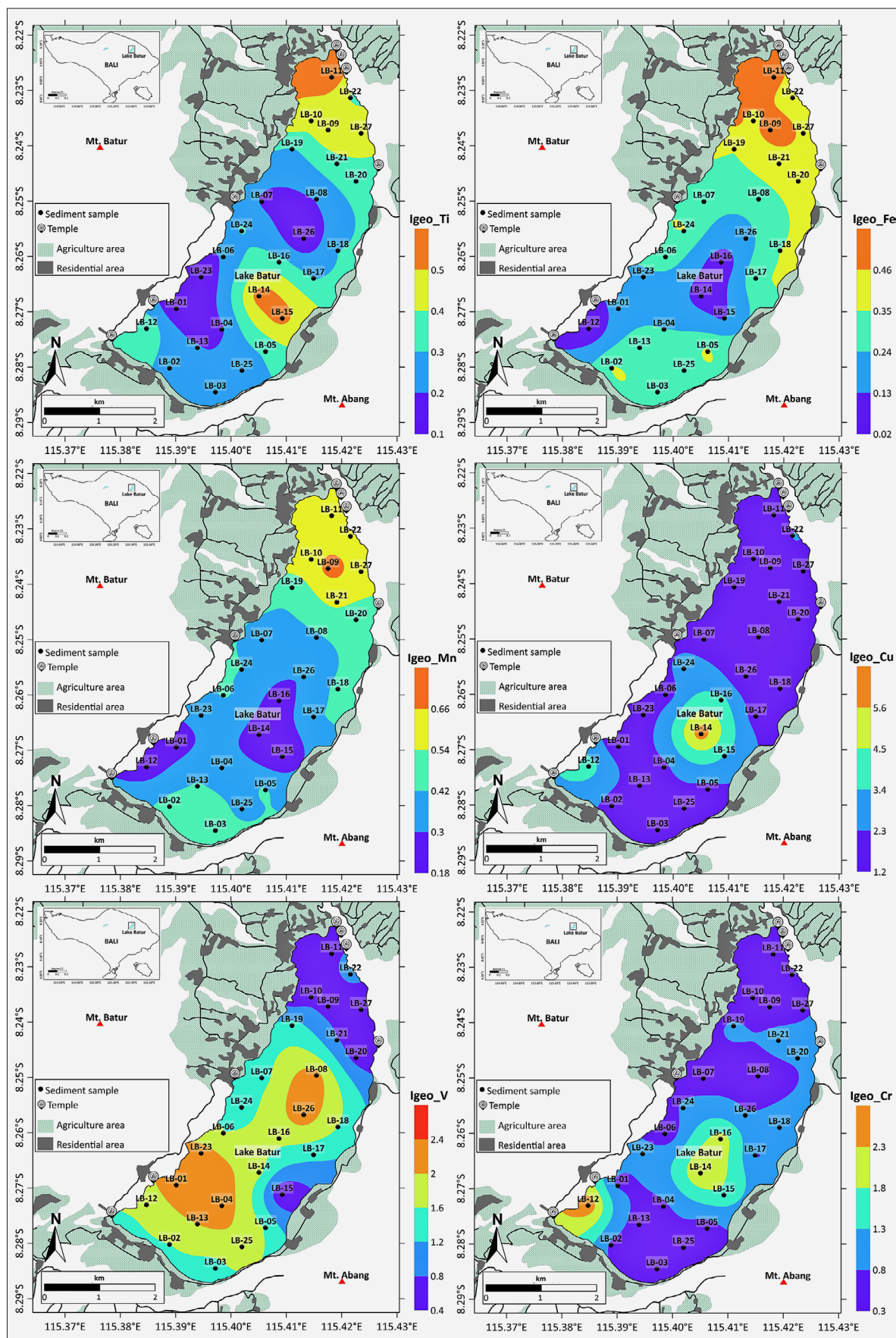


Figure 4. Spatial distribution of Igeo for Ti, Fe, Mn, Cu, V, and Cr elements in Lake Batur sediments. The white area around the lake is part of Mount Batur and Mount Abang without anthropogenic activity.

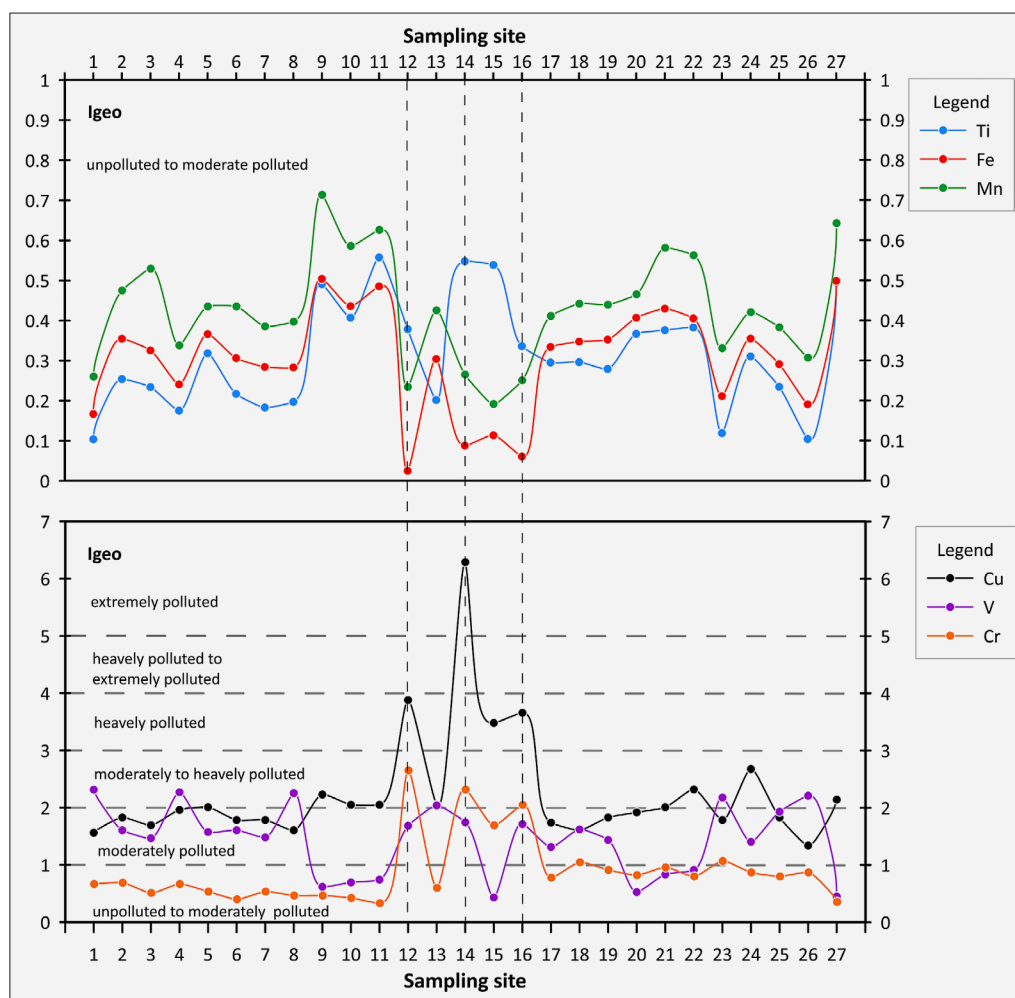


Figure 5. Igeo value curve and its classification for each sample site.

and PC_2 representing approximately 54.5% and 37.4% or around 91.9% of the total variance. The loading plot of the principal component in **Figure 9a** shows the presence of 4 groups of heavy metals, namely group 1 Fe and Mn, group 2 is Ti, group 3 is Cu and Cr, and group 4 is V. In the PCA plot, Fe and Mn are in the negative position on PC_1 , indicating a common source. Ti is in a strong positive position on PC_2 , Cu and Cr are in a strong positive position on PC_1 , and V is in the positive position on PC_1 . PC_1 indicates an anthropogenic metal source, and PC_2 indicates a lithogenic metal source. From the HCA analysis, 3 heavy metal clusters were obtained: cluster 1 is Ti, cluster 2 is Fe, and cluster 3 is Mn, Cu, Cr, and V (see **Figure 9b**).

Based on the multivariate analysis (Spearman correlation, PCA, and HCA) showing the presence groups of heavy metals, the source of heavy metals found in the lake surface sediment can be estimated. The results of the correlation analysis reveal a very strong correlation between iron (Fe) and manganese (Mn) ($r = 0.949$), suggesting a lithogenic source. The presence of Fe is influenced by natural processes such as rock weathering, with the primary source of Fe being the weathering of

the Earth's crust, which then becomes deposited in sediment (Riley and Chester, 1971; Ranjan et al., 2016). Additionally, titanium (Ti) shows a strong positive correlation with magnetic susceptibility (χ_{LF}) ($r = 0.784$), indicating a connection to magnetic minerals derived from the host rock. In contrast, vanadium (V) shows a strong negative correlation with χ_{LF} ($r = -0.814$) and Ti ($r = -0.737$), suggesting that this element does not originate from lithogenic sources, but is likely a result of anthropogenic input. PCA results support these findings, as lithogenic elements like Ti, Fe, and Mn load onto different components compared to heavy metals such as V and Cr. Notably, Ti has a high loading in the second component, indicating a distinct lithogenic source separate from the heavy metals. HCA depicted in the dendrogram shows that Cu, Cr, Mn, and V form a single cluster, implying a potential contribution from anthropogenic activities. Conversely, Fe and Ti tend to form separate clusters, further supporting the interpretation that they represent lithogenic input. Overall, the positive correlations of χ_{LF} with Ti, Fe, and Mn, alongside the negative correlations with V and Cr, highlight a clear distinction between natural (lithogenic) and anthropogenic sources in the sedimentary system of Lake Batur.

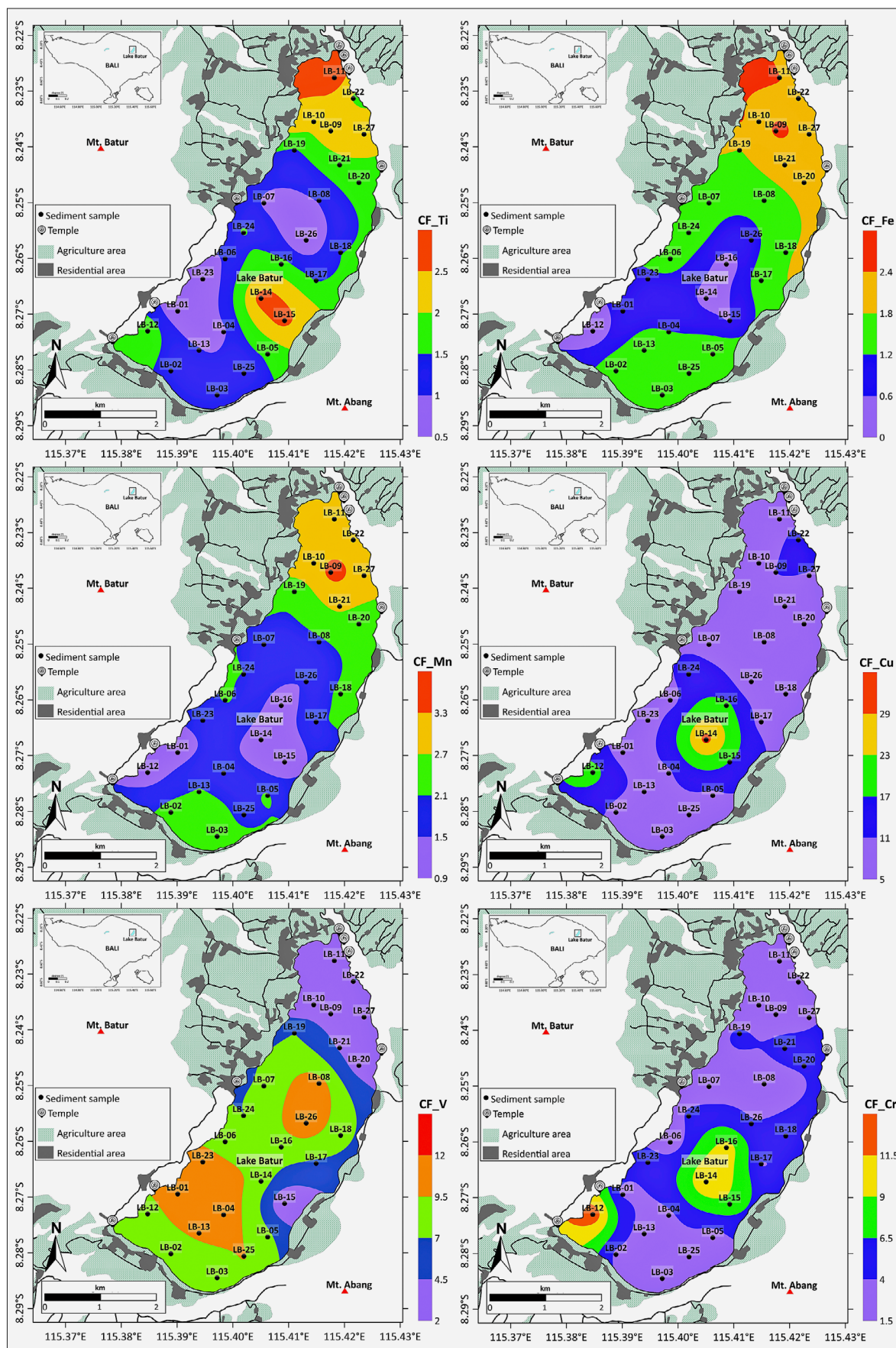


Figure 6. Spatial distribution of CF for Ti, Fe, Mn, Cu, V, and Cr elements in Lake Batur sediments. The white area around the lake is part of Mount Batur and Mount Abang without anthropogenic activity.

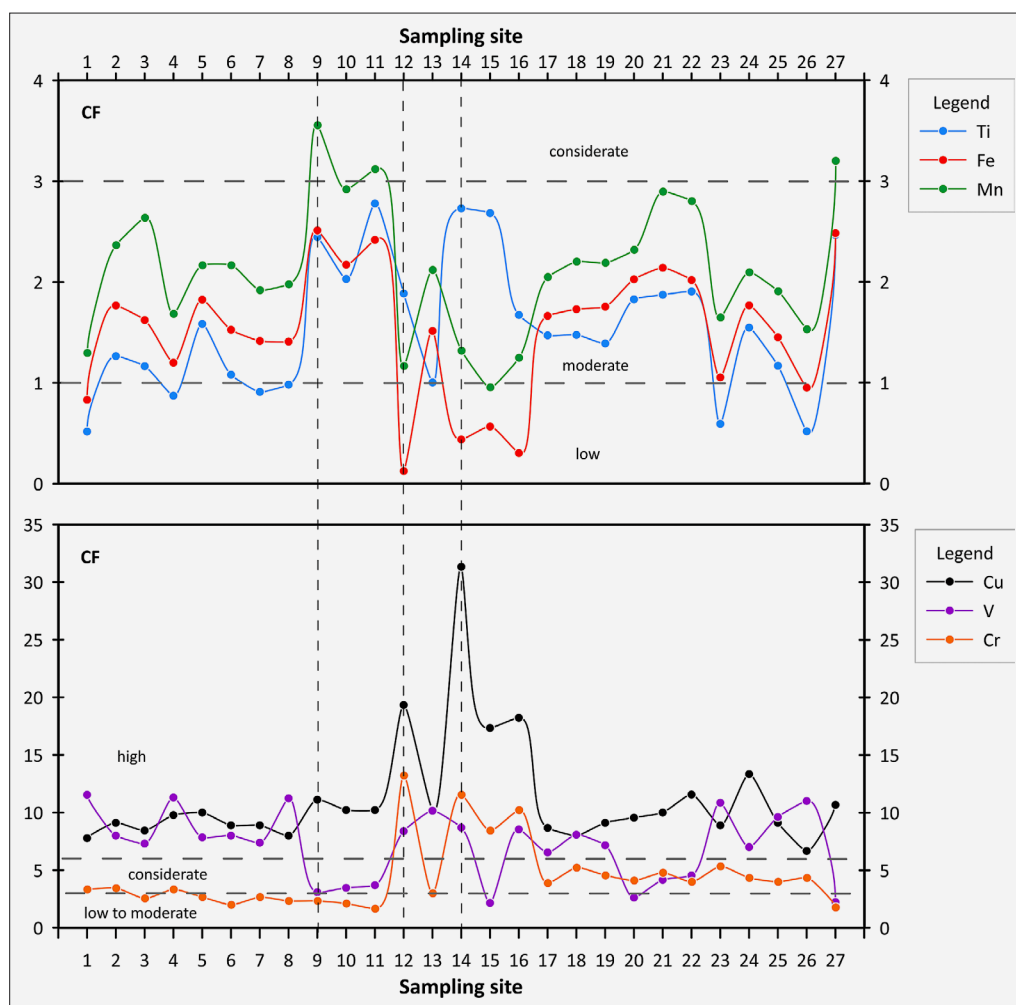


Figure 7. CF value curve and its classification for each sample site.

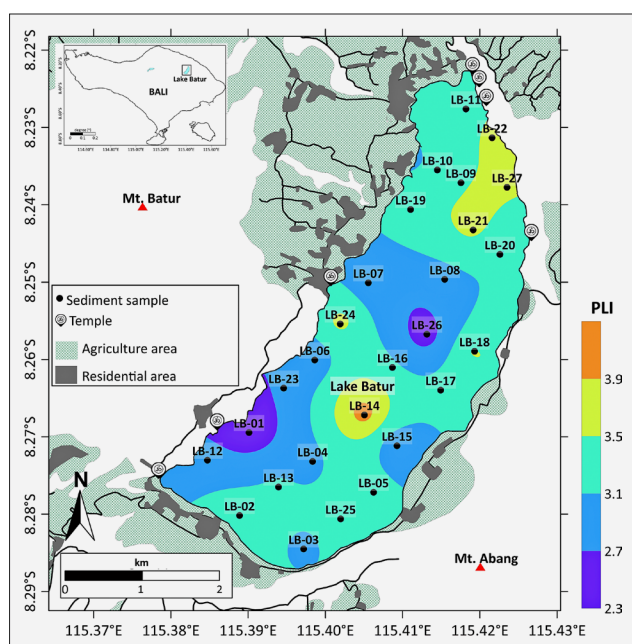
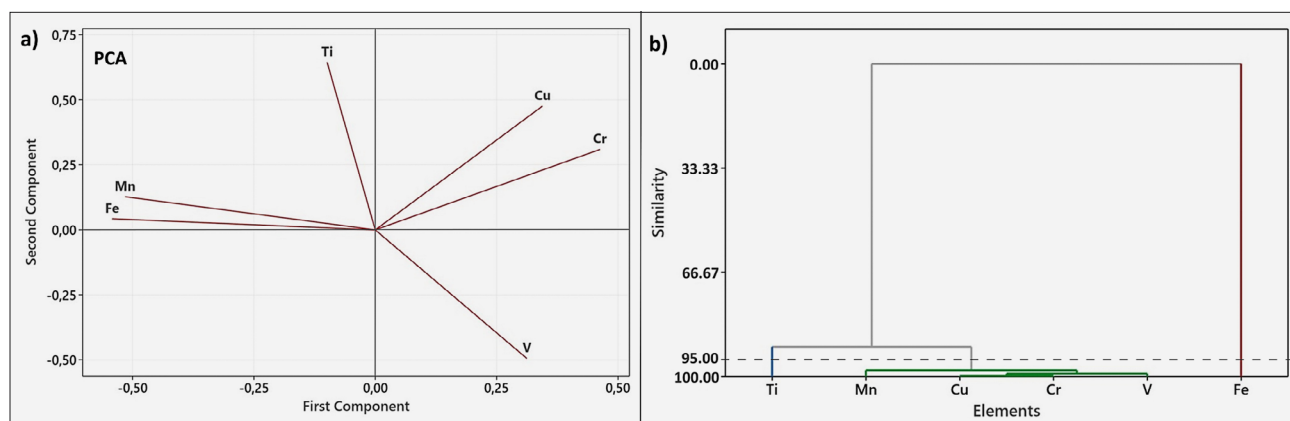


Figure 8. Spatial distribution of PLI in surface sediments of Lake Batur. The white area around the lake is part of Mount Batur and Mount Abang without anthropogenic activity.

Based on the EF index value, it is known that points LB-12, LB-14, and LB-16 have the highest enrichment levels for all observed heavy metal elements, especially Cu elements. Point LB-12 is located in the southwest of the lake (see Figure 2), near this point there are settlements and the Pancuran Solas Temple. Concentrations of trace metals such as Cu found in high concentration in the lake area that is close to the temple (Suandayani et al., 2023). The high Cu enrichment index is mainly found near the Pancuran Solas Temple, which is a temple with high religious activity. It is suspected that one of the main sources of Cu in the area is related to the melukat religious ceremony and prayer by the Balinese Hindu community. These activities use offerings, or canang, one of which contains kepeng (ancient copper coins), or the use of offerings in the form of pripihan (fish-shaped metals made of iron, copper, or precious metals), which are thrown into Lake Batur (Arwati, 1991; Suandayani et al., 2023). Burton (2002) identified eight elements: As, Cd, Cr, Cu, Pb, Hg, Ni, and Zn as markers of lake sediment quality associated with anthropogenic contamination. Two of these elements, Cu and Cr, were found in Lake Batur sediments, strongly suggesting an anthropogenic source. The concentration of Cu and Cr can be impacted by a variety

Table 4. Spearman correlation of heavy metals with magnetic susceptibility in sediment samples of Lake Batur.

	χ_{LF}	% χ_{FD}	Ti	Fe	Mn	Cu	Cr
% χ_{FD}	-0.126						
Ti	0.784	-0.330					
Fe	0.694	0.109	0.419				
Mn	0.619	0.048	0.369	0.949			
Cu	0.449	-0.243	0.767	0.073	0.007		
Cr	-0.245	-0.207	0.065	-0.547	-0.596	0.251	
V	-0.814	-0.037	-0.737	-0.694	-0.611	-0.403	0.195

**Figure 9.** a) Plot first and second component of PCA. b) Dendrogram of cluster analysis.

of human activities near Lake Batur, including settlements, tourism, and religion (Sun et al., 2013; Suandayani et al., 2023; Gopal et al., 2023). The use of paint on boats and metal coatings, as well as ship maintenance in the port area, are examples of anthropogenic activities that are likely to be the cause of the high concentration of Cr in Lake Batur sediments (Gopal et al., 2023), because in Lake Batur the use of shipping is quite high for tourism and managing floating cage fisheries.

4. Conclusions

Assessment of heavy metal pollution of Fe, Ti, Mn, Cu, Cr, and V in lake surface sediments using the EF, Igeo, CF, and PLI indices shows that lake sediments are currently polluted by heavy metals, especially the high enrichment of Cu and Cr. According to PLI, the sediments from Lake Batur are classified as highly contaminated at every location. The results of magnetic susceptibility and multivariate analysis show that the sources of heavy metals in Lake Batur can be grouped into 3 categories, namely 1) Fe and Ti are dominated by lithogenic sources such as weathering of surrounding rocks, 2) Cu and Cr are dominated by anthropogenic sources, and 3) Mn and V are influenced by a combination of lithogenic and anthropogenic factors, with Mn being more lithogenic and V being more anthropogenic. The source of Cu enrichment comes from anthropogenic sources, especially religious activities in temples around Lake Batur. The use of paint and metal coatings on boats, as well as ship maintenance

in the port area, are examples of anthropogenic activities that are likely to be the cause of the high Cr in Lake Batur. For the concentration of heavy metals in water samples in decreasing order $Zn > Fe > Mn > As > Cu > Cr > Pb > Cd$. The concentration of all heavy metals in water samples is still below the standard given by WHO, unlike in sediments where there is a high concentration. This is likely related to the level of heavy metal sedimentation in Lake Batur so that some elements in the sediment have high concentrations. The quality of this polluted sediment can affect the condition of the lake ecosystem and the surrounding community. Therefore, proper monitoring and management are needed to maintain the condition of Lake Batur from declining quality.

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SAŽETAK

Teški metali u površinskim sedimentima jezera Batur, Bali, Indonezija: prostorna razdioba, procjena rizika i raspodjela izvora

Cilj je ovoga istraživanja procijeniti uvjete okoliša jezera Batur, Indonezija, zatvorenoga alkalnog jezera. U istraživanju je identifikacija teških metala provedena korištenjem 27 uzoraka sedimenta i 13 uzoraka vode. Metode korištene u studiji uključuju magnetnu osjetljivost, geokemijsku i multivarijantnu analizu. Koncentracija teških metala u uzorcima sedimenta slijedi redoslijed $\text{Fe} > \text{Ti} > \text{Mn} > \text{V} > \text{Cu} > \text{Cr}$ (wt%). Rezultati procjene onečišćenja (EF, Igeo, CF i PLI) u sedimentu upućuju na to da je jezerski sediment trenutačno onečišćen. PLI pokazuje da je sediment jezera Batur u kategoriji visoke kontaminacije na svim mjestima uzorkovanja, posebno zbog visokoga obogaćivanja bakra i kroma (Cu i Cr). Vjeruje se da je uporaba metala (kepeng) u vjerskim aktivnostima u hramovima u blizini jezera Batur izvor obogaćivanja bakra (Cu). Rezultati multivarijantne analize i magnetne osjetljivosti otkrivaju tri skupine teških metala u sedimentu jezera Batur na temelju njihovih glavnih izvora: 1) željezom i titanom (Fe i Ti) dominiraju litogeni čimbenici, 2) bakrom i kromom (Cu i Cr) dominiraju antropogeni čimbenici, 3) mangan i vanadij (Mn i V) pod utjecajem su kombinacije litogenih i antropogenih čimbenika. Koncentracije su teških metala u uzorcima vode sljedeće: $\text{Zn} > \text{Fe} > \text{Mn} > \text{As} > \text{Cu} > \text{Cr} > \text{Pb} > \text{Cd}$ (ppb). Uzorci vode pokazuju da su koncentracije teških metala još uvijek ispod minimalnoga praga za pitku vodu Svjetske zdravstvene organizacije (WHO).

Ključne riječi:

jezero Batur, teški metali, procjena jezera, magnetna osjetljivost, geokemija

Author's contribution

Ulvienin Harlianti (M.Eng., Geophysical Engineering with expertise on rock magnetism in lakes and palaeomagnetism): conceptualization, investigation, data acquisition, visualization, methodology, writing – original draft, writing – review & editing. **Satria Bijaksana** (PhD, Professor, expert on rock magnetism): conceptualization, investigation, methodology, supervision, writing – original draft, writing – original draft and writing – review & editing. **Irwan Iskandar** (PhD, expert on hydrogeochemical): methodology, validation, supervision, and writing – review & editing. **Rachmat Fajar Lubis** (PhD, expert in hydrogeology and limnology): acquisition data, supervision, and writing – review & editing. **Putu Billy Suryanata** (PhD, Geophysical Engineering with expertise in rock magnetism for volcanoes): investigation, data acquisition, and writing – review & editing. **Ni Komang Tri Suandayani** (PhD, Geophysical Engineering): investigation, data acquisition, and writing – review & editing. **Silvia Jannatul Fajar** (PhD, Geophysical Engineering): investigation, data acquisition, and writing – review & editing.

All authors have read and agreed to the published version of the manuscript.

A preliminary study of the effect of alteration on breakage properties of andesites from Tállya and Recsk (Hungary)

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Preliminary communication



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Abstract

This preliminary study investigates the influence of post-magmatic alteration on the breakage behaviour of andesitic rocks during comminution, with particular emphasis on the Chemical Index of Alteration (CIA) and smectite content. Six representative samples from two Hungarian quarries (Recsk and Tállya) exhibiting broadly similar mineralogical and textural properties but varying degrees of alteration were subjected to single particle breakage tests across multiple size fractions. Although the limited dataset does not allow for broad generalisation, the results provide a first indication that increased CIA values and higher smectite contents are associated with greater fragmentation susceptibility, as reflected by elevated $A \times b$ parameters. The study demonstrates that alteration indices can provide valuable predictive information on breakage response in andesitic rocks. These findings suggest the importance of integrating alteration metrics alongside traditional mineralogical and textural parameters when evaluating the breakage behaviour of andesitic rocks for aggregates production. While smectite quantification highlights the role of secondary phyllosilicate minerals in reducing the strength of andesitic rocks, CIA offers a more broadly applicable measure of alteration intensity that may be transferable across different volcanic contexts. The results are presented as a case study that highlights the potential of CIA and smectite quantification as predictive tools, while acknowledging the need for further research with larger datasets to confirm these trends.

Keywords:

andesite; aggregate production; drop weight test; alteration; smectite

1. Introduction

The optimisation of comminution processes – namely crushing and grinding – has been a central focus in mineral processing over the past few decades (Napier-Munn et al., 1996, 2012; Morrell, 2004a; Dominy et al., 2018), given their status as some of the most energy-intensive operations within the mining sector (Howarth & Rowlands, 1987; Jeswiet & Szekeres, 2016). While numerous studies and industrial efforts have aimed to enhance the efficiency of comminution circuits in ore processing (Pauw & Maré, 1988; Morrell, 2004b; Wills & Napier-Munn, 2006; Jankovic et al., 2015), similar advancements in the aggregate industry remain limited and underexplored (Csóke et al., 1996; Adel et al., 2006). The limited progress in the aggregate sector can largely be attributed to the historically low energy costs, which permitted higher tolerances for by-products and reduced emphasis on end-product quality. However, rising energy demands, increasing costs, and stricter

policies on waste reduction have created a pressing need for process optimisation in aggregate production. A key pathway toward cost-efficient production lies in model-based prediction of crushing behaviour, an area to which the present preliminary study seeks to contribute.

In terms of production volume, crushed aggregates constitute the largest segment of the mining industry, and they rank second in economic value (Menegaki & Kaliampakos, 2010; Přikryl, 2021). According to data from the European Aggregates Association (URL 1), a total of 4.35 billion tonnes of aggregates were produced across Europe in 2023 from 30116 extraction sites, of which crushed rock accounted for 2.13 billion tonnes. The types of rocks used for aggregate production largely depend on the geological characteristics of the production region (McNally, 1998; Piasta et al., 2018). In many areas, magmatic rocks such as andesite, granite, and basalt are the primary sources of aggregates. Metamorphic rocks, including quartzite and gneiss, are used less frequently, while sedimentary rocks, such as limestone and dolomite, are generally considered lower in priority but are still utilised where locally available. Due to having one of the lowest average values per unit weight among all mineral commodities, transportation

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plays a significant role in the overall cost of aggregates (**Drew et al., 2002; Příkryl, 2017**); as a result, extraction typically occurs near the point of use.

The rising energy costs and associated CO₂ emissions, coupled with the depletion of high-quality mineral resources for aggregate production, make process optimisation essential (**Legendre & Zevenhoven, 2014; Liu et al., 2018; Vasilyeva et al., 2023**). Achieving this requires a thorough understanding of the factors influencing crushing operations. The primary factors affecting the crushing processes are the type of equipment used for crushing (**Cleary & Sinnott, 2015; Sinnott & Cleary, 2015; Kamani & Ajalloeian, 2020**) and the geological characteristics of the materials (**Brattli, 1992; Akseli & Leinonen, 2015; Comakli & Cayirli, 2019**).

The influence of geological characteristics on the comminution of rocks has been extensively investigated in literature. These studies can be broadly categorised into two main groups. The first group focuses on ore-bearing rocks, examining their mineralogical composition and identifying the optimal degree of mineral liberation to enhance ore recovery. For example, **Oyarzún & Arévalo (2011)** demonstrated that mineralogical heterogeneity governs fragmentation pathways in porphyry ores; while **Mwaga et al. (2015)** reviewed how geometallurgical approaches integrate comminution testing with ore texture to predict processing performance. **Yuce (2017) and Abdelhaffez (2020)** similarly highlighted that fracture energy and breakage characteristics are strongly dependent on mineralogical composition and pre-existing microstructures. **More recently Semsari Parapari et al. (2020)** showed that ore texture exerts a stronger influence than stress loading conditions on breakage behaviour, while their follow-up study (**Semsari Parapari et al., 2022**) quantified how multivariate textural parameters control mineral liberation, fracture energy, and fragmentation outcomes. The second group addresses rocks used in aggregate production, analysing how mineralogical and microtextural features affect strength parameters and product quality. **Miskovsky et al. (2004)** showed that feldspar-rich granitoids display reduced resistance to impact, whereas fine-grained rocks with interlocked textures perform better under mechanical loading. **Zhang & Subasinghe (2012)** highlighted the importance of particle shape, angularity, and surface texture, showing that these factors control compaction and shear resistance in aggregate-based applications. **Akseli & Leinonen (2015) and Afolagboye et al. (2016)** confirmed that mineralogical variability and microstructural features directly affect crushing strength and long-term performance of construction aggregates.

The mechanical performance of aggregates is strongly controlled by their petrographic and textural attributes. **Ajalloeian & Kamani (2017)** showed that image-analysis-derived texture parameters (grain shape, circularity, orientation) influence Los Angeles abrasion results in carbonate aggregates. **Adomako et al. (2021)**, in a compre-

hensive review, further highlighted that mineralogy, porosity, and texture collectively govern Los Angeles and Micro-Deval outcomes. The importance of sample preparation and crushing conditions was demonstrated by **Räisänen & Mertamo (2003)**, who showed that laboratory crusher type and settings significantly affect aggregate shape and thereby test results. Similarly, **Hofer et al. (2013)** found that within railway ballast, petrographic variability plays a greater role in Los Angeles test values than particle geometry. **Köken (2020)** expanded this understanding by linking cone crusher size reduction ratios with Shore hardness, abrasion resistance, and textural characteristics across multiple rock types.

Beyond texture, the role of alteration has been repeatedly emphasised. **Török & Czinder (2017)** established correlations between strength parameters and abrasion resistance in Hungarian andesites, while **Czinder & Török (2019, 2021)** confirmed that petrographic variability and progressive alteration reduce both strength and durability indices. **Lampropoulou et al. (2020)** documented similar effects in Greek mafic and ultramafic rocks, where serpentinization and chloritization produced poorer quality aggregates, reflected in higher LA values and greater water absorption. In volcanic rocks, **Petrounias et al. (2018a, 2018b)** demonstrated that secondary phyllosilicate minerals, particularly smectite, are especially detrimental to mechanical behaviour. **Four-nari & Ioannou (2019)** corroborated this relationship in crushed fine aggregates from Cyprus, reporting strong correlations between mineralogical composition and durability indicators such as soundness, Micro-Deval resistance, and water absorption.

At a broader scale, decision-support approaches such as the Analytic Hierarchy Process (**Köken et al., 2020**) integrate mineralogical, physical, and mechanical parameters to rank aggregate quality, showing that andesites tend to perform poorest among common igneous rock types. **Strzałkowski et al. (2021)** reviewed the Los Angeles and Micro-Deval methods, underscoring the combined role of petrography, particle morphology, and alteration in fragmentation and abrasion resistance. Site-specific investigations (**Åkesson et al., 2001; Apaydın & Yılmaz, 2021; Okogbue & Aghamelu, 2013; Pomonis et al., 2007; Urueña et al., 2022**) similarly confirm that aggregate quality cannot be decoupled from petrography, alteration, and microstructural attributes.

Magmatic rock quarries usually extract material from a single intrusive body, resulting in relatively uniform mineral composition and texture, although signs of post-magmatic or hydrothermal alteration are often present (**Pereira et al., 2024**). While the influence of mineral composition and texture on grindability and breakage properties has been widely studied, the effect of alteration – particularly the formation of smectite – has received comparatively less attention. Recent laboratory tests on altered andesite have shown that alteration can significantly weaken the rock and influence its failure

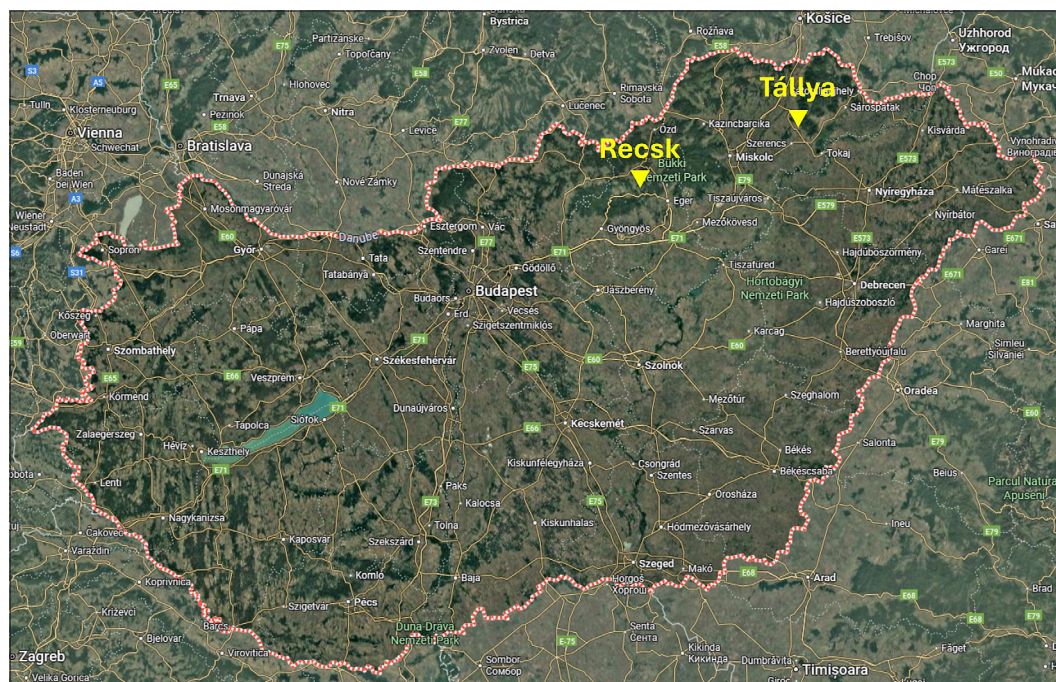


Figure 1. Geographical position of the two studied andesite quarries in Hungary (source: Google Maps)

behaviour (Pola et al., 2014; Lampropoulou et al., 2020; Pereira et al., 2024). Supporting this, studies in related fields highlight the importance of alteration intensity on comminution: Yildirim et al. (2014) developed the Process Alteration Index (PAI) to predict metallurgical responses linked to alteration, while Darwish et al. (2025) demonstrated that the Chemical Index of Alteration (CIA) effectively reflects mechanical weakening in hydrothermally altered uranium-bearing rocks. These findings underscore the need to consider alteration effects – alongside mineralogy and texture – in understanding grindability and breakage behaviour in aggregate production.

The present study provides a preliminary investigation into how alteration intensity and related mineralogical changes affect the breakage behaviour of andesitic rocks during comminution. Six representative samples from two Hungarian quarries were analysed; although limited in number, they were selected to capture a clear contrast in alteration state while keeping mineralogy and texture broadly comparable. The primary aim is to assess whether quantitative alteration indices – specifically the Chemical Index of Alteration (CIA) – and smectite content can be linked to the $A \times b$ breakage parameter obtained from drop-weight testing. By doing so, the research seeks to advance understanding of how post-magmatic alteration influences fragmentation susceptibility in volcanic rocks. Although exploratory in scale, this approach contributes new insight by testing the applicability of alteration indices as predictive tools for breakage properties, thereby opening pathway toward more efficient evaluation of crushing behaviour in industrial aggregate production.

2. Materials

For this study, samples were collected from two quarry sites: Recsk and Tállya (see Figure 1). Both locations extract andesite-type magmatic rocks formed during Neogene volcanic activity associated with the Inner Carpathian Volcanic Chain. The Tállya quarry is located within the Tokaj Mountains of northeast Hungary, where pyroxene-andesite was formed as a result of volcanic processes during the Sarmatian stage (approximately 12 million years ago) (Haas et al., 2012). The andesite quarried at Tállya is a porphyritic volcanic rock with a vitrophyric matrix, containing fine pyroxene needles and lamellar plagioclase. It exhibits columnar jointing, vesicular zones, and characteristic alteration near the margins, where the originally dark grey rock fades to greenish-grey due to hydrothermal processes. Secondary minerals such as sphaeroidite, opal, smectites, and chalcedony frequently occur within the vesicles (Cseh et al., 1990).

The Recsk quarry, situated in the Mátra Mountains of northern Hungary, also extracts pyroxene-andesite, characterised by a light grey colour, carbonate-altered glassy matrix, unaltered hypersthene, and clinopyroxenes of diopside composition. These rocks originated from an Upper Tortonian volcanic event, dated to approximately 11.5 million years ago. The quarried material at Recsk is a light grey pyroxene-andesite with a carbonate-altered, microholocrystalline matrix containing plagioclase and carbonate minerals. The rock features unaltered hypersthene and clinopyroxenes of diopside composition, along with porphyritic plagioclase, siderite, and magnetite. The intrusive body is rich in



Figure 2. Photographs of the analysed rock samples. Samples labelled with “T” originate from the Tállya quarry, while those marked “R” are from the Recsk quarry. (a – T₁; b – T₂; c – T₃; d – R₁; e – R₃; f – R₄).

voids and secondary mineral fillings, resulting from volatile enrichment caused by the assimilation of Mesozoic carbonate rocks during magma ascent (Budai et al., 2015). Despite differences in the timing and location of the volcanic events, the andesite types extracted from the two sites are comparable, exhibiting only minor variations in geochemistry and post-volcanic alteration processes.

Three andesite types were distinguished within the Tállya quarry, from which representative samples were collected. The first sample (T₁) comes from the lower quarry levels and consists of dark grey, microcrystalline andesite with plagioclase phenocrysts (0.5–1 mm), minimal vesicles, and negligible alteration (see Figure 2a). The second sample (T₂) was taken from intermediate levels, characterised by lighter grey, moderately vesicular andesite with larger plagioclase crystals (1–2 mm) and signs of moderate alteration (see Figure 2b). The third sample (T₃) originates from the upper levels, where strongly altered, vesicle-rich andesite with iron oxide crusts and secondary mineral fillings are present (see Figure 2c).

Three andesite types with varying alteration levels were also sampled from the Recsk quarry. The first sample (R₁) originates from the lower quarry levels and consists of medium grey, dense andesite with a microcrystalline matrix, feldspar, quartz, and biotite phenocrysts, and carbonate-filled vesicles (see Figure 2d). Alteration is minimal, appearing as scattered greenish-yellow spots. The second sample (R₃) was collected from mid-levels and shows distinct greenish-grey and purplish-brown zones, with biotite and occasional quartz phenocrysts preserved mainly in the less altered areas (see Figure 2e). The third sample (R₄) comes from the upper quarry levels and represents strongly weathered, friable andesite with yellowish-brown iron oxide coat-

ings and spheroidal weathering structures; feldspar phenocrysts are present but heavily altered (see Figure 2f).

3. Methods

The mineralogical composition of samples was determined by X-ray powder diffraction (XRD) on a Bruker D8 Discover instrument (Cu-K α radiation, 40 kV, 40 mA generator settings) in Bragg-Brentano geometry. Recording was done with a LynxEye XE-T position sensitive detector (PSD), 2° window opening. Crystalline phases were identified by Search/Match, on the ICDD PDF2 (2005) database (Bruker DiffracPlus EVA), and phase amounts were calculated with Rietveld refinement in Bruker TOPAS4.

Bulk chemical composition was determined by wavelength dispersive X-ray Fluorescence Spectrometry (WD-XRF) on Cereox cemented powder pellets on a Rigaku Supermini200 type instrument with the Pd-source operated at 50 kV and 4 mA.

The textural features were observed with transmitted light optical microscopy on rock polished thin section in polarised light, using a Zeiss AXIO Imager.M2m microscope equipped with an AxioCam MRc 5 digital camera.

Single particle breakage tests are widely applied to investigate the breakage behaviour of rocks, as they eliminate the machine-induced effects typical of conventional crushing equipment. Among these, the Drop Weight Test (DWT) is a standard method for determining the relationship between applied impact energy and particle size reduction. In this method, a mass is dropped from a controlled height onto a single particle, inducing breakage through compressive and tensile stresses, which allows for the assessment of specific breakage energy and fragmentation characteristics. For this study, a laboratory device operating on the principles of the

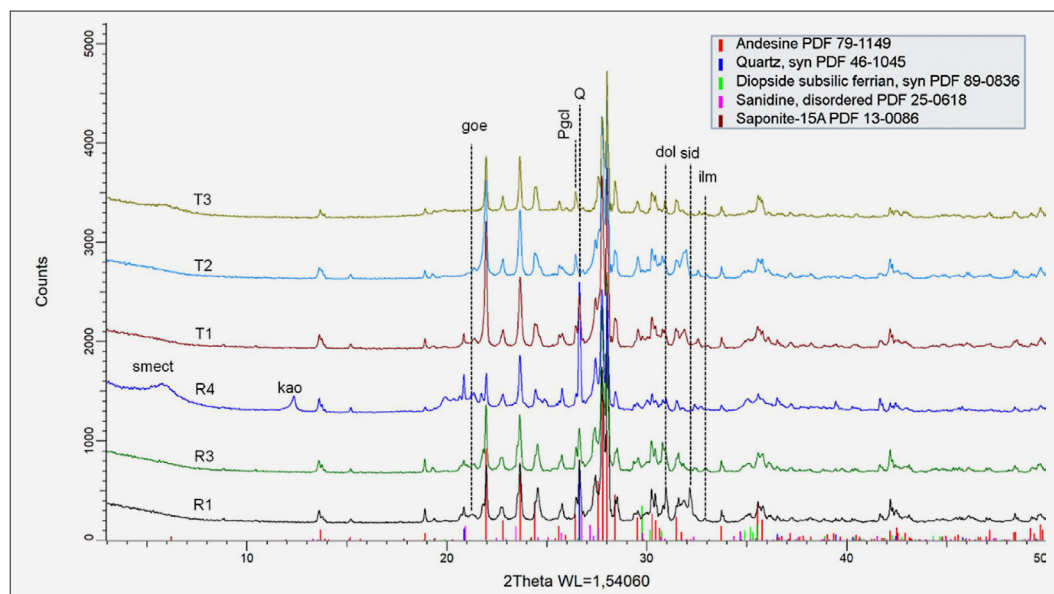


Figure 3. XRD diffractogram of the samples

DWT was constructed and utilised to perform controlled impact tests on the rock samples.

The breakage energy applied during the tests was determined from the mass of the falling weight and the drop height, as expressed by the following equation:

$$E_a = m_w * g * (h_i - h_f) \quad (1)$$

Where:

- E_a – the breakage energy ($\text{m}^2 \text{ kg/sec}^2$),
- m_w – weight of the drop weight (kg),
- g – the gravitational acceleration (9.81 m/s^2),
- h_i – initial height of the drop weight (m),
- h_f – final height (after breakage) of the drop weight (m).

The specific breakage energy was calculated by relating the applied impact energy to the mass of the tested particle, as shown in the following equation:

$$E_{cs} = E_a / m_p \quad (2)$$

Where:

- E_{cs} – specific breakage energy (kWh/t),
- E_a – the breakage energy ($\text{m}^2 \text{ kg/sec}^2$),
- m_p – mass of the particle (g).

For breakage energy calculations, the difference between the initial and final drop heights in **Equation 1** was defined using the mean particle size. For the specific breakage energy, the particle mass in **Equation 2** was not measured individually; instead, the total mass of the test sample was recorded and divided by the number of particles to obtain an average particle mass.

Breakage tests were conducted on five specific particle size fractions: 40–45 mm, 25–31.5 mm, 20–22.5 mm, 12.5–16 mm, and 8–11.2 mm. The size fractions were produced by crushing the quarry samples with a jaw crusher, followed by dry sieving. To minimise the

influence of particle shape, flaky fragments were removed using a bar sieve with an aperture equal to half the upper size limit ($D_i/2$) of each fraction. For every andesite type, fraction size range, and impact energy level (levels 1, 2, and 3), a defined number of particles were tested – more for smaller fractions (up to 70) and fewer for larger ones (minimum 20), in total approximately 1900 particles were tested. Each particle was broken individually, the fragments appertaining to one setup were collected, and the resulting size distribution was determined. The entire procedure was repeated three times for each parameter set to ensure reproducibility.

4. Results

4.1. Mineralogical composition

The mineral composition of the samples was analysed by X-ray powder diffraction (XRD), with the results shown in **Figure 3**. Both quarry sites display similar mineralogical characteristics, dominated by plagioclase feldspars (andesine, oligoclase, labradorite), potassic feldspars (sanidine, microcline), quartz, and pyroxenes (diopside, enstatite). Accessory minerals include titanomagnetite and ilmenite, while alteration products such as dolomite, siderite, and smectite were also identified. Amorphous phases, likely linked to both volcanic glass and secondary alteration, were present in all samples. Notable differences include goethite in the Recsk samples and kaolinite in R_4.

Quantitative mineralogical analysis (see **Table 1**) confirmed overall compositional similarities between the sites but also revealed significant variations in individual mineral proportions. These differences reflect both distinct rock genesis and post-intrusion processes,

Table 1. Quantitative mineralogical composition of samples (weight percent, error +/- 5 relative percent)

Sample	T_1	T_2	T_3	R_1	R_3	R_4
Andesine	8.1	8.8	33.3	6.7	23.4	7.9
Quartz	4.2	1	0.6	4.6	3.5	8.5
Sanidine Na0.35	14.4	11.7	0.1	12.3	11.0	7.9
Smectite	1.4	1.4	5.7	2.3	3.1	11.9
Diopside	4.1	5	1.1	4.0	3.2	0.4
Titanomelag-netite	0.3	0.2	0.5	0.2	0.3	0.3
Oligoclase An25	27.8	24.5	22.1	15.3	12.0	9.5
Dolomite	0.6	1.1	0.5	0.74	0.3	0.7
Labradorite An55	13.2	16.1	8.4	29.1	17.7	9.2
Ilmenite	1.2	0.8	0.5	0.3	0.4	1.0
Microcline	2.6	1.2	0.4	0	3.6	8.2
Cristobalite	5.8	6.6	1.2	1.2	1.8	1.0
Enstatite	3.4	3.3	4.9	6.4	7.1	0
Siderite	3.2	3.8	0	5.23	0	0
Kaolinite	0	0	0	0	0	21.0
Geothite	0	0	0	0.82	1.9	2.9
amorphous	9.7	14.8	20.7	10.3	10.7	9.5

including alteration. Feldspar minerals – andesine, sanidine, oligoclase, and labradorite – occur in varying amounts across the samples. In the Tállya quarry samples, andesine increases toward the intrusion margins (8.1–33.3%), while the Recsk quarry samples show no clear trend (6.7–23.4%). Sanidine content rises toward the intrusion margins for samples from both sites (Tállya: 0.1–14.4%; Recsk: 7.9–12.25%). Labradorite varies between 8.4–16.1% in Tállya and 9.2–29.1% in Recsk samples. Total plagioclase content is higher in Tállya samples (49.1–64.2%) compared to those from Recsk (26.6–53.1%). Potassium feldspars (sanidine and microcline), linked to autometamorphic processes, show contrasting trends near intrusion margins, with lower contents in Tállya samples and variable amounts in those from Recsk.

4.2. Textural observations

The Tállya quarry samples (T_1, T_2, and T_3) all exhibit characteristic porphyritic textures, with phenocrysts of plagioclase, pyroxene, amphibole, and occasional alkali feldspars set in a microcrystalline to

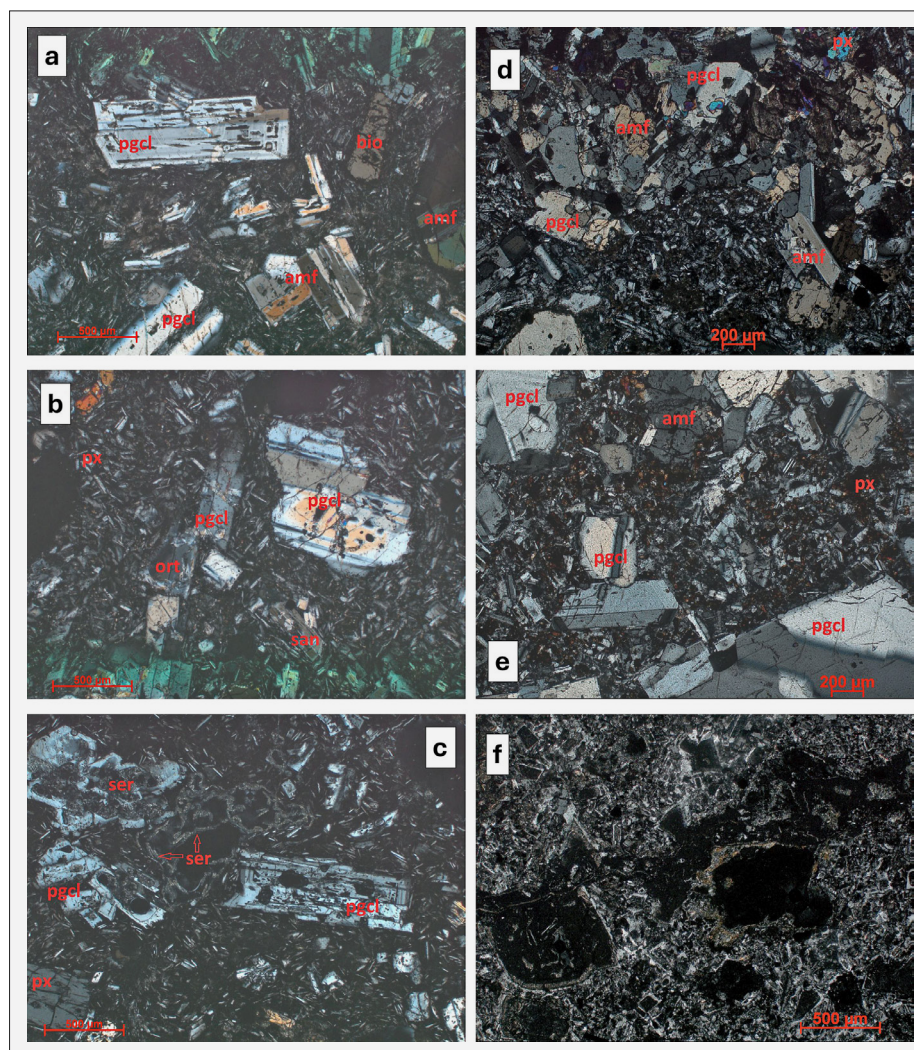


Figure 4. Photomicrographs illustrating the representative textures of the investigated samples. Samples labelled with “T” originate from the Tállya quarry, while those marked “R” are from the Recsk quarry. (a – T_1; b – T_2; c – T_3; d – R_1; e – R_3; f – R_4)

cryptocrystalline groundmass. In the least altered sample, T_1, the phenocrysts are well-formed, idiomorphic (see **Figure 4a**). Sample T_2 shows moderate alteration, the phenocrysts being idiomorphic and hypidiomorphic, with slightly rounded edges, although the overall texture remains largely intact (see **Figure 4b**). In the most altered samples, T_3, a reduction in phenocryst size can be observed. The phenocrysts are altered and the presence of alteration products, such as smectite, can be identified. The groundmass remains consistently fine-grained across all three samples, with only minor variations in its grain size; sample T_3 shows a slight increase (see **Figure 4c**).

The Recsk quarry samples present more pronounced textural differences. Sample R_1, sourced from deeper levels of the quarry, displays a coarser texture with abundant, well-preserved phenocrysts, some forming aggregates, set in a relatively fine-grained matrix (see **Figure 4d**). Sample R_3, originating from the intermediate quarry levels, contains notably coarser phenocrysts, particularly plagioclase, while the groundmass grain size remains comparable to that of R_1. However, alteration is more irregular, with Fe-oxide phases partially masking the matrix and signs of phenocryst edge degradation becoming apparent (**Figure 4e**). The uppermost and most altered sample, R_4, differs markedly; phenocrysts are fewer, highly weathered, and reduced in size, recognisable only based on their outline. The groundmass is overprinted by pervasive iron oxide alteration, resulting in a more heterogeneous texture and generally finer matrix compared to the less altered samples (see **Figure 4f**).

Table 2. Chemical index of alteration (CIA) values of the samples

Sample	Chemical Index of Alteration
T_1	58.91
T_2	59.50
T_3	63.99
R_1	58.93
R_3	59.83
R_4	76.41

4.3. Alteration index

Chemical alteration indices are widely used tools for assessing the intensity and nature of rock alteration based on major element geochemistry. Since they rely only on major element compositions, alteration indices can be easily applied to a wide range of geological datasets. The Chemical Index of Alteration (CIA), introduced by Nesbitt & Young (1982), is a widely recognized geochemical metric for quantifying the degree of chemical weathering in rocks:

$$CIA = \left[\frac{Al_2O_3}{Al_2O_3 + CaO^* + Na_2O + K_2O} \right] * 100 \quad (3)$$

Calculated using the molar proportions of major oxides, specifically Al_2O_3 , the amount of CaO incorporated in silicates, Na_2O , and K_2O , the CIA provides insight into the extent of feldspar decomposition and the relative enrichment of alumina due to the leaching of mobile cations during weathering processes. This index can sensitively capture subtle variations in alteration degree, even in rocks where mineralogical composition appears broadly consistent.

The Chemical Index of Alteration (**Equation 3**) was calculated from the XRF-derived major element compositions; the results can be found in **Table 2**. Samples from Tállya present slight variation, the T_3 sample being the most altered. In the case of samples from Recsk, sample R1 and R3 present similar alteration, while R4 is strongly altered.

4.4. Breakage properties

Breakage test results were evaluated using the t_n model introduced by Narayanan & Whiten (1983). The response of a rock to a given energy input can be described with the following equation:

$$t_n = A * (1 - e^{-b * E_{cs}}) \quad (4)$$

Where:

- A – represents the asymptotic limit to the t_{10} value with increasing impact energy,
- b – the curvature of the exponential decay,
- E_{cs} – the applied specific energy (kWh/t).

The most commonly used parameter to describe particle breakage is the t_{10} value, which expresses the percentage of product particles passing a size corresponding to one-tenth of the initial mean particle size of the tested material. This breakage index is widely applied in comminution studies as it provides a simple yet effective way to quantify the extent of fragmentation resulting from impact forces. In this study, the t_{10} parameter was determined for each sample based on the post-breakage size distribution. The relationship between the t_{10} values and the applied specific breakage energy, which reflects the energy input per unit mass of the particles, is presented in **Figure 5**.

The A and b values obtained from the model fitting (**Equation 4**) can be used to calculate the $A \times b$ value, which represents a single value that represents the susceptibility of a rock to impact breakage (Powell et al., 2014). In this study, the results were evaluated separately for each initial particle size fraction (see **Figure 5**), with the t_{10} model fitted individually to each size range. The corresponding $A \times b$ values for the samples are summarised in **Table 3**. The obtained $A \times b$ values clearly reflect the influence of both particle size and material properties on the breakage behaviour of the tested samples. The $A \times b$ values generally decrease with decreasing particle size across all samples, which aligns with typical breakage behaviour, where smaller particles show

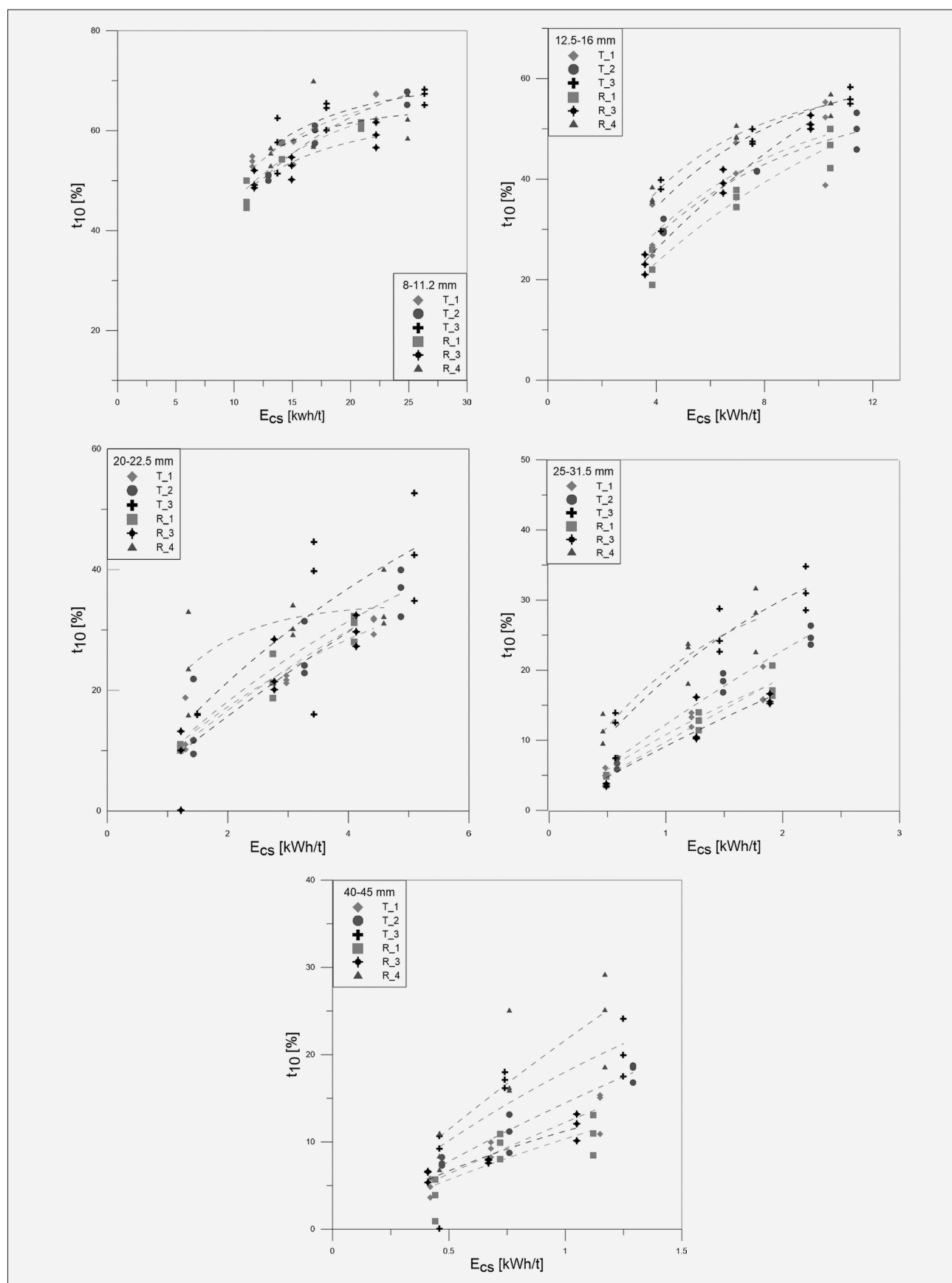


Figure 5. Relationship between t_{10} and specific breakage energy (E_{cs}) for the samples, grouped by initial particle size fraction

Table 3. The $A \times b$ value of the samples

Sample	Fraction size	$A \times b$	Fraction size	$A \times b$	Fraction size	$A \times b$	Fraction size	$A \times b$	Fraction size	$A \times b$
T_1	40 – 45 mm	13.24	25 – 31.5 mm	12.58	20 – 22.5 mm	10.62	12.5 – 16 mm	10.28	8 – 11.2 mm	8.44
T_2		16.70		13.21		10.58		9.87		6.62
T_3		28.59		23.79		17.36		12.42		8.94
R_1		15.01		10.06		9.35		6.67		7.62
R_3		16.12		9.91		10.61		6.75		8.36
R_4		24.24		28.98		29.84		14.21		9.77

higher resistance. However, some deviations from this trend were observed. For instance, in the 12.5–16 mm and 20–22.5 mm fractions, sample T_2 exhibited lower $A \times b$ values than the less altered T_1, suggesting localized heterogeneities or mineralogical variations influencing breakage susceptibility. Similarly, in the 25–31.5 mm fraction, R_1 showed a lower $A \times b$ value compared to R_3, despite both representing relatively unaltered to moderately altered samples.

Overall, the most altered samples (T_3 and R_4) consistently showed the highest $A \times b$ values across fractions, highlighting the dominant effect of alteration on increasing breakage susceptibility. Conversely, the least altered samples (T_1 and R_1) mostly exhibited lower $A \times b$ values, indicating greater resistance. The intermediate alteration samples (T_2 and R_3) displayed variable behaviour in some size ranges, which may reflect subtle microstructural or compositional differences.

5. Discussion

The influence of mineral composition and texture on particle breakage has been extensively discussed in literature (Lindqvist et al., 2007; Tavares & das Neves, 2008; Wang, 2015). However, the present study revealed only minor variations in the mineralogical composition across the investigated samples, largely associated with localised differences in alteration intensity rather than fundamental changes in the primary rock-forming minerals. All samples exhibited broadly similar mineral assemblages typical of andesitic rocks, dominated by plagioclase, pyroxenes, amphibole, and potassium feldspars. Similarly, while porphyritic textures with idiomorphic to hypidiomorphic plagioclase, pyroxene, and amphibole phenocrysts embedded in a microcrystalline to cryptocrystalline groundmass were consistently observed, only subtle textural variations related to alteration progression were present. These included the rounding of phenocryst edges, partial degradation of crystal boundaries, and, in the most altered samples, the near-complete loss of original mineral shapes.

In contrast, the degree of post-magmatic alteration showed a measurable effect on breakage behaviour. To quantify alteration intensity, the Chemical Index of Alteration (CIA) was applied, providing a geochemical proxy based on the depletion of mobile elements (Ca,

Na, K) relative to immobile aluminium. Although widely used in geochemistry, sedimentology, and weathering studies, CIA remains relatively underutilised in research focused on the mechanical performance of aggregates.

In this study the relationship between the Chemical Index of Alteration (CIA) and the $A \times b$ breakage parameter was examined to explore weather alteration intensity influences fragmentation behaviour (see Figure 6). Scatter plots comparing CIA with $A \times b$ breakage parameter revealed a consistent tendency for samples with higher CIA values to exhibit greater susceptibility to fragmentation. This trend was clearest in the 20–22.5 mm and 25–31.5 mm fractions, while it was less distinct in the finest and coarsest fractions. These observations suggest that increasing alteration, reflected by higher CIA values, weakens the rock and enhances breakage efficiency, although the strength of the effect appears to vary by particle size. Where the trend was weaker, additional geological factors such as microcracks, porosity or subtle microstructural variability may also have influenced the breakage response. Although the dataset is limited, the observed tendencies are in agreement with broader studies showing that alteration indices provide meaningful predictors of rock behaviour. Yildirim et al. (2014), for example, introduced the Process Alteration Index (PAI) as a geometallurgical tool for linking alteration to comminution response in porphyry copper systems, while Darwish et al. (2025) demonstrated that CIA effectively reflects mechanical weakening in hydrothermally altered uranium-bearing rocks. Pereira et al. (2024) further emphasised that post-magmatic alteration in volcanic rocks – particularly the formation of secondary clays – reduces their mechanical performance. Taken together, these findings indicate that CIA can serve as a useful geochemical proxy for evaluating the breakage response of altered andesites.

Scatter plots comparing smectite content with the $A \times b$ breakage parameter showed similar overall tendency: higher smectite contents were consistently associated with increased fragmentation susceptibility (see Figure 7). The effect was particularly noticeable in the coarser fractions, where even modest smectite enrichment corresponded to pronounced increases in $A \times b$ values. In finer fractions, the influence appeared less distinct, suggesting that additional geological factors may also contribute to the breakage response. Smectite, a

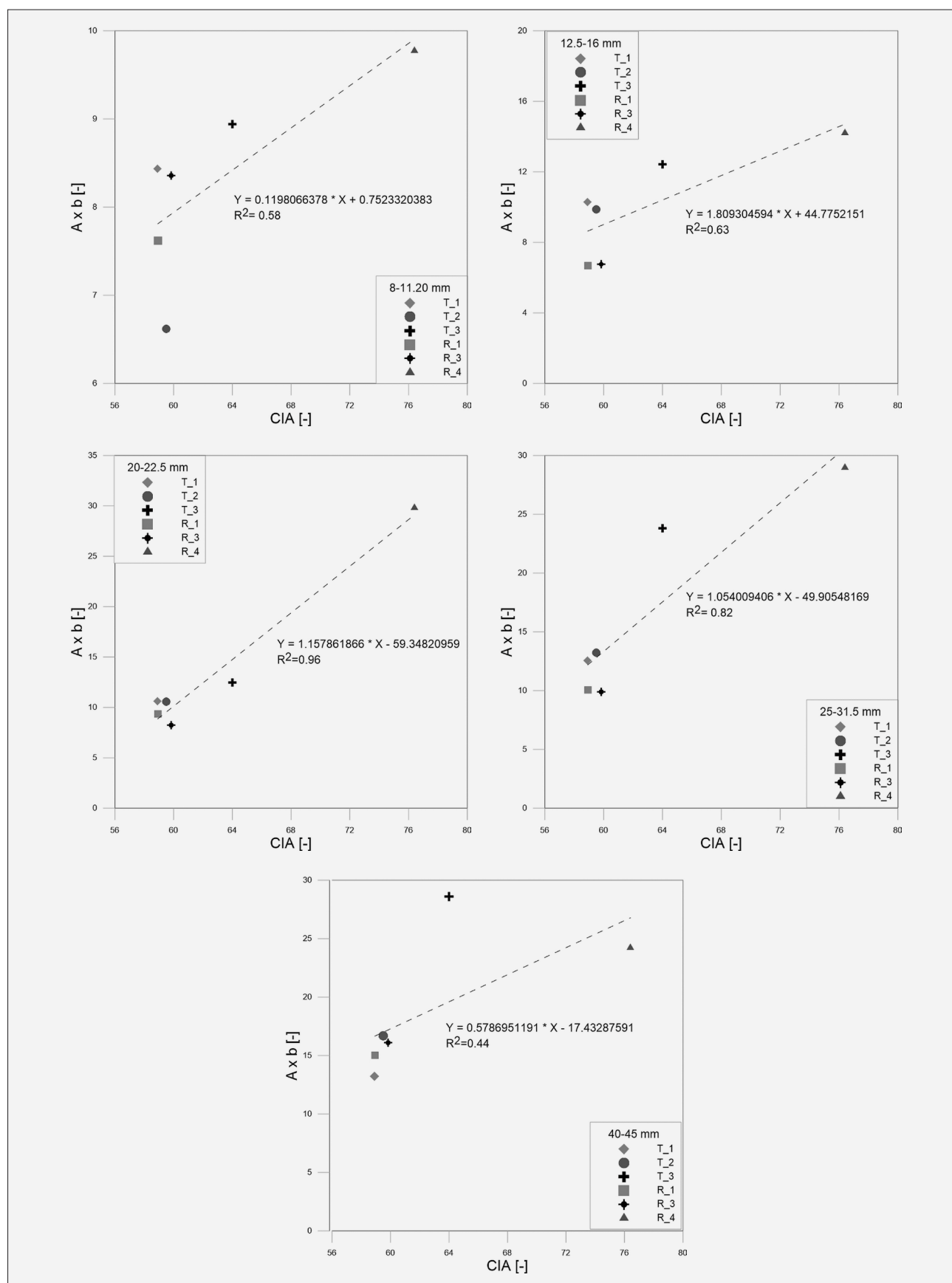


Figure 6. Plots showing the relationship between the Chemical Index of Alteration (CIA) and the Axb breakage parameter for different particle size fractions. The dashed lines are visual aids only, intended to emphasise the overall trend of increasing fragmentation susceptibility with higher smectite content.

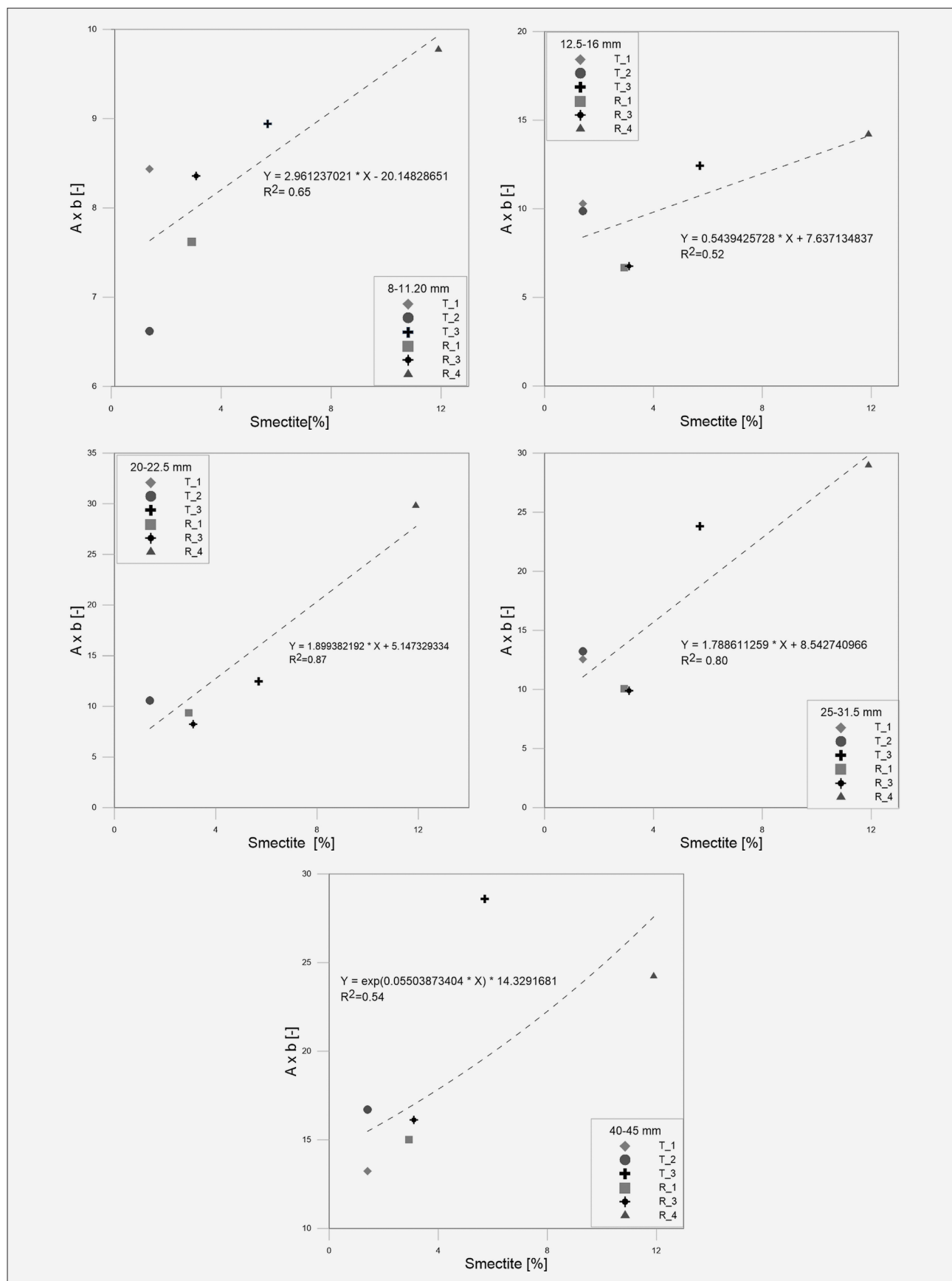


Figure 7. Plots illustrating the relationship between smectite content and the Axb breakage parameter across the investigated particle size fractions. The dashed lines are visual aids only, intended to emphasise the overall trend of increasing fragmentation susceptibility with higher smectite content.

secondary clay mineral formed mainly through low-temperature hydrothermal or weathering processes (Marfil & Maiza, 2012), is well known for weakening rock strength, promoting disintegration, and reducing durability due to its swelling properties and high water retention (Petrounias et al., 2018a). Even small amounts were linked in our dataset to noticeably higher $A \times b$ values, emphasising its disproportionate influence on fragmentation behaviour. These observations are consistent with previous work demonstrating that smectite and other phyllosilicates reduce strength and durability indices in volcanic aggregates (Petrounias et al., 2018b; Pola et al., 2014). The present results extend this evidence to controlled comminution testing, confirming the critical role of smectite in rock weakening.

Although smectite quantification captured a clear weakening tendency in our samples, a practical advantage of CIA is its broader applicability across alteration styles. CIA reflects the progressive depletion of mobile cations (Ca, Na, K) regardless of which specific secondary minerals form, making it suitable for felsic, intermediate, and mafic rocks (Choi et al., 2012). In contrast, clay-specific metrics (e.g. smectite content) are alteration-pathway dependent and may be less transferable where other assemblages (e.g. chlorite, kaolinite, carbonate) dominate (Mathieu, 2018). Given that andesitic systems can host multiple low-temperature assemblages – commonly smectite $\pm$ silica $\pm$ Fe-sulfates in acid-sulfate settings (Salaün et al., 2011) – CIA offers a more general first-order proxy for predicting breakage susceptibility across varied volcanic contexts, while mineralogical quantification remains valuable for mechanistic interpretation.

These exploratory findings complement earlier studies on volcanic and other magmatic rocks, which consistently report that alteration and secondary mineralisation lower aggregate quality and mechanical strength (Pola, 2014; Czinder & Török, 2019, 2021; Lampropoulou et al., 2020). They also align with reviews of aggregate performance tests, which highlight petrography, alteration, and microstructure as key determinants of fragmentation and abrasion resistance (Strzalkowski et al., 2021). By explicitly linking geochemical and mineralogical alteration indices to drop-weight test results, the present study contributes to bridging a gap between geological characterisation and comminution behaviour.

Although based on a limited dataset, the observed tendencies suggest that alteration indices such as CIA and smectite quantification could serve as first-order indicators of comminution performance. If validated on larger datasets, such metrics could provide quarry operators with practical tools to forecast crushing response before production, thereby supporting process optimisation, energy efficiency, and improved aggregate quality assessment. This preliminary contribution highlights the value of incorporating alteration parameters alongside mineralogical and textural descriptors in evaluating the mechanical response of volcanic rocks.

6. Conclusions

Given the overall uniformity of mineralogical and textural properties across the investigated andesite samples, alongside clear variations in alteration intensity and secondary mineral formation, a focused evaluation of alteration effects on breakage behaviour is particularly justified. While the influence of mineralogical composition and textural properties on fragmentation has been extensively studied, the role of alteration has received far less attention in context of comminution. The present study shows that incorporating alteration parameters such as the Chemical Index of Alteration (CIA) and smectite content provides valuable complementary information on the weakening mechanism that governs rock breakage. The CIA quantitatively captures the progressive chemical weathering, while smectite content directly reflects the presence of swelling clay minerals that weaken rock strength and promote fragmentation.

The observations indicate that both CIA and smectite exhibit consistent tendencies toward increased fragmentation susceptibility under impact loading. These results are in line with previous findings that emphasised the detrimental effect of alteration and phyllosilicate formation on the mechanical behaviour of volcanic rocks. However, detailed experimental approaches to quantify these effects, such as the one presented here, remain scarce and need to be pursued more extensively in future research.

Although the dataset is limited to six samples from Hungarian quarries – and the findings should therefore be regarded as a preliminary case study rather than representative of all volcanic aggregates – the applied methodology provides a foundation for future large-scale measurement campaigns and points toward the development of machine learning-based predictive approaches.

Despite these limitations, the study highlights the potential value of integrating alteration indices into the evaluation of comminution behaviour. Similar to geo-metallurgical approaches developed in ore processing, alteration metrics could, if confirmed on larger and more diverse dataset, serve as a practical predictive tool for assessing crushing performance in andesitic rocks. Such an approach would complement traditional petrographic methods, supporting more reliable aggregate quality assessments, better resource management, and improved process efficiency in industrial application.

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SAŽETAK

Preliminarno istraživanje utjecaja alteracije na svojstva usitnjavanja andezita iz kamenoloma Tállya i Recsk (Mađarska)

Ova preliminarna studija istražuje utjecaj postmagmatske alteracije na ponašanje andezitnih stijena tijekom usitnjavanja s posebnim naglaskom na kemijski indeks alteracije (CIA) i sadržaj smektita. Šest reprezentativnih uzoraka iz dvaju mađarskih kamenoloma (Recsk i Tállya), koji pokazuju uglavnom slična mineralna i teksturna svojstva, ali različite stupnjeve alteracije, podvrgnuto je ispitivanjima lomljenja pojedinačnih čestica u više granulometrijskih frakcija. Iako ograničen broj podataka ne omogućuje široke generalizacije, rezultati pružaju početne pokazatelje da su viši CIA indeksi i veći sadržaji smektita povezani s povećanom sklonošću fragmentaciji, što se očituje kroz povišene $A \times b$ parametre. Studija pokazuje da indeksi alteracije mogu pružiti vrijedne prediktivne informacije o odgovoru andezita na usitnjavanje. Dobiveni rezultati upućuju na važnost uključivanja parametara alteracije uz tradicionalne mineralne i teksturne karakteristike prilikom procjene ponašanja andezitnih stijena u proizvodnji agregata. Kvantifikacija smektita naglašava ulogu sekundarnih filosilikatnih minerala u smanjenju čvrstoće andezitnih stijena, dok CIA predstavlja šire primjenjivu mjeru intenziteta alteracije koja se može primijeniti u različitim vulkanskim kontekstima. Rezultati se predstavljaju kao studija slučaja koja ističe potencijal CIA indeksa i kvantifikacije smektita kao alata za procjenu, uz naglasak na potrebu za dodatnim istraživanjima s većim brojem uzoraka radi potvrde uočenih trendova.

Ključne riječi:

andezit, proizvodnja agregata, ispitivanje lomljivosti udarnim opterećenjem, alteracija, smektit

Author's contribution

Izabella Rebeka Márkus (PhD candidate): methodology, investigation, data curation, formal analysis, and writing – original draft. **Ádám Rác** (Associate Professor): conceptualization, methodology, supervision, and writing – review & editing. **Gábor Mucsi** (Professor): conceptualization, and writing – review & editing. All authors have read and agreed to the published version of the manuscript.

An Innovative Approach to Optimize the Comminution Circuit of Micronized Powder Production Plant

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Original scientific paper



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Abstract

This research was conducted to investigate and optimize the comminution circuit of the Arak Company in which bentonite micronized powder is produced. The criterion for evaluating was the optimal performance of grinding systems and the efficiency of the devices, and simultaneous optimization was considered in feed and product sizes, capacity, and energy. In addition to the Bond formula, Morrell and Austin relations, as an innovative approach, have also been employed to study the different parameters such as rotation speed and mill filling percent. In this unit, the main grinding operation is performed by a tube ball mill that is located in a closed circuit with two air separators. The size of the final product is finer than 75 microns, and 48 kilowatt-hours of energy are consumed to produce one ton of bentonite. About 59% of the total plant energy consumption was related to the grinding circuit of tube mill. The size of the tube mill feed was 3500 microns (d_{80}), the percentage of charge and accumulation were 21 and 14% respectively, the average diameter of the steel balls was 60 mm and the relative rotation speed of the mill was 79%. The results showed that the efficiency of the grinding circuit is poor, and it was merely about 30%. By increasing the percentage of charge of the tube mill from 21 to 70%, increasing the size of the mill feed by 7000 microns, using balls with diameter of <40 mm, and reducing the relative rotation to 60%, the efficiency of the grinding circuit can be increased by 50%. It would be noted that about 16% of the coarse particles in tube mill's product are agglomerated pieces. Therefore, reducing this phenomenon will have a direct effect on the reducing energy consumption and increasing grinding efficiency, as well.

Keywords:

micronized powder; efficiency; tube mill; bentonite; Morrell and Austin relations

1. Introduction

Bentonite is one of the important non-metallic minerals whose micronized powder is widely used in industry (Kutlić et al., 2012; Vetyugov and Matveeva, 2024). Bentonite refers to clay soil that is essentially composed of montmorillonite (Kutlić et al., 2012; Ngcobo et al., 2022). Its color is often white, pale green, pale blue (fresh surface) to cream (weathered surface), gradually tending to yellow, red and brown (Kutlić et al., 2012). Feldspar, biotite and quartz minerals are usually found together with bentonite (Grim and Guven, 2011). Bentonites have exchangeable ions of sodium, calcium and magnesium (Kutlić et al., 2012), and after zeolites, they show the highest ion exchange capacity among minerals (Bentonite, 2005; Kutlić et al., 2012).

Each of the various applications of bentonite requires specific properties, which are summarized below. For

drilling mud, mud recovery (the amount of bentonite mud with an apparent viscosity of 15 centipoise obtained from one ton of clay), gel strength (the difference in weight recovery over a 10-minute period after mixing), wall-forming property (the amount of water loss through a filter paper when a bentonite pulp with an apparent viscosity of 15 centipoise is subjected to 100 psi), and particle size (97.5% finer than 75 microns) are among the important properties (Kutlić et al., 2012).

In the case of casting, the chemical composition of bentonite is usually 92% montmorillonite, 3% quartz, and 5% feldspar, 6-12% moisture, pH 8.3, green compressive strength of 656 kPa, and a particle size of 65-95% finer than 75 microns. In pelletizing, particle size is a very significant issue, typically 70-90% finer than 45 microns, with moisture content of up to 10% being appropriate (Bentonite, 2005; Stojiljković and Stojiljković, 2017). In the case of using bentonite to make a floor or wall impermeable, clay with 80-90% bentonite with particle size of 840 to 300 microns is required (Kutlić et al., 2012). The use of bentonite as an adsorbent for removing heavy metals from wastewater also

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depends on pH, contact time, temperature, and amount of adsorbent used (Alsaed et al., 2022; Rockson-Itiveh et al., 2023; Lamrani et al., 2025). Bentonite clay is known for its exceptional water absorption and swelling properties, primarily due to its composition of the clay mineral montmorillonite. This clay can absorb significant amounts of water, expanding its volume considerably, and also exhibits high cation exchange capacity and low permeability. Specific gravity: 2.8 ± 0.03 , Room water content: 6–8%, Montmorillonite content: 53%, Main accessory minerals: quartz, feldspar, plagioclase, calcite, Content of particles of size $<5 \mu\text{m}$: 73%, Liquid limit: 505%; Plastic limit: 45%, and Cation exchange capacity: 71.9 meq/100 g are necessary for water absorption and swelling properties (Wang et al., 2024).

Due to the abundance of bentonite in nature and the extensiveness of its reserves in most countries of the world, high-quality reserves are usually extracted. As a result, bentonite processing is in most cases limited to crushing and grinding, which only includes drying and breakage, using various mills. Therefore, bentonite must be of good initial quality, because no separation operations are performed on it (Kutlić et al., 2012). The production of bentonite powder is often used by steelmaking industries and drilling companies and is purchased in bulk. The characteristics of the product desired by the two steel and drilling companies are given in Table 1.

Table 1. Product characteristics

Employer	Steel Company - Drilling Company
Size distribution	Maximum 3% remaining on 45 microns sieve
Montmorillonite content by XRD analysis	92%
Mud recovery	22 (one ton of bentonite powder has the ability to produce 22 cubic meters of drilling mud with a viscosity of 15 centipoise)
Water absorption	600%
Moisture	8-12%

In general, comminution including crushing and grinding system is the most important and fundamental stage of processing various ores, because it is at the beginning of the mineral processing stages and accounts for the highest fixed and operating/current costs (50-70% of energy consumption) (Bogdanov et al., 2022; Li, 2024). Therefore, optimizing energy consumption in comminution systems will have a great impact on reducing energy consumption in all mineral processing plants (Khurramatov and Mukhamedbaev, 2023). Considering the above, implementing optimization systems in mining units and related industries is inevitable (Asa'd and Levesque, 2024; Elbendari and Ibrahim, 2025; Khan et al., 2025; Yildirim et al., 2025).

The main purpose of this research is to study and investigate the performance of the devices in the Arak micronized powder production plant and, based on the results, to provide necessary optimization solutions, with an innovation in employing Austin and Morrell equations.

1.1. Research Objectives

- The process of producing bentonite powder is usually carried out using a ball mill, and in this research, the use of a tube mill instead of a ball mill was investigated and an attempt was made to optimize it.
- One of the properties of bentonite, like other clays, is its re-adhesion after the micronized process. This issue was observed and investigated in this research.
- The comminution of material, and classification in air classifier was evident in this research and was addressed.
- Providing a scientific and operational method for examining the performance of the production line.
- Providing solutions and suggestions for further comparative studies.

1.2. Description of the production process

First, the ore is supplied from the mines with initial sizes up to 30 cm and is deposited, and is reported for further size reduction process. Then, these materials are conducted into a jaw crusher with an opening of 15 cm. Of course, particles larger than 15 cm are crushed on site. It should be noted that due to the smaller dimensions of bentonite than the outlet opening of the jaw crusher, they do not usually tolerate the breakage, and merely pass the jaw crusher with no changes to their size. However, jaw crusher product is then fed into the dryer, by a conveyor belt until their moisture content reaches the permissible limit (Kutlić et al., 2012). Then, the materials enter the hammer mill and, after being crushed to a size finer than 12 mm, are transferred to the material storage bin, by a bucket elevator. From the bin, they are directed to a tube mill by a feeder to be micronized into particles finer than 75 microns. The milled product is forwarded to two air classifiers, and after separation, the coarse particles are transported by screws to the beginning of the mill inlet (circulating load), and the fine particles (final product) are directed to the product bunker.

1.2.1. Tube mill

In most micronized powder plants, a jaw crusher, hammer mill, and ball or roller mills are normally used, respectively. This plant has two independent micronized powder production lines. In this production unit, the materials crushed by the hammer mill enter a 15-ton bin and from there, they enter to the tube mill along with the

Table 2. Specifications of the tube mill

Type of mill	Tube mill (ball-ball)
Discharge type	full screen
Internal mill diameter	1.54 m
Internal length of the mill	5.2 m
Internal volume	9.3 m ³
Length of each chamber	2.6 m
Middle screen opening	5 mm
End screen opening	3 mm
Grinding load	steel balls in sizes 85, 55 and 40 mm
Specific mass of balls	7.5 g/cm ³
Liner type	Steel type
Driven force type	electric motor and gearbox
Nominal motor power	250 kW
Rotation speed	26 rpm

circulating load. The amount of materials entering the tube mill from the bin is adjusted manually by the valve. One of the characteristics of tube mills is the presence of a diaphragm between the two chambers or compartments, which performs the particles classification. The diaphragm separates the two chambers of the mill from each other, and prevents the passage of coarse particles to the next one. The diaphragms could control the material level inside the chambers and therefore prevent dead space in the breakage areas, by using the material flow mechanism.

This tube mill consists of two chambers with a length of 2.6 meters. The materials in the first chamber are ground due to the presence of a middle screen with an opening of 5 to 15 millimeters and enter the second chamber for the grinding and micronized stage. The opening of the final screen is 3 mm. The materials were ground in the first chamber pass through the screen by the air flow and the pressure of the load inside the mill. At the end of the mill, a fan with a cyclone is installed to accelerate the movement of the materials to the mill and the dust and particles resulting from this process are collected and directed to the cyclones as well. The fan motor rotation speed is 1300 rpm and at the end of each 8-hour work shift and/or for every 20 tons of products, about 400 kg of fine particles are collected which are transferred to the classifier inlet again. Considering that the main burden of the grinding operation is mostly related to the tube mill and the highest energy consumption is accordingly by this device, the focus of this research is on examining the tube mill grinding circuit. The specifications of the tube mill are given in **Table 2**.

1.3. Mechanism and relevant parameters in comminution circuit

One of the most important and fundamental units of mineral processing is comminution system which con-

sists of crushing and grinding stages (**Matsanga et al., 2023; Upadhyay, 2025**). The goals of comminution include releasing valuable minerals, producing particles with specific dimensions and shapes, and increasing the specific surface area for various reactions (**Khan et al., 2025; Yildirim et al., 2025**). With the optimal performance of the comminution circuit, in addition to significant energy saving, the optimization of subsequent processing stages is also facilitated (**Chimwani and Bwalya, 2021; Shields et al., 2024; Elbendari and Ibrahim, 2025; Wan et al., 2024**).

In order to optimize each size reduction line, four main criteria (feed and product sizes, capacity, and energy) are needed to be in their optimal state (**Lowrison, 1974; Prasher, 1987; Mular et al., 2002**). The relationships and interactions between these four criteria are expressed by Bond's equation. Bond's equation is the most common approach to estimate the required energy by crushers and mills. Of course, this method also has some shortcomings, for example, the critical speed, the filling amount and the particles residence time in the mill, and the portion percentage of feed particles which are finer than the product are not considered. If the kinetics and the mode of breakage, as well as the time of grinding are known, in fact, all aspects of grinding are accordingly considered. The kinetics of grinding and the mode of breakage are called the selection and breakage functions, respectively, and the grinding time is also described by the residence time distribution. The breakage function parameter does not change with variation of the grinding conditions, and therefore is not involved in the optimization criteria. However, the selection function depends on the grinding conditions such as mill diameter, volume and diameter of balls used, mill rotation speed and the filling percentage the mill by powder (**Bond, 1961a; Bond, 1961b; Lowrison, 1974; Austin et al., 1984; Prasher, 1987; Mular et al., 2002**). Therefore, in addition to the Bond relation, which is based on the main parameters of the comminution circuit such as the feed and product sizes, the formulas and relations of Morrell and Austin have also been employed which is an innovation in order to calculate and investigate the effect of secondary parameters such as the rotation speed and the degree of filling of the mill (**Morrell, 2019b; Austin, 1990; Golpayegani and Rezai, 2022**).

In this research, after presenting the circuit grinding mechanisms, the effective parameters in optimizing the grinding circuit were investigated, for which the applied procedure is shown in **Figure 1**.

1.3.1. Ball trajectory tracking with image processing system

Usually, optimization and design of milling circuits is based on laboratory and semi-industrial studies. One of the methods of validating the experiments is tracking the ball trajectory and monitoring the mill power draw on a

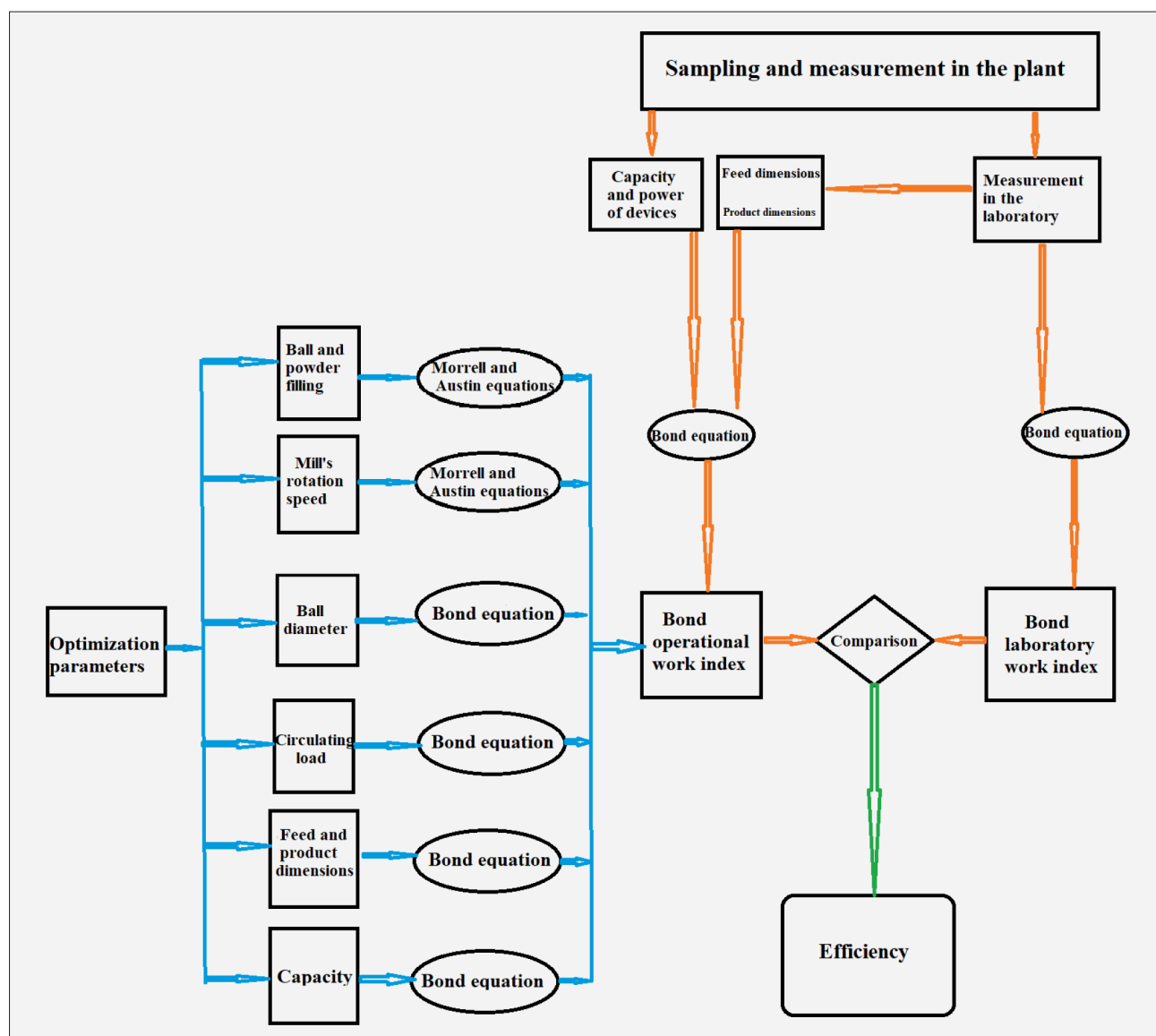


Figure 1. Summary of operations for calculating efficiency and optimizing the grinding line

laboratory scale (Li et al., 2022). The balls trajectory tracking and velocity monitoring are also performed with an image processing system (Maleki-Moghaddam et al., 2013; Makgoale, 2019; Bian et al., 2017). The results of a series of image processing experiments using a camera to record the motion of the charge under different operating conditions with a high-intensity light source and a laboratory-scale ball mill, with a constant rotation speed of 52.75% of the critical speed (37.31 rpm) and varying the liner type and percentage of charge (0.5, 20, 40 and 60) and measuring the shoulder and heel angle parameters, which indicate the following (Mori et al., 2004):

- The liner type has a significant effect on the charge profile and the improvement of the cascade motion is a function of the load level in the mill.
- Increasing the load level from 20-40% reduces the cascade. The velocity of balls is balanced, the dis-

tance between the load surface and the heel is reduced and the ball impact velocity at the heel is also reduced. Therefore, its effect also reduces the kinetics energy resulting from the impact of the balls, accordingly.

- As shown in Figure 2, increasing the load level by 60% reduces the cascade effect. The type of liner has a significant effect and under these operating conditions the mill product becomes finer.

1.3.2. Bond Work Index

The relationship between the ore breaking ability and the energy required for the grinding device is expressed by Bond's equation. The energy required for the size of ore from the feed size $d_{80,F}$ to the product size $d_{80,P}$ is given by Bond's equation, which is defined in Equation 1 with P_0 in terms of (kWh/t) (Bond, 1961a; Bond, 1961b).

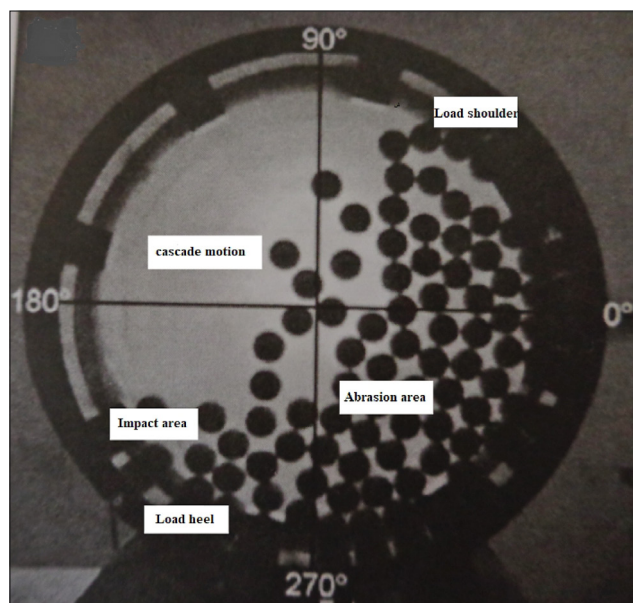


Figure 2. Charge movement profile and mechanism in mill at 60% occupancy (Fuerstenau and Han, 2003)

$$P_0 = 10 w_i \left[\frac{1}{(d_{80,P})^{0.5}} - \frac{1}{(d_{80,F})^{0.5}} \right] \quad (1)$$

The work index (w_i) is defined as the reference energy required to reduce hypothetically one short ton (907 kg) of material from very large size (theoretically infinite/extreme size) to reach to product size of 100 microns. This index is normally used to determine the energy required for equipment design, such as crushers and some tumbling grinding mills (rod and ball mills), optimization of an active circuit to reduce energy consumption and increase efficiency. The control of the energy required for the process and the determination and selection of mills are also evaluated with this parameter. The larger this index, the more resistant the ore is to be ground, 7-10 kWh/t for soft ores, 10-15 kWh/t for medium to hard ores, and up to 25 kWh/t for relatively very hard materials as well (Morrell, 2019b).

In Equation 1, feed and product d_{80} are in microns and the sizes are conventionally the screen sizes which have 80% of the particles passing through it. The ores work index value is determined by a standard laboratory method. Based on the definition of Bond, there are standard studies to measure the value of the Bond work index to accurately obtain the power required for a wet ball mill. In this method, an overflow type ball mill with 2.44 m diameter has been specified, operating in a closed circuit with a classifier at 250% of circulating load. The ore used is of very coarse size which has to be reached 80% finer than 100 microns, and the amount of energy consumed will accordingly be equal to the work index of the used ore being tested. Given the difficulty of this method for determining the work index, the standard Bond method was experimentally defined (Bond, 1961a;

Bond, 1961b). It should be noted that the work index of a specific ore, as measured using the standard laboratory method, is usually not directly comparable to its grinding conditions in an industrial environment and some relevant correction factors must be applied. In addition, to evaluate a ball or rod mill power that is to grind W t/h of material, it is necessary to calculate the power required for grinding from Equation 2 (Lowrison, 1974):

$$P = P_0 \times W \quad (2)$$

1.3.2.1. Bond Laboratory and Operational Work Index

In order to determine the laboratory work index, the Bond standard ball mill method is usually used. In this test, the grinding and classification operations are carried out in a dry manner to achieve equilibrium conditions. The dimensions of the required mill are 305×305 mm (diameter × length) rotating at a speed of 70 rpm. Its balls load is 285 steel balls weighing 22.311 kg. Using the Bond formula (Equation 3), the laboratory work index is obtained using the Bond standard ball mill procedure (Bond, 1961a; Bond, 1961b).

$$w_{i,lab} = \frac{44.5}{[(P_1^{0.23}) \times (G_i^{0.82})]} \times \left(\frac{10}{\sqrt{P_{80}}} - \frac{10}{\sqrt{F_{80}}} \right)^{-1} \quad (3)$$

Where w_i is the work index (kWh), F_{80} and P_{80} are the sizes which 80% of the feed and final product are finer, respectively. P_1 is the control screen (microns) and G_i is the weight of particles finer than the control screen in grams produced from one mill cycle (rotation).

The operational work index $w_{i(op)}$ is calculated by measuring the net power consumed by the mill in a given time interval to grind a given tonnage of mineral material and by substituting it into the bond formula (Equations 1 and 2), based on Equation 4.

$$w_{i(op)} = \frac{W}{Q \left(\frac{11}{\sqrt{P_{80}}} - \frac{11}{\sqrt{F_{80}}} \right)} \quad (4)$$

Where:

- $w_{i(op)}$ – operating work index (kWh/t),
- Q – mill input tonnage (t/h),
- P_{80} – Mill product size (microns),
- F_{80} – Mill feed size (microns),
- W – net power (kW).

1.3.2.2. Energy consumption and efficiency

In general, the energy consumption in the mineral comminution line is very high and directly affects the consumption costs of the plant as well. Therefore, periodic monitoring of the operation and efficiency of the devices is accordingly inevitable (Golpayegani and Rezai, 2022). In order to determine the grinding effi-

Table 3. Efficiency classification based on the ratio of the bond work index (Lowrison, 1974)

Efficiency	$w_{i(\text{lab})}/w_{i(\text{opt})}$
Ideal	1
Good	0.9
Acceptable	0.7
Poor	Less than 0.7

ciency, based on **Table 3**, the ratio of the laboratory and operational work index is used (Bond, 1961a; Bond, 1961b).

Two types of mill inefficiency could happen within the grinding process: indirect and direct inefficiency (Austin et al., 1984; Kelly and Spottiswood, 1989; Morrell, 2009). Indirect inefficiency takes place when the mill can break ores efficiently, but energy is wasted in the overgrinding of materials which are fine enough, and consequently more fines are produced. This state is mostly observed when the circulating load is not adjusted. The second type is direct inefficiency, which occurs when the mill conditions cause poor breakage. The reasons for poor breakage could stem from overfilling of the load and powder inside the mill, and therefore the ball-powder-ball is weak because of the thick mass cushion. Another issue is underfilling of the load and powder inside mill, which causes energy to be used for ball-ball-liner action, and is not efficiently applied on particles (Austin et al., 1984; Kelly and Spottiswood, 1989; Morrell, 2009).

It is worth mentioning that one more type of inefficiency could happen, which is related to defects in the energy supply and transmission system (dynamo, shaft, gearbox, etc.), and this is not due to process conditions.

1.3.3. Morrell and Austin relationships

In order to predict the tensile strength of ball, autogenous (AG) and semi-autogenous (SAG) mills, valid equations and models have been presented by Morrell and Austin (Austin, 1990; Morrell, 1993; Morrell, 2016; Morrell, 2019a; Morrell, 2019b; Golpayegani and Rezai, 2022). These relations have been used to calculate the net power of the tube mill and to select the optimization parameters (Equations 5, 6 and 7) (Morrisson and Morrell, 1997; Morrell, 1996; Morrell, 2004).

$$\text{Gross power} = \text{net draw power by load} + \text{power at no load} \quad (5)$$

$$P_t = K D_m^{2.5} L_e \rho_c \alpha \delta \quad (6)$$

$$P_e = 1.68 D_m^{2.5} [\varphi_c (0.667 L_d + L)]^{0.82} \quad (7)$$

Where:

P_t – Gross power (kWh),

P_e – No-load power (kWh),

D_m – Internal diameter of the mill (m),

L_e – Effective length of the mill, including the conical end (m),

ρ_c – Specific gravity of the total load of materials inside the mill (including the crushed load and pulp inside the mill),

K – Calibration constant that varies with the type of discharge (for mills with overflow discharge it is 7.98 and for mill with grate discharge it is 9.1),

L_d – Average length of the two conical ends and is calculated from half the difference between the central length of the mill and the length of its cylindrical section.

Austin also proposed the following relations for calculating α and δ (Austin, 1990):

$$\alpha = J_t (1 - 1.03 J_t) \quad (8)$$

$$\delta = \varphi_c \left[1 - \left(0.1 / 2^{9-10\varphi_c} \right) \right] \quad (9)$$

φ_c – Mill speed relative to critical speed,

J_t – Part of the mill occupied by the total load,

α – Factor related to the relative degree of filling,

δ – Factor related to the rotation speed.

1.3.4. Circulating Load

In many industries, the milled product must be finer than a certain size, but the presence of excess fines is also undesirable. The presence of less fines in product, results in a steeper size distribution curve, which means the product distribution would be a narrow size. Therefore, an important and general principle in grinding is to prevent excess fine production. It is therefore essential for materials that have been sufficiently fined are removed from the circuit quickly, in order to prevent the overgrinding of particles. In an open circuit where there is no size classification device (classifier) in the circuit, sufficiently fine particles move through the mill and become finer, while at the same time coarse particles are ground as well. The presence of a classifier or a closed circuit means that the mill operates at a higher flow rate (fresh feed plus circulating load), resulting in the particles having a shorter residence time. If the initial flow rate is Q t/h and the circulating load is T t/h, the whole feed of mill is $Q+T$. This flow rate, higher than Q , causes the material to exit the mill more quickly. Therefore, the fines are separated inside the classifier and the coarse particles return to the mill for further breakage. The final effect would be that the size distribution particles inside the mill would shift to the presence of coarser particles and the finer particles have a shorter residence time. Accordingly, less over-grinding of fine particles and reducing the amount of very fine particles production occurs. Therefore, circulating load in grinding circuits would play a key role in order to control the amount of fines production (Wills, 1997).

2. Materials and Methods

2.1. Evaluation of the comminution circuit

In this study, the comminution circuit of Arak bentonite Micronized Powder Company was evaluated. In order to evaluate the comminution circuit, the current line should be reviewed and parameters which are effective in optimization should be calculated and compared with the initial design values (if any). To evaluate the current line, the following seven steps were considered:

- Sampling from different points of circuit;
- Measuring the input and output tonnage of different parts of the production line, the input load to the plant, the input and output of the mills and classifiers;
- Measuring the electric currency of each device from the electrical panel to calculate the power consumption;
- Running sieve analysis tests and determining the particle size, and also determining the laboratory bond index;
- Calculations related to energy consumption and determining the devices efficiencies;
- Material and energy balance of the comminution circuit;
- Calculations related to other parameters effective in optimization.

2.2. Equipment used for testing

The equipment used in this research is divided into two parts:

- Required and handmade sieves for granulating the incoming load from the mine in the production unit;
- Standard laboratory equipment including:
 - ASTM standard laboratory sieves;
 - Digital scale with an accuracy of one hundredth of a gram;
 - Bond ball mill;
 - Sample divider.

2.3. Sampling

In order to control the operations in a mineral processing plant and adjust it, to achieve appropriate conditions, it is necessary to examine the load of different plant streams, in terms of quality and quantity. This requires having samples that represent the load of those streams. Sampling may be manual or automatic, and measurement of the desired parameters in each stream was carried out on the samples taken. It was obvious that the desired tests must also be carried out with sufficient accuracy, otherwise subsequent analyses would be disrupted (Wills, 1997).

According to Table 4, the minimum sample weight required from the initial load of the plant, and the hammer mill output was calculated as 3768 and 3 kg, respectively (based on Gy's equation), and in the implementation, the weight of the tested samples was considered close to the calculated weights. The results of the calculations to determine the minimum sample weight of the tube mill and classifier output (9, 21 and 0.05 g) were very low and not applicable. Therefore, by modelling and reviewing similar research studies (Dehghani et al., 2016; Dehghan et al., 2008), samples with an approximate weight of 350 and 90 g were supplied.

Table 4. Sampling location and amount

Row	Sampling location	Number of samples
1	Initial material Heap	1
2	Hammer mill outlet	four 5 kg samples
3	Tube mill outlet	four 3 kg samples
4	Coarse grain of classifier	four 3 kg samples
5	Fine grain of classifier	four 3 kg samples

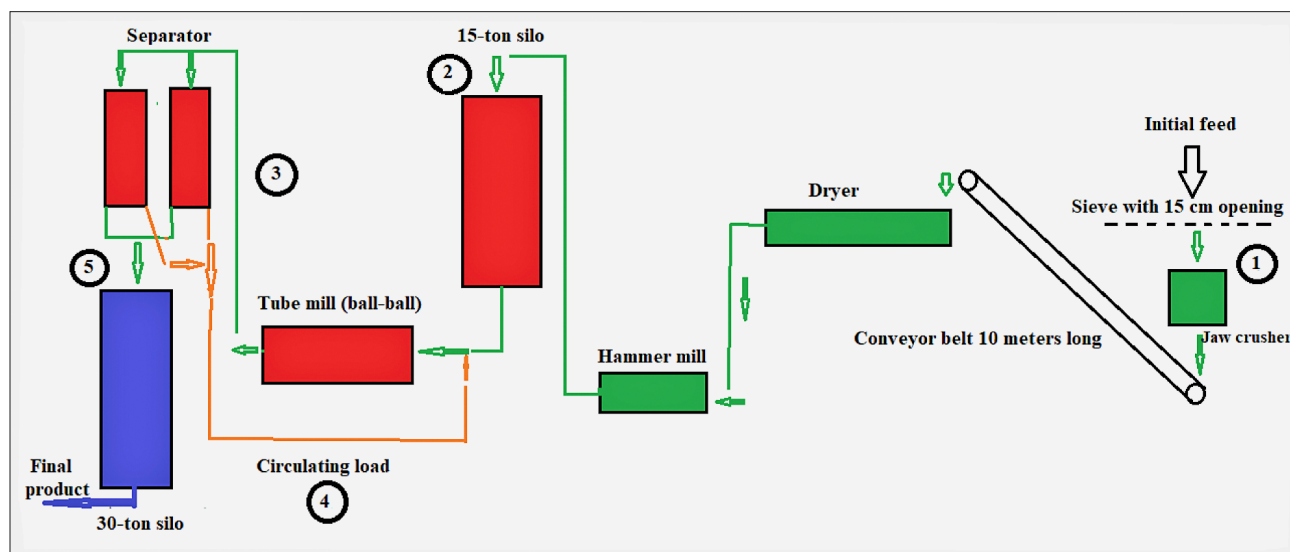


Figure 3. Flowsheet of the micronized powder production line, and sampling points

2.3.1. Sampling from the plant's feed (run-off-mine)

To supply from the plant's feed, 4 trucks were unloaded in a cone shape with about 72 tons. Using a large loader, a quarter of the load weighing approximately 18 tons was separated and placed in a cone, at another location, and from this load, another quarter weighing approximately 4 tons was transferred by a small loader as a representative sample. Initially, large pieces of mineral material with dimensions greater than 15 cm were crushed. After running a sieve analysis test, the particle size distribution was determined by sieves with openings of 10, 7.5, 4.5, 3.2, 2.5 and 1.1 cm, and a graph of cumulative percentage passing through the sieve was drawn to determine relevant d_{80} .

2.3.2. Sampling from the production line

Initially, flow rates were measured and samples were taken from different points of the plant, numbers 2 to 5 according to the flow sheet in **Figure 3**, twice per shift (at 4-hour intervals) over 2 consecutive days. Sampling

was performed manually from the flanges of the connection pipes of the grinding circuit.

3. Results and discussions

Based on sampling and sieve analysis tests, the results of the particle size distribution of each stage of comminution circuit were determined, including the plant input, from the hammer mill output, the tube mill input, the classifiers input, from circulating load, and finally from plant's output. A summary of the performed tests results which are required for further and subsequent calculations is given in **Table 5**.

Using the information in **Table 5** and assuming a control screen of 150 microns, the work index value was calculated, according to **Equation 3**, which is equal to 5.9 kWh/st, or 6.37 kWh/t by applying a coefficient of 1.1 (converting short to metric ton). According to the classification presented in the energy consumption and efficiency section, the calculated work index was lower than 7 kWh/t, and it therefore is classified as a very soft material.

3.1. Material and energy balance

Since most of the energy required for the comminution circuit is supplied by electrical energy, so by examining the average consumption in two months, and the tonnage of the product for each month, the average energy needed for bentonite breakage to a size of 75 microns was determined, which is presented in **Table 6**.

The results in **Table 6** indicate that the average energy required to produce one ton of bentonite product (finer than 75 microns) was calculated to be 48 kWh. In order to measure the tonnage of material flow rate and energy in different parts of plant, it was measured during 4 times with 4-hour intervals, and its average was recorded as the material flow rate. Then, by referring to the control room and electrical panels, and measuring the frequencies (ampere) consumption values for each device during 4 times, the average electrical ampere was determined to calculate the power consumption in kilowatts. Then, the material and energy balance in the comminu-

Table 5. Results of Sieve Analysis Tests

d_{80} plant's feed	73 mm
d_{80} hammer mill product	8.5 mm
d_{80} tube mill feed	3350 μ m
d_{80} classifier feed	380 μ m
d_{80} classifier coarse part (circulating load)	380 μ m
d_{80} classifier fine part (product)	48 μ m

Table 6. Electricity consumption and product tonnage at the Arak Company in two months

Time period	Electricity consumption (kWh)	Product tonnage	Energy required for one ton (kWh)
First month	21600	440	49
Second month	14500	305	47
Total	36100	745	48

Table 7. Material and energy balance of different parts of the production line

	Energy consumption (kWh)	Material flow rate (t/h)	Energy consumption for 1 ton (kWh)	Percentage share of total consumption
Hammer mill	25.2	9	2.8	5.9
Tube mill	102	5.5	18.5	38.5
classifiers	54	5.5	9.8	20.4
Fine-grained part of classifiers		2.2		
Coarse-grained part of classifiers		3.3		
Other parts (fans, cyclones, conveyors, elevators, etc.)	----	----	16.9	35.2
The whole set of grinding line	----	----	48	100

tion circuit was examined. A summary of the results is presented in **Table 7**.

3.2. Net power of the mill using Morrell and Austin models

Since it is not possible to measure the net power of the mill on site, therefore, using **Equations 5 to 9** and also **Equations 10 to 14 (Austin, 1990)**, first some parameters of **Table 8** were determined and then the values of α , ρ_c , P_t and P_e were obtained as 0.167, 3.8 t/m³, 66.3 kW and 15.8 kW, respectively. Finally, the net power of the tube mill was calculated as 50.5 kW. Therefore, the ratio of net power (50.5) to gross power (66.3) was obtained as 76%, which will be applied in calculations related to the operational work index.

Table 8. Parameters required in Morrell and Austin relations

Inside diameter of the mill (m)	D_m	1.54
Effective length of the mill (m)	L_e	5.2
Specific weight of the load (t/m ³)	ρ_c	3.8
Calibration constant	K	9.1
Length of the cylindrical section of the mill (m)	L_d	5.2
Speed of the mill relative to the critical speed	ϕ_c	0.79
Part of the mill occupied by the total load	J_t	0.214
Factor related to the relative degree of filling	A	0.167
Factor related to the speed of rotation	Δ	0.75

$$\alpha = J_t(1 - 1.03J_t) \quad (10)$$

$$\delta = \phi_c \left[1 - \left(0.1 / 2^{9-10\phi_c} \right) \right] \quad (11)$$

$$\rho_c = \frac{(1 - \phi)J_t \left(\frac{\rho_R}{M_R} \right) + 0.6 J_B \left(\rho_b - \frac{\rho_R}{M_R} \right)}{J_t} \quad (12)$$

$$P_t = K D_m^{2.5} L_e \rho_c \alpha \delta \quad \text{kW} \quad (13)$$

$$P_e = 1.68 D_m^{2.5} [\phi_c (0.667 L_d + L)]^{0.82} \quad (14)$$

In order to determine the maximum value of α , the derivative of **Equation 10** with respect to J_t is set equal to zero (**Equation 15**).

$$\alpha' = 0 \rightarrow 1 - 2.06J_t = 0 \rightarrow J_t = 0.485 \quad (15)$$

The value of α_{max} by using $J_t = 0.485$, is 0.243.

3.3. Efficiency of the comminution circuit

In order to optimize the comminution circuit, the entire circuit must be evaluated and the criterion for this evaluation is the calculation of the efficiency of each device. Therefore, this decision was made that at the beginning, with the efficiency of tube mill to be calculated. Next, the

efficiency of the closed grinding circuit (tube mill and classifier) was investigated and finally, the efficiency of the hammer mill (primary crushing) was studied.

3.3.1. Efficiency of the tube mill

By referring to the plant electrical and control panel, the average frequency consumption (ampere) of the tube mill was measured over 4 days which was 170 amperes. According to the ϕ in **Equation 16**, the power consumption of the mill's dynamo was calculated to be 102 kW (0.6 kW of energy is consumed per ampere) (**Abdulkareem et al., 2021**).

$$p = \sqrt{3}VI \cos \phi \quad (16)$$

Where:

- p – the power consumption (kW),
- V – the 3-phase electrical voltage in volts which is approximately 380 v,
- I – the current consumption of the device in amperes,
- $\cos \phi$ – considered to be 0.9 according to the technical specifications of the dynamo.

Table 9. Parameters required to calculate the ball mill operating work index

Mill feed size	3350 μm
Mill product size	380 μm
Mill feed Tonnage	5.5 t/h
Measured power	102 kW
* Pure power	77.5 kW

* The net power is achieved by multiplying the measured power by the factor 0.76 (net power/measured power=0.76).

According to the data in **Table 9** and the power consumption of the tube mill (102 kW), the operational work index was obtained from **Equation 17** as 37.7 kWh/t.

$$w_{i(op)} = \frac{W}{Q \left(\frac{11}{\sqrt{P_{80}}} - \frac{11}{\sqrt{F_{80}}} \right)} \quad (17)$$

Where:

- $w_{i(op)}$ – operating work index (kWh/t),
- Q – mill feed flow rate (t/h),
- P_{80} – Mill product size (microns),
- F_{80} – Mill feed size (microns),
- W – net power (kW).

In order to calculate the efficiency of the mill, the ratio of the laboratory work index $w_{i(lab)}$ to the operational work index $w_{i(op)}$ should be used (**Equation 18**) (**Wikedzi, 2020**).

$$EF = \frac{w_{i(lab)}}{w_{i(op)}} \quad (18)$$

The calculated operational work index cannot be directly included in the efficiency equation because it is not comparable with the laboratory work index. For this purpose, some coefficients must first be applied to achieve the normalized work index value. These coefficients include the circuit dryness coefficient (1.3), the ball mill closed circuit coefficient (1), the circulating load coefficient (1.05), the mill diameter coefficient (1.1), the particle fineness coefficient (1.06), the crushing ratio coefficient (1), and the coefficient related to energy losses (1.2). By applying these coefficients, the operational work index was obtained as 19.7 kWh/t. Finally, the efficiency value (the ratio of the laboratory work index to the operational work index) was calculated as 32%.

3.3.2. Efficiency of the grinding Circuit

The efficiency of the grinding circuit depends on two factors: the efficiency of the grinding operation and the efficiency of the classification system. In other words, a greater match between the grinding product and the classifier separation limit indicates a greater efficiency of the operation. Given that the grinding circuit consists of mills and classifiers, the sum of the measured powers of the mills and classifiers was used as the circuit consumed power in the Bond relation.

3.3.2.1. Consumed power of the classifier

By referring to the control room, the power consumption of each classifier was measured 4 times at 4-hour intervals and the average was 45 amperes. According to **Equation 16**, the consumed power of the device was obtained as 27 kWh. The solid flow rate of 2.75 t/h was considered for the classifier, therefore the share of energy consumed by all classifiers to produce one ton of product was calculated as 9.8 kWh. Moreover, the energy consumption of the classifier in the no-load state was obtained as 15.8 kWh by **Equation 7**.

Table 10. Parameters required to calculate the operating work index of the tube mill

Feed size	8500 μm
Product size	48 μm
mill Circuit Capacity	2.2 t/h
*Pure Power of mill	77.5 kWh
consumed Power of classifiers	54 kWh

* Net power is obtained by multiplying the measured power by a factor of 0.76.

According to **Table 10** and **Equation 16**, the operating work index of the tube mill circuit was calculated to be 40.7 kWh/t, and by applying the relevant coefficients, it was calculated to be 21.3 kWh/t, and finally its efficiency coefficient was 30%.

3.3.3. Efficiency of the hammer mill

According to the size distribution tests, the d_{80} of the feed and product of the hammer mill were estimated as 72 and 8.5 mm, respectively. By referring to the electrical panel of the machine and measuring the amount of consumed electricity, the power consumption of the machine was calculated as 42 amperes, equal to 25.2 kWh. Using the empirical formula of the Bond and the tonnage of the hammer mill feed (9 t/h), the operational work index at this stage was estimated as 35.8 kWh/t. In this regard, the correction factor for the dryness of the mill circuit was considered as 1.3 and the correction factor related to energy losses (same as impact crusher) (**Wills, 1997**) was considered as 1.6. Therefore, the operational index was calculated as 17.2 kWh/t. As a result, in the next stage, the hammer mill efficiency coefficient, which is the ratio of the laboratory to the operational work index, was obtained as 37.03%.

3.4. Circulating load and its effect on the circuit

3.4.1. Circulating load measurement

In order to measure the circulating load, the sliding door under the classifier screw was opened for 10 minutes and the coarse part of the classifiers was collected, which was 550 kg. Therefore, the circulating load tonnage was obtained as 3300 kg/h and equal to 150%, or a coefficient of 1.5.

3.5. Classifier Efficiency

The efficiency of the classifier was obtained using **Equation 19** and considering parameters values, was equal to 66.3%. Also, based on the results of the classification of coarse and fine parts of classifier samples, the values of the distribution coefficient in different classification ranges were calculated, which are presented in **Table 11** and **Figure 4**. In addition, using **Equation 20**, the calculated circulating load was equal to 300%.

$$E = \frac{v(f-u)(1-u)(v-f)}{f(v-u)^2(1-f)} \quad (19)$$

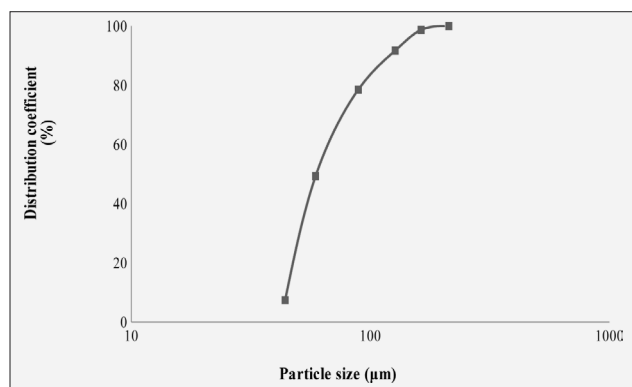
$$CL = \frac{u-f}{f-v} \quad (20)$$

Where:

- E – classifier efficiency (%),
- CL – calculated circulating load (%),
- f – percent of material coarser than the cut size in the initial load, classifier feed (65.6),
- v – percent of material coarser than the cut size in the coarse part of the classifier (85.3),
- u – percent of material coarser than the cut size in the fine part of the classifier (6.6).

Table 11. Determining the classifier distribution coefficient

Size fraction (μm)	Average size (μm)	Weight of coarse part (g)	Weight of fine part (g)	Distribution coefficient (%)
+1180	-	9.9	-	100
+710-1180	945	17.3	-	100
+500-710	605	24.1	-	100
+355-500	427	22.9	-	100
+250-355	302	33.6	-	100
+177-250	213	48.9	-	100
+150-177	163	37.5	0.5	98.7
+105-150	127	77.8	7	91.7
+74-105	89	28.9	7.9	78.5
+44-74	59	36.6	37.7	49.3
-44	-	15.1	186.7	7.4
-	-	352	236	-

**Figure 4.** Classifier distribution coefficient curve

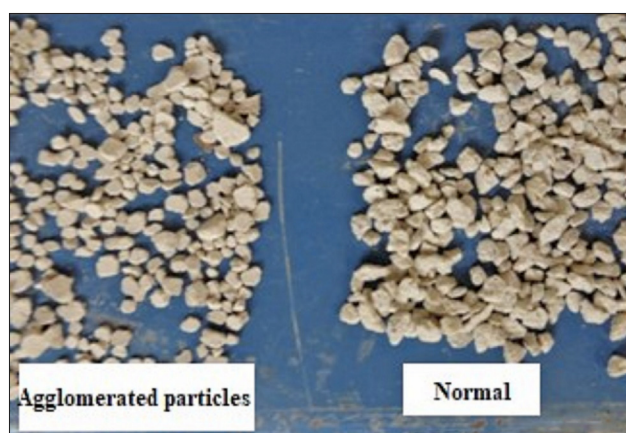
It is worth noting that the main reason for the discrepancy between the measured and calculated circulating load is the segregation of particles which happens inside the classifier. About 5% of the incoming load to the classifier, due to the agglomeration of fine particles to each other, and the creation of particles in size fractions of -1180 and +710 microns, which are broken again, and therefore are transferred to finer fractions. According to the distribution coefficient curve in **Figure 4** and calculations related to the efficiency of the classifier, the operating parameters of the classifiers are given in **Table 12**.

3.6. Effect of agglomeration on the grinding circuit

Agglomeration in bentonite is the process where individual clay particles come together to form larger, loosely bound clusters or aggregates. This phenomenon reduces the purity of the product and creates a wide particle size distribution (**Zhang et al., 2024**). At the outlet of the tube mill and circulating load, the agglomerated particles of **Figure 5** constitute about 90% of the fractions coarser than 500 microns. This increases the weight of

Table 12. Operating parameters of classifiers at the Arak micronized powder plant

Separation limit	d_{50}	60 μm
Defect coefficient	$\frac{d_{75} - d_{25}}{2 \times d_{50}}$	0.31
Accuracy index	$\frac{d_{25}}{d_{75}}$	0.56
Fine part tonnage (product)	-	2.2 t/h
Coarse part tonnage (circulating load)	-	3.3 t/h
Measured circulating load	-	150 %
Ideal circulating load	-	190 %
Efficiency	-	66.3 %

**Figure 5.** Comparison of agglomerated particles 0.5 to 3 mm with normal particles

the particles with coarser sizes to the mill, reduces the grinding efficiency, and causes regrinding, as well.

In these classifiers, the sizes of some particles are reduced due to the following reasons:

- Direct collision of particles with blades,
- Softness of minerals (bentonite),
- Looseness and softness of particles in the initial or parent fractions of the particles that are formed due to the agglomeration phenomenon.

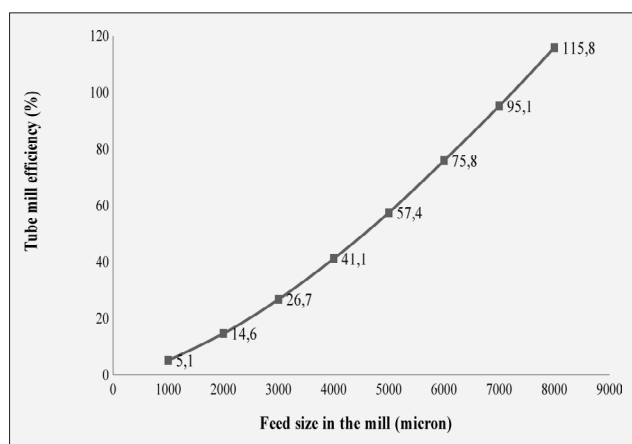
The breakage which carried out in the classifier neutralizes the agglomeration process and reduces the percentage of coarse particles in the circulation load and, as a result, increases the efficiency of the grinding circuit. This is clearly evident in the size fractions of +1180 and +710-1180 of the tube mill product and the coarse part of the classifiers. However, the d_{80} of coarse part of the classifier is almost equal to the d_{80} of mill's product, instead of being coarser.

3.7. Effective parameters in optimization

According to the measurement and calculation of the power and energy consumption of different devices, and the determination of the grinding circuit efficiency, the changeable parameters are examined below.

Table 13. Effect of changes in the size of the tube mill's feed on the efficiency of the grinding circuit

	Efficiency (%)	Corrected Operating Work Index (kWh/t)	Operating work index (kWh/t)	Average size of balls (mm)	Feed size (μm)
Row	E	D	C	B	A
1	5.1	123.8	301.3	0.06	1000
2	14.6	43.8	106.5	0.06	2000
3	26.7	23.9	58.0	0.06	3000
4	41.1	15.5	37.7	0.06	4000
5	57.4	11.1	26.9	0.06	5000
6	75.8	8.4	20.5	0.06	6000
7	95.1	6.7	16.3	0.06	7000
8	115.8	5.5	13.3	0.06	8000

**Figure 6.** The effect of changes in the size of the mill feed on the efficiency of the grinding circuit

3.7.1. Effect of mill feed size on the grinding circuit efficiency

In this section, by applying changes to the size of tube mill's feed and referring to the Bond relation, and assuming that other parameters such as mill dimensions, rotation speed, ore density and ball diameter remain constant, the operational work index was directly calculated. Referring to **Table 13** and **Figure 6**, the following results were accordingly achieved:

- Under the current operating conditions of the tube mill: 80 to 40 mm balls diameter, specific gravity of 1500 kg/m³, mill diameter of 1.54 m and relative rotation speed of 79%, the conditions of comminution circuit would be convenient (work index of 20 kWh/t). Considering the work index, it could clearly be postulated that this is in contrast to the characteristics of bentonite, which is a soft material. Therefore, by increasing the size of the feed entering to tube mill, the conditions for grinding soft materials (work index lower than 7 kWh/t) can be changed.
- By increasing the size of the feed entering to tube mill from 3000 microns to 7000 microns, the efficiency of the mill increases linearly up to 60%.

According to **Equation 21** (the equation for calculating the maximum diameter of the ball), the operating work index was calculated by **Equation 22** which was 301.3 kWh/t. Using the correction coefficients (F_1 , F_3 , F_4 , F_6 and F_8 described earlier) and their multiplication (which was 1.91), the corrected operating work index from **Equation 23** (0.78Δ) was 123.8 kWh/t, and finally the efficiency from **Equation 24** was 0.0514 or 5.14%.

$$B = K \times F^{0.5} \times \left(\frac{\sigma \times W_i}{100 \times C_s \times \sqrt{D}} \right)^{\frac{1}{3}} \quad (21)$$

Where:

- B – Ball diameter (m),
- w_i – Ore work index (6.37 kWh/st),
- F – Input charge size (based on 80% passing) in meters (0.0034 m),
- σ – Ore density in kg/m³ (1500 kg/m³),
- D – Mill internal diameter (1.45 m),
- C_s – Mill rotation in terms of critical speed (0.79),
- K – Constant value (equal to 0.114 for dry grinding and 0.111 for wet grinding).

$$C_1 = W_i = \frac{100 \times C_s \times \sqrt{D} \times B^3}{\sigma \times K^3 \times F^{1.5}} \quad (22)$$

$$D_1 = W_{ic} = \frac{W_i \times \Delta}{F_1 \times F_3 \times F_4 \times F_6 \times F_8} \quad (23)$$

$$E_1 = \frac{6.37}{D_1} \quad (24)$$

3.7.2. Effect of ball sizes on the tube mill efficiency

To study on the effect of ball size on the tube mill efficiency, the optimal and necessary diameter of ball was first calculated and then compared with the diameter of the used balls. According to the Bond ball relation, by changing the ball diameter and keeping the other physi-

cal parameters of the mill constant, the changes in the work index were examined. To calculate the maximum diameter, **Equation 21** was used and it was equal to 0.031 m.

Therefore, the maximum optimal diameter of the mill's balls was considered to be 40 mm. The mixture of the proposed balls is given in **Table 14**.

Using **Equation 25** and setting the value of 0.03 for B, 0.0034 for F, 0.114 for K, and 0.79 for C_s , the work index value was estimated as 6.1 kWh/t. Similarly, by including the various correction coefficients which was 1.91, the corrected work index was calculated 2.5, using **Equation 26** ($\Delta = 0.78$). Finally, the efficiency coefficient was calculated 254.8%, using **Equation 27**.

$$C_1 = W_i = \frac{100 \times C_s \times \sqrt{D} \times B^3}{\sigma \times K^3 \times F^{1.5}} \quad (25)$$

$$D_1 = W_{ic} = \frac{W_i \times \Delta}{F_1 \times F_3 \times F_4 \times F_6 \times F_8} \quad (26)$$

$$E_1 = \frac{6.37}{2.5} = 254.8 \% \quad (27)$$

Referring to **Table 15** and **Figure 7**, it can be concluded that by reducing the average size of the balls to 40 and 30 mm, the efficiency of the mill increases exponentially by 55 and 107%, respectively. Therefore, it is suggested to use balls with an average diameter of 40 mm instead of 60 mm, whereby the tube mill efficiency will increase by 55%.

3.7.3. Effect of production capacity on the tube mill efficiency

In this section, by placing the capacities in the Bond relation, and assuming that the parameters of the feed

and product sizes and the work index remain constant, the ideal power consumption was accordingly calculated. Then, using the scale conversion factor, the amount of operational consumed power of the device in the real state was estimated. Finally, the operating work index was determined and the related efficiency was accordingly calculated. The results of these changes are presented in **Table 16** and **Figure 8**.

Considering that the tonnage of charge entering to the mill is 2.5 times of the production capacity, the following calculations are accordingly made (**Equations 28-32**):

$$B_1 = A + A \times 1.5 = A \times 2.5 = 1 \times 2.5 = 2.5 \text{ t/h} \quad (28)$$

$$C_1 = B_1 \times W_i \times \left(\frac{11}{\sqrt{380}} - \frac{11}{\sqrt{3350}} \right) = 2.5 \times 6.37 \times 0.374 = 5.9 \text{ kWh} \quad (29)$$

$$D_1 = C_1 \times 5.9 = 34.8 \text{ kWh} \quad (30)$$

$$E_1 = \frac{D_1}{B_1 \left(\frac{11}{\sqrt{380}} - \frac{11}{\sqrt{3350}} \right) \times F_1 \times F_3 \times F_4 \times F_6 \times F_8} = \frac{34.8}{2.5 \left(\frac{11}{\sqrt{380}} - \frac{11}{\sqrt{3350}} \right) \times 1.91} = 19.5 \frac{\text{kWh}}{\text{t}} \quad (31)$$

$$F_{1=} = \frac{6.37}{E_1} = 32.6 \% \quad (32)$$

Based on the results in **Table 16**, it can be postulated that changing the production capacity, while keeping other parameters constant, does not have a significant effect on the grinding system efficiency.

3.7.4. Effect of filling on the tube mill efficiency

According to the measurements inside the tube mill, the material height and the balls surface are 112 and 121 centimeters, respectively. Therefore, using **Equation 33**, the percentage of filling of the materials and the balls were estimated as 21.4 and 14% for the materials and the balls, respectively. In **Equation 33**, D and H are the inside diameter of the mill, and the distance between the

Table 14. Comparison of used and estimated balls

Diameter of used balls (mm)	Estimated balls diameter (mm)	Estimated balls weight %
85	---	---
55	40	51%
40	25	49%

Table 15. Effect of changing ball dimensions on tube mill efficiency

	Efficiency (%)	Corrected Operating work index (kWh/t)	Operating work index (kWh/t)	Feed size (μm)	Average diameter of balls (m)
Row	E	D	C	B	A
1	254.8	2.5	6.1	3350	0.03
2	107.9	5.9	14.2	3350	0.04
3	55.4	11.5	27.8	3350	0.05
4	32.2	19.8	48.1	3350	0.06
5	20.3	31.4	76.3	3350	0.07
6	13.6	46.8	113.9	3350	0.08

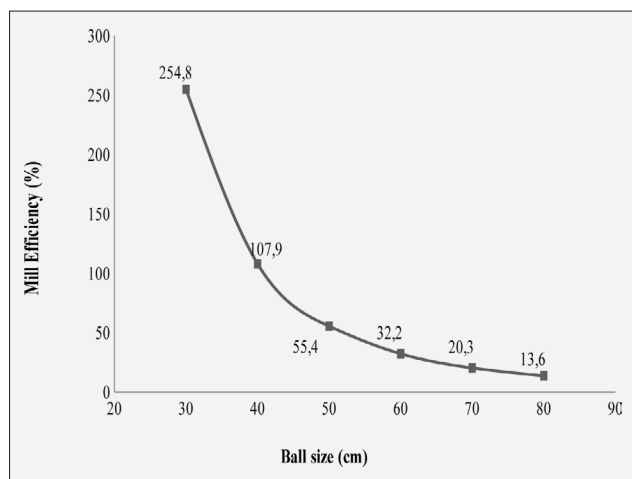


Figure 7. Effect of changing the size of the balls on the efficiency of the tube mill

$$B_1 = \delta = \varphi_c \left[1 - \left(0.1 / 2^{9-10\varphi_c} \right) \right] = 0.79 \left[1 - \left(0.1 / 2^{9-7.9} \right) \right] = 0.75 \quad (34)$$

$$C_1 = \alpha = J_t (1 - 1.03 J_t) = A_1 \times (1 - 1.03 \times A_1) = 0.09 \text{ kW} \quad (35)$$

$$D_1 = P_t = K D_m^{2.5} L_e \rho_c \alpha \delta = 9.1 \times 1.54^{2.5} \times 5.2 \times 3.8 \times 0.09 \times 0.75 = 35.7 \text{ kW} \quad (36)$$

$$P_e = 1.68 \times 1.54^{2.5} [0.79 \times 5.2]^{0.82} = 15.8 \text{ kW} \quad (37)$$

$$E_1 = D_1 - 15.8 = 19.9 \text{ kW} \quad (38)$$

Table 16. The effect of changes in production capacity on mill's efficiency

	Efficiency (%)	Operating work index (kWh/t)	Estimated net operating power (kW)	Ideal power (kW)	Incoming tonnage to mill (t/h)	Production capacity (t/h)
Row	F	E	D	C	B	A
1	32.6	19.5	34.8	5.9	2.5	1
2	32.6	19.5	52.7	8.1	3.75	1.5
3	32.6	19.5	70.2	10.8	5	2
4	32.6	19.5	87.8	13.5	6.25	2.5
5	32.6	19.5	105.3	16.2	7.5	3
6	32.6	19.5	122.9	18.9	8.75	3.5
7	32.6	19.5	140.5	21.6	10	4

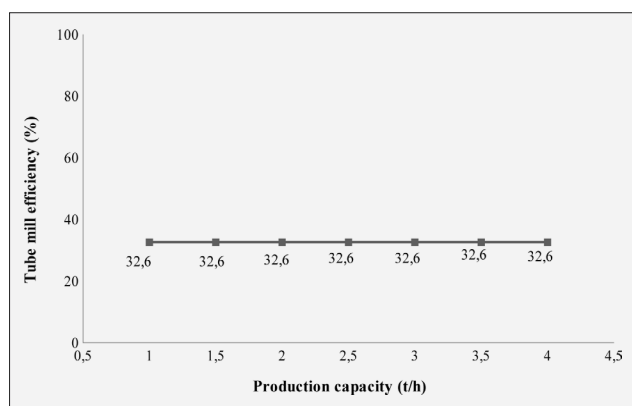


Figure 8. Impact curve of changes in production capacity on mill's efficiency

surface of the balls and to the upper point of the mill, respectively.

$$113 - 126 \frac{H}{D} \quad (33)$$

Therefore, the percentage of the mill charge, based on the measurement of the material bed height, is 21.4% for each of the mill chambers.

$$F_1 = E_1 \times 1.5 = 29.9 \text{ kW} \quad (39)$$

$$G_1 = \frac{F_1}{5.5 \left(\frac{11}{\sqrt{380}} - \frac{11}{\sqrt{3350}} \right) \times 1.91} = 7.6 \frac{\text{kWh}}{\text{t}} \quad (40)$$

$$H_1 = \frac{6.37}{G_1} = 83.8 \% \quad (41)$$

According to the Austin relations, the effect of changes in the mill filling from 10 to 85% on the efficiency were calculated, using **Equations 34-41** and are given in **Table 17** and the calculated values of efficiencies versus mill filling are presented in **Figure 9**. According to **Figure 9** and **Table 17**, the following results were achieved:

- With increasing mill filling, the efficiency decreases and reaches to its minimum level at 48.5% and increases thereafter, as well.
- The rate of change in efficiency at low filling (10-15%) or high filling (75-80%) is much higher than at medium filling.
- By comparing rows 3 and 9 in **Table 17**, it can be postulated that the amount of energy consumed at

Table 17. Effect of changes in ball and powder loading on mill efficiency

	Efficiency (%)	Operating work index	Estimated net operating power (kW)	Net power (kW)	Gross power (kW)	Coefficient α	Coefficient δ	Percentage of filling
Row	H	G	F	E	D	C	B	A
1	83.8	7.6	29.9	19.9	35.7	0.09	0.75	10
2	48.3	13.2	51.8	34.5	50.4	0.127	0.75	15
3	35.4	18	71	47.3	63.1	0.159	0.75	20
4	24.8	25.7	101.3	67.5	83.3	0.21	0.75	30
5	21.5	29.6	116.4	77.6	93.4	0.235	0.75	40
6	20.7	30.7	120.5	80.3	96.1	0.242	0.75	50
7	22.2	28.7	112.8	75.2	91	0.229	0.75	60
8	27.0	23.6	92.6	61.7	77.5	0.195	0.75	70
9	32.2	19.8	77.9	51.9	67.7	0.171	0.75	75
10	41.6	15.3	60.2	40.1	55.9	0.141	0.75	80
11	63.7	10	39.3	26.2	42	0.106	0.75	85

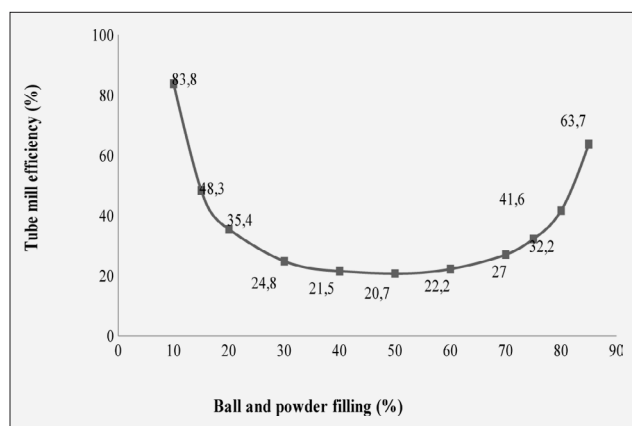


Figure 9. Tube mill efficiency variation curve based on percentage of filling

20% and 75% filling is almost equal (35.4% and 32.2%). Therefore, by increasing the ball and materials filling to 75% and assuming that the particles residence time inside the mill remains constant, the capacity and ultimately the efficiency (indirectly) increases by up to 3 times (by 60%) without the need for more energy consumption.

3.7.5. Calculation of the ideal tube mill filling

By considering the laboratory Bond work index as the ideal value and the capacity of 5.5 t/h and assuming that the sizes of feed and product are constant, the ideal energy consumption of the tube mill was achieved using **Equations 42 and 43**.

$$P = 5.5 \left[6.37 \left(\frac{11}{\sqrt{380}} - \frac{11}{\sqrt{3350}} \right) \right] = 13.1 \left(\frac{\text{kWh}}{\text{t}} \right) \quad (42)$$

$$P_c = P \times 1.3 \times 1.05 \times 1.1 \times 1.06 \times 1.2 = 25.1 \left(\frac{\text{kWh}}{\text{t}} \right) \quad (43)$$

The ideal consumed energy value is considered in Austin relation, and assuming that other parameters are constant, the ideal filling rate of the tube mill was accordingly calculated as follows, using **Equations 44-46**:

$$P_c = P_t - P_e \quad (44)$$

$$KD_m^{2.5} P_c L_e \rho_c \alpha \delta - 15.8 = 25.1 \quad (45)$$

$$\alpha = 0.103 = J_t(1 - 1.03J_t) \rightarrow J_t = 88\% \text{ \& } 12\% \quad (46)$$

Thus, referring to whole calculated values, it can be seen that theoretically, by applying 12 and 88 percent of charge and ball filling, the ideal consumed energy can be achieved.

3.7.6. Effect of relative rotation speed on the tube mill efficiency

The measured tube mill rotation speed was 26 rpm. The inside mill diameter is 1.54 m, and as a result, the critical speed is 34.1 rpm (**Equation 47**). If the ratio of the mill rotation speed to the critical speed is considered 79% (**Wills, 1997**), the rotation speed was calculated to be 27 rpm, which is almost equal to the measured one (26 rpm).

$$N_c = \frac{42.3}{\sqrt{1.54}} = 34.1 \quad (47)$$

Using Austin's equation, the effect of relative percentage changes in mill rotation speed from 40 to 100% on consumed power and mill efficiency were calculated using **Equations 48-55**, which are presented in **Table 18** and the graph in **Figure 10**.

$$B_1 = \delta = \varphi_c \left[1 - \left(\frac{0.1}{29 - 10\varphi_c} \right) \right] = 0.4 \quad (48)$$

Table 18. Effect of rotation speed on mill efficiency

	Efficiency (%)	Operating work index (kWh/t)	Estimated net operating power (kW)	Net power (kW)	No-load power (kW)	Gross power (kW)	α value	δ value	Circulation speed (φ_c)
Row	I	H	G	F	E	D	C	B	A
1	63.1	10.1	29.3	26.4	9.0	35.4	0.167	0.4	40
2	49.8	12.8	50.1	33.4	10.8	44.2	0.167	0.5	50
3	41.4	15.4	60.6	40.4	12.6	53.0	0.167	0.6	60
4	35.0	18.2	71.4	47.6	14.3	61.9	0.167	0.7	70
5	32.2	19.8	77.8	51.9	15.3	67.2	0.167	0.76	80
6	30.1	21.2	83.3	55.5	16.1	71.6	0.167	0.81	90
7	30.5	20.9	82.2	54.8	15.9	70.7	0.167	0.8	100

$$C_1 = \alpha = J_t(1 - 1.03J_t) =$$

$$= 0.214 \times (1 - 1.03 \times 0.214) = 0.167 \text{ kW} \quad (49)$$

$$D_1 = P_t = KD_m^{2.5} P_c L_e \rho_c \alpha \delta =$$

$$= 9.1 \times 1.54^{2.5} \times 5.2 \times 3.8 \times 0.167 \times 0.4 = 35.4 \text{ kW} \quad (50)$$

$$E_1 = P_e = 1.68 \times 1.54^{2.5} [0.4 \times 5.2]^{0.82} = 9.0 \text{ kW} \quad (51)$$

$$F_1 = D_1 - E_1 = 26.4 \text{ kW} \quad (52)$$

$$G_1 = E_1 \times 1.5 = 39.6 \text{ kW} \quad (53)$$

$$H_1 = \frac{F_1}{5.5 \left(\frac{11}{\sqrt{380}} - \frac{11}{\sqrt{3350}} \right) \times 1.91} = 10.1 \frac{\text{kWh}}{\text{t}} \quad (54)$$

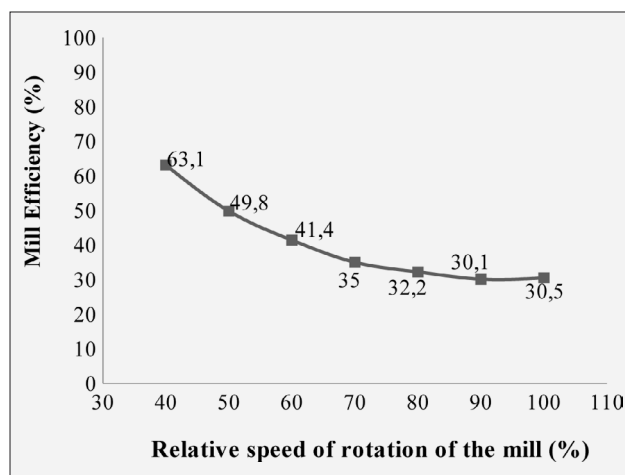
$$I_1 = \frac{6.37}{H_1} = 57.3 \% \quad (55)$$

According to **Figure 10** and **Table 18**, the following results were achieved:

- By reducing the relative rotation speed of the mill from 100 to 80%, there is no significant change in energy consumption.
- By reducing the relative rotation speed of the mill from 80 to 40%, the energy consumption decreases exponentially with a slow slope, and as a result, the efficiency increases by increasing the abrasion mechanism in the mill.
- By changing the relative rotation speed of the mill from the current 79% to 60 to 50%, the mill efficiency increases by 15%.

3.7.7. Average residence time

In order to measure the particles average residency time in the mill, the volume of material inside the mill was divided by the capacity of the mill. By measuring the height of the material and the balls, the volume of the

**Figure 10.** Curve of the effect of rotation speed on the efficiency of the mill

sum of these two was calculated, and considering the tonnage and density of the balls, the volume of the balls was subtracted from this value and the volume of material inside the mill was adjusted accordingly. Therefore, the apparent volume of the balls and the sum of the powder and balls were calculated, using **Equation 33** as 1.3 and 2 m³, respectively. If the volume of the empty space between the balls is considered to be 40% (**Arjmand et al., 2012**), the actual volume of the powder inside the mill is 1.22 m³ and the volume of powder flow in the mill (is the ratio of the capacity to the apparent density of the ore), is 4.4 m³/h. Therefore, the particle residence time was calculated as the result of dividing the actual volume of powder inside the mill (1.22) by the volume of powder flow in the mill (4.4), which would be 0.28 h (16.6 min). Given that reducing the residence time indirectly reduces energy consumption, mill efficiency can accordingly increase by reducing the residence time.

4. Conclusions

According to the measurements, tests and calculations carried out on the Arak Company's comminution circuit using bentonite, the following results and suggestions are presented:

- The efficiency of the comminution system was determined to be about 30%, which is very low and urgently needs troubleshooting and optimization.
- 48 kWh of energy is consumed to break one ton of feed with product size finer than 75 μm . 59% of this amount is related to the tube mill.
- The average diameter of the steel balls used is 60 mm, which is larger than the optimal and calculated ball diameter, and it is better to use smaller balls with a maximum diameter of 50 mm in the first chamber and 30 mm in the second chamber. In this case, the mill efficiency will increase by 50%.
- Changing the production capacity, keeping other parameters constant, will not effect on the efficiency of the grinding system.
- By reducing the relative rotation speed of the mill from the current 79% to 50-60%, the energy consumption is reduced exponentially with a slow slope, and as a result, by increasing the abrasion mechanism in the mill, the efficiency increases by 15%.
- By increasing the filling amount of the first and second chambers in tube mill, by 60 and 70%, respectively, the abrasion mechanism will increase. As a result, the capacity increases with no more energy, and the efficiency increases by 60%.
- By increasing the tube mill size from 3000 to 7000 μm , the mill efficiency increases linearly by 60%.
- The tube mill circulating load was 150%, which suggests an increase to the ideal circulating load (190%).
- About 16% of the coarse particles, in tube mill product, are agglomerated pieces. Therefore, reducing this phenomenon will have a direct impact on reducing energy consumption and increasing efficiency.
- In order to reduce agglomeration, additives can be used to prevent materials from sticking to each other and thus increase mill efficiency. Among the additives, and for further study, cellophane, calcium stearate, polyphenol, alcohol, acetate, glycol, amine and even water would be tested.

Therefore, the changes in tube mill circulating load, the filling amount of the first and second chambers, the tube mill size, energy consumption of the tube mill, average diameter of the steel balls of the first and second chambers, respectively have the greatest impact on improving the efficiency of the grinding process.

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SAŽETAK

Inovativni pristup optimizaciji kruga mljevenja u postrojenju za proizvodnju mikroniziranoga praha

Istraživanje je provedeno s ciljem analize i optimizacije kruga mljevenja u proizvodnome postrojenju tvrtke Arak, specijaliziranome za proizvodnju mikroniziranoga bentonitnog praha. Kriteriji vrednovanja obuhvaćali su optimalne performanse sustava mljevenja, energetske učinkovitost opreme te istodobnu optimizaciju ulazne i izlazne granulacije, kapaciteta i specifične potrošnje energije. Uz Bondovu formulu u analizi su kao inovativan pristup primijenjene i Morrellove te Austinove jednadžbe s naglaskom na utjecaj radnih parametara poput brzine vrtnje i stupnja ispunjenosti mlina. Glavna operacija usitnjavanja u predmetnome postrojenju odvija se u cilindričnome mlinu s kuglama, koji je konfiguriran u zatvorenome krugu s dvama zračnim separatorima. Konačni proizvod dostiže finoću manju od 75 μm , uz specifičnu potrošnju energije od 48 kWh po toni bentonita. Analiza je pokazala da se približno 59 % ukupne potrošnje energije postrojenja odnosi na krug mljevenja mlina s kuglama. Ulazna veličina čestica (d_{80}) iznosila je 3500 μm , stupanj popunjenosti i akumulacije materijala bili su 21 % i 14 %, prosječni promjer kugli iznosio je 60 mm, a relativna brzina vrtnje mlina 79 %. Rezultati su uputili na nisku učinkovitost kruga mljevenja, tek oko 30 %. Provedene simulacije i prijedlozi optimizacije pokazuju da bi se povećanjem stupnja popunjenosti mlina s kuglama od 21 % na 70 %, povećanjem ulazne granulacije na 7000 μm , uporabom kugli promjera manjega od 40 mm te smanjenjem relativne brzine vrtnje na 60 % mogla ostvariti povećana učinkovitost kruga mljevenja i do 50 %. Dodatno je utvrđeno kako se približno 16 % krupnih čestica u proizvodu javlja u obliku aglomerata, pri čemu njihovo smanjenje ima izravan utjecaj na smanjenje specifične potrošnje energije i povećanje ukupne učinkovitosti procesa mljevenja.

Ključne riječi:

mikronizirani prah, energetska učinkovitost, cilindrični mlin s kuglama, bentonit, Morrellove i Austinove jednadžbe

Author's contribution

Alireza Ghorbanifar (Master's degree, Department of Mining Engineering, Islamic Azad University) gathered samples, characterized the samples, and contributed to the crushing, grinding and separation processes and described the characterization and evaluation of the final products. **Marzieh Hosseini Nasab** (Associate Professor, Faculty of Mining Engineering, University of Sistan and Baluchestan) also contributed to the crushing, grinding and separation processes. Supervision, validation, visualization, writing – original draft and writing – review & editing were her other responsibilities for this research. **Javad Alibabaii** (Master's degree, School of Mining Engineering Tehran) and **Mohammad Noaparast** (Professor of Mineral Processing, Faculty of Mining Engineering, Department of mineral processing, University of Tehran) evaluated the results, reviewed the draft manuscript, and provided technical suggestions. All authors have read and agreed to the published version of the manuscript.

Case Study on Optimizing Disc Cutter Spacing Based on Vertical Force Threshold in Colorado Red Granite Cutting Using LS-DYNA Software

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Abstract

This research initially employed a Lagrangian algorithm to simulate two uniaxial compressive and Brazilian tests for validating the calibrated structural model, with errors recorded at 2.5% and 13%, respectively. Subsequently, using mesh-free Galerkin particles and the Johnson-Holmquist concrete material model, simulations of linear shear cutting of Colorado red granite were performed, achieving errors of 10% for vertical force and 13% for rotational force compared to the experimental results from Gertsch and colleagues. These results indicate that the modelling possesses sufficient validity. Instead of determining the optimal spacing through specific energy, a method based on 80% of the maximum vertical force tolerable by the cutting disc is proposed, which aligns with the specific energy method that has significant rigidity and drawbacks, demonstrating that this alternative approach is considerably advantageous and simpler. The optimal spacing calculated for 17-inch discs is determined to be 76 mm.

Keywords:

cutting discs; LS-DYNA; rock cutting; cutter forces; Tunnel Boring Machine

1. Introduction

Full-face tunnel boring machines (TBMs) have become a primary choice for modern tunnel construction across sectors like transportation and infrastructure. Among their components, the cutter head plays a pivotal role, where its design directly affects operational efficiency. Key design factors include the diameter of the cutters, the total number of disc cutters, applied vertical and torque forces, penetration depth, and the spacing arrangement between adjacent cutting discs.

Among these parameters, shear forces, spacing, and penetration depth are key factors affecting cutting efficiency (Cho et al., 2010). The cutting disc is the primary tool used for rock fragmentation in full-face tunnel boring machines. Therefore, analysing the forces acting on the cutting disc and examining the effects of penetration depth and spacing is essential for optimizing cutter head design and improving cutting efficiency (Ma et al., 2024; Wang et al., 2021).

To determine the aforementioned forces, full-scale linear cutting tests (LCM) can be employed, which is a reliable method that many researchers have utilized in their studies (Chang et al., 2006; Cho et al., 2013; Gertsch et al., 2007; Rostami and Ozdemir, 1996).

The most significant research conducted using this method pertains to Rostami in the years 1993 and 1997, who presented a set of relationships for estimating the forces applied on the shear disc of a constant cross-section. His primary relationship is based on the distribution of various pressures in the contact area between the shear disc and the rock for different cross-sectional profiles of the shear disc. This research was further extended through laboratory tests to develop a relationship with equivalent dimensions for estimating shear forces (Rostami, 2013; Rostami and Ozdemir, 1993).

Linear shear testing, despite its numerous advantages, requires substantial cost and time for each sample (Kazemi et al., 2024). In addition to theoretical modelling, recent experimental and numerical investigations have demonstrated the significant influence of operational and geomechanical parameters on excavation performance and tool wear. Using a custom-designed TBM laboratory simulator, it has been shown that factors such as cutter head rotation speed, penetration rate, and soil moisture content can drastically alter the wear rate of cutting tools and overall energy consumption during tunnelling (Mousapour et al., 2023). Integrated geomechanical analyses and slope stability modelling, in surface coal mining operations have further emphasized the role of accurate input parameters in ensuring design safety and compliance with geotechnical standards (Ahmeti and Maliqi, 2023). These studies highlight the growing importance of advanced simulation tools – such as LS-DYNA – in captur-

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ing complex interactions between excavation tools and geological media under varying site conditions.

To address this issue, various predictive models for the performance of full-face tunnel boring machines have been developed, including the Colorado School of Mines (CSM) model and the Norwegian University of Science and Technology (NTNU) model (Bruland, 1998; Rostami and Ozdemir, 1993). Previous research has produced numerous theoretical and semi-theoretical formulas; however, all these analytical models can only provide an approximate estimation of the forces acting on the disc. For instance, Foul, and Roxborough and Phillips examined shear force based on rock resistance and penetration, while Wang, Sanyo, and Farrokh focused solely on the rate of penetration (Farrokh et al., 2012; Fowell, 2016; Roxborough and Phillips, 1975; Sanio, 1985; Wang and Ozdemir, 1978). The shear process was optimized using the shear disc through Particle Swarm Optimization (PSO) methods, employing parameters such as RMR, RQD, and compressive and shear strength (Zhou et al., 2020).

Linear shear testing, in conjunction with numerical modelling, represents one of the best methods for predicting the performance of shear discs. In this approach, linear shear testing is utilized as a means of validating the results of modelling, subsequently leading to the development of models for other scenarios. Numerous researchers have employed numerical modelling to simulate rock shearing, with most opting for 2D modelling using the finite element method with Lagrangian algorithms to reduce computational costs and time. A challenge of this type of modelling, aside from its lack of three-dimensionality, is defining the erosion number for removing elements from the rock that have reached a certain strain level to prevent the divergence of the problem (Cardu et al., 2021; Fattahi et al., 2024).

Given the objectives outlined, the aim of this project is to investigate the effects of penetration depth and spacing on the vertical and rotational forces applied to a shear disc using the Smoothed Particle Galerkin (SPG) method and LS-DYNA software, focusing on maximizing the shear disc's resistance to the applied vertical force. The advantages of this approach include reduced costs and time, the elimination of the need for repeated experiments upon changes in any variable, and the potential for generalization to various disc and rock types. Furthermore, many researchers, such as Chen et al. and Gertsch et al., have utilized special energy to attain optimal spacing, while Yadong Geo has investigated the effects of slope and direction in addition to spacing (Gertsch et al., 2007; Xue et al., 2021; Xu et al., 2022). The influence of a shear disc traversing a new path or crossing a shear zone created by a previous disc, all employing special energy that is considerably more complex to calculate than vertical force, has been analysed (Li et al., 2022). It is important to note that special energy refers to the amount of force expended to shear a unit volume of rock.

To ensure the accuracy of the simulations, the rock sample used in this study is the red granite from Colorado, as utilized by Gertsch et al. (2007). The uniaxial compressive strength and shear resistance of this rock were determined through simulations of uniaxial compressive and Brazilian tests, subsequently compared with laboratory values. Following this, a simulation of the 17-inch A30581 disc was conducted in accordance with the tests performed by Gertsch et al. After achieving highly accurate results, further modelling of the same shear disc was carried out with varying penetration depths and spacings.

In this study, the Colorado Red Granite was selected as the reference rock type due to its well-documented mechanical behaviour and extensive prior use in experimental investigations. This granite originates from the Beulah region in the Wet Mountains of southern Colorado, United States (approximate coordinates: 38.08°N, 104.98°W), an area known for its homogeneous granitic formations of Precambrian age. The geological and mechanical consistency of this granite has made it standard material in linear cutting experiments, as previously employed in the study conducted by Gertsch et al. (2007), which forms the experimental basis for the validation of the present numerical simulations.

2. Structural Model of Rock

The Colorado Red Granite utilized in this study is a coarse-grained, porphyritic granite of Precambrian age, geologically located in the Wet Mountains region of southern Colorado, USA. The area is part of the southern Rocky Mountains and comprises crystalline basement rocks formed during the Proterozoic Eon, primarily as a result of magmatic intrusions associated with regional tectonic activity. These intrusions underwent slow cooling at depth, resulting in the formation of granitic bodies with well-developed crystalline structures. The granite exhibits a high degree of mineralogical homogeneity and structural integrity, making it suitable for controlled rock mechanics studies. Its evolutionary history is marked by multiple phases of tectonothermal activity, which contributed to the formation of its present-day mechanical and petrographic characteristics (Gertsch et al., 2007; Tweto, 1979; Wobus and Hedge, 1982).

The Johnson–Holmquist (JH) model was originally formulated to represent the dynamic response of brittle materials like concrete under conditions involving elevated pressures and strain rates (Holmquist and Johnson, 2011). A key feature of this model is its ability to differentiate between material behaviour in tension versus compression. By establishing a relationship between internal pressure and deviatoric stress in the damaged state, the JH model effectively estimates the material's resistance characteristics under dynamic loading.

$$\frac{\tau}{f_c} = \left[A(1-D) + B(p^*)^N \right] \left[1 + C \ln \ln(\dot{\epsilon}^*) \right] \quad (1)$$

Where:

Symbols:	Descriptions:
$\tau = \left(\frac{1}{2}\right) \sigma_{eq} \left[1 + \left(\frac{1}{Ks}\right) - \left(1 - \left(\frac{1}{Ks}\right)\right) \left(\frac{1}{Ks}\right)^3 \right]$	Shear stress
$\sigma_{eq} = \sqrt{3J_2} = \sqrt{\left(\frac{3}{2}\right) S_{ij} S_{ij}}$	
$r^3 = \left(\frac{9}{2}\right) S_{ij} S_{jk} S_{kj} = \left(\frac{27}{2}\right) J_3$	
S_{ij}	
J_2	Second variable of the shear stress tensor
J_3	Third variable of the shear stress tensor
f_c	Uniaxial quasi-static compressive strength
D	Compressive damage parameter
$p^* = \frac{p}{f_c}$	Normalized pressure
P	Actual pressure
$\dot{\varepsilon}^* = \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}$	Normalized strain rate
$\dot{\varepsilon}_0$	Reference strain rate
A	Normalized cohesion (the stress measured in the laboratory that leads to material failure due to shear)
B	Normalized pressure hardening coefficient
N	Compressive stiffness coefficient
C	Strain rate coefficient
$T^* = \frac{f_t}{f_c}$	Maximum normalized hydrostatic tensile pressure
f_t	Uniaxial tensile strength
Ks	Shape parameter of the yield surface in the shear plane

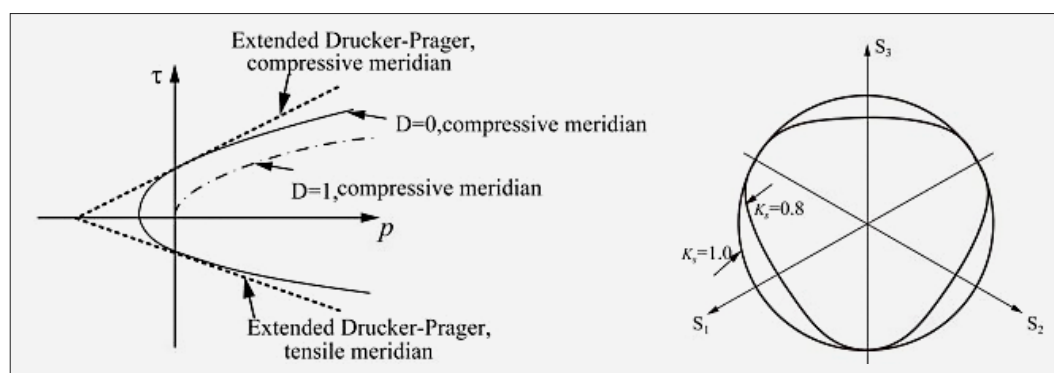


Figure 1. the adopted failure criterion of the material model in two projections: (a) the meridional plane and (b) the deviatoric plane (Hibbitt and Sorensen, 2005).

Shear stress (τ) behaviour under tensile and compressive conditions can be analysed using the parameter Ks , which typically ranges from 0.778 to 1.0 to maintain the convex nature of the yield surface. Setting Ks equal to 1.0 removes the influence of the third invariant of shear stress, effectively simplifying the model back to the clas-

sical Drucker–Prager formulation. The corresponding yield surface for this condition is depicted by **Equation 1** in **Figure 1** (Hibbitt and Sorensen, 2005).

The hydrostatic pressure within the model is determined through an equation of state, structurally similar to that introduced by Holmquist et al., which character-

izes the relationship between pressure and volumetric changes (Hibbitt and Sorensen, 2005). Moreover, the volumetric strain (which is dimensionless) is defined based on the principal strain components and can be represented as follows:

$$\mu = \frac{V - V_0}{V_0} = (1 + \varepsilon_{11})(1 + \varepsilon_{22})(1 + \varepsilon_{33}) - 1 \approx \varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33} \quad (2)$$

Here, V_0 and V denote the initial and deformed volumes of the material, respectively. When subjected to high hydrostatic pressures, the volumetric strain behaviour of rocks can be divided into three distinct zones, as illustrated in Figure 2. In this context, P_{crush} (MPa) represents the pressure at which the pores are completely compacted, while μ_{crush} corresponds to the volumetric strain within the elastic threshold. During uniaxial compression experiments, P_{lock} (MPa) and μ_{lock} mark the pressure and strain associated with the onset of material compaction. To quantify the evolution of plastic strain, a non-associated plastic flow rule is applied, with the plastic potential function g formulated as follows:

$$g = \sqrt{3J_2} \quad (3)$$

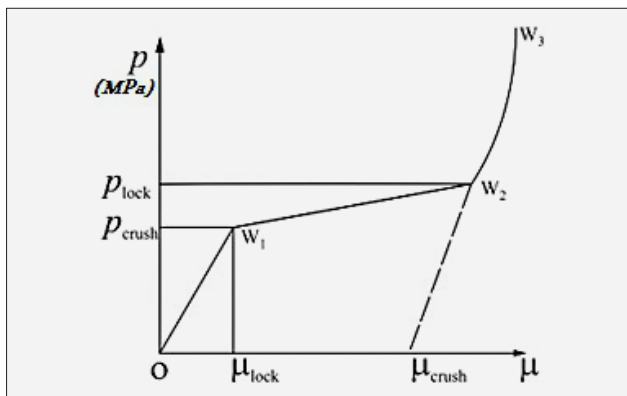


Figure 2. The relationship between pressure and volumetric strain (Hibbitt and Sorensen, 2005).

The amount of plastic strain is described as follows:

$$d\varepsilon_{ij}^p = \lambda \frac{\partial g}{\partial \sigma_{ij}} \quad (4)$$

Where λ is referred to as plastic strain.

Fracture-induced damage is modelled through a cumulative approach analogous to that of the original formulation. This accumulated damage, derived from both equivalent plastic strain and volumetric plastic strain, is quantified using a compressive damage parameter as defined by Hibbitt and Sorensen (2005).

$$D = \sum \frac{\Delta \varepsilon_{eff}^p + \Delta \mu_p}{\varepsilon_p^f + \mu_p^f} \quad (5)$$

Where $\Delta \varepsilon_p$ and $\Delta \mu_p$ represent the equivalent plastic strain and volumetric plastic strain, respectively, and de-

notes the plastic strain required for failure under constant pressure p , which is expressed as follows:

$$\varepsilon_p^f + \mu_p^f = D_1 (p^* + T^*)^{D_2} \geq \varepsilon_{fmin} \quad (6)$$

Where D_1 and D_2 are constants, and p^* is the constant pressure as previously defined. This is designated to generate a limited amount of plastic strain for the failure of materials (Hibbitt and Sorensen, 2005). The parameters extracted by Hyun Lee et al., as shown in Table 1, have been utilized in the simulations for this structural model (Li and Du, 2016).

Table 1. Parameters of Colorado Red Granite Used in Numerical Analysis with the Johnson-Holmquist Material Model (Li and Du, 2016).

ρ (kg/m ³)	E (GPa)	G (GPa)	ν	K (GPa)	A
2600	41	16.61	0.234	25.69	0.3
B	C	N	M	f_c (MPa)	f_t (MPa)
2.04	0.007	0.7	1.5	158	6.78
ε_0	ε_{fmin}	P_{crush} (GPa)	μ_{crush}	P_{lock} (GPa)	μ_{lock}
1	0.01	0.0527	0.0002	0.8	0.1
D_1	D_2	K_1 (GPa)	K_2 (GPa)	K_3 (GPa)	K_s
0.04	1	85	-171	208	0.8

3. Validation of Structural Model Parameters

The calibration of the structural model for accurately simulating the behaviour of rocks requires the execution of a series of complex and costly experiments. These experiments include uniaxial and triaxial compression tests, Brazilian tests, point load tests, and even more specialized tests, such as the split-Hopkinson pressure bar test. To reduce costs and save time, all parameters utilized in this study have been sourced from the research conducted by Hyun Lee et al., which comprehensively addresses the calibration of numerical models and provides various parameters from compressive and tensile tests for different types of rocks under various conditions (Li and Du, 2016).

To ensure validity, two fundamental tests uniaxial and Brazilian were first simulated. These tests serve as key tools for evaluating and validating the numerical models used in this research. Initially, the uniaxial test was simulated to measure the compressive strength of Colorado red granite samples, and the results were then compared with experimental data. Subsequently, the Brazilian test was conducted to measure the indirect tensile strength of the samples.

3.1. Simulation of the Uniaxial Test

The uniaxial test is one of the primary and widely used experiments for assessing the compressive strength

of materials, particularly in rock and concrete samples. This test is designed to measure a material's ability to withstand compressive loads without failure, and it is extensively employed in civil engineering and mining research. In the simulations conducted for this study, a Colorado red granite sample with a diameter of 54 mm and a height of 116 mm was selected. These dimensions conform to the general standards for uniaxial compression tests for construction materials (Bieniawski, 2020).

During the simulation process, the load is applied uniformly through the upper jaw of the testing apparatus to the rock sample, while the lower jaw remains fixed. This loading condition closely resembles laboratory settings and is essential for accurately assessing the compressive strength of the rock. **Figure 3** illustrates the geometry designed in the LS-PREPOST software, in which the geometry of the rock sample and the loading conditions have been fully modelled and simulated.

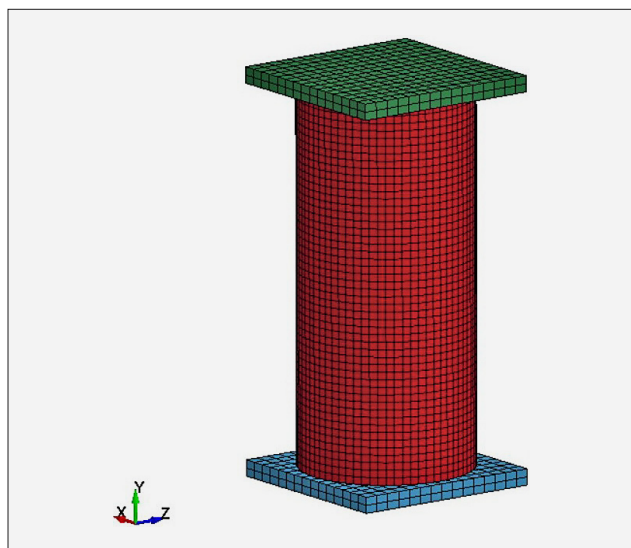


Figure 3. View of the Geometry of Uniaxial Testing.

Based on numerous uniaxial tests conducted on Colorado red granite, the uniaxial compressive strength of this rock has been determined to be 158 megapascals. This value was calculated to be 162 megapascals in simulations carried out using calibrated coefficients referenced in the research conducted by **Li and Du (2016)** and **Gertsch et al. (2007)**. This value corresponds to the peak point in the graph illustrated in **Figure 4**. The error obtained from comparing the simulation results with laboratory data is approximately 2.5%, which is quantitatively low and indicates a reliable accuracy of the model in the simulated model and its suitable alignment with experimental reality. **Figure 5** presents a view of the simulated rock sample after the completion of the simulation process, effectively demonstrating the changes and failures that occurred within the sample. This simulated image clearly illustrates how the rock behaved under compressive loading in the numerical model and highlights the potential failures that occurred.

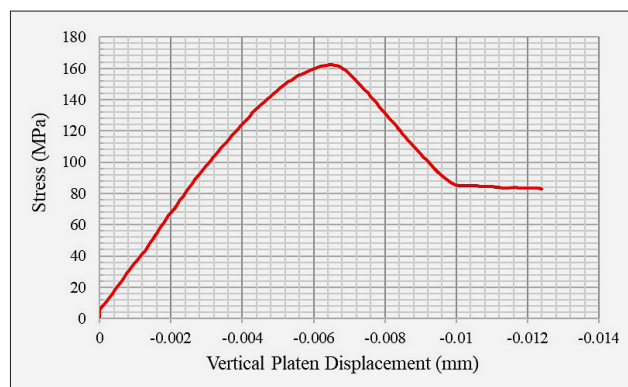


Figure 4. The stress (MPa)- displacement (mm) curve obtained from the simulated uniaxial test.

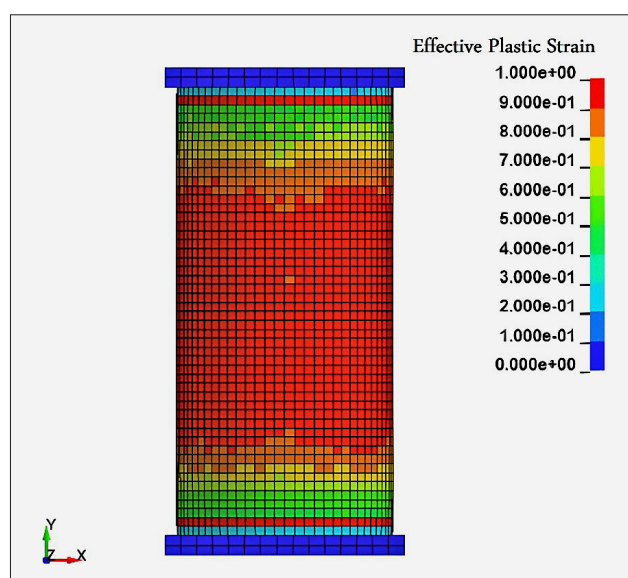


Figure 5. A view of the rock sample following the completion of the uniaxial test simulation.

3.2. Brazilian Test Simulation

The Brazilian test is a widely used method for indirectly measuring the tensile strength of rock and concrete specimens. This test is particularly relevant in rock engineering, as rock samples are prone to sudden failure when subjected to direct tensile forces. During the test, the specimen is subjected to compressive loading, with the standard requirement that the diameter of the sample should be twice its length.

In the simulation conducted for this research, the specimen's diameter was set at 54 mm, and its length was 27 mm. The geometry of the simulated Brazilian test is illustrated in **Figure 6**, which depicts the manner in which the load is applied and the stress distribution within the sample.

In the conducted experiments, the tensile strength of Colorado red granite was calculated to be 6.8 megapascals. This value was estimated to be 7.7 megapascals in the simulations performed. The tensile strength corre-

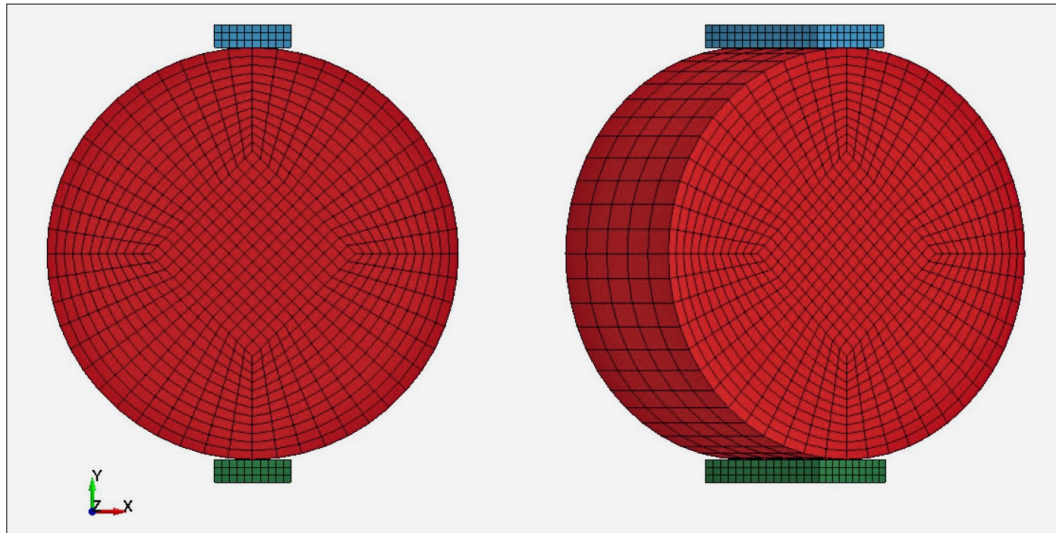


Figure 6. The geometry of the Brazilian test on Colorado Red Granite.

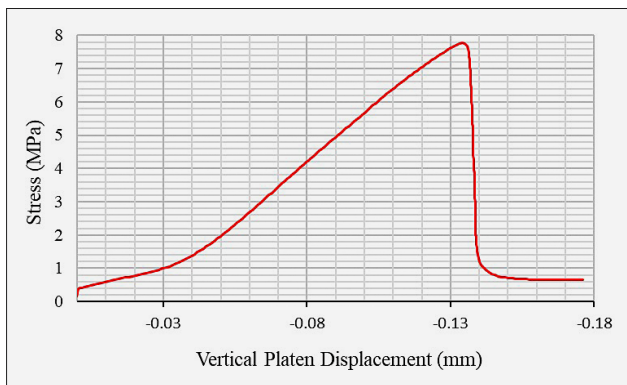


Figure 7. The stress (MPa)-displacement (mm) graph obtained from the Brazilian test simulation.

sponds to the maximum value indicated in the graph shown in **Figure 7**. Additionally, a representation of the Colorado red granite sample is illustrated in **Figure 8**.

Based on the results from the uniaxial and Brazilian test simulations, utilizing the calibrated values provided by Hyun Lee et al. the errors in the compressive and tensile strengths calculated through LS-DYNA simulations are less than 2.5% and 13%, respectively. This level of error indicates a high degree of accuracy in the calibrated structural model and demonstrates that the simulation results align satisfactorily with experimental values. This correlation enhances the credibility of numerical models and facilitates their application in more complex simulations, such as linear shear simulations of rocks using a cutting disk.

3.2. Petrophysical Properties of Colorado Red Granite

While **Table 1** presents the numerical parameters used in the Johnson–Holmquist material model, the fundamental petrophysical properties of the Colorado Red

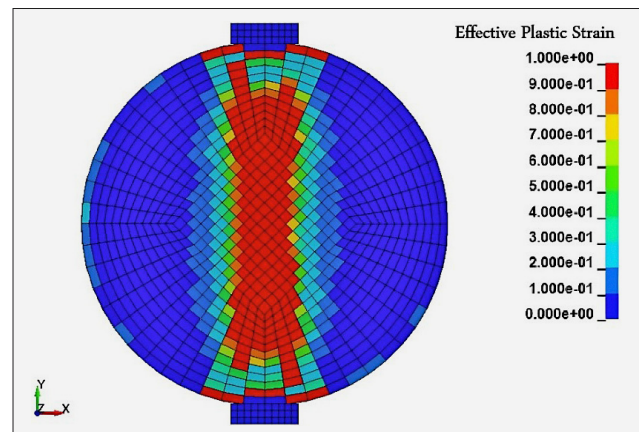


Figure 8. A view of the simulated rock specimen following the completion of the Brazilian test simulation.

Table 2. Petrophysical Properties of Colorado Red Granite (Gertsch et al., 2007; Li and Du, 2016).

ρ (kg/m ³)	f_c (MPa)	f_t (MPa)
2600	158	6.78
G (GPa)	E (GPa)	ν
17.3	41.0	0.234
Age	Dynamic E (GPa)	p-Wave velocity (m/s)
1.4 by (Precambrian)	48.6	4557
Constituents	Porosity (%)	s-Wave velocity (m/s)
Quartz, feldspar, biotite (coarse-grained)	1.2 – 1.5	2886

Granite are summarized in **Table 2**. These values have been obtained from experimental investigations and literature sources and are used to validate the material behaviour simulated in this study. Presenting these properties independently offers a broader perspective on the

physical characteristics of the rock, beyond model-specific parameters.

4. Characteristics of Linear Shear Modelling

LS-DYNA offers multiple finite element solvers tailored for dynamic simulations, including the Lagrangian method, Smoothed Particle Hydrodynamics (SPH), and the Smoothed Particle Galerkin (SPG) approach. The SPG method, an advanced evolution of SPH, is grounded in Galerkin-based formulations, and both techniques are categorized as mesh-free methods (Wu et al., 2015). According to Rokhy et al., in their investigation of rock shearing using LS-DYNA, mesh-free methods like SPH and SPG delivered more accurate outcomes compared to traditional Lagrangian approaches, primarily due to their independence from erosion-related limitations (Bhat and Maji, 2022; Rokhy et al., 2021).

In the present study, the Lagrangian solver was selected as the main computational framework for simulating uniaxial and Brazilian tests, with the intent of reducing overall computational demands. This method was also used for linear shear analyses involving the cutter disk and the surrounding rock segments not directly affected by cutting. Conversely, the SPG solver was selectively employed in the zone directly influenced by the cutter, defined by a depth equal to ten times the penetration depth and a width approximately three to four times the spacing of the cutter. The complete shear modelling arrangement is depicted in Figure 9.

In the SPG simulations, the particle spacing in all three directions (DX, DY, DZ) was set to 0.3 mm, which ensured sufficient resolution of crack initiation and propagation while maintaining computational efficiency. The time step was automatically controlled in LS-DYNA with a stability scale factor of 0.67, following the recommendations in the LS-DYNA manual. Boundary

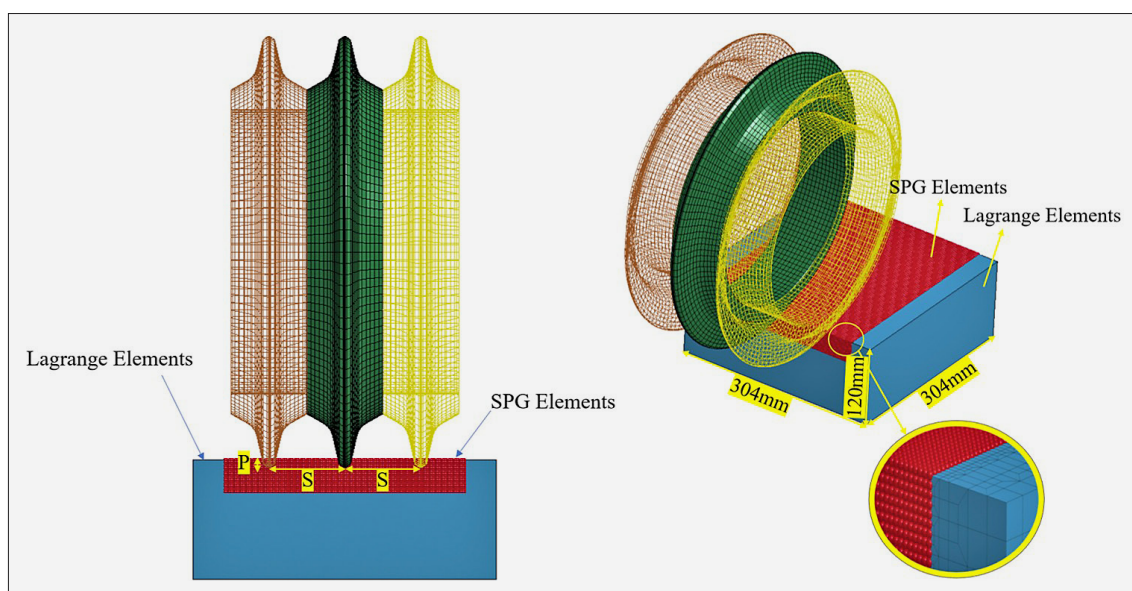


Figure 9. Overview of linear shear modelling of rock in LS-DYNA.

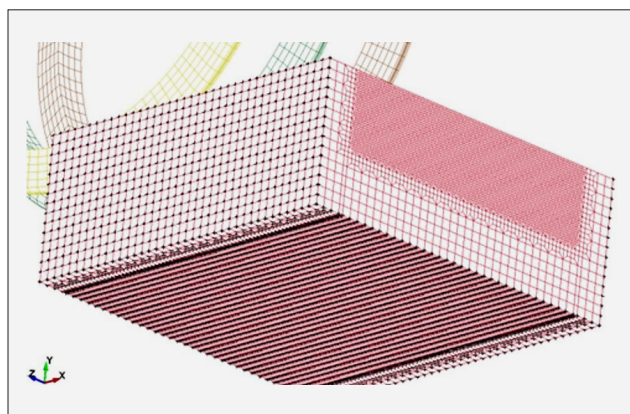


Figure 10. Boundary conditions governing the problem implemented in LS-DYNA software

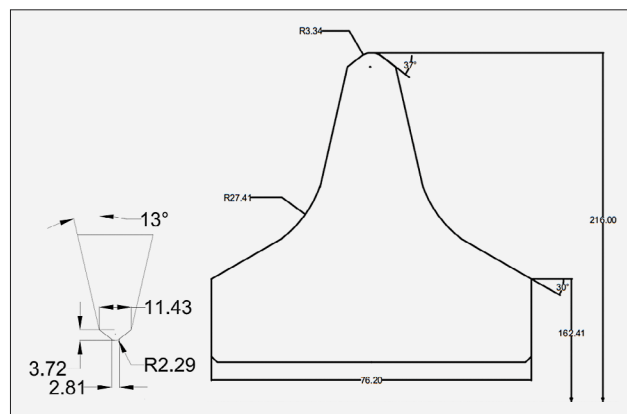


Figure 11. View of the 17-inch A30581 disk used at the Colorado School of Mines for linear shear tests on Colorado red granite (Gertsch et al., 2007).

conditions were applied such that the movement of the rock specimen was restricted at the bottom and lateral faces, consistent with the configuration of the uniaxial compression test shown in **Figure 10**, while the upper surface was free to interact with the cutter. For the kernel function, the Semi-pseudo Lagrangian kernel was employed, as it provides stable particle interaction and accurate stress transfer within SPG formulations. These settings ensured stable and reproducible simulations across all penetration depths and cutter spacings investigated. All simulations were executed on a workstation with an Intel Core i9-12900K CPU and 64 GB RAM (no GPU). With 0.3 mm particle spacing and a stability scale factor of 0.67, each linear-cutting case completed in approximately 24–36 hours of wall-clock time, depending on penetration depth and cutter spacing, supporting the practical computational efficiency of the adopted setup.

The disk employed in all simulations is the same 17-inch A30581 disk used by the Colorado School of Mines for linear shear testing. A representation of this 17-inch shear disk is shown in **Figure 11**.

5. Validation of Linear Cutting Simulations

The results obtained from validation simulations are of significant importance. The closer these simulation results are to the values derived from laboratory experiments and field results, the greater the accuracy and reliability of the simulations that lack corresponding experimental and field data. Consequently, every effort has been made to ensure that all relevant conditions governing the experimental setup, including boundary conditions, loading rates, disk movement velocities, and all other parameters, are meticulously adhered to during these simulations.

To validate the simulations and determine the error margin, twelve different simulations were conducted in accordance with the linear cutting tests performed by **Gertsch et al. (2007)**, under the following conditions:

- Rock strength: 158 MPa,
- Disk rotational speed: 0.0015 radians per millisecond,
- Disk linear cutting speed: 0.33 millimetres per millisecond,
- Penetration depths: 2.5, 5.1, and 6.4 millimetres,
- Spacings: 25, 51, and 76 millimetres.

Given that three disks with specified spacings were utilized, the forces recorded in all sections pertain to the central disk. Due to the significant fluctuations in forces reported from the disks at both ends of the rock – attributable to the boundary conditions – it is preferable to consider the average forces in the middle of the rock, particularly during the time frame when the cutting disk is approximately positioned in the middle of the modelled rock (with a length of 304 millimetres), which oc-

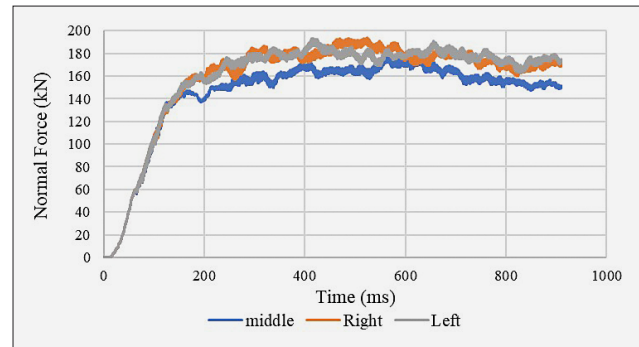


Figure 12. Simulated vertical force of the disk at a penetration depth of 6.4 millimetres and a spacing of 76 millimetres.

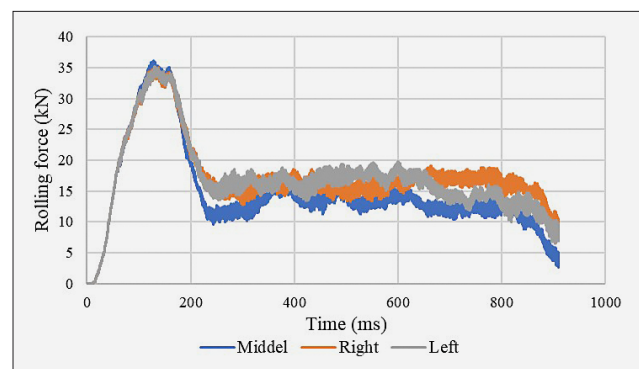


Figure 13. Simulated rotational force of the disk at a penetration depth of 6.4 millimetres and a spacing of 76 millimetres.

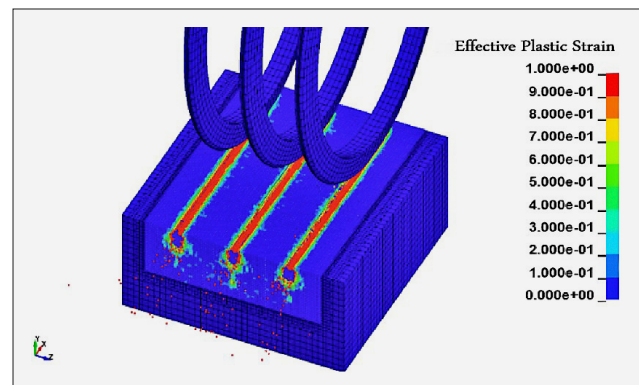


Figure 14. View of the simulated linear cutting of the rock.

curs between 400 and 600 milliseconds. At this point, boundary conditions are minimal, and the forces are in equilibrium. This average is taken as the effective vertical and rotational forces exerted by the rock on the cutting disk. For instance, **Figures 12** and **13** illustrate the vertical and rotational forces obtained using the Lagrangian-SPG coupled solution method and the Johnson-Holmquist concrete behaviour model, based on the simulations with a spacing of 76 millimetres and a penetration depth of 6.4 millimetres. **Figure 14** presents a view of the simulated linear cutting of the rock.

Table 3. Results from the simulations and linear cutting experiments conducted by Gertsch et al. (2007)

Percentage Error of Force Modelling		Rotational Force (kN)		Vertical Force (kN)		Penetration Depth (mm)	Distance (mm)
Rotational	Vertical	Actual	Modelling	Actual	Modelling		
-6.4	1.6	3.9	3.6	58	58.9	1.9	25
-3.5	9.9	7.3	7	81	89	3.8	
-3.2	5.5	12.4	12	116	122.4	6.4	
11.2	-6.1	4	4.5	73	68.5	1.9	51
12.9	-1.8	8.5	9.6	93	94.7	3.8	
-7.3	6.6	14.5	13.4	121	128.9	6.4	
-11	6.2	5	4.4	100	106.2	1.9	76
10.5	-2.6	11.4	12.6	121	117.8	3.8	
-5.9	1.8	19.2	18	147	149.7	6.4	

Given that three disks with specified spacings were utilized, the forces recorded in all sections pertain to the central disk. Due to the significant fluctuations in forces reported from the disks at both ends of the rock – attributable to the boundary conditions – it is preferable to consider the average forces in the middle of the rock, particularly during the time frame when the cutting disk is approximately positioned in the middle of the modelled rock (with a length of 304 millimetres), which occurs between 400 and 600 milliseconds. At this point, boundary conditions are minimal, and the forces are in equilibrium. This average is taken as the effective vertical and rotational forces exerted by the rock on the cutting disk.

Figures 12 and 13 illustrate the vertical and rotational forces, based on the simulations with a spacing of 76 millimetres and a penetration depth of 6.4 millimetres. In both figures, the forces show a rapid increase during the initial engagement of the disks with the rock, followed by strong fluctuations before reaching a relatively stable trend between 400 and 600 milliseconds. These oscillations indicate progressive crack initiation and interaction within the crushed zone, which is consistent with laboratory observations. **Figure 14** presents a view of the simulated linear cutting of the rock.

A comparison of the results in **Table 3** and **Figures 15 and 16** shows that the simulated vertical forces deviate less than 10% from experiments, while rotational forces differ by about 13%. In both figures, vertical and rotational forces increase consistently with penetration depth and spacing. However, the error of the vertical force does not follow a fixed trend relative to the experimental results, indicating that local fracture mechanisms and disc–disc interactions influence the accuracy of the model. In contrast, the error of the simulated rotational forces generally decreases with penetration depth, except for the case of 51 mm spacing at 3.8 mm penetration depth, where the deviation is slightly higher than at 1.9 mm.

6.1. Investigation of Optimal Spacing

There are various perspectives regarding the examination of optimal spacing; however, this research refer-

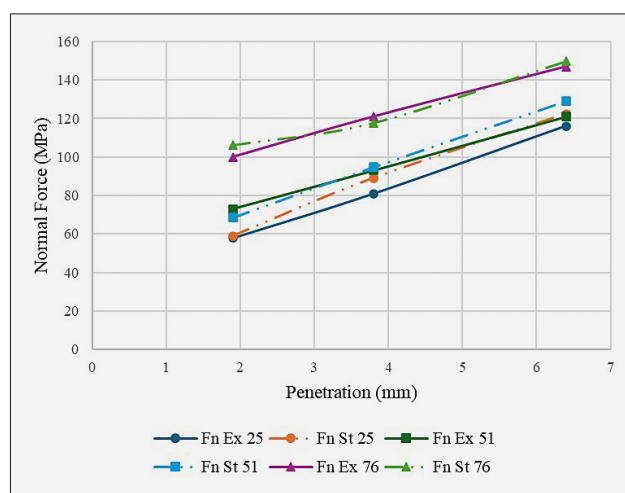


Figure 15. The vertical force obtained from the simulation compared to the experimental results for three spacings of 25, 51, and 76 millimetres and three penetration depths of 1.9, 3.8, and 6.4 millimetres.

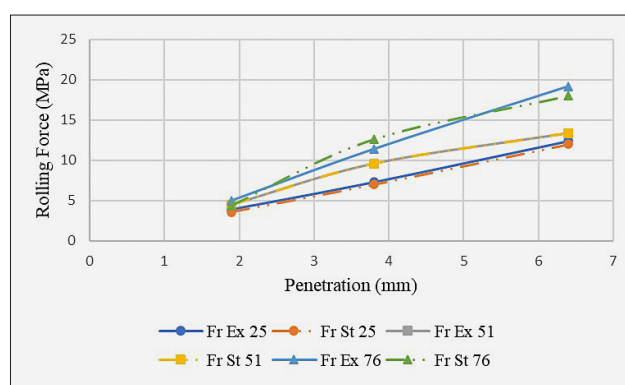
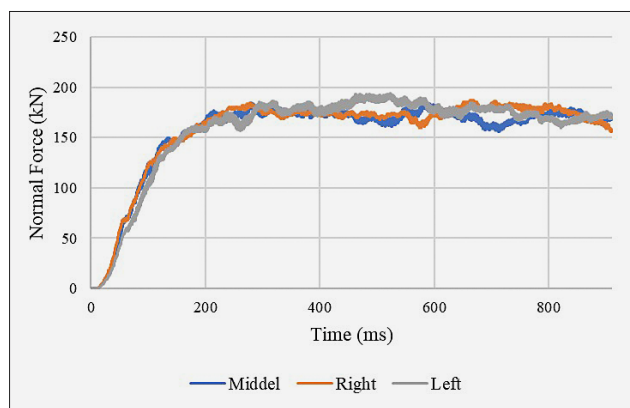
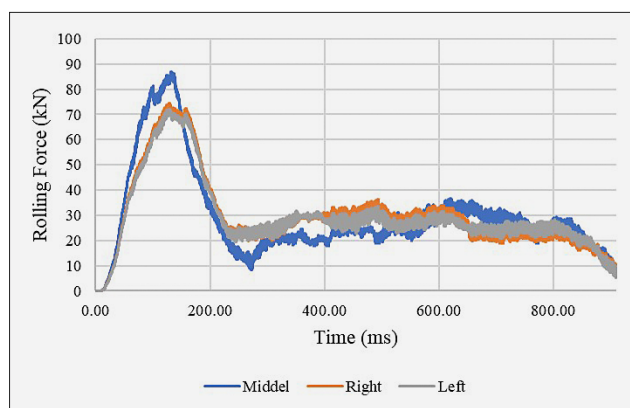


Figure 16. The rotational force obtained from the simulation alongside the experimental results for the same three spacings of 25, 51, and 76 millimetres and three penetration depths of 1.9, 3.8, and 6.4 millimetres.

ences the findings of Roby, which indicate that the maximum vertical force a 17-inch disk can withstand is 215 kN (Roby et al. 2008). According to Farokh, to enhance the service life of shear disks, the maximum vertical

Table 4. Results from the Simulation of Shear Disk at Increased Penetration Depth and Spacing.

Rotational Force (kN) Model	Vertical Force (kN) Model	Penetration Depth (mm)	Spacing (mm)
14.5	134.6	7.6	25
17.9	143.7	7.6	51
23.6	164.3	7.6	76
9.3	118.4	1.9	100
16.8	132	3.8	
27.1	193.8	6.4	
31.7	208.6	7.6	

**Figure 17.** Simulated Vertical Force on the Disk at a Penetration Depth of 6.4 mm and Spacing of 100 mm.**Figure 18.** Simulated Rotational Force on the Disk at a Penetration Depth of 6.4 mm and Spacing of 100 mm.

force applied to these disks should not exceed 80% of this value, equating to 180 kN (Farrokh et al., 2012). Consequently, based on the results obtained from preliminary modelling presented in Table 1, it was observed that the vertical force exerted on the shear disk did not reach this threshold at any of the penetration depths and spacings examined. Therefore, a penetration depth of 7.6 mm and a spacing of 100 mm were also investigated, with the results detailed in Table 4.

The results obtained from the simulations indicate that at a spacing of 100 mm, since the maximum vertical

force exerted on the shear disk must equal 80% of the maximum vertical force the disk can withstand (180 kN), the penetration depth cannot exceed 5.1 mm. This limitation on increasing the penetration depth leads to a reduction in the penetration rate and efficiency of the tunnel boring machine. Additionally, as shown in Figures 12 and 13, at a spacing of 76 mm, the two side shear disks influence the central disk, resulting in lower vertical and rotational forces on this disk compared to the two side disks. However, at a spacing of 100 mm, for all penetration depths examined, the disks do not influence each other, resulting in a single-disk cutting scenario (where the cutting forces on the central disk equal those on the side disks), as depicted in Figures 17 and 18 for vertical and rotational forces, respectively. This condition leads to significantly higher forces exerted on the disks, which may prevent crack connectivity and the formation of a crushed zone in the rock. This behaviour highlights that the disks' interaction is essential for crack coalescence and efficient rock fragmentation, which explains why 76 mm emerges as the optimal spacing.

Based on the results obtained and their comparison with the findings of Gertsch and colleagues, the optimal spacing of the disks is approximately 76 mm. This is because at spacings less than this, the force exerted on the rock, which is equal to the force exerted on the shear disk in the opposite direction, is significantly less than the shear disk's resistance. Conversely, at spacings greater than 76 mm, such as 100 mm with a penetration depth of 5.1 mm, the vertical force exerted on the shear disk reaches the critical region (80% of the maximum resistance of the disk against vertical force). Therefore, it is not feasible to increase the penetration depth of the disks to enhance the penetration rate.

6.2. Statistical Analysis of the Effects of Penetration Depth and Spacing on Vertical and Rotational Forces

The objective of this statistical analysis is to quantify the influence of penetration depth and cutter spacing on the forces acting on the disc cutter, and to provide an empirical model for predicting these forces in support of cutter head design optimization.

In order to investigate the effects of penetration depth and spacing on the vertical (F_v) and rotational (F_r) forces acting on the shear disc, a multiple linear regression analysis was employed. Linear regression is a fundamental statistical method that models the relationship between a dependent variable and one or more independent variables by fitting a linear equation to the observed data (Fayyazi and Doostmohammadi, 2022; Kutner, 2004; Montgomery, 2017). This method allows for the quantification of how each predictor variable influences the target response and is widely used in engineering and applied sciences for predictive modeling (Draper, 1998).

The general form of the regression model used is:

$$Y = \beta_0 + \beta_1 S + \beta_2 P + \varepsilon \quad (7)$$

where Y is the dependent variable (either vertical force F_n or F_r), S and P are the independent variables, spacing and penetration depth respectively, β_0 is the intercept, β_1 and β_2 are the regression coefficients, and ε is the error term accounting for residuals.

To assess the validity and significance of the regression models, three key statistical criteria were considered. First, the p -value measures the probability that the observed relationship is due to chance. A p -value less than 0.05 indicates that the corresponding coefficient is statistically significant and that the predictor meaningfully contributes to explaining the variance in the dependent variable (Montgomery, 2017). Second, the Variance Inflation Factor (VIF) quantifies the degree of multicollinearity between predictor variables; a VIF below 10 suggests that multicollinearity is not problematic, ensuring reliable coefficient estimates (Kutner, 2004). Third, the coefficient of determination (R^2) reflects the proportion of variance in the dependent variable explained by the model, with values closer to 1 indicating stronger predictive power (Draper, 1998).

The regression analysis yielded the following predictive equations:

$$F_n = 7.39 + 0.84S + 13.51P \dots R^2 = 0.95 \dots \\ \dots P\text{-Value} = 0.00 \dots VIF = 1.00 \quad (8)$$

$$F_r = -9.46 + 0.16S + 2.79P \dots R^2 = 0.92 \dots \\ \dots P\text{-Value} = 0.00 \dots IF = 1.00 \quad (9)$$

These results indicate a strong and statistically significant positive relationship between penetration depth and spacing with both vertical and rotational forces exerted on the shear disc. The very low p -values (<0.001) confirm the importance of both predictors in the models, while the VIF values demonstrate that multicollinearity is negligible. The coefficients further imply that penetration depth has a more pronounced effect on the forces than spacing, which is consistent with the mechanical behaviour observed in previous experimental and numerical studies (Gertsch et al., 2007; Rostami, 2013).

These regression models not only confirm the trends observed in the simulations but also enable engineers to estimate cutting forces based on input parameters without performing additional simulations, which can save time and computational resources in TBM design projects.

In summary, the regression models provide a reliable empirical basis for predicting cutting forces based on key operational parameters, facilitating the optimization of cutter head design and improving tunnelling efficiency.

7. Conclusions

In this study, a comprehensive three-dimensional numerical model was developed using the mesh-free

Smoothed Particle Galerkin (SPG) method in LS-DYNA to simulate the linear cutting behaviour of hard rock by disc cutters. The Johnson-Holmquist (JH2) constitutive model was used to accurately capture the dynamic response of Colorado Red Granite under disc cutting conditions.

To validate the model, numerical simulations of uniaxial compressive strength (UCS) and Brazilian tensile strength (BTS) tests were performed. The differences between numerical and laboratory results were 2.5% and 13%, respectively, demonstrating acceptable accuracy. Furthermore, the model was calibrated and validated against experimental results from Gertsch et al. (2007), who conducted full-scale linear cutting tests on Colorado Red Granite at the Colorado School of Mines.

Specifically, the average results of the nine initial simulations reported in Table 3 – each corresponding to cutting conditions that were experimentally tested by Gertsch et al. – showed strong agreement with laboratory data. The average errors in vertical and rotational forces obtained from the simulations were 4.67% and 7.99%, respectively, relative to experimental values. This close match confirms the high reliability and validity of the proposed model. Accordingly, simulations performed under different spacing and penetration conditions (as presented in Table 4), for which experimental data are not available, can also be considered valid and trustworthy.

The model also introduced a new approach for optimizing disc cutter spacing using 80% of the disc's vertical force capacity instead of specific energy, which is commonly used in literature but requires more complex calculations. The optimal disc spacing determined through this method was 76 mm, which closely aligns with the 80 mm optimal value obtained from Gertsch's experiments – showing less than a 5% deviation. This demonstrates that vertical force threshold is a viable and simpler alternative for practical design purposes.

It should be noted, however, that the 80% vertical force threshold is a deliberately simplified criterion aimed at providing a practical and field-deployable guideline. While it captures the fundamental mechanical limit of the cutter, it does not explicitly consider additional operational factors such as wear progression, rock anisotropy, cutter-head vibration, or crack propagation dynamics. These aspects are highly relevant to long-term performance and will be incorporated in future extensions of this framework through multi-objective optimisation approaches.

Parametric analysis confirmed that increases in both spacing and penetration depth lead to significant increases in vertical and rotational forces, which is consistent with the trends reported in prior experimental and analytical studies. The regression models developed for force prediction also achieved high accuracy, with R^2 values exceeding 0.9.

While classical models such as those of **Rostami (1993, 2013)** and **Gertsch et al. (2007)** have provided valuable frameworks for analysing disc cutter forces, they are limited by the reliance on complex specific energy calculations and simplified analytical assumptions. The present study aimed to overcome these limitations in several ways. First, the simulations were performed using the Smoothed Particle Galerkin (SPG) method in LS-DYNA. Unlike conventional Lagrangian approaches, which require an erosion number to delete highly deformed elements – often violating mass and energy conservation – SPG eliminates this need and fully preserves conservation laws, resulting in more accurate and stable rock-cutting simulations. Second, instead of adopting the conventional specific energy criterion, a simpler and more practical approach was introduced based on 80% of the maximum allowable vertical force on the cutter. This criterion not only shows strong agreement with experimental results but is also much easier to obtain in laboratory and even field conditions, making it directly applicable to TBM design and operation. Third, in addition to validation against UCS, Brazilian, and Gertsch's linear cutting data, a statistical regression model was developed to predict cutting forces rapidly and at low computational cost using spacing and penetration depth as input parameters. Collectively, these contributions move the present study beyond a reiteration of previous models and provide a framework that combines numerical accuracy with practical applicability for TBM cutter design.

In conclusion, the combination of advanced numerical modelling, experimental validation, and a simplified optimization criterion offers a powerful and practical tool for cutter design and TBM performance prediction. The model's accuracy, validated against reliable laboratory data, supports its application in various tunnelling and rock excavation scenarios.

Future studies may explore the extension of this model to simulate rock cutting under more complex conditions, such as the presence of joints, anisotropy, and heterogeneity within the rock mass. Investigating the influence of wear and thermal effects on cutter-rock interaction can also enhance the realism of simulations. Additionally, coupling the SPG method with real-time data from TBM operation could pave the way for intelligent prediction systems. Finally, validating the model against additional rock types and full-scale TBM tunnelling data can broaden its applicability and reliability in field-scale engineering problems.

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SAŽETAK

Studija slučaja o optimizaciji razmaka disk rezača na temelju granične vrijednosti vertikalne sile pri rezanju crvenoga granita iz Colorada korištenjem softvera LS-DYNA

U ovome istraživanju najprije je primijenjen Lagrangeov algoritam za simulaciju dvaju ispitivanja: jednoosno tlačnog ispitivanja i brazilskoga testa radi validacije umjerenoga strukturnog modela, pri čemu su zabilježene pogreške od 2,5 % i 13 %. Nakon toga korištenjem metode Galerkinovih čestica bez mreže te Johnson-Holmquistova modela betona provedene su simulacije linearne smične obrade crvenoga granita iz Colorada. Dobivene su pogreške od 10 % za vertikalnu silu i 13 % za rotacijsku silu u usporedbi s eksperimentalnim rezultatima koje su objavili Gertsch i suradnici. Ovi rezultati upućuju na dovoljnu valjanost modeliranja. Umjesto određivanja optimalnoga razmaka na temelju specifične energije predložena je metoda zasnovana na 80 % maksimalne vertikalne sile koju disk rezač može podnijeti. Ta se metoda pokazala usklađenom s pristupom temeljenim na specifičnoj energiji koji ima izraženu rigidnost i nedostatke, pri čemu se novi pristup pokazuje znatno povoljnijim i jednostavnijim. Određen je optimalni razmak od 76 mm za disk rezače promjera 17 inča.

Ključne riječi:

disk rezači, LS-DYNA, rezanje stijena, sile rezanja, stroj za bušenje tunela (TBM)

Author's contribution

Shahin Fattahi (MSc. Student): formal analysis, investigation, methodology, and writing – original draft. **Ebrahim Farrokh** (Associate Professor): writing – review & editing, and validation. **Hesam Dehghani** (Associate Professor): investigation, methodology, supervision, and validation. **Aref Fayazi** (PhD Student): formal analysis and software. All authors have read and agreed to the published version of the manuscript.

Investigation of Geothermal System Using Advanced Processing and Inversion of Gravity Data in Lainea Non-Volcanic Geothermal Field, Indonesia

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Original scientific paper



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Abstract

Indonesia is a country that has abundant geothermal resources. The purpose of this research is to investigate the geothermal system in the Lainea non-volcanic geothermal field, Southeast Sulawesi Province, Indonesia. This includes (i) estimating the geothermal reservoir basins, cap rocks, and basements; (ii) estimating the heat source; and (iii) evaluating the subsurface faults. The first two objectives were achieved by using the improved structural gravity inversion. The third objective was achieved by using advanced processing techniques, namely 3-D Euler deconvolution, tilt angle of horizontal gradient (TAHG), and fast sigmoid edge detection (FSED). Inversion of gravity data exhibits the reservoir basins that are located at depths from 600 m to 900 m with a density range of $2865 \leq \rho < 2942 \text{ kg/m}^3$. Several rock blocks with densities ranging from 2608 to 2865 kg/m^3 function as caprock. The caprock is located at depths ranging from several tens of meters to 1000 m. The basement underlying the reservoir rock is the integration of rock layers with densities of $2948 \leq \rho < 3045 \text{ kg/m}^3$ and $3046 \leq \rho \leq 3122 \text{ kg/m}^3$. The upper boundary of the basement is located at a depth of several ten meters to 1500 m below sea level. Intrusive plutonic rocks with maximum density of 3174 kg/m^3 are located at depths ranging from 1500 m to more than 3000 m. The TAHG and FSED demonstrate the presence of subsurface faults with northwest-southeast and southwest-northeast trends. Euler deconvolution results support the fault model of the TAHG and FSED.

Keywords:

gravity; geothermal reservoir; heat source; underground fault; Lainea field

1. Introduction

There are two categories of geothermal potential in Indonesia: volcanic and non-volcanic. A collection of volcanically active islands in Sumatra, Java, and Nusa Tenggara, part of the Sunda Arc, host volcanic geothermal energy. The southern Sulawesi region categorizes geothermal as non-volcanic (Idral, 2010). Several main factors, including heat sources, reservoirs and fluids, cap rock, and fault systems, influence the existence of a geothermal system (Gupta and Roy, 2010). In non-volcanic geothermal systems, the presence of a pretertiary basement is an important aspect of interpreting heat sources. The pretertiary basement horizon is a zone where intrusive heat sources (intrusive bodies) occur in non-volcanic geothermal systems (Tamanyu and Sakaguchi, 2003; Gupta and Roy, 2010).

There hasn't been much research on Indonesia's non-volcanic geothermal potential. Only a few papers discuss this topic, such as Nahli et al. (2016), Rony et al. (2019), Arrofi et al. (2022), and Kusmita et al. (2023). The researchers have conducted several geological, geochemical, and geophysical studies at the Lainea non-volcanic geothermal field (LNVGF) in the Southeast Arm of Sulawesi. Estimating temperatures in geothermal reservoirs using geochemical methods (Idral, 2010), forward modelling of subsurface by gravity method (PSDG, 2010), and interpreting intrusive rocks as heat sources by combining magnetotelluric and time domain electromagnetic methods (Zarkasyi, 2014) are some of the studies that have been done in this geothermal field. PSDG (2010) did not present a geometry model of the reservoir basins, basements, and heat source based on the gravity data inversion approach as well as subsurface faults based on advanced gravity processing techniques. Although several studies have been conducted, there are still insight gaps regarding the components that build and control the geothermal system at the LNVGF.

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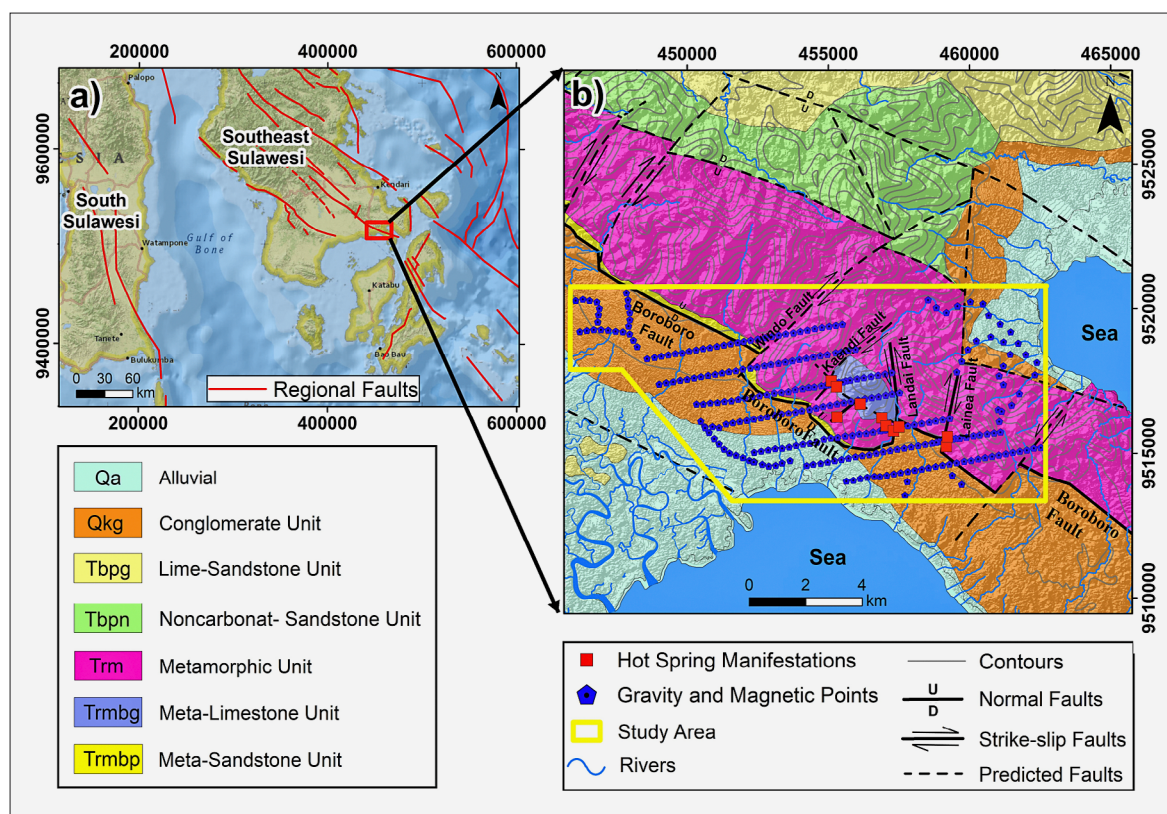


Figure 1. Geological setting of the Lainea geothermal area: a) southeast arm of Sulawesi Island; b) geological map, edited from Hadi et al. (2010).

The gravity method is a geophysical exploration approach that is commonly employed in geothermal studies (Geng et al., 2000; Lewerissa et al., 2000; Xu et al., 2021; Ozsoz, 2021; Carrillo et al., 2022; Li, 2023; and Perez-Flores et al., 2024). Advanced gravity data processing techniques, such as 3-D Euler deconvolution (Marson and Klingele, 1993), tilt angle of the gradient amplitude-TAHG (Ferreira, 2013), and fast sigmoid edge detection-FSED (Oksum et al., 2021), have been developed and are widely used to determine the depth of anomalous sources and confidently estimate the configuration of geological structures (Safani et al., 2023; Pham, 2024; Dogan and Sayin, 2024). Furthermore, inversion techniques for gravity data are widely utilized to evaluate geothermal models (Bekhit et al., 2024; Gaber et al., 2024; Boling et al., 2024). Camacho et al. (2021) created a growth inversion, which is one of the novel inversion modelling techniques for structural gravity inversion. The benefits and limitations of this inversion approach have been explored in a variety of applications, including the identification of elongated thin bodies (Bodi et al., 2023) and the interpretation of volcanic unrest (Vadja et al., 2023).

The lack of detailed understanding of reservoir basins, cap rocks, basements, heat sources, and subsurface faults that control the geothermal system at the LNVGF necessitates the use of new approaches. Therefore, this research utilizes the advanced data processing and inver-

sion techniques for gravity data with the aim of i) estimating geothermal reservoir basins, cap rocks, and basements, ii) estimating heat sources, and iii) evaluating the subsurface active fault that controls the Lainea geothermal system.

2. Geological Settings

The research area is in Lainea Village, South Konawe Regency, Southeast Sulawesi Province. This area is located on the southeast arm of Sulawesi Island, Indonesia (see Figure 1a). According to Hadi et al. (2010), the Lainea non-volcanic geothermal area is made up of seven rock units that range in age from Triassic to Recent. These are the metamorphic rock units (Trm), the meta-limestone unit (Trmbg), the meta-sandstone unit (Trmbp), the non-carbonate sandstone unit (Tbpm), the calcareous sandstone unit (Tbpg), the conglomerate unit (Qkg), and the alluvium deposits (Qa) (see Figure 1b).

The constituent rocks of the metamorphic unit consist of slate, phyllite, schist, and quartzite. The central part of the study area distributes metamorphic rock units, stretching from west to east to form a range of steep hills with rough relief. This unit exhibits numerous surface hot water and alteration locations, particularly in the vicinity of the Kaendi, Amowolo, Landai, and Lainea rivers. This unit has experienced a strong deformation process (PSDG, 2010).

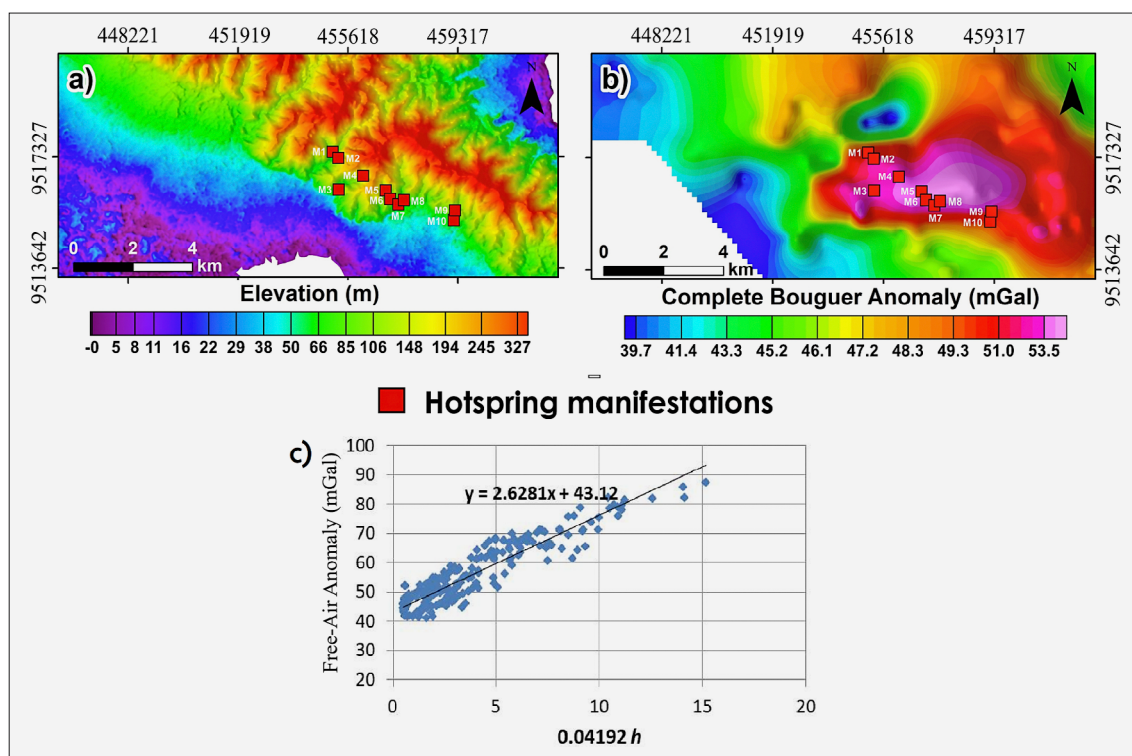


Figure 2. Research data (a) Topography (DEMNAS, 2023), (b) Complete Bouguer Anomaly (CBA), (c) Bouguer density estimation using Parasnis approach, where the gradient of the straight line represents the Bouguer density.

Metamorphized limestone makes up the meta-limestone unit, which is located around the Landai area. This unit has undergone changes to form clay minerals and has experienced strong deformation. Numerous intense cracks, reaching a width of up to 10 cm, are present filled by the mineral calcite, a hydrothermal solution. This unit reaches a thickness of >300 m. The meta-limestone unit is Triassic in age, the same as the meta-sandstone and metamorphic units. In contrast to the meta-limestone unit, whose outcrop appears in the center of the study area and has lithological contact only with the metamorphic unit, the outcrop of the meta-sandstone unit runs along the Boroboro Fault from the northwest to the center of the study area. The meta-sandstone unit has lithological contact with the metamorphic unit in the north and the conglomerate unit in the south (Hadi et al., 2010).

The northern and southwestern parts of the investigation area contain sandstone-limestone units. This unit is Late Miocene to Pliocene in age. The non-carbonate sandstone unit unconformably overlies this unit, which deposited itself in shallow to neritic marine environments. On the southern side of the metamorphic unit (and also the meta-sandstone unit), the conglomerate unit dominates. This rock unit acts as the lithological contact for metamorphic units and meta-sandstone units along the Boroboro Fault in the study area. Alluvial deposits are located to the south of the conglomerate unit (PSDG, 2010).

The main fault that controls the Lainea geothermal system is the Boroboro Fault. The northwest-southeast trend of this fault aligns with metamorphic units (Sugianto et al., 2011). The large plates around it, namely the Australian Plate moving to the North and the Pacific Plate colliding with the East Asian Plate to the West, activate this fault. Subsequent tectonic activity produced faults trending southwest-northeast and north-south, such as the Kaendi Fault, Landai Fault, Lainea Fault, Windo Fault, and Demba Fault. These secondary faults play a role in the formation of fractures, thereby producing a subsurface permeable layer that acts as a reservoir in the Lainea geothermal system (Hermawan et al., 2011). Around the Boroboro Fault in the Lainea area, there are approximately 10 geothermal manifestations with a northwest-southeast trend following the direction of the Boroboro Fault. This geothermal manifestation is associated with three rock units, namely metamorphic rock, meta-limestone, and meta-sandstone (see Figure 1b).

3. Dataset and Methods

3.1. Gravity data

This study uses elevation data from the Indonesia Digital Elevation Model (DEMNAS), as shown in Figure 2a, as well as complete Bouguer gravity anomaly data (see Figure 2b). The gravity data we utilize is a combination of field data we measured and data from the Indonesian

Geological Resources Centre (PSDG). The total number of data points is 344. A total of 216 data points have regular grids with intervals of 250 m spanning from west to east, while the remaining 128 data points have intervals ranging from 250 m to 550 m. Hot springs, represented by red squares, are located on the hillside.

We calculate the complete Bouguer anomaly (CBA) data by applying several corrections to the observed gravity data. This correction begins with tidal correction, instrument height correction, latitude correction, free-air correction, Bouguer correction, and terrain correction. The last two corrections are very dependent on the Bouguer density, namely the density of the rock layer between the mean sea level (MSL) and the measurement points. The Bouguer density used was 2.6281 g/cm³. The estimated Bouguer density was calculated using the Parasnis method, which is represented by the gradient of the elevation scale (0.04192 *h*) versus the free-air gravity anomaly (see **Figure 2c**). This estimated density is comparable to those presented by the **PSDG (2010)**, which used an average density of 2.65 g/cm³ for field rock samples. **Figure 2b** shows the CBA contour, which varies in the range of 39 mGal to 55 mGal. The distribution of CBA forms a trend in the northwest-southeast and northeast-southwest directions. Geothermal manifestation points are located around high gravity anomalies with a value range of 50 mGal to 55 mGal. The presence of high-density rocks or the position of the basement near the surface may be associated with high gravity anomalies.

3.2. Upward continuation

This step involves the process of separating residual and regional anomalies. For this purpose, we use the upward continuation technique on CBA data. This technique applies a mathematical filter that amplifies data at low frequencies associated with regional anomalies. In contrast, this upward continuation technique weakens high-frequency data associated with residual anomalies (**Chisenga et al., 2019; Kebede et al., 2020**). Therefore, this technique emphasizes regional scale anomalies.

Figure 3 shows the upward continuation technique. The gravitational attraction per unit mass, *dm*, of an anomalous body at mean sea level, *B*(*x*₀, *y*₀, *z*₀ = 0), and a distance *R* from the source point, *B*(*x*, *y*, *z*), may be determined using the following equation (**Jacobsen, 1987; Kebede et al., 2020**):

$$dg = \frac{Gdm}{R^2} = \frac{Gdm}{(x-x_0)^2 + (y-y_0)^2 + (z-z_0)^2} \quad (1)$$

The source's gravity anomaly, Δg_0 , at the mean sea level point, is given by the vertical component, dg_z .

$$\begin{aligned} dg_z = \Delta g_0 &= \frac{Gdm}{R^2} \frac{z}{R} = Gdm \frac{z}{R^3} = \\ &= Gdm \frac{z}{[(x-x_0)^2 + (y-y_0)^2 + (z)^2]^{3/2}} \end{aligned} \quad (2)$$

At the upward continued surface, point A, the source's gravity anomaly, dg_p , equals

$$\begin{aligned} dg_p &= \frac{Gdm}{S^2} \frac{z+h}{S} = Gdm \frac{z+h}{S^3} = \\ &= Gdm \frac{z+h}{[(x-x_0)^2 + (y-y_0)^2 + (z+h)^2]^{3/2}} \end{aligned} \quad (3)$$

3.3. Edge detection technique

Several recent edge detection techniques are often used to analyze the Bouguer gravity map and refine the edges/boundaries of the subsurface causative bodies. Numerous mathematical strategies are available for enhancing the accuracy of gravity gradient data in edge detection. As a result, distinct lineaments appear at slightly different spatial coordinates. This study used two edge detection approaches, which will be discussed below.

According to **Ferreira et al. (2013)**, the TAHG (tilt angle of the gradient amplitude) is the arctangent of the gradient amplitude's derivative ratio. The TAHG filter highlights both shallow and deep geological contacts that cause gravity anomalies at the surface (**Pham et al., 2023; Safani et al., 2023**). It can be expressed as follows:

$$\text{TAHG} = \text{atanatan} \left(\frac{\partial HG}{\partial z} / \sqrt{\left(\frac{\partial HG}{\partial x} \right)^2 + \left(\frac{\partial HG}{\partial y} \right)^2} \right) \quad (4)$$

Where $\partial HG/\partial x$ and $\partial HG/\partial y$ are the first-order horizontal derivatives of the horizontal gradient magnitude (HG), and $\partial HG/\partial z$ the first-order vertical derivative.

$$HG = \sqrt{\left(\frac{\partial G}{\partial x} \right)^2 + \left(\frac{\partial G}{\partial y} \right)^2} \quad (5)$$

Where $\partial G/\partial x$ and $\partial G/\partial y$ are the first-order horizontal derivatives of the gravity field in the *x* and *y* directions.

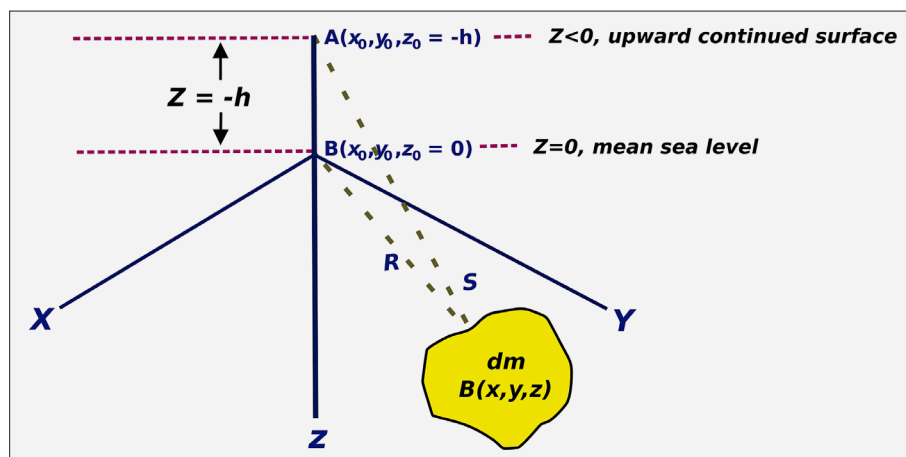
An additional technique for enhancing source edges is presented by **Oksum et al. (2021)**. This filter is known as fast sigmoid edge detection (FSED), which operates on gradient amplitudes. This filter can strengthen the edges of shallow and deep structures simultaneously. The mathematical equation is as follows:

$$FSED = \frac{R-1}{1+|R|} \quad (6)$$

Where:

$$R = \frac{\partial HG}{\partial z} / \sqrt{\left(\frac{\partial HG}{\partial x} \right)^2 + \left(\frac{\partial HG}{\partial y} \right)^2} \quad (7)$$

Figure 3. Illustration of the upward continuation technique (Kebede et al., 2020).



3.4. Euler deconvolution depth solutions

Recently, the Euler deconvolution (ED) methodology has emerged as a highly effective method for semi-quantitative analysis of potential field data (Hinze et al., 2013; Chen et al., 2022; Safani et al., 2023). The ED approach has been applied to gravity data to enhance the characterization of geological structures and ascertain their depth. Marson and Klingele (1993) devised the Euler deconvolution for vertical gravity data to enable this method to function with grid gravity data sets, as illustrated in the equation below:

$$(x - x_0) \frac{\partial^2 G}{\partial z \partial x} + (y - y_0) \frac{\partial^2 G}{\partial y \partial z} + (z - z_0) \frac{\partial^2 G}{\partial z^2} = N \frac{\partial G}{\partial z} \quad (8)$$

Where (x_0, y_0, z_0) denotes the coordinates of the anomaly's source in the (x, y, z) axis. G represents the gravitational force at the coordinates (x, y, z) . N represents the degree of homogeneity as a structural indicator (SI). The index structure delineates the geological conditions that produce the anomaly (Marson and Klingele, 1993; Pham et al., 2023). $\partial G / \partial x$ and $\partial G / \partial y$ represent horizontal derivatives in the x and y planes, respectively, whereas $\partial G / \partial z$ denotes a vertical derivative.

4. Results

4.1. Residual gravity anomaly

The complete Bouguer anomaly (CBA) combines both local and regional anomalies. We use the upward continuation technique to separate the two anomalies. The continuation process involves several elevation levels, starting from an elevation of 100 m to 700 m above mean sea level (MSL) to obtain representative regional anomalies. We chose a continuation result, 500 m above MSL, to represent the regional gravity anomaly (see Figure 4a). This is because the contour patterns in these results tend to be stable, and the influence of local anomalies tends to diminish. Subtracting the regional gravity anomaly from the complete Bouguer anomaly produces a local Bouguer anomaly with varying values ranging from -7.7 mGal to 8.8 mGal (see Figure 4b).

Negative gravity anomalies shown in Figure 4b may indicate the extent of sedimentary layers from the surface to the sedimentary basin layer. Meanwhile, positive gravity anomalies, with a maximum value of 8.8 mGal, may indicate the presence of harder, thicker rocks surrounding the sedimentary rocks. This assumption will be discussed further in the inversion model of gravity data.

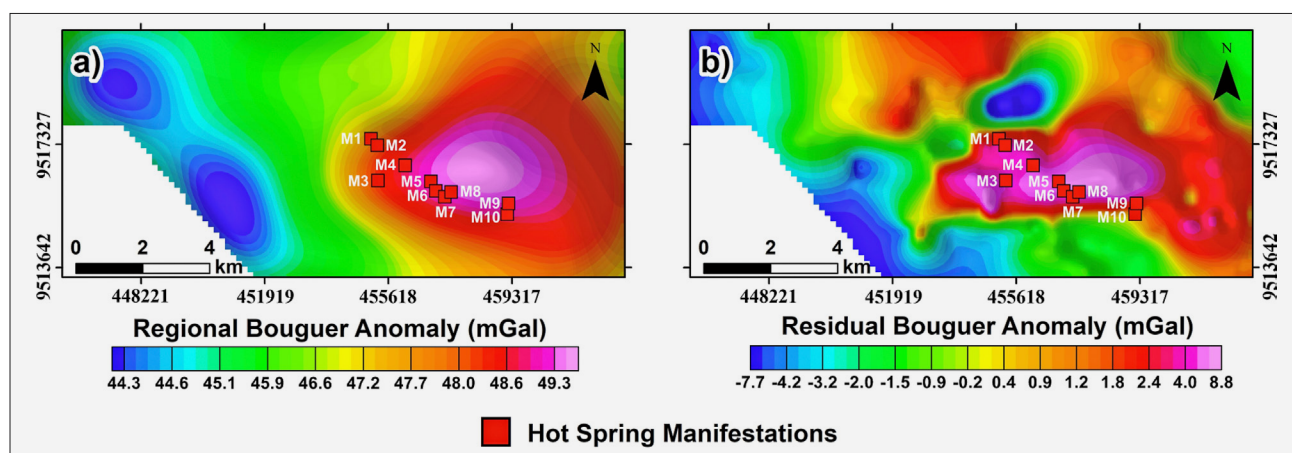


Figure 4. Separation of gravity anomalies a) regional anomaly data and b) residual gravity anomaly data.

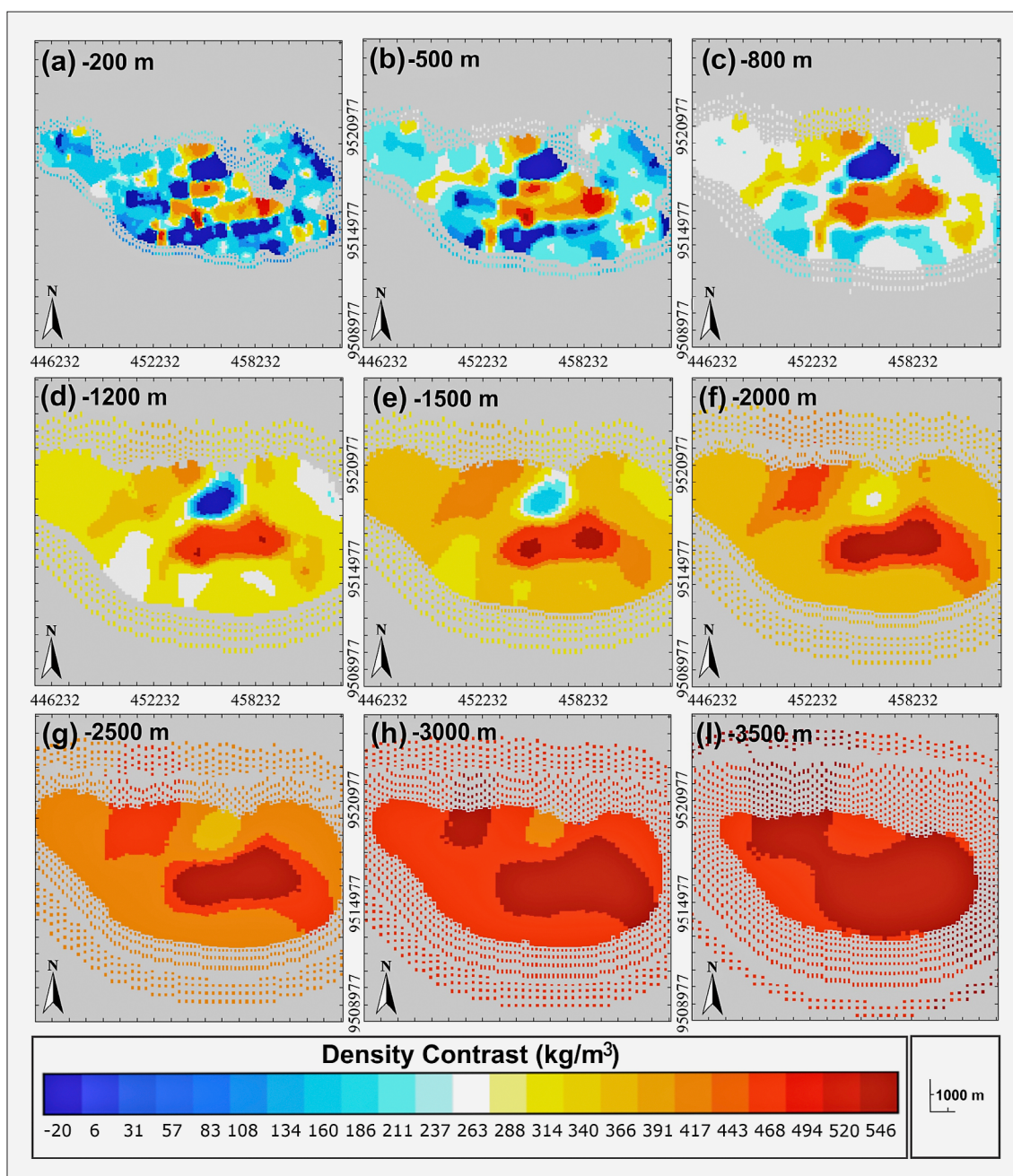


Figure 5. Horizontal depiction of subsurface layers at various depths: a) 200 m, b) 500 m, c) 800 m, d) 1200 m; e) 1500 m, f) 2000 m, g) 2500 m, h) 3000 m, and i) 3500 m below sea level (bsl). Red indicates high density contrast and blue indicates low density contrast.

In general, however, we can see the correlation between gravity anomalies and rock units representing the surface geology of the study area. A correlation of the gravity data with the geological map (see **Figure 1b**) shows that positive anomalies are generally associated with metamorphic, meta-sandstone, and meta-limestone units. Gravity anomalies ranging from -2.0 mGal to -0.2 mGal are generally associated with conglomerate rock units. Smaller gravity anomalies (i.e. less than -0.2 mGal to -7.7 mGal) are more prevalent in alluvial units. Hot spring manifestations are generally located in the high gravity anomaly zone, with gravity anomalies ranging

from 1.8 to 8.8 mGal. Some coincide with the transition zone between positive and negative anomalies, such as hot springs M1 and M10.

4.2. Inversion of gravity data

The study aims to estimate the three-dimensional structure of the subsurface layers of the Lainea geothermal region, utilizing gravity data and the GROWTH 3.0 tool developed by Camacho et al. (2021). This package offers both default values and user-specified options. This coding package utilizes all default values, except

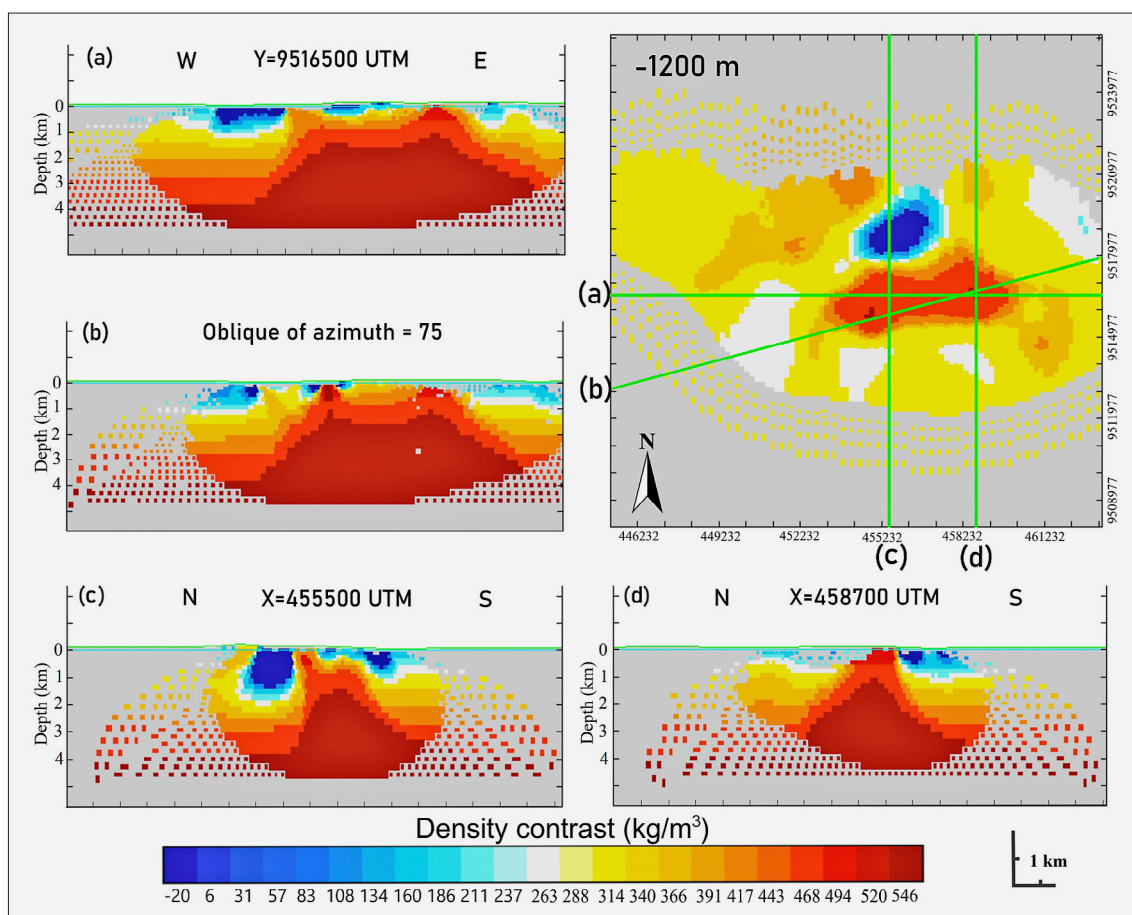


Figure 6. Vertical depiction of the subsurface layer in various directions: a) West-East direction at latitude 9516500 UTM, b) Southwest-Northeast direction with an azimuth of 75° , c) North-South direction at longitude 455500 UTM, and d) North-South direction at longitude position 458700 UTM. Red indicates high density contrast, and blue indicates low density contrast. The position of the four vertical slices is shown in the uppermost right figure.

for a few specific ones. Through trial and error, we selected a balance factor of 800 rather than the package's default of 80, as an increased balance factor results in a greater percentage of cell filling in the subsurface layer. We used a flattening coefficient of 10 and a lateral smoothing value of 0.3 (selected after trying various options) to enhance cell filling stability.

The inversion results of the residual gravity data describe the subsurface layer in two ways: horizontally (see Figure 5) and vertically (see Figure 6).

Figure 5 presents the horizontal slicing at depths of 200, 500, 800, 1200, 1500, 2000, 2500, 3000, and 3500 meters below sea level (bsl). The horizontal slicing reveals an intrusive rock pattern with a density contrast of 546 kg/m^3 . The peak of the intrusive rock (dark-red) occurs at a depth of roughly 1500 meters bsl and is consistent in deeper zones. The pattern of intrusive rock branches from west to east. In shallower zones ($< 1200 \text{ m}$), density contrast varies from -20 to 366 kg/m^3 . These may demonstrate the diversity of rock types in the shallow zone.

The high-density contrast (red) in **Figure 5** is associated with the high-gravity anomaly in **Figure 4b**, while

the lower-density contrast (blue) is correlated with the lower-gravity anomaly. The lower-density mass anomaly in the shallow zone, extending to a depth of about 1,500 meters below sea level (see **Figures 5a to 5e**), contributes to the lower-gravity anomalies in the study area. Surface hot spring manifestations are generally located at the boundaries between areas of high and low-density contrasts. The presence of near-surface mass anomalies with large density contrast gaps around hot springs may indicate weak zones caused by geological structures, such as fractures and/or faults. The Boroboro Fault, Kaendi Fault, Landai Fault, and Lainea Fault, as shown in **Figure 1**, support the above interpretation. These faults are located around hot springs or the boundary zones between high- and lower-density contrasts.

The vertical slicing of the inversion model is presented in three variants based on direction: West-East, North-South, and oblique slices with certain azimuth angles. **Figure 6** shows four vertical slices through the peaks of maximum anomalies, which actually coincide with the hot spring manifestations. The image in the top right of **Figure 6** is included only to show where the four vertical

slices are located. These slices are labelled (a), (b), (c), and (d). The first vertical slice runs West-East through latitude 9516500 UTM (see **Figure 6a**). **Figure 6b** illustrates the vertical slice's oblique direction, positioned at an azimuth angle of approximately 75° . These two models clearly indicate the presence of the vertical intrusive rock model with a maximum density contrast of 546 kg/m^3 in the West-East and Southwest-Northeast orientations. Furthermore, the layering system's strata, which are defined by density contrast differences ranging from -20 kg/m^3 (dark-blue) to 546 kg/m^3 (dark-red), are plainly evident. In addition, the layering model reveals the presence of basin-shaped and fault patterns in the environment surrounding the intrusive rock body. These basins are characterized by layers with varying density contrasts ranging from 237 kg/m^3 (light blue) to 314 kg/m^3 (light orange), where the layer with a density contrast of 263 kg/m^3 (very light gray) complements the basin's central zone.

Figures 6c and **6d**, respectively, represent the vertical slice model trending North-South at longitude positions 455500 UTM and 458700 UTM. Each of these slices passes through the top of an intrusive rock. The intrusive rock model, characterized by a density contrast value of 546 kg/m^3 (a dark-red color), is modelled very clearly. The model also shows layering strata according to their density contrast and displays the presence of basin and fault patterns.

5. Discussion

5.1. Geothermal system at LNVGF

In this section, we discuss the geothermal system at the LNVGF, which includes reservoir basins, basements, heat sources, and subsurface faults that control geothermal activity. For this purpose, we created two geological models (namely, **Figures 7a** and **7b**), utilizing the gravity inversion model from **Figures 6a** and **6c**. The choice of these two inversion models is considered appropriate because they represent two different cutting directions and cross the area where hot water manifestations occur. This model improves the interpretation models of **PSDG (2010)**, **Sugianto (2011)**, and **Zarkasyi et al. (2014)**, especially in describing the patterns and geometry of basins, basements, and heat sources.

The two geological models show the underlying layout in the research area, which determines the mechanisms of the geothermal system. We interpreted six rock units in the LNVGF based on rock density values. The first rock units have a density range of $2608 \leq \rho < 2762 \text{ kg/m}^3$. These density values are the sum of density contrasts ($-20 \leq \Delta\rho < 134 \text{ kg/m}^3$) and Bouguer density (2628 kg/m^3). The second rock units have a density range of $2762 \leq \rho < 2865 \text{ kg/m}^3$, after summation of the Bouguer density and the density contrast $134 \leq \Delta\rho < 237 \text{ kg/m}^3$. The density range of the third rock units is $2865 \leq \rho < 2942 \text{ kg/m}^3$ (with the range of density contrast of $237-$

314 kg/m^3). The fourth rock units have a density range of $2948 \leq \rho < 3045 \text{ kg/m}^3$ (the density contrast in this stratum ranges from 315 to 417 kg/m^3). The fifth rocks have a density of $3046 \leq \rho \leq 3122 \text{ kg/m}^3$ and a density contrast $418 \leq \Delta\rho < 494 \text{ kg/m}^3$. The sixth rock unit, which is the bottom layer, has a density of $\rho = 3174 \text{ kg/m}^3$ or a density contrast 546 kg/m^3 , indicating the presence of an intrusive rock shape.

Figure 7a shows subsurface basin formed at depths ranging from 500 m to about 1200 m represented by the rock units with the density range of $2865 \leq \rho < 2942 \text{ kg/m}^3$. This basin appears deeper on the West and East sides of the cross-section than the one in the middle. The maximum thickness of this layer is about 300 m . The formation of the basin and its flanking faults is associated with metamorphic exhumation that began in the Middle Miocene and continued into the Pliocene (**Mawaleda et al., 2018; Muzani et al., 2023**). Furthermore, the development of the basin and its associated normal and strike-slip faults was predominantly driven by persistent extension caused by Banda rollback (**Nugraha and Hall, 2022**). This extension caused crustal thinning and magmatic activity, creating an environment conducive to pull-apart basin formation. These basins created optimal conditions for geothermal activity and hot spring formation. Based on these characteristics, the central basin zone likely acts as a reservoir basin in the LNVGF. The central basin zone has depths ranging from approximately 600 to 900 meters . Using magnetotelluric and time domain electromagnetic methods, **Zarkasyi et al. (2014)** estimated the existence of a reservoir at a depth of $750-1000 \text{ m}$, which is comparable to the reservoir estimate from this study. This reservoir layer is likely composed of metamorphic rocks (**PSDG, 2010; Zarkasyi et al., 2014**) with densities ranging from 2865 kg/m^3 to 2942 kg/m^3 .

Above the reservoir basin there are several rock blocks with various densities that act as cap rock. The cap rock layer is located at a depth of several tens of meters above sea level (asl) to a depth of about 1000 m bsl (see **Figures 7a** and **7b**). **PSDG (2010)** and **Zarkasyi et al. (2014)** suspect that the cap rock comes from altered metamorphic/sedimentary/limestone rocks. Our study also suspects the potential of the altered metamorphic, meta-sandstone and meta-limestone rocks to function as cap rock in the LNVGF. Rocks with density ranges of $2608 \leq \rho < 2762 \text{ kg/m}^3$ (interpreted as meta-limestone) and $2762 \leq \rho < 2865 \text{ kg/m}^3$ (interpreted as meta-sandstone), as well as altered metamorphic rocks (with densities equivalent to meta-sandstone), located in the western to southern zones of the Boroboro Fault, act as caprock. In the northern to eastern zones, a combination of altered metamorphic rocks and meta-limestone acts as caprock.

Under the reservoir layer, there are two high-density rock units with the density range of $2948 \leq \rho < 3045 \text{ kg/m}^3$ and $3046 \leq \rho \leq 3122 \text{ kg/m}^3$, respectively. These rock outcrops appear on the surface and represent metamorphic rocks (see **Figure 1b**). The difference in density

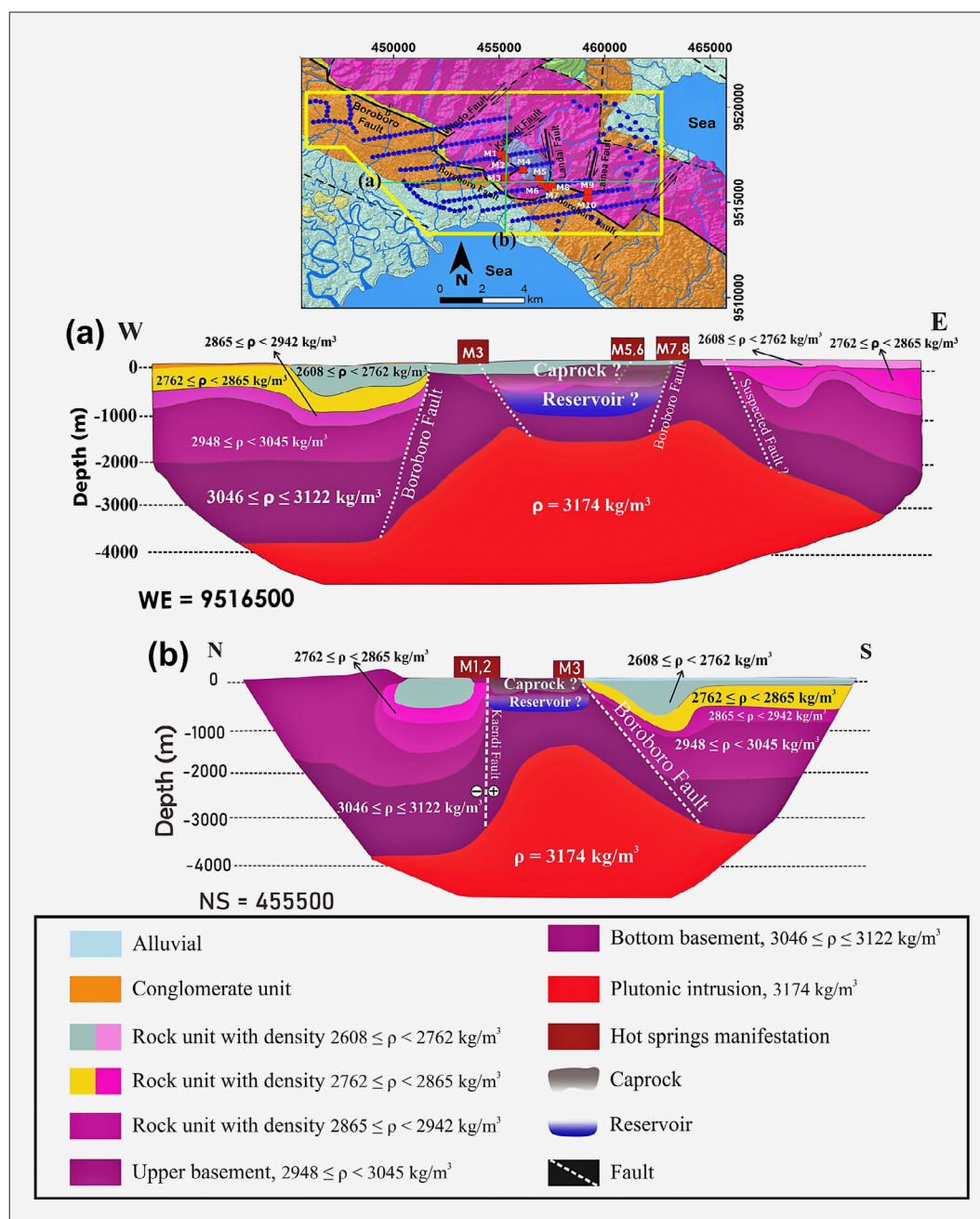


Figure 7. Geological model of the Lainea geothermal system: a) West-East direction at latitude 9516500; b) North-South direction at longitude 455500. The top image shows the positions of Lines (a) and (b), which represent the West-East and North-South positions of the geological model, respectively.

between these two metamorphic rocks may be due to the different pressures and mineral deposits they experienced during their alteration. The higher density of the metamorphic rocks at depths of 2-4 km is considered to result from a combination of intrusive bodies located directly below it and mineral deposition from thermal water in that depth zone. This condition resembles the geothermal field depicted in the Imperial Valley, California (Gupta and Roy, 2010). These two metamorphic layers located on the left and right sides of the cross-section can be thousands of meters thick. However, the exhumation and extension during Miocene-Pliocene uncon-

formity (Nugraha et al., 2022) cause the metamorphic rocks thinning in the center of the research area.

The interpretation of the faults in Figure 7 is based on the geometric pattern of the resulting density model (see Figures 6a and 6c), as well as the geological information in the area (see Figure 1b). The interpretation of the Boroboro Fault as a normal fault in Figures 7a and 7b aligns with the geological data (see Figure 1b), which indicates that the northwest-southeast trending Boroboro Fault is a normal fault. Figure 7a shows the location of the Boroboro fault on the west side of the M3 hot spring manifestation. However, this visual cannot explain the

western Boroboro fault as a conduit for the M3 hot spring. The Boroboro Fault also lies beneath the M7 and M8 manifestations, and it is suspected that this fault acts as a conduit for both. The faults beneath the M5 and M6 manifestations may be part of the Boroboro Fault system due to their similar fault patterns and proximity to the hot spring manifestations. The Boroboro Fault and the Landai Fault are suspected to act as conduits for the M5, M6, M7, and M8 hot springs due to the confluence of the two faults around the four manifestations. The fault beneath the M3 hot spring in **Figure 7a** is suspected to be associated with the Boroboro Fault but requires confirmation with additional evidence. Meanwhile, the suspected fault located east of the M7 and M8 hot springs is based solely on gravity model interpretation; there is no geological evidence to confirm it. These estimated faults are located at depths ranging from a few hundred meters to about 2000 m bsl. The Boroboro Fault extends into the upper basement at a depth of approximately 2000 m bsl.

Figure 7a also demonstrates the existence of intrusive/plutonic rocks at depths ranging from 1500 m to more than 3000 m. The form is quite vast, widening from west to east, with the peak located in the center of the track. This intrusive rock contains branches that produce two dome summits. This rock is the result of magmatic activity after metamorphic exhumation and crustal thinning resulting from extension driven by the Banda rollback in the eastern part of the SE arm (Nugraha and Hall, 2022). The intrusive plutonic rock serves as a heat source in the Lainea geothermal system. In line with this study, Zarkasyi and Widodo (2014) demonstrated the presence of the plutonic rock model at the depth of 1500 m using a magnetotelluric method. The gravity-based inversion model in this study has the advantage of presenting a model of underlying layered strata based on rock density contrast, which makes interpretation easier.

Figure 7b shows the geological model in the North-South direction, which cuts perpendicular to the West-East cross-sectional model (see **Figure 7a**) at the longitude position 455500 UTM. The shape of plutonic rocks in the North-South cross-section is much narrower than the shape in the West-East direction. This represents the orientation of the extension process, which tends to be west-east due to the Banda Rollback, which is located east of the Southeast Sulawesi arm. As previously explained, tectonic processes such as metamorphic exhumation, extension, crustal thinning, and magmatism centered in the central part of the study area cause the northern and southern basins to become thicker and deeper than the middle basin. The northern fault in **Figure 7b** is suspected to be the Kaendi Shear Fault, which is associated with the M1 and M2 hot spring manifestations. The southern fault is suspected to be the Boroboro Fault, which acts as a conduit for the M3 manifestation.

The basement is the layer underlying the reservoir rock. Based on the geological model in **Figure 7**, the basement is the integration of rock layers with densities of $2948 \leq \rho < 3045 \text{ kg/m}^3$ and $3046 \leq \rho \leq 3122 \text{ kg/m}^3$,

which are metamorphic rock groups. Geological information (see **Figure 1b**) confirms the occurrence of the upper and bottom basement on the surface, which is represented by the same rock formation (i.e. metamorphic rock units). The identification of the basement is very important. It is a zone where plutonic intrusions occur, which are the heat sources of non-volcanic geothermal energy. Based on the model in **Figure 7**, the upper boundary of this basement is located at a depth of several meters asl to a depth of 1500 m bsl.

5.2. Subsurface fault lineament model

Fault systems play a crucial role in geothermal systems, serving as permeable conduits for the ascent of hot fluids or steam from the reservoir to the surface, as well as facilitating heat transfer from thermal sources into shallower strata. Advanced gravity data processing approaches, including tilt angle horizontal gradient (TAHG), fast sigmoid edge detection (FSED), and Euler deconvolution, demonstrate dependability in estimating subsurface faults (Safani et al., 2023).

Figure 8 illustrates the application of TAHG and FSED techniques to residual gravity anomaly data. The TAHG method shows a very clear contrast between the strong (red) and weak (blue) amplitudes of the gravity anomaly (see **Figure 8a**). Meanwhile, the FSED method emphasizes positive amplitudes by degrading negative amplitudes (see **Figure 8b**). Both edge detection methods exhibit analogous positive amplitude patterns. The highest amplitude reveals the edges of anomalous sources that appear to depict subsurface fault characteristics (thick black lines) inside the research area. This is because the alignment of the identified subsurface faults exhibits two directional trends, northwest-southeast and southwest-northeast, which typically correlate with the pattern of surface faults observed using the geological approach (yellow). The orientation of the Boroboro Fault, identified as a normal fault, indicates that its northwestern and southeastern ends were once aligned. Additionally, the Windo and Kaendi faults, which are strike-slip faults, consistently bend in a southwest-northeast orientation. This type of fault aligns with the geological information presented in **Figure 1b**. The core of these evolving faults aggregates all geothermal manifestations. The activity of these faults and the fractures they generate significantly influence the migration of hot fluids to the surface. Further discussion of the identified subsurface faults using other geophysical approaches is needed. There is very minimal evidence of earthquake activity around the faults during the period 1972-2024. Only two earthquakes (yellow asterisks in **Figure 9**) are recorded throughout that period.

Euler deconvolution (available in Oasis Montaj software) was applied to the gravity anomaly data in order to estimate the depth of the anomaly source. The solution was found through trial and error while considering the deconvolution window size. After trying various options,

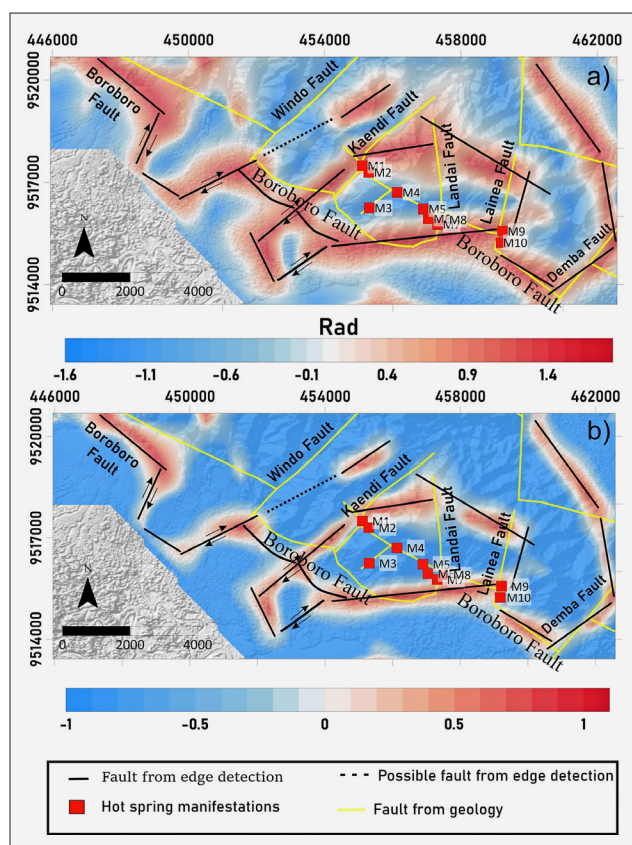


Figure 8. Subsurface fault alignment model at LNVGF, Southeast Sulawesi, Indonesia: a) from the TAHG technique; b) from the FSED technique.

the optimal deconvolution window size for estimating the depth of anomalous sources was found to be 10×10 . This study used a structural index (N) of 0 to represent the geological contact response formed in the study area. This index is suitable for estimating geological structures, such as faults (Pham et al., 2023; Safani et al., 2023). Figure

9 depicts the solution of Euler Deconvolution represented by dots with colors varying from dark blue to dark red. This figure illustrates depth variations of subsurface geological structures ranging from 168.6 to 1998.4 m. These depth variations align with the fault depth interpretation shown in Figure 7. The hot springs in the central part of the study area are surrounded by shallow geological structures (blue dots), while deeper structures (light pink to dark red dots) surround the hot springs at more distant positions. This pattern of structure depths also illustrates the uplift pattern that occurred in the area. Figure 9 shows the locations of geological structures associated with strike-slip fault lineaments in the study area. These include the Windo Fault, Kaendi Fault, Lainya Fault, and Demba Fault. These strike-slip faults have shallow depths, as indicated by the blue dots.

The solution of the Euler deconvolution reveals subsurface anomaly direction trends that are analogous to those estimated with TAHG and FSED. This good agreement may be due to selecting an appropriate index structure ($N = 0$) to describe the geological contact in the form of a fault. Figure 8 and Figure 9 illustrate the northwest-southeast (NW-SE) oriented Boroboro Normal Fault, which developed during the extensional process, followed by crustal thinning. Strike-slip faults trending NE-SW cut the Boroboro Fault relatively shallowly after crustal thinning. These strike-slip faults formed as secondary faults after the main fault developed during the Miocene-Pliocene deformation phase. The rose diagram of the resultant data constructed from the FSED's predicted faults indicates that the predominant orientation of the geological structures is southwest-northeast, succeeded by northwest-southeast. The presence of two earthquake occurrences (yellow asterisks) in the center of Figure 9 indicates the dynamic nature of the geological features in the studied area.

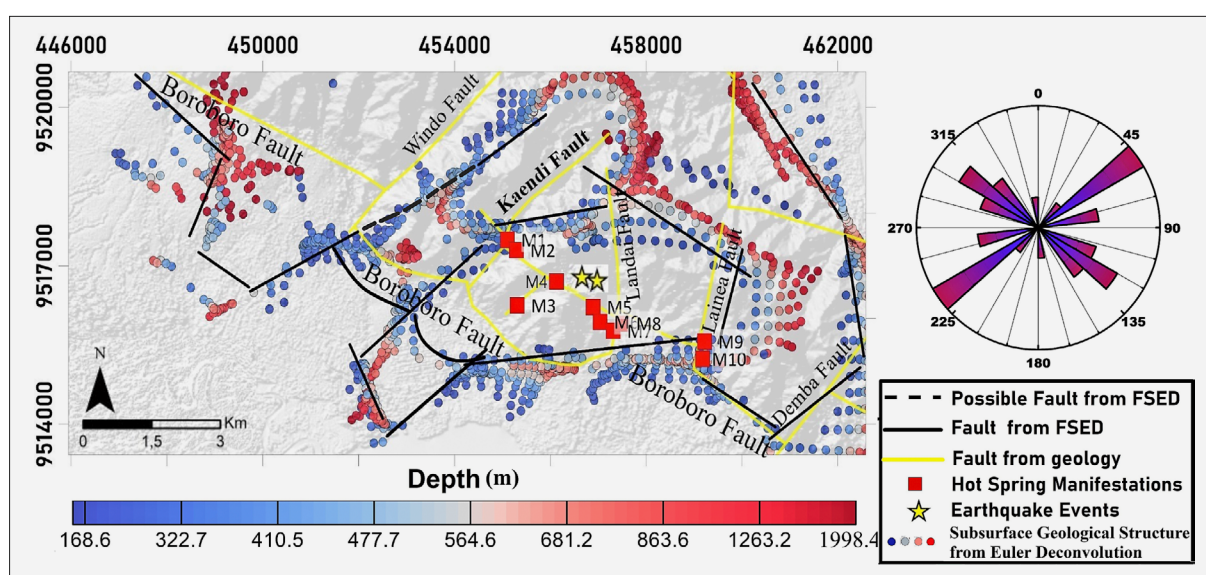


Figure 9. Euler deconvolution depth solution for the Lainya geothermal system, Southeast Sulawesi, Indonesia. Dots with various colors from dark blue to dark red represent variation depths of subsurface geological structure of the area.

6. Conclusions

We present several conclusions based on studies using advanced data processing techniques and inversion methods for gravity data:

- 1) The reservoir basins are located at depths from 600 m to 900 m with a density range of $2865 \leq \rho < 2942 \text{ kg/m}^3$. The caprock covering the reservoir layer consists of several rock blocks with densities ranging from 2608 to 2865 kg/m^3 . The caprock is located at a depth of several tens of meters above sea level to a depth of approximately 1000 m below sea level. The basement underlying the reservoir rock is the integration of rock layers with densities of $2948 \leq \rho < 3045 \text{ kg/m}^3$ and $3046 \leq \rho \leq 3122 \text{ kg/m}^3$, which are metamorphic rock groups. The upper boundary of the basement is located at a depth of several meters above sea level to a depth of 1500 m below sea level.
- 2) Intrusive plutonic rocks with maximum density of 3174 kg/m^3 are located at depths ranging from 1500 m to more than 3000 m. The intrusive plutonic rocks act as heat sources of geothermal energy at the LNVGF.
- 3) The use of TAHG and FSED edge detection techniques demonstrates the presence of subsurface faults with northwest-southeast and southwest-northeast trends. These subsurface faults correspond to surface fault trends from a geological standpoint. Euler deconvolution shows subsurface anomaly direction trends that are similar to the TAHG and FSED techniques. Geological structural anomalies (estimated faults) from the Euler deconvolution show depth variations ranging from 168.6 to 1998.4 m, which aligns with the modelled fault depths from gravity data inversion.

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SAŽETAK

Istraživanje geotermalnoga sustava korištenjem napredne obrade i inverzije gravitacijskih podataka u nevulkanskome geotermalnom polju Lainya, Indonezija

Indonezija je zemlja koja ima obilne geotermalne resurse. Svrha je ovoga istraživanja ispitati geotermalni sustav u nevulkanskome geotermalnom polju Lainya, pokrajina Jugoistočni Sulawesi, Indonezija. To uključuje (i) procjenu geotermalnih bazena rezervoara, krovnih i temeljnih stijena, (ii) procjenu izvora topline i (iii) procjenu podzemnih rasjeda. Prva dva cilja postignuta su korištenjem poboljšane strukturne gravitacijske inverzije. Treći cilj postignut je korištenjem naprednih tehnika obrade, i to 3D Eulerove dekonvolucije, kuta nagiba horizontalnoga gradijenta (TAHG) i brze detekcije rubova sigmoidom (FSED). Inverzija gravitacijskih podataka pokazuje bazene rezervoara koji se nalaze na dubinama od 600 m do 900 m s rasponom gustoće od $2865 \leq \rho < 2942 \text{ kg/m}^3$. Nekoliko blokova stijena s gustoćama u rasponu od 2608 do 2865 kg/m^3 funkcionira kao krovna stijena. Krovna stijena nalazi se na dubinama u rasponu od nekoliko desetaka metara do 1000 m. Temeljna stijena ispod stijene rezervoara jest integracija slojeva stijena s gustoćama od $2948 \leq \rho < 3045 \text{ kg/m}^3$ i $3046 \leq \rho \leq 3122 \text{ kg/m}^3$. Gornja granica bazne stijene nalazi se na dubini od nekoliko desetaka metara do 1500 m ispod razine mora. Intruzivne plutonske stijene s maksimalnom gustoćom od 3174 kg/m^3 nalaze se na dubinama u rasponu od 1500 m do više od 3000 m. TAHG i FSED pokazuju prisutnost podzemnih rasjeda sa smjerovima pružanja sjeverozapad-jugoistok i jugozapad-sjeveroistok. Rezultati Eulerove dekonvolucije podržavaju model rasjeda TAHG i FSED.

Ključne riječi:

gravitacija, geotermalni rezervoar, izvor topline, podzemni rasjed, polje Lainya

Author's contribution

Jamhir Safani (Dr.Eng.): conceptualization, methodology, formal analysis, review, and supervision. **Rezki Wirawan** (M.Sc student): data acquisition and visualization. **Khalil Ibrahim** (Ph.D student): data acquisition, visualization, writing, and editing. **Masri** (M.Sc): methodology, writing, and validation. **Hasmina T. Mokui** (Ph.D): validation, writing, review, and editing.

All authors have read and agreed to the published version of the manuscript.

Geotechnical Properties and Applications of Iron Ore Tailings-Amended Lateritic Soil for Road Construction

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Abstract

The abundance of lateritic soils in Nigeria has made them one of the most used materials for road construction. However, many of these soils exhibit substandard geotechnical properties, necessitating improvements before their deployment in road construction. This study aims to evaluate the geotechnical properties and practical applications of iron ore tailings (IOTs)-amended lateritic soils for road construction. The lateritic soil obtained from a road construction borrow-pit as well as the mixture with IOTs were subjected to mineralogical and geotechnical tests. The lateritic soil contains appreciable amounts of clay (29.1%), fines (52.4%) and sand (46.6%) with a small quantity of gravel (1.0%). Thus, they can be described as clayey sand. In addition, an investigation of its consistency limits indicates that the soil plots above the A-line and classified as highly plastic clay based on their position on the Unified Soil Classification System (USCS) chart. The results of the geotechnical properties indicate a significant improvement in the geotechnical properties of the lateritic soil with the addition of IOT. There was an increase in maximum dry density and California bearing ratio (CBR) with a reduction in the values of liquid limit, plasticity index, linear shrinkage, and unconfined compressive strength. This study demonstrates that the geotechnical properties of the lateritic soil can be modified to fulfil the standard required for utilization as a road subbase and the minimum required can be suitably achieved by mixing about 20% IOTs with lateritic soil.

Keywords:

geotechnical; iron ore tailings-amended lateritic soil; subbase

1. Introduction

Lateritic soils are formed from the intense weathering and leaching of iron and/or aluminium-bearing parent rocks due to alternate wet and dry seasons prevalent in the subtropical and tropical regions of the world (Basu and Sinha, 2021). The process of laterization begins with the alteration of primary minerals of the parent rocks to clay minerals with subsequent leaching of the mobile constituents like bases and silica while the oxides of iron and aluminium are retained as residues in the uppermost layers (Sinha and Basu, 2021). Thus, the development and properties of lateritic soil profile depend largely on the climatic conditions, parent rock types and the laterization process (Daramola et al., 2024). Lateritic soils are abundant in tropical and subtropical regions, and they are commonly utilized for various con-

struction purposes ranging from ancient structures to smooth roads. Moreover, the abundance and general consideration of lateritic soils as good construction materials have been the major justification, due to their utilization for various construction purposes ranging from spectacular ancient structures to smooth roads. On this basis, research has been executed on the determination of suitability for different purposes (Oyelami, 2017; Daramola et al., 2024). Similarly, the influence of the factors controlling the formation of lateritic soils on their geotechnical properties has been investigated by various researchers. For example, the influence of the parent rock types on the geotechnical properties of lateritic soils has been extensively investigated (Adeyemi, 2003; Mesida, 2006; Ngo'o Ze et al., 2019; Basu and Sinha, 2021). In addition, the effects of climatic conditions on the geotechnical properties of lateritic soils have been documented by a few researchers (Mvindi et al., 2017) who emphasized the role of weathering intensity and seasonal variability.

However, lateritic soils derived from charnockite and charnockitic rocks from southwest Nigeria have been

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shown to exhibit unique geotechnical characteristics. As such, the lateritic soils usually contain excessive amounts of fines (clays and silt) commonly characterized by high plasticity levels which can be attributed to the mineralogical properties of their parent rocks. This is due to the lower quartz content, higher proportions of feldspar, biotite and pyroxene content which would yield soils with suboptimal characteristics for engineering applications (Fatoyinbo et al., 2024; Afolagboye et al., 2024). Therefore, they are usually problematic when utilized for road construction as they exhibit geotechnical properties that fail to meet the required specifications for road construction, thereby resulting in road failure and not justifying their huge cost of road construction. However, soils with substandard geotechnical properties are commonly treated through a process termed stabilization to bring them to the required standard. The process of stabilization involves the addition of different organic and inorganic materials, such as lime, cement, bitumen, and even sawdust, to enhance soil properties and render them suitable for engineering applications (Etim et al., 2017; Ojuri et al., 2017; Chompoorat et al., 2019).

Stabilization has helped address several engineering-related problems and improve the sustainability of public infrastructure. For example, Chompoorat et al. (2019) applied cement to enhance the stability of waste soil derived from lakebed deposits, making it suitable for road construction. Also, Chompoorat et al. (2023) utilized cement-treated sands (CTSs) combined with fibre - referred to as cement-treated sand reinforced with fibre (CTSf) - to address the brittle nature of CTS and enhance its suitability as a base and subbase material in pavement and civil engineering structures. Similarly, Chindaprasirt et al. (2021) applied seven distinct types of synthetic fibres to significantly improve the mechanical performance of CTSf for road and pavement applications. Yoobanpot et al. (2020b) combined Ordinary Portland Cement (OPC) with fly ash (FA) to stabilize sediments from bottom of dams for use in construction. The study found that combining FA with OPC provides an effective way of stabilizing dredged sediments for utilization as construction materials. Yoobanpot et al. (2020b) investigated cement fly ash gravel (CFG) columns as an alternative to deep cement mixing (DCM) for embankments on soft clay, demonstrating significantly higher strength and permeability, with optimal performance achieved when 15% of cement was replaced with fly ash. Additionally, Chompoorat et al. (2021b) found that the shrinkage and swelling of OPC-stabilised sediment reduced by as much as 40% and 2.8%, respectively, when 20% FA was added. Chompoorat et al. (2021a) attempted to understand the physicochemical effects of dredged sand through stabilization. It was found, amongst others, that the improvement in the strength and stiffness of the sand is brought about by a series of physicochemical effects, including the hydration reaction, the pozzolanic reaction, flocculation, and agglomeration. More importantly, these findings im-

ply that alternative cementitious composites, like CFG columns, can significantly enhance soil stability and performance - supporting the broader application of iron ore tailings-amended lateritic soils in road construction as sustainable and effective geotechnical materials.

Recent studies have also investigated the stabilization of soils through eco-friendly media and microbial-induced processes in addition to the use of chemical approaches. As an illustration, Chompoorat et al. (2021c) examined the performance of alkali-activated, cement-based controlled low-strength materials (CLSMs). In the study, the CLSM was produced by mixing fly ash, steel slag, sodium hydroxide, and water with bottom ash (BA) aggregate. The findings indicate that the inclusion of slag in a proportion of 10-30% improves the strength of the mix, and higher slag content shortens the setting time and leads to a lower bleeding rate, providing viable perspectives in pavement and other construction applications. Similarly, Chompoorat et al. (2025) explore the use of cup lump rubber (CLR), an agricultural by-product, as a component in CLSM by developing two distinct CLSM mixtures: one based on cement and the other on alkali activation. The study found that some CLSM mixtures, both cement-based and alkali-activated, met the requirements for soil cement bases and subbases. Punmoi et al. (2021) utilized microbially induced calcite precipitation (MICP) in improving the suitability of soft clays for engineering applications. The study found that both vegetative cells and bacterial spores can effectively enhance the strength and modulus of clays by inducing MICP to generate calcite crystals. Similarly, Arpajirakul et al. (2021) applied the MICP technique to improve the engineering properties of soft soil in a sustainable, environmentally friendly, and energy-saving manner. Overall, some materials that have been explored for the stabilization of soils include metakaolin (Muhammad et al., 2020), fly ash (Sharma et al., 2012; Yoobanpota et al., 2020a, 2020b; Chompoorat et al., 2021a, 2021b), tin and gypsum waste (Apriyanti et al., 2019), quarry stone dust (Mishra et al., 2019), coal waste (Mansouri et al., 2021), sand dune (Sharma et al., 2016), palm fibre (Chindaprasirt et al., 2021), amongst others. Notably, these studies consistently demonstrate the prospect for significant improvements in geotechnical characteristics, such as increased load-bearing capacity with a corresponding reduction in plasticity.

Some of the several notable benefits of soil stabilization include the reduction of swelling potential and plasticity, enhancement of bearing capacity, as well as cost savings by significantly reducing the thickness of pavement. Specifically, the stabilization of lateritic soils using cement and lime has been shown to yield significant improvements, as evidenced by enhancements in strength characteristics and reductions in plasticity (Biswal et al., 2018). However, evidence from literature has shown that one key concern with chemical stabilization is the potential toxicity of the treated soils. Thus,

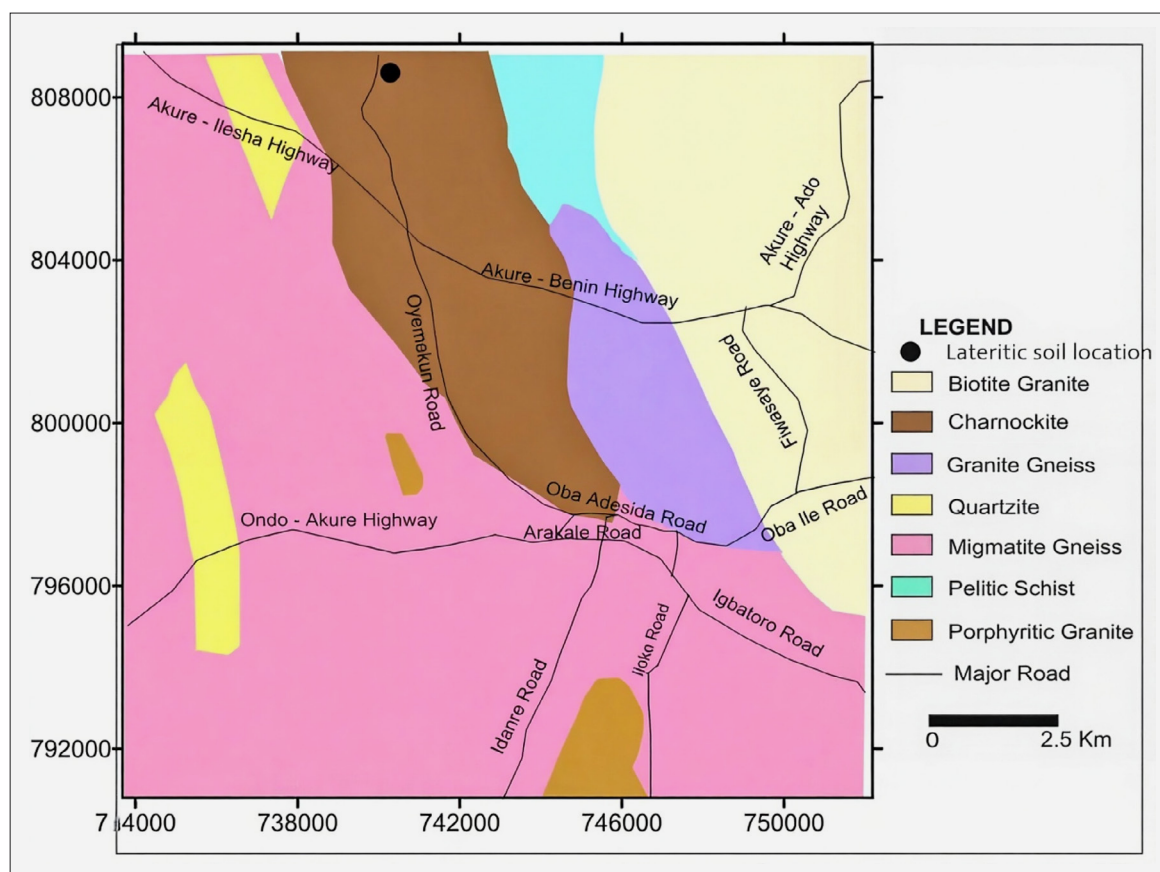


Figure 1. Geology Map of the Study Area (Modified from Falowo et al., 2019)

several studies have investigated assessment of toxicity arising from stabilization, and the potential mitigation techniques. For example, **Leelarungraj et al. (2018)** studied the leaching mechanisms of arsenic, chromium, lead, and zinc from cement and fly ash stabilized soils, and found that chemical compounds (CaO and MgO) on fly ash surfaces can control the pH of the fly ash and soil leachant. Similarly, **Wasino et al. (2019)** investigated phytoremediation with vetiver in relation to heavy metal-contaminated soil and successfully reduced heavy metal contamination in the treated soil. In contrast, **Dontrios et al. (2020)** adopted solidification-stabilization to treat heavy metals arising from municipal-solid-waste-incineration fly ash (MSWI FA), with the study presenting a positive outcome.

Despite the enormous literature on the stabilization of lateritic soils, there is a dearth of research focusing on the stabilization of charnockite-derived lateritic soils. This gap is particularly significant given the challenging geotechnical properties of these soils. Although the utilization of additives such as cement and lime has gained positive results, the costs of incorporating these additives are excessively high and prohibitive. This has turned the attention of researchers and engineers to the utilization of various domestic and industrial waste for stabilization purposes. Prominent among these waste materials are waste generated from mining activities which are com-

monly referred to as mine tailings. The recent efforts to diversify the Nigerian economy have resulted in a sporadic increase in mining activities, as well as an attendant increase in the number of mine tailings generated (**Owolabi and Daramola, 2024**). This study therefore examines the possibility of utilizing some IOTs for improving lateritic soils derived from charnockite for road construction. In doing this, the IOTs were added to the lateritic soils at various mixing ratios. This paper envisages evaluation of the effects of IOTs on the geotechnical properties of the lateritic soils and establishes the appropriate mixing ratio for effective utilization in road construction. This study will be a positive contribution to the effective reuse of mine wastes as a cost-effective alternative to expensive industrially manufactured additives, such as lime and cement for use in highway lateritic soil stabilization. Moreover, the utilization of IOTs will promote the reduction of mine waste, thereby reducing the environmental impacts associated with the storage of mine tailings. Thus, by addressing this issue, road construction materials can achieve enhanced performance, longevity, and sustainability. Furthermore, this research provides a practical solution for enhancing the performance of lateritic soils in road construction and underscores the potential for integrating waste materials into engineering practices, paving the way for sustainable and cost-effective infrastructure development.

Table 1. Summary of the testing program

S/N	Analysis type	Analytical method/category	Standard Used	Sample type	No. of Replicates	Mix Proportions (Soil:IOT)
1	Index Properties	Grain size distribution	British Standard Institution (BSI) (1990)	Air dried	3	100:0, 0:100
2		Atterberg limits	British Standard Institution (BSI) (1990)	Air dried	3	100:0, 95:5, 90:10, 85:15, 80:20, 70:30
3		Specific gravity	British Standard Institution (BSI) (1990)	Air dried	3	100:0, 95:5, 90:10, 85:15, 80:20, 70:31
4	Compaction	Standard Proctor	British Standard Institution (BSI) (1990)	OMC/Max. Dry Density	3	100:0, 95:5, 90:10, 85:15, 80:20, 70:32
5	Strength Tests	UCS	British Standard Institution (BSI) (1990)	7, 14, 28 days curing	3	100:0, 95:5, 90:10, 85:15, 80:20, 70:33
6		CBR	British Standard Institution (BSI) (1990)	Soaked/unsoaked	3	100:0, 95:5, 90:10, 85:15, 80:20, 70:34
7	X-ray fluorescence (XRF)	Major oxide geochemistry		powdered	1	100:0, 0:100
7	X-ray diffraction (XRD)	mineralogical composition		powdered	1	100:0, 0:100

2. Methods

This section of the paper provides a description of the study area. It further presents the method of sample collection, as well as the experimental and analytical techniques used in the analysis of samples collected from the field study.

2.1. Description of sample location

The lateritic soils used in this study are located near Ipinsa town approximately 12 km East of the city center of Akure in southwestern Nigeria (see **Figure 1**). The lateritic soil forms parts of the deposit used as subbase materials and forms the road subgrade of sections of the road linking the city center to Ipinsa Township. Geologically, the area is situated within the Precambrian basement complex province of southwestern Nigeria where the dominant parent rocks are syenite, granodiorites, granites, migmatite charnockite, and quartzite (see **Figure 1**). Specifically, the deposit from which the studied lateritic soil sample was taken is derived from charnockite. The elevation of the area ranges between 372 and 405 m above sea level with dominant gentle slopes which progressively increase in elevation towards the north-western part. The study area lies within the tropical rain forest, characterized by alternating wet and dry seasons with annual rainfall ranging between 1000–1500 mm. Humidity is moderately high in the wet season and low during the dry season. Temperature varies from 21.9°C to 30.4°C throughout the year (**Akintorinwa and Oluwole, 2018**). The vegetation is characterized by thick forest while several stream channels trending approximately east-west and north-south direction flow through the study area.

2.2. Iron ore tailings (IOTs)

The IOTs used in the research were collected from Itakpe, Kogi State, Nigeria. The material was transported in bags to the engineering geology laboratory of the Federal University of Technology, Akure and subjected to various laboratory tests.

2.3. Analytical Methods

The basic index properties including consistency limits, grading characteristics, and specific gravity are determined according to the specifications of the British Standard Institution (BSI) (1990). The soils used for the particle size distribution analysis were carefully soaked with Calgon for twenty-four hours before wet sieving to ensure adequate disaggregation. In addition, geotechnical properties, such as California bearing ratio (CBR), unconfined compressive strength (UCS) and compaction were determined in accordance with the guideline stipulated by BSI (1990). The geochemical and mineralogical properties of the lateritic soil and mine waste were determined by using X-ray fluorescence (XRF) and X-ray diffraction (XRD). The major oxide composition was determined using a Genius IFI Xenometrix XRF. A tungsten Carbide milling pot was used to mill the samples to achieve particle sizes of less than one hundred and fifty microns. Furthermore, the D8 advance diffractometer coupled with an automated flip stick multi-position sample stage was deployed to collect XRD data from the samples at the raw materials research laboratory, in Zairia, Nigeria. The analyses were conducted by means of the standard polystyrene sample holder in θ – θ configuration with exit slit, anti-divergent slit and a Goebel mirror with Ni-filtered Cu radiation ($\lambda = 1.5406 \text{ \AA}$) while the phases were identified and quantified by means of

Table 2. Geotechnical properties of the lateritic soil.

Properties	n	Range	mean	sd	cov
Natural moisture content (%)	3	6.65-6.78	6.71	0.07	0.01
Clay (%) (<0.002mm)	3	29.1-29.4	29.27	0.15	0.01
Silt (%) (0.002-0.075mm)	3	23.2-29.5	23.33	0.15	0.01
Gravel (%) (>4.75mm)	3	1	1.00	0.00	0.00
Sand (%) (0.075-4.75mm)	3	45.4-47.7	46.57	1.15	0.02
Specific Gravity	3	2.65-2.65	2.65	0.00	0.00
Plasticity index (%)	3	30.8-30.9	30.83	0.06	0.00
Liquid limit (%)	3	55.9-56.7	56.33	0.40	0.01
Plastic limit (%)	3	25.3-25.7	25.53	0.21	0.01
Linear shrinkage (%)	3	8.5-8.9	8.70	0.20	0.02
Optimum moisture content, OMC (%)	3	21.2-21.5	21.33	0.15	0.01
Maximum dry density, MDD (Kg/m ³)	3	1909-1912	1910.33	1.53	0.00
Unsoaked CBR (%)	3	20.3-20.43	20.36	0.07	0.00
Soaked CBR (%)	3	12.8-13.2	13.03	0.21	0.02
AASHTO classification	3	A-7-6	A-7-6		
USCS classification	3	CH	CH		

ICDD PDF-4 + Software. Subsequently, the soil stabilized with 5%, 10%, 20%, and 30% IOTs. Afterwards, the mixtures were subjected to basic index and geotechnical laboratory tests to study the effect of IOTs on the properties of the lateritic soil. All the laboratory geotechnical experiments performed followed the specifications of BSI (1990). Each test was carried out three times for each lateritic soil-iron ore tailing mixture to ensure the reproducibility and repeatability of the test results. A summary table outlining the testing program is presented in **Table 1**.

3. Results and Discussion

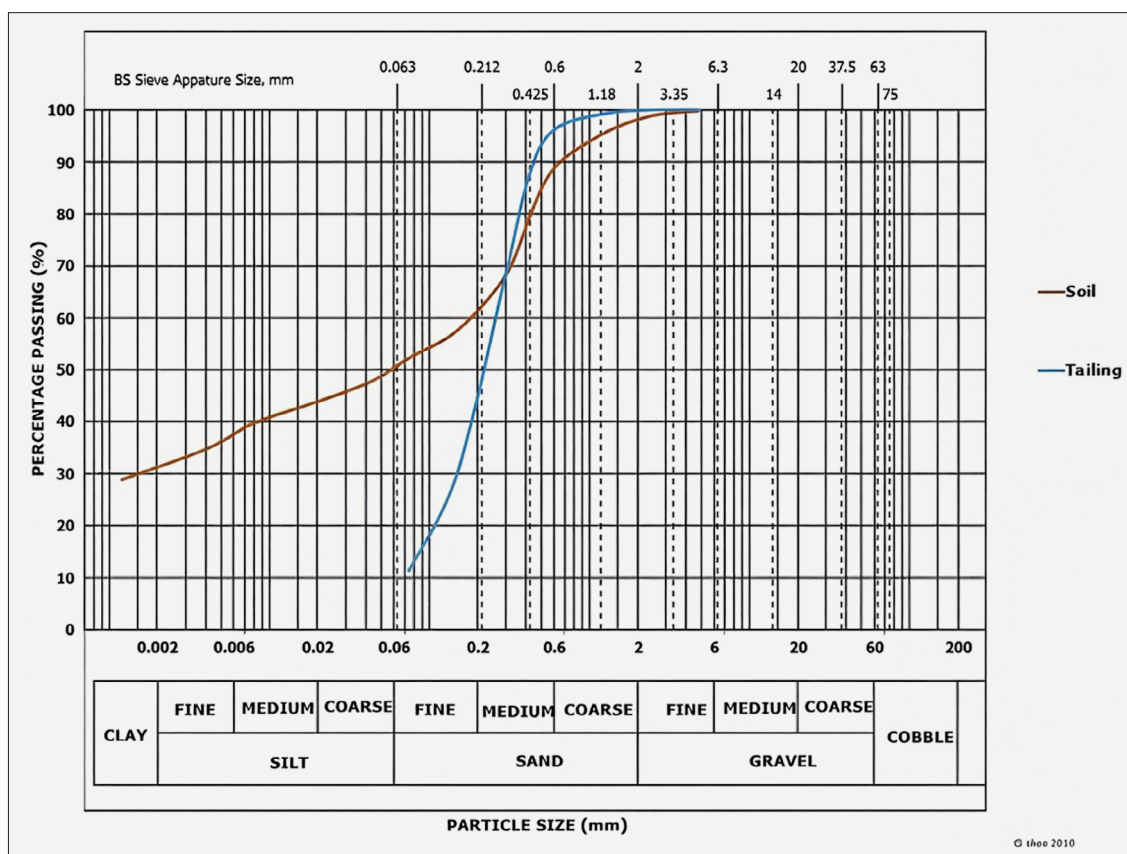
The results from the field study and laboratory experiments are presented in this section.

3.1. Properties of the Lateritic Soil

The geotechnical properties of the lateritic soil were first examined to establish a baseline for evaluating the effects of iron ore tailings amendment. These properties provide critical insight into the soil's suitability for road construction applications under varying engineering conditions.

3.1.1. Geotechnical properties

The geotechnical properties of the studied lateritic soils are presented in **Table 2** while the distribution of

**Figure 2.** Particle size distribution of the iron ore tailing and lateritic soil.

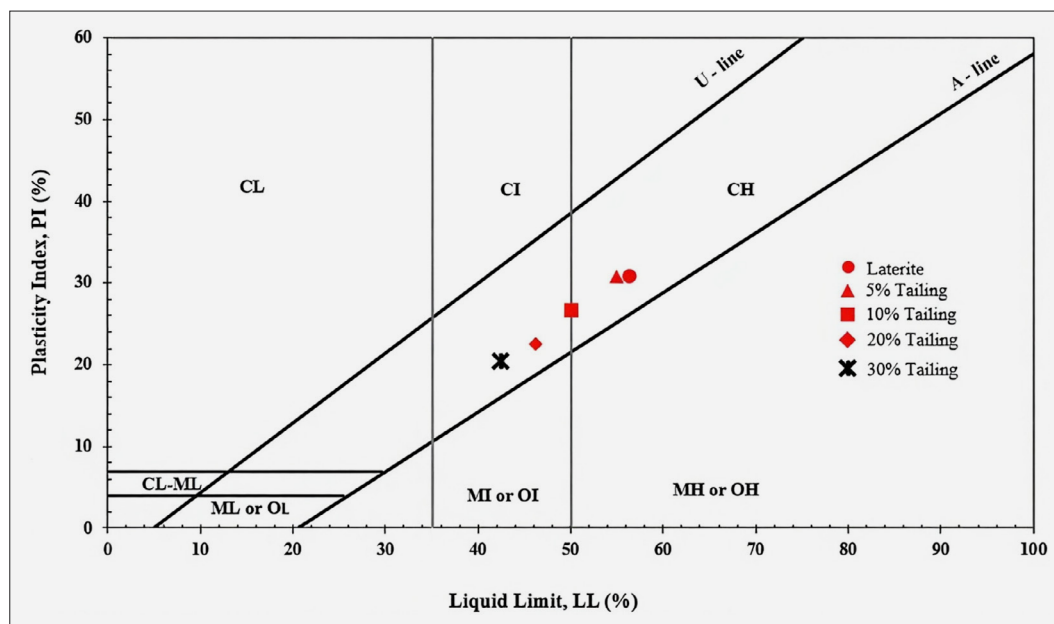


Figure 3. Position plots of the lateritic soil and the various mixes on the plasticity chart.

Table 3. Major oxide composition of the lateritic soil and IOT.

Oxides (wt%)	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	Y ₂ O ₃	Nb ₂ O ₅	K ₂ O	Ag ₂ O	SO ₂	MgO	TiO ₂	P ₂ O ₅	Na ₂ O
Lateritic soils	68.30	7.53	5.57	2.44	2.34	2.33	2.93	2.92	1.33	1.06	0.79	0.78	0.65
IOTs	63.09	16.88	8.35	0.67	1.43	1.06	2.28	1.44	0.93	0.44	2.19	0.28	0.31

the various grain sizes of the raw, untreated lateritic soil is presented in **Figure 2**.

The soil contains an appreciable amount of clay (29.1%), fines (52.4%) and sand (46.6%) with a meagre quantity of gravel (1.0%). Thus, they can be described as clayey sand. Additionally, an investigation of its consistency limits indicates that the lateritic soil plots above the A-line and classified as highly plastic clay based on their location on the USCS classification chart (**Figure 3**). The lateritic soils also exhibit a fairly high shrinkage potential according to their linear shrinkage value suggesting that they would exhibit a critical degree of expansion. The soil recorded a maximum dry density, UCS and CBR values which suggest that they possess a good strength characteristic as the UCS value indicates that the lateritic soils could be classified as very stiff. However, a significant decrease in strength is observed as the soil recorded a soaked CBR of 13% implying a 35% reduction in strength. This raises concern and could be a major cause of road failure in the study area as the soaked CBR is significantly less than the specified minimum of 25% recommended for subbase by the Nigerian Ministry of Works (**FMWH, 2013**).

3.1.2. Geochemical and mineralogical properties of the lateritic soil

The distribution of the major oxide in the lateritic soil investigated is presented in **Table 3**.

The result indicates that the soil is essentially dominated by silica, alumina and iron oxide which constitute approximately 88 wt% of the tested lateritic soil. In summary, they are classified as a silico-alumino-ferruginous type. Other oxides present in lesser quantities include Y₂O₃, CaO, Nb₂O₅, K₂O and Ag₂O while the rest occur in trace quantities. Additionally, a classification of the soil based on the silica and the content of sesquioxide of aluminium and iron indicates that the soils under consideration are weakly laterized (**Oyelami and Van Rooy, 2018; Daramola et al. 2024a**). The x-ray diffraction pattern (see **Figure 4**) indicates that the dominant clay mineral in the soil is kaolinite while the non-clay minerals include muscovite, quartz and albite. Thus, the dominance of kaolinite suggests that they would not exhibit excessive shrinkage and swelling upon intake of water. Additionally, the lateritic soil will tend to demonstrate low to marginal swelling due to wetting and low shrinkage on drying as kaolinite is renowned to exhibit the minimum affinity for water among the different types of clay minerals. In addition, soils with low swelling potential do not crack on drying. This suggests that the lateritic soil will perform well as road construction material, however, the presence of muscovite calls for caution as they are likely to cause field compaction problems.

3.2. Properties of the IOTs

The result of the sieve analysis (see **Figure 2**) showed that 100 % of the air-dried IOTs passed BS No. 200 sieve

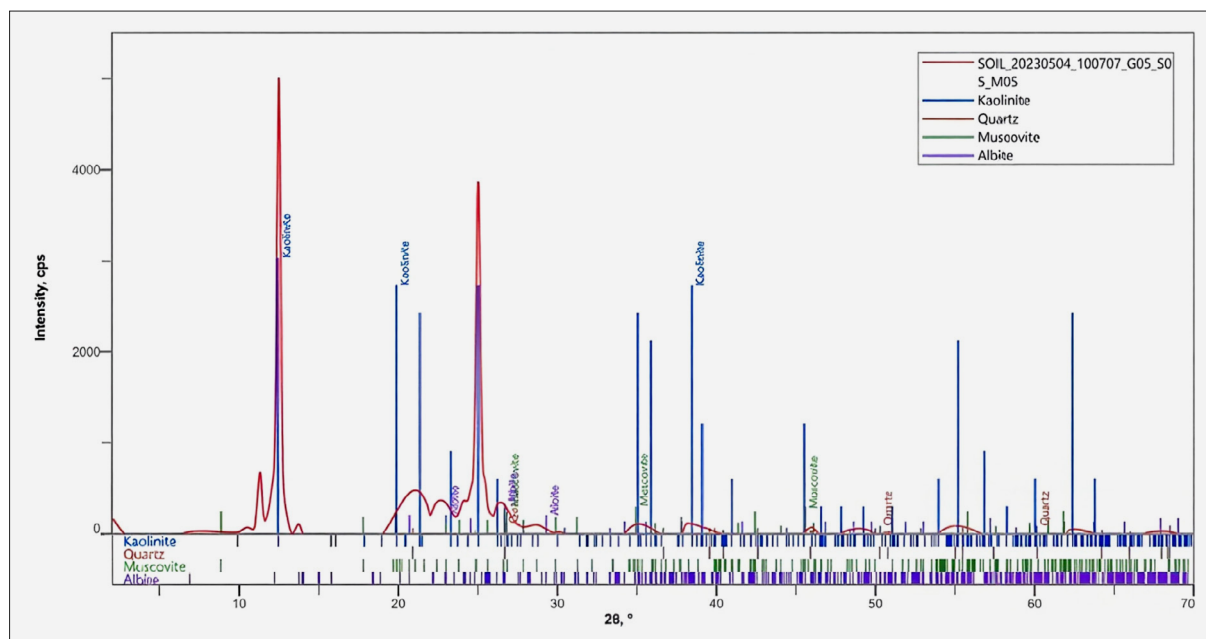


Figure 4. X-ray diffraction pattern of the lateritic soil.

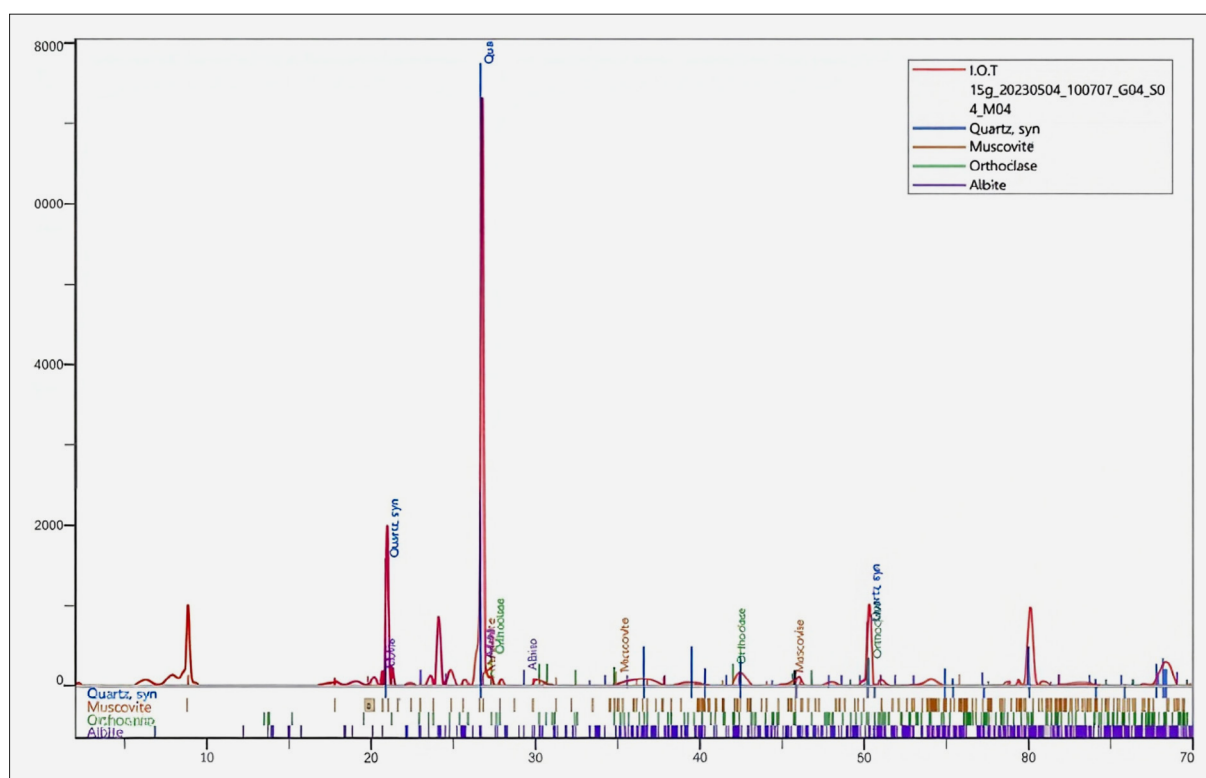


Figure 5. X-ray diffraction pattern of the IOTs.

while they are dominantly made up of sand size particles (90%) with the minor quantity of fines (10%) and as such, they are non-plastic. The oxide composition as well as the properties of the IOTs are reported in **Table 2**. Additionally, their mineralogical composition presented in **Figure 5** reveals that the IOTs are dominantly composed of quartz, muscovite, orthoclase and albite in various quantities. The dominance of sand-size particles

and the absence of deleterious clay minerals indicates that the tailings will not detrimentally shrink and swell within a pavement structure upon intake of water.

3.3. Stabilization

To assess the impact of iron ore tailings on the engineering behaviour of the lateritic soil, a series of stabili-

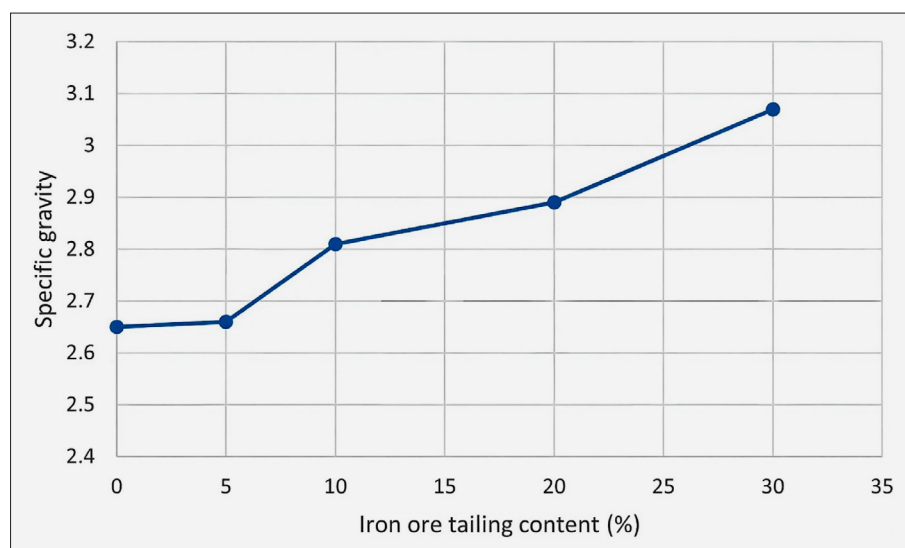


Figure 6. Plot of specific gravity of laterite soil – IOT mixture.

zation tests were conducted. The focus was on key parameters such as consistency limits, compaction characteristics, and CBR, which are essential indicators of soil performance in road construction.

3.3.1. Consistency limits and specific gravity

The consistency limits of the raw lateritic soils as well as the mixtures of soil and tailings (see **Figure 3**) generally depict a reduction with an increase in the tailings content. Specifically, the lateritic soil mixtures containing 10% tailings may be classified as inorganic clays of high plasticity (CH), while the mixtures with 20-30% IOTs are classified as inorganic clays of intermediate plasticity according to the Casagrande classification chart (see **Figure 3**). This implies a reduction in the plasticity characteristics with increased IOT content. This trend is consistent with the observation of previous research on soil-mine tailing mixtures (**Ojuri et al., 2017; Etim et al., 2017; Yohanna et al., 2020**). The general reduction in the liquid limits and plasticity index could be attributed to the increase in the sand fraction which reduces the affinity for water and the expansive capacity of the soil-tailing mixture (**Karakan, 2022; Tanyildizi et al., 2023**). **Figure 6** presents the plots of specific gravities of lateritic soil against IOT concentration. The values of the specific gravity of laterite soil increased from 2.655 to 3.12 when treated with 40% IOT content. This increase may be attributed to the fairly- high value of the specific gravity of the IOT (3.4) compared to that of laterite soil (2.655). A continuous increase was observed for the laterite soil when treated with up to 30% IOT due to the increasing density of the mixtures.

3.3.2. Compaction

The addition of the mine tailing resulted in an increase of the maximum dry density and a decline in organic moisture content according to the moisture-densi-

ty relationships of the soil-tailing mixtures presented in **Figure 7**. Comparable trends were observed in previous investigations on the impact of mine tailings on laterite soils. The maximum dry densities of laterite soils increased from 1910 kg/m³ to 1928 kg/m³, 1936 kg/m³, 1949 kg/m³ and 1955 kg/m³, respectively, with additions of 5%, 10%, 20%, and 30% of the IOTs. Conversely, the OMC reduced from 21.3 % to 20.6, 19.7, 18.9 and to 18.3% respectively with the addition of 5%, 10%, 20%, and 30% of the IOTs with the raw lateritic soils. The increase in the maximum dry densities could be attributed to the higher specific gravity of the grains of the tailings replacing the soil particles, which have a lower specific gravity (2.66). Similar observations were reported in previous studies by **Osinubi et al. (2015)**, **Etim et al. (2017)**, who reported increases in MDD and reductions in OMC when lateritic or clayey soils were blended with iron-rich tailings. Unlike the reduction in MDD and increase in optimum moisture content (OMC) reported by Champoorat et al. (2021c) for OPC and FA-treated soils, the present study observed the reverse trend (higher MDD and lower OMC with iron ore tailings addition), underscoring that IOT improves soil compaction mainly through its high specific gravity and filler effect rather than chemical hydration. Additionally, the increased additions of the IOTs reduce the plasticity index, indicating a corresponding reduction in the affinity for water, thereby reducing the optimum moisture content of the mixture (**Afolagboye et al., 2017**). Furthermore, the introduction of the IOTs, which is essentially dominated by fine sands, could have also contributed to the reduction in the organic moisture content due to the tendency to reduce the amount of water held by such a mixture.

3.3.3. CBR

A summary of the results of the CBR is presented in **Figure 8**, where it is apparent that the addition of IOTs to the mixture significantly increases the CBR values.

Figure 7. Compaction curves of the lateritic soils and various mixtures of lateritic soils and tailings.

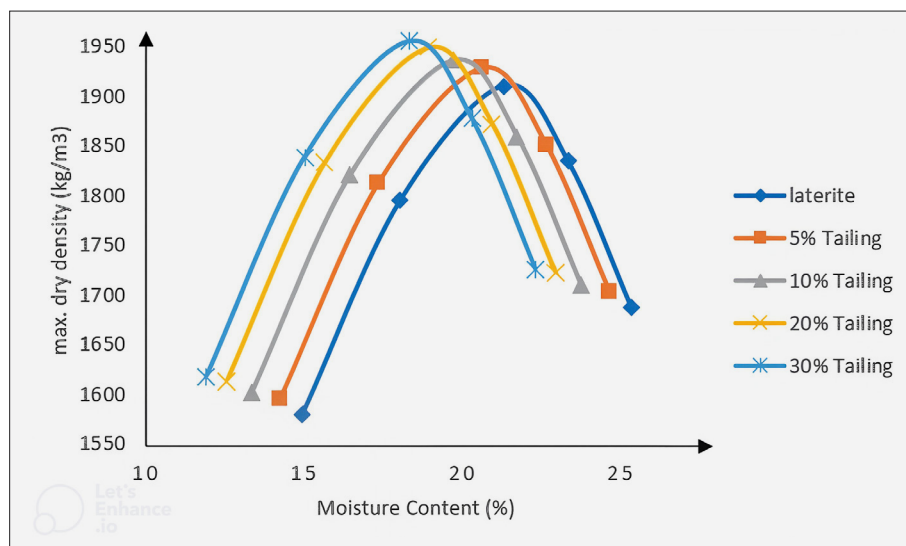
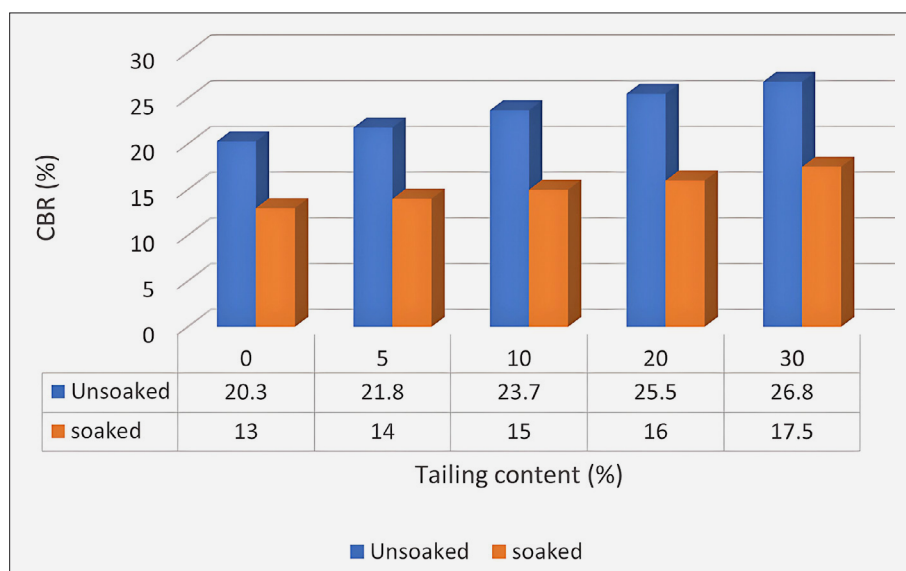


Figure 8. Unsoaked and soaked CBR of the lateritic soils and various iron ore tailing mix.



Similar trends have been reported in some previous studies by **Mohammed et al. (2018)**, **Akinbinu et al. (2022)** and **Ishola et al. (2023)**. The unsoaked and soaked CBR of the lateritic soils were 20.3 and 13 respectively. However, the unsoaked CBR of the mixtures increased to 21.8, 23.7, 25.5 and 26.8 while the soaked CBR increased from 14, 15, 16 and 17.5 upon the addition of 5, 10, 20 and 30% of the IOTs respectively. This signifies an improvement in strength upon the addition of the IOTs suggesting an improved performance when used for road construction. The increase in the CBR values may be attributed to the particle size distribution that improves the compaction and interlocking of soil particles (**Mohammed et al., 2018**). Better grain size distribution often leads to higher density and improved load-bearing capacity which is reflected in an increased CBR. However, despite the general increase in strength as indicated by the CBR, a general reduction in the CBR value was observed upon soaking with the percentage reduction ranging from 34.7 to 37.3%. Thus, careful

consideration should be taken to ensure adequate drainage facilities are provided to impede the ingress of water whenever they are used as construction materials.

3.3.4. UCS

The result of the UCS test is shown in **Figure 9**. The UCS of the IOT-modified lateritic soil samples strikingly decreased with a corresponding increase in the quantity of the IOTs added. The UCS of the raw lateritic soil was 274.1 kPa while the addition of 5, 10, 20 and 30% IOT slightly reduced the corresponding UCS to 256.4 kPa respectively. This represents a percentage reduction of 1.02, 1.39, 1.68, and 6.53% for the uncured UCS.

Previous studies reported by **Akinbinu et al. (2022)** also found a similar trend of reduction in the strength of IOT-amended lateritic soils. In a study by **Chompoorat (2021c)**, the UCS of cement-stabilised soil sediments with 7% and 10% OPC increased with the addition of 25% FA. This finding contrasts with the present study,

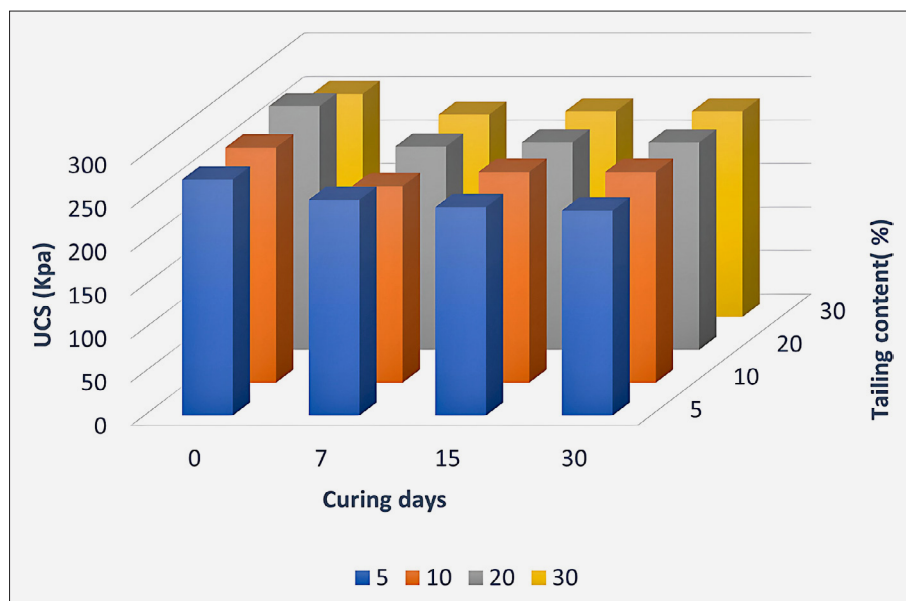


Figure 9. UCS of the lateritic soils and various iron ore tailing mix.

where the UCS of lateritic soil decreased slightly with increasing iron ore tailings content, reflecting the absence of cementitious reactions in IOT compared with the hydration and pozzolanic effects of OPC and FA. The structural change in the soil caused by the presence of IOT can be a plausible explanation for the reduction in strength. Additionally, the IOT may not contribute to higher UCS due to the dominance of sand-sized particles in the IOT. Thus, the reduction in the UCS could be due to a lack of proper bonding between the particles under the compressive load. In addition, the curing of soil mix revealed an initial reduction in UCS, while the UCS value increased after 14 days and showed no significant change after 30 days. A plausible explanation for the initial reduction could be due to the uneven moisture distribution and incomplete chemical reactions. However, moisture redistributes, and the chemical reaction progresses over the next fourteen days, thereby enhancing bond formation and increasing the unconfined compressive strength. Thereafter, significant structural changes stabilize, and no further substantial changes occur for days. This trend reflects an initial adjustment, reaction phases and eventual equilibrium in the properties of the mix during curing.

3.4 Applicability of the Lateritic soil – IOT mix as a suitable material for road construction

The suitability of soils for the construction of roads is significantly determined by their mineralogical and geotechnical properties. Accordingly, various standards and specifications determine the optimal selection of soils for a particular use in terms of index and engineering properties. However, the methods of testing adopted, and the limiting values vary from one country or organization to another, depending on the applications (base or subgrade) and climatic conditions/ material availability and type (Paige-green et al. 2015; Afolagboye et al. 2016). The limiting values specified for the various sec-

Table 4. Specification for road and bridge materials.

Road Layer	Properties of soil	Material specification	Source
Sub-base course	Liquid limit	< 35	FMWH, 2013
	Plasticity index	< 16	FMWH, 2013
	CBR (24 hrs. soaked)	≥ 25	FMWH, 2013
	Linear shrinkage	< 8	Madedor, 1983
Base course	Liquid limit	≤ 30	FMWH, 2013
	Plasticity index	≤ 13	FMWH, 2013
	Unsoaked CBR	≥ 80	FMWH, 2013
	% Passing sieve No. 200 (%)	5 – 15	FMWH, 2013
	UCS (kN/m ²)	> 103	FMWH, 2013

tions of flexible pavement by the FMWH (2013) are presented in Table 4.

Thus, the properties of the lateritic soils and IOT mixtures were compared with the different specifications (see Table 3) and evaluated by their availability for road construction purposes. The suitability of the lateritic soils and the effects of the IOT on the determined properties for various sections of the highway are discussed as follows.

The untreated lateritic soil contains an excessive quantity of fines, higher plasticity index and lower CBR with respect to the stipulated standard for soils designated for utilization as subbase. Thus, the soils can be adjudged unsuitable for utilization as sub-base and sub-grade based on the properties. This is because the excessive plasticity index and fines content exhibits the tendency to swell. This is corroborated by the classification of the soils into groups A-7-6 of the AASHTO system, which implies poor clayey soil with poor quality as subgrade material. Thus, this underscores the need for thorough stabilization

of the soils with a view to improving its engineering properties. The specific gravity values increased tremendously suggesting that the various mixtures would exhibit a good to excellent performance in road construction as higher specific gravity has been correlated with higher strength (**Daramola et al., 2018**). The addition of IOT to the soils significantly reduced the plasticity index as well as the liquid content of the soils. Thus, it could be noted that there could be a corresponding reduction in the compressibility of the lateritic soils as a high liquid limit usually corresponds to an increase in compressibility. Similarly, the reduction in plasticity index could imply a reduction in the tendency for shrinkage. Furthermore, the addition of IOT reduced the tendency of the lateritic soils to shrink excessively. Specifically, the addition of 30% IOT is required to significantly reduce the linear shrinkage to 7.9%, a value lower than the 8% specified by **Madedor (1983)** for road subbase materials. However, a comparison of the properties of the various mixes with the standard specifications (see **Table 3**) indicated that an addition of 10% IOTs yielded a mix that could be adjudged suitable for utilization as road subgrade. Additionally, an evaluation of the suitability of the mix for utilization as a subbase based on the standard requirement indicates that they are unsuitable for such a purpose.

The maximum dry density of the lateritic soils suggests that both the untreated lateritic soils and the various percentage IOT mixtures are favourable for various construction purposes based on the recommendations of **Aghamelu and Okogbue (2011)**. Additionally, the MDD values recorded by the untreated and treated lateritic soils are notably higher than the minimum recommended by **FMWH (2013)** for use as a road subbase. Also, CBR is one of the most important criteria for the selection of soils in road construction. The CBR values of the treated laterite soils are generally lower than the 80% minimum required for subgrade soil by **FMWH (2013)**. Similarly, the soaked CBR values of the treated lateritic soils are generally less than twenty-five percent. Notably, the soils designated for subbase must fulfil the requirements of soaked CBR greater than 25%. It is worth noting that the untreated lateritic soils initially had a CBR of 13% which fails to meet the required standard specified by **FMWH (2013)**. Thus, the test result indicates that the addition of IOT significantly improved the CBR. While mixed with 20% IOTs, the measured CBR value of the soil mixture is 25.5% thereby fulfilling the minimum material requirement stipulated for the construction of the road subbase. Hence, at least 20% IOT content should be mixed with raw lateritic soil before utilizing it for the construction of the road subbase. The results of the geochemical analysis revealed the absence of toxic metals like Pb, Zn, and Mn. This is consistent with the mineralogy of iron ore tailings, which are dominated by quartz, feldspars, and stable iron silicates, rather than sulfide minerals that commonly host these toxic elements (**Hu et al., 2023; Shen et al., 2023**). Moreover, the reduced quantity of iron oxide can be at-

tributed to its incorporation into aluminosilicate lattices, which reduces its availability in free oxide form and decreases its bulk geochemical signal. This mineralogical characteristic minimizes the risk of heavy metal mobilization thereby highlighting the environmental safety of the reuse of iron ore tailings in road construction. The absence of hazardous trace metals further enhances the sustainability of using IOT in road construction by reducing potential ecological and human health risks while contributing to resilient infrastructure. Generally, the toxicity risks posed by iron ore tailings are lower than sulfide-rich tailings although long-term leaching under acidic conditions can mobilize trace elements (**Dold, 2014; Wang et al., 2023**). **Onyia et al. (2021)** indicated that such risks could be mitigated by employing stabilization strategies such as blending with lime, cement, or pozzolanic additives. Therefore, while the current work establishes the engineering suitability of iron ore tailings-amended soils, future studies should incorporate environmental assessment tests, such as the leaching index to comprehensively evaluate toxicity risks.

From the foregoing, the findings of this study apparently demonstrate that iron ore tailings can be effectively incorporated into lateritic soil for road construction, to enhance their strength and durability while minimizing reliance on natural borrow materials. These findings not only demonstrate the technical viability of IoT-modified soils for road construction but also highlight their sustainability value. As shown by **Leknoi and Likittlersuang (2020)**, and **Hong-in et al. (2024)**, the value of simple, cost-effective solutions for sustainable land management in rural communities, the reuse of iron ore tailings as construction material offers a practical pathway to sustainability. By transforming mining waste into a resource for road and infrastructure projects, such reuse supports resilient rural and urban development while advancing SDGs 9, 11, and 12. Reusing iron ore tailings, a major mining by-product, reduces disposal-related hazards and conserves natural soil resources. This apparently enhance pavement durability and lowers the needs for maintenance and its attendant costs, thereby contributing directly to the sustainable development goals of the United Nations in terms of **sustainable communities, resilient infrastructure, and responsible consumption** through the valorization of mining waste. Therefore, the adoption of IOT-amended soils in road construction offers a cost-effective and eco-friendly pathway toward sustainable infrastructure development.

4. Conclusions

This study investigates the geotechnical properties of charnockite-derived lateritic soil and their mixtures with various quantities of IOTs. It further identifies the best lateritic soil- IOTs mixture, which could yield suitable geotechnical properties that conform to the required specification for road subbase. The results demonstrated that the addition of IOTs significantly influenced the geotechnical

properties of the various mixes. The results and evaluation of the geotechnical properties of the soils and IOTs mixtures presented in this study have shown that the geotechnical properties of the lateritic soil can be modified to fulfil the standard required for utilization as a road sub-base. The minimum required can be suitably achieved by mixing about 20% IOTs with lateritic soil. The results of the geochemical analysis revealed the absence of toxic metals like Pb, Zn, and Mn. This is consistent with the mineralogy of iron ore tailings, which are dominated by quartz, feldspars, and stable iron silicates. This mineralogical characteristic minimizes the risk of heavy metal mobilization, thereby highlighting the environmental safety of the reuse of iron ore tailings in road construction applications. Moreover, the absence of hazardous trace metals enhances the sustainability of the utilization of iron ore tailings in road construction by reducing potential ecological and human health risks while contributing to resilient infrastructure. Although, this research establishes the engineering suitability of iron ore tailings-amended soils, future studies should incorporate environmental assessment tests such as the leaching index to comprehensively evaluate toxicity risks.

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SAŽETAK

Geotehnička svojstva i primjena u izgradnji cesta lateritnoga tla poboljšanoga jalovinom od flotacije željezne rude

Velika rasprostranjenost lateritnih tala u Nigeriji učinila ih je jednim od najčešće korištenih materijala za izgradnju cesta. Međutim, mnoga od tih tala pokazuju nezadovoljavajuća geotehnička svojstva, zbog čega je prije njihove primjene u cestogradnji nužno provesti poboljšanja. Cilj je ovoga istraživanja ocijeniti geotehnička svojstva i praktičnu primjenu lateritnoga tla poboljšanoga jalovinom od flotacije željezne rude (IOT) u svrhu izgradnje cesta. Lateritno tlo prikupljeno iz iskopa za cestogradnju, kao i njegove mješavine s jalovinom od flotacije željezne rude, podvrgnuti su mineralnim i geotehničkim ispitivanjima. Lateritno tlo sadržavalo je znatan udio gline (29,1 %), sitnih frakcija (52,4 %) i pijeska (46,6 %) uz manju količinu šljunka (1,0 %), pa se može klasificirati kao glinoviti pijesak. Nadalje, analiza granica konzistencije pokazala je da tlo prema položaju na USCS (*Unified Soil Classification System*) dijagramu leži iznad A-linije te se klasificira kao glina visoke plastičnosti. Rezultati geotehničkih ispitivanja uputili su na znatna poboljšanja svojstava lateritnoga tla dodatkom jalovine od flotacije željezne rude. Utvrđen je porast maksimalne suhe gustoće i CBR (*California Bearing Ratio*) vrijednosti, uz smanjenje vrijednosti granice tečenja, indeksa plastičnosti, linearnoga skupljanja i jednoosne tlačne čvrstoće. Ovo istraživanje pokazuje da se geotehnička svojstva lateritnoga tla mogu modificirati tako da zadovolje standarde potrebne za primjenu u sloju donje podloge kolnika, a minimalni zahtjevi mogu se postići dodavanjem oko 20 % jalovine od flotacije željezne rude u lateritno tlo.

Ključne riječi:

geotehnika, lateritno tlo poboljšano jalovinom od flotacije željezne rude, podloga kolnika

Author's contribution

Sunday Olabisi Daramola (Dr): conceptualization, writing – original draft, investigation and software. **Ayodele Olumuyiwa Owolabi** (Professor): visualization, methodology and validation. **Olushola Daniel Eniowo** (Dr): writing – review & editing. **Hendrik Grobler** (Professor): resources, supervision, visualization and validation. **Moshood Onifade** (Professor): resources, supervision, visualization and validation. **Manoj Khandelwal** (Professor): resources, supervision, visualization and validation.

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The analysis of wellbore instability based on the Hoek-Brown failure criterion using geomechanical units and discontinuities evaluation

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Original scientific paper



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Abstract

The accuracy of wellbore instability assessment becomes reliable when sufficient geomechanical model data and appropriate failure criteria parameters are used. The Hoek-Brown failure criterion is widely used in wellbore instability analysis; however, limited focus has been given to parameter determination and the specific conditions for its application (intact rock or rock mass) within wells. In this study, theoretical wellbore analysis was conducted using various failure criteria, with a primary focus on comparing the Hoek-Brown criterion for both intact rock and rock mass conditions. A geomechanical model was developed using petrophysical logs, laboratory tests, and downhole measurements. The geomechanical units of the wellbore were determined through clustering algorithms, supported by downhole plugs. Natural discontinuities within the wellbore were identified using image logs, and their distribution was mapped for each geomechanical unit. The parameters for intact rock in the Hoek-Brown criterion were derived from laboratory test results, while those for the rock mass condition were determined using the rock mass rating (RMR) and geological strength index (GSI). The results indicate that applying the Hoek-Brown criterion assuming intact rock does not provide a reliable estimation of wellbore instability. However, by using the criterion under rock mass conditions, wellbore failures can be accurately predicted according to the wellbore conditions. Additionally, evaluating the wellbore conditions based on geomechanical units improves the theoretical analysis's accuracy and identifies stable and unstable zones.

Keywords:

Hoek-Brown criterion; geomechanical unit; rock mass classification; wellbore instability

1. Introduction

The economic loss caused by wellbore instability worldwide exceeds one billion dollars annually (Zeynali, 2012), accounting for over 40% of non-productive wellbore time (Zhang et al., 2009). In one of the wells located in southwest Iran, instability led to a 51-day drilling suspension, resulting in an estimated loss of \$2,550,000 (Abdideh & Navadeh Tayyebi, 2020). Hydrocarbon wells play a critical role in the extraction of oil and gas, essential resources for global energy needs. With increasing demand, wells are often drilled in close proximity to each other, in complex geological formations, or in challenging environments. This proximity and complexity can raise concerns regarding wellbore stability, which is crucial for safe and efficient resource extraction.

Understanding the mechanical behaviour of formations is further complicated by the fact that rocks in nature are rarely ideal or uniform. A Discontinuous, Inho-

mogeneous, Anisotropic, Non-Elastic (DIANE) rock is the material with which the engineer has to deal. There is a connection between each of the characteristics of discontinuousness, inhomogeneity, anisotropy and non-elasticity (Hudson & Harrison, 2000). Wellbore instability analysis can be conducted under different assumptions, such as Non-elastic behaviour (Garavand et al., 2020), the presence of discontinuities in intact rocks (Jamshidi & Amani, 2014), and account for heterogeneity (Wang et al., 2023) and anisotropy (Asaka & Holt, 2021), thus offering a more realistic representation of rock behaviour.

Depending on the problem type, available data, and specific objectives, a suitable modelling approach is selected – often neglecting the simultaneous consideration of all these factors. Investigating each of these characteristics individually or collectively is a fundamental challenge in addressing geomechanical and wellbore stability problems. For instance, the role of discontinuities and anisotropy in shale formations has been emphasized in various studies (Ostadhassan, 2016). Similarly, the behaviour of fractured reservoirs has been modelled using non-elastic approaches to account for the mechanical

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effects of discontinuities (Mehrabian, 2016). The application of uncertainty modelling has also been explored to assess wellbore stability in heterogeneous formations (Agheshlui & Matthai, 2017).

However, most studies either assume intact rock or incorporate limited fracture information in wellbore stability assessments (Kang et al., 2009), and the use of rock mass assumptions for wellbore instability analysis has not been commonly practiced. In this study, the Hoek–Brown failure criterion is used to compare intact rock and rock mass conditions in wellbore stability analysis. Discontinuities and fractures were identified to estimate rock mass parameters, and geomechanical units were constructed to reflect the heterogeneity observed in the wellbore. For intact rock conditions, the modelling assumed isotropic mechanical properties, no fractures, and an elasto-plastic constitutive law, whereas for the rock mass condition, heterogeneity and discontinuities were incorporated through zonation and strength index calibration.

2. Literature Review

For well design, the initial analysis of wellbore instability is generally performed based on data from drilled wells and evaluated using empirical methods (Zadavec & Krištafor, 2018). Subsequently, the most suitable solutions, empirical methods, and recommendations are applied for the design of subsequent wells. Failure criteria are among the most significant parameters influencing analysis and design. The Hoek–Brown failure criterion, with its unique structure, has gained attention as a widely used criterion in geomechanical issues, such as cavern stability (Suchowerska et al., 2012), rock slope stability (Yang et al., 2004), and tunnel design (Jear-siripongkul et al., 2022).

2.1. Failure mechanism in wellbore instability

Wellbore instability can arise from four main causes: mechanical (shear and tensile failures), structural (e.g. weak formations with weak layering), drilling-induced issues, and chemical reactions between the drilling fluid and the formation (Pašić et al., 2007). The accurate selection of an appropriate failure criterion that accounts for these causes – especially mechanical failures and geological structure – is crucial for aligning the analysis with real wellbore conditions. Furthermore, considering the influence of the parameters used in the criterion can enhance the alignment between the analysis and actual wellbore conditions (Rahimi & Nygaard, 2018).

2.2. Hoek–Brown criteria

The Hoek–Brown failure criterion, known for its comprehensive framework incorporating both the strength properties of intact rock and geological observations, is one of the most widely used criteria for rock mass-related challenges (Rafiei Renani & Cai, 2022). The Hoek–

Brown failure criterion introduced in the early 1980s, as shown in Equation 1, this criterion was designed to predict the strength limits of intact rock and rock mass. In this equation, the parameters represent s as the rock integrity, while m is a constant dependent on the rock type (Brown & Hoek, 1980).

Despite the common practice of determining intact rock properties through laboratory tests, estimating geological features, particularly for rock mass, presents significant challenges (Wei et al., 2020). Several relationships have been proposed to estimate the m and s parameters within the Hoek–Brown criterion. For example, Zuo et al. (2008) developed a method based on crack propagation theory, while Wei et al. (2020) introduced relationships involving uniaxial compressive strength and fracture characteristics.

Additionally, the estimation of the parameters m and s based on two classification indices, rock mass rating (RMR'_{76}) (Hoek & Brown, 1988) and geological strength index (GSI) (Hoek, 1994), has been proposed and revised, as shown in Equations 2 and 3 (Hoek & Brown, 2019). These relationships have been employed by various researchers in different fields, including wellbore stability (Elyasi & Goshtasbi, 2015; Ma et al., 2018; Yamashiro et al., 2018). The optimal value for m_i in this equation is determined based on the best fit of the failure envelope drawn from laboratory data and the value of D (the damage factor) depending on the drilling used.

Various methods have been proposed to determine the values of GSI and RMR, though the approach for determining GSI and RMR in wellbore stability studies has received less attention. The GSI classification was initially introduced qualitatively based on the visual structure of the rock mass, and subsequently, many methods for its quantitative determination were proposed (Yang & Elmo, 2022). Kang et al. (2017) introduced a method based on the average spacing of discontinuities and the surface condition index of the discontinuities, which was also utilized in this study. The RMR classification (Bienawski, 1976) were modified to this classification to provide more reliable estimates of the Hoek–Brown criterion parameters using this classification (Hoek & Brown, 1988). The use of Hoek–Brown criterion in wellbore instability analysis has also been significant, although in some cases, this application has occurred without adequate attention to the methods and importance of determining the parameters of this criterion.

2.2.1. Hoek–Brown criterion Equations

The Hoek–Brown failure criterion is formulated as follows (Brown & Hoek, 1980):

$$\sigma_1 = \sigma_3 + (m\sigma_c\sigma_3 + s\sigma_c^2)^a \quad (1)$$

Where:

σ_1 – major principal stress (MPa),

σ_3 – minor principal stress (MPa),

m – material constant dependent on rock type,
 s – rock integrity parameter,
 σ_c – uniaxial compressive strength (MPa).

The parameters m and s are estimated using the following relationships (Hoek, 1994; Hoek & Brown, 1988):

$$m = m_i \exp\left(\frac{(GSI \text{ or } RMR'_{76}) - 100}{28 - 14D}\right) \quad (2)$$

$$s = \exp\left(\frac{(GSI \text{ or } RMR'_{76}) - 100}{9 - 3D}\right) \quad (3)$$

Where:

m_i – initial material constant,
 GSI – Geological Strength Index,
 RMR'_{76} – Rock Mass Rating (1976),
 D – damage factor.

2.2.2. Other Criteria equation

The remaining failure criteria for intact rock conditions have been compared with the Hoek-Brown criterion, as presented in Table 1.

2.3. Previous studies

Researchers have widely applied the Hoek-Brown criterion in the analysis of wellbore instability, often comparing it with other criteria. For instance, in studies where wellbore stability was modelled, this criterion has frequently shown better alignment with actual wellbore conditions compared to the Mohr-Coulomb model, though exceptions exist. Zhang et al. (2010) suggested using the Hoek-Brown criterion with assumed parameters for intact rock, alongside the Mogi-Coulomb criterion, to predict the safe mud weight window.

Further studies, such as Gholami et al. (2014), have evaluated the Hoek-Brown, Mohr-Coulomb, and Mogi-Coulomb failure criteria in designing safe mud weight windows for wells from carbonate reservoirs in the southwest of Iran. Their research found that the Mogi-Coulomb criterion exhibited better agreement with wellbore observations, recommending it for safe mud weight design. Although, the assumptions about intact rock versus rock mass and the Hoek-Brown criterion parameters were not fully addressed in this study.

Similarly, Rahimi and Nygaard (2015) examined thirteen different failure criteria for safe mud weight de-

Table 1. Rock failure criteria equations

Failure criteria	Governing equation	References	Eq
Mohr-Coulomb	$\sigma_1 = \sigma_c + \frac{1 + \sin \varphi}{1 - \sin \varphi} \sigma_3$	(Jaeger et al., 2007)	(4)
Stasi Dalia	$J_2 = \frac{(\sigma_c - \sigma_t)I_1 + \sigma_c \sigma_t}{3}$	(Stassi-D'Alia, 1967)	(5)
Mogi Columb	$\tau_{oct} = a + b\sigma'_{m,2}$ $a = \frac{2\sqrt{2}}{3}C \cos \varphi, b = \frac{2\sqrt{2}}{3} \sin \varphi$	(Al-Ajmi & Zimmerman, 2005)	(6)
Inscribed Drucker-Prager	$\sqrt{J_2} = a + \frac{bI_1}{3}$ $a = \frac{3\sigma_c \cos \varphi}{2\sqrt{q}\sqrt{9 + 3\sin^2 \varphi}}, b = \frac{3\sin \varphi}{\sqrt{9 + 3\sin^2 \varphi}}, I_1 = \sigma_1 + \sigma_2 + \sigma_3$	(Veeken et al., 1989)	(7)
Circumscribed Drucker-Prager	$\sqrt{J_2} = a + \frac{bI_1}{3}$ $a = \frac{\sqrt{3}\sigma_c}{2 + q}, b = \frac{\sqrt{3}(q - 1)}{2 + q}$	(Zhou, 1994)	(8)
Modified Lade	$\frac{I_1^3}{I_3} = 27 + \eta$ $I_1'' = (\sigma_1 + S) + (\sigma_2 + S) + (\sigma_3 + S), I_3' = (\sigma_1 + S)(\sigma_2 + S)(\sigma_3 + S), \eta = \frac{4\lg \varphi^2(9 - 7\sin \varphi)}{(1 - \sin \varphi)}, S = \frac{C}{\lg \varphi}$	(Ewy, 1999)	(9)

σ_1 – Maximum principal stress (MPa), σ_2 – Intermediate principal stress (MPa), σ_3 – Minimum principal stress (MPa), σ_c – Uniaxial compressive strength (MPa), σ_t – Tensile strength (MPa), C – Rock cohesion (MPa), φ – Internal friction angle ($^\circ$), J_2 – Second stress invariant (MPa²), I_1 – First stress invariant (MPa), τ_{oct} – Octahedral shear stress (MPa), $\sigma'_{m,2}$ – Mean effective stress (MPa), S – Strength parameter (MPa), q – Drucker-Prager coefficient, η – Failure criterion parameter.

termination in shale, sandstone, and siltstone formations. Their findings suggested that the Stassi-D'Alia, modified Griffith, and Hoek-Brown criteria were more sensitive to variations in rock mechanical parameters, making them less suitable. **Ma et al. (2018)** used both the Hoek-Brown (assuming rock mass) and Mohr-Coulomb criteria in a numerical model to assess wellbore instability across three stress regimes. Their findings revealed that the failure zone predicted by the Hoek-Brown criterion was larger than that of the Mohr-Coulomb model, requiring higher mud pressure for stability, highlighting the importance of correctly estimating the m and s parameters.

More recent research by **Lakirouhani et al. (2021)** compared the Hoek-Brown and Fairhurst failure criteria on laboratory samples of granite and marble. The samples (and the parameters) were in intact rock and the results show that both criteria provided acceptable outcomes. **Abazari et al. (2022)** utilized three criteria – Hoek-Brown, Mohr-Coulomb, and Mogi-Coulomb – to evaluate the failures of a wellbore in the carbonate oil field of Kopal. In this study, the GSI index was used to estimate the parameters for the Hoek-Brown criterion under rock mass conditions. As a result, the Hoek-Brown criterion gave an intermediate limit between the other two criteria.

3. Solution method

In this study, the most appropriate methods for constructing the geomechanical model were introduced and applied based on laboratory and wellbore test results in one of the Persian Gulf carbonate reservoirs. Subsequently, the geomechanical units (GMUs) were identified from petrophysical logs using three clustering approaches – hierarchical clustering (with various metric and linkage criteria), density-based clustering, and k -means – and were then evaluated using core test results and the silhouette index. The parameters related to the RMR and GSI indices for the rock mass were determined based on the interpretation of image logs and the identification and evaluation of wellbore discontinuities, separately for each geomechanical unit (GMU). The parameters m and s in the Hoek-Brown failure criterion were estimated for both intact rock – based on laboratory test results (m_i) – and rock mass conditions based on two classification systems, RMR_{76} and GSI. These estimations were performed separately for each geomechanical unit (GMU) and also as an overall evaluation for the entire wellbore. Theoretical wellbore analysis using the Hoek-Brown criterion was first conducted under intact rock conditions. In two scenarios – based on estimated parameters for each geomechanical unit and for the entire wellbore – the results were compared with six failure criteria: Mohr-Coulomb, Stasi-Dalia, Mogi-Coulomb, Inscribed Drucker-Prager, Circumscribed Drucker-Prager, and Modified Lade. Finally, theoretical wellbore

analysis using the Hoek-Brown criterion for rock mass conditions was performed under four scenarios (1) using RMR values for each geomechanical unit (HB-RG), (2) using a single RMR value for the entire wellbore (HB-RT), (3) using GSI values for each geomechanical unit (HB-GG), and (4) using a single GSI value for the entire wellbore (HB-GT). These results were compared and evaluated against the two previous scenarios based on intact rock conditions.

4. Case Study

The wellbore under analysis is located in a field on the shared border between Iran and one of the Arab countries. This field is situated in the Coastal Fars geological zone and has an anticlinal structure. Structurally, it is a domal and uplifted structure, with the main cause of the uplift being the rise of the Qatar-Fars arch (**Klemme, 1984**). The information analyzed pertains to two formations: the Kangan and Dalan formations, where the Kangan Formation belongs to the Early Triassic period, and the Dalan Formation dates back to the Permian period. The Kangan Formation (Lower to Middle Triassic) and the Upper Dalan Formation (Upper Permian) are equivalent to the Khuff Formation, consisting of a carbonate-evaporite sequence overlying the anhydrites of the Nar Formation. The Kangan and Dalan formations are divided into sections K1 to K4 based on reservoir properties, with their stratigraphic column shown in **Figure 1 (Tavakoli, 2015)**.

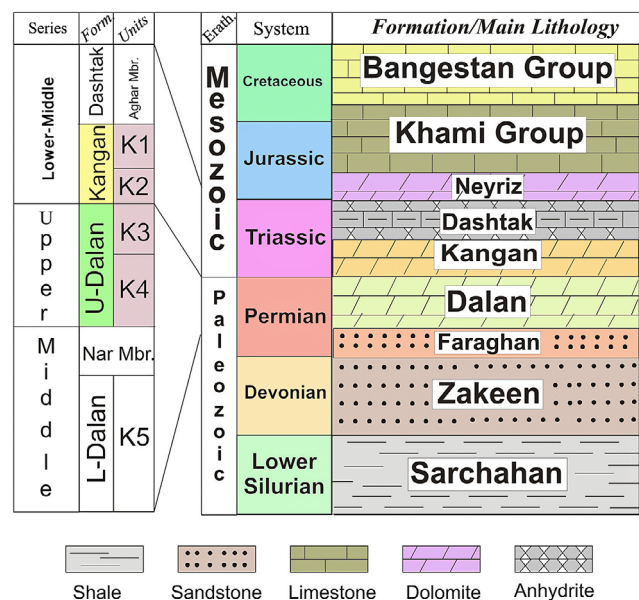


Figure 1. Stratigraphic Column in the Central Part of the Persian Gulf (**Tavakoli et al., 2018**)

4.1. Geomechanical Model

Building the geomechanical model and identifying the key parameters for assessing wellbore stability is the

Table 2. Average Results of Density, Triaxial, and Uniaxial Tests on Plugs.

GMU	Density (gm/cm ³)	UCS (MPa)	Friction Angle (degree)	Young's modulus (Gpa)	Poisson's ratio
V	2.66	145.7	-	44.0	-
X	2.56	116.5	30.8	34.8	0.28
Y	2.26	42.0	15.0	15.1	0.24
Z	2.01	22.4	11.1	10.7	0.26

first step in wellbore analysis. **Abdollahipour et al. (2019)**, categorized the key parameters influencing wellbore stability for both soft and hard rock types based on the results of numerical model analysis. Their research shows that for soft rock (with an average Young's modulus of 5 GPa), the most important factors are in-situ stress, pore pressure, internal friction angle, Young's modulus, and cohesion. For hard rock (with an average Young's modulus of 15 GPa), the most critical factors are in-situ stress, drilling fluid pressure, and Young's modulus, respectively.

The constructed geomechanical model typically includes the elastic properties of rocks, such as elastic modulus, Poisson's ratio, and strength parameters like compressive strength, cohesion, and internal friction angle. Additionally, other critical elements of a geomechanical model are variations in pore pressure and the in-situ stress conditions of the region being studied (**Zoback, 2010**). The dynamic Young's modulus and Poisson's ratio were estimated as the first step in constructing the geomechanical model.

Many relationships have been proposed for estimating uniaxial compressive strength, Poisson's ratio, Young's modulus, and static Poisson's ratio for carbonate rocks. Most of them were evaluated in this study for use in constructing the geomechanical model. Ultimately, empirical relationships were selected based on the carbonate origin of the wellbore and laboratory results. To improve the reliability and precision of the geomechanical model, core plug data were thoroughly used for calibration and were integrated into each geomechanical unit.

Most of the core plugs within each GMU were taken at very close intervals, which greatly contributed to the uniformity and homogeneity of the plugs and the results for each category. A total of 25 uniaxial and triaxial compressive strength tests were conducted, with 11 of them being uniaxial tests. The characteristics of the samples and a summary of the tests performed are presented in **Table 2**. The results of the triaxial tests were also used to estimate uniaxial compressive strength and for calibration along the wellbore path. Testing could not be conducted on samples from the W geomechanical unit due to a shortage of specimens, so its values were estimated using petrophysical logs and calibrated based on other results. The test results show that the internal friction angle for X, Y, and Z geomechanical units is 30.8°, 15.0°, and 11.1°, respectively, while the cohesion values are 30.7 MPa, 18.4 MPa, and 11.4 MPa, respectively.

The pore pressure was estimated using an equation provided by **Azadpour et al. (2015)** for a gas field in the Persian Gulf. Since the MDT (Modular Formation Dynamics Tester) test was conducted at certain points in the well, the estimated value was refined using the MDT results. In this equation, the total porosity is derived from the logs, and the effective stress is calculated as the difference between the total stress gradient and the hydrostatic pressure gradient (10.5 MPa/km). The constant γ' was proposed to be 0.96 for the gas reservoir.

The in-situ stress state was determined using borehole breakouts and field leak-off tests. In this well, the FMI (Formation Micro-Imager) log was used to identify breakouts and estimate the direction of the in-situ stress. The results from the image log and the bedding orientations indicate that the overburden stress is one of the principal stresses. Based on the shear and tensile failures observed within the well, the maximum and minimum horizontal stress directions were estimated to be 40° and 130°, respectively.

For building the geomechanical model in this wellbore, the poroelasticity relationships were used to estimate the horizontal stress. Estimating these stresses requires an approximation of the tectonic strains and a trial-and-error solution. Other parameters in these equations, such as Young's modulus, Poisson's ratio, pore pressure, and vertical stress, had been estimated in previous stages.

4.1.1. Geomechanic's Equations

Here are the equations for Dynamic Young's modulus and Poisson's ratio given in **Equations 10** and **11** as follows (**Fjaer et al., 2008**):

$$E_{dyn} = \rho V_s^2 \left(\frac{3V_p^2 - 4V_s^2}{V_p^2 - V_s^2} \right) \quad (10)$$

$$\nu_{dyn} = \frac{V_p^2 - 2V_s^2}{2(V_p^2 - V_s^2)} \quad (11)$$

Where:

E_{dyn} – dynamic Young's modulus (GPa),

ν_{dyn} – dynamic Poisson's ratio,

ρ – density (kg/m³),

V_p – compressional wave velocities (m/s),

V_s – shear wave velocities (m/s).

Empirical relationships **12** through **15** respectively were selected for an estimation of static Young's modulus (**Aboutaleb et al., 2018**), static Poisson's ratio (**Ane-**

mangely et al., 2019), uniaxial compressive strength (Farquhar et al., 1994), and friction angle (Edimann et al., 1998) based on the carbonate origin of the wellbore and laboratory results.

$$E_s = -31.23 + 131.5\nu_{dyn} + 0.45E_{dyn} \quad (12)$$

$$\nu_s = \nu_{dyn} \quad (13)$$

$$UCS = 174.8 \exp(-0.093n) \quad (14)$$

$$\phi = 41.92 - 0.7779n \quad (15)$$

Where:

- E_s – static Young's modulus (GPa),
- ν_s – static Poisson's ratio,
- UCS – uniaxial compressive strength (MPa),
- ϕ – friction angle (degree),
- n – porosity (%).

The pore pressure gradient estimation equation (Azadpour et al., 2015):

$$P_{pg} = \left(\frac{(1-\emptyset)\sigma_{eff}}{1-2\emptyset} \right)^\gamma \quad (16)$$

Where:

- P_{pg} – static Young's modulus (GPa),
- $\emptyset$ – total porosity (fraction),
- σ_{eff} – difference between the total stress gradient and the hydrostatic pressure gradient (MPa/km),
- γ – proposed to be 0.96 for the gas reservoir.

The overburden stress and horizontal stress estimation using relationships (Fjaer et al., 2008):

$$S_v = \rho_w g Z_w + \int_{Z_w}^z \rho(z) g dz \approx \rho_w g (Z_w + (Z - Z_w)) \quad (17)$$

$$S_h = \frac{\nu}{1-\nu} (S_v - \alpha P_p) + \alpha P_p + \frac{E}{1-\nu^2} (\epsilon_h + \nu \epsilon_H) \quad (18)$$

$$S_H = \frac{\nu}{1-\nu} (S_v - \alpha P_p) + \alpha P_p + \frac{E}{1-\nu^2} (\epsilon_H + \nu \epsilon_h) \quad (19)$$

Where:

- S_v – overburden stress (MPa),
- ρ_w – water density (kg/m³),
- Z_w – water depth (m),
- $\rho(z)$ – overburden density (kg/m³),
- Z – overburden depth (m),
- g – gravity (m/s²),
- S_h – minimum horizontal stress (MPa),
- S_H – maximum horizontal stress (MPa),
- P_p – Pore pressure (MPa),
- α – Biot's coefficient,
- ϵ_h – minimum tectonic strain,
- ϵ_H – maximum tectonic strain.

4.2. Geomechanical Units

Defining geomechanical units alongside a geomechanical model aids in better understanding geomechan-

ical variations within the wellbore and helps analyze related geological issues. For example, constructing a geomechanical model and identifying five GMUs in a wellbore from the Persian Gulf reservoirs aimed at determining optimal drilling parameters (such as direction and angle) and creating stable conditions for each identified geomechanical unit (Kadkhodaie, 2021). Geomechanical units are often defined in studies based on petrophysical logs, seismic data, apparent rock indices, engineering judgment, or intelligent clustering methods. Mehrgini et al. (2016) identified geomechanical unit boundaries using compressional and shear sonic logs, density, and neutron porosity logs, relying on engineering-based interpretation. Subsequently, five geomechanical units were distinguished, and thin section analysis was performed using three samples per meter to evaluate their microscopic features. Nazari Sarem and Riahi (2020) identified geomechanical units in the Mansouri field using seismic data and Multiresolution Graph-based Clustering. Gharechelou et al. (2022) visually defined five geomechanical units for a carbonate formation in southwest Iran based on apparent plug characteristics, including mineral composition, microscopic features, visual porosity, cementation, and dolomitization. Pourreza et al. (2023) applied hierarchical clustering using shear sonic log data to identify geomechanical units. Ruiz and Batezelli (2024) classified a Brazilian field using a K-means clustering approach based on laboratory measurements, wellbore data, logs, and thin section analyses. Al-Kaabi et al. (2024) employed and compared three methods – graph-based clustering, self-organizing maps (SOM), and hierarchical clustering – to identify geomechanical units in the Kangan and Dalan formations.

The geomechanical units in this study were determined based on petrophysical logs using various clustering algorithms. The output was evaluated using core plug samples and the silhouette index for each clustering method. The advantage of determining geomechanical units using log data is that the same method can be applied to other wells when the log data is available. The dynamic Young's modulus and Poisson's ratio were determined using Equations 10 and 11 to compare the geomechanical units.

The log data, including density, neutron, gamma, compressional and shear sonic logs in the 8.5-inch borehole, were fully utilized, and the statistical analysis of the data was conducted in the same interval. Five logs – density, neutron, gamma, compressional and shear sonic logs – were used for classification. The mineral log was not directly considered in this classification, and the gamma log was employed as a guide for lithology variations. Three logs – density, compressional, and shear sonic logs – were selected as parameters related to the sample behaviour in the equations. Porosity, being an important factor in rock behaviour (Dalirnasab et al., 2024), was also considered to improve the consistency

between the defined geomechanical units and the core plug samples.

To help determine the appropriate number of geomechanical units, 38 mm diameter core plugs were first classified into five categories using non-destructive measurements based on rock type, porosity, and permeability. The purpose of this classification was to use the sample's depth for calibrating and evaluating the accuracy of geomechanical units. However, placing samples into distinct category came with challenges, especially for plugs located near the boundary of two units. Significant differences in porosity and permeability were observed between some plugs taken from the same depth. In such cases, the plugs were categorized based on the results of strength tests. Accordingly, with the help of depth and rock type logs, the initial classification of the plugs into five categories was made, as shown in **Figure 2**. Samples in Category 1 (Z's GMU) had the highest porosity, while Categories 4 and 5 (W and V GMUs) exhibited the lowest porosity. The fifth plug category showed porosity comparable to Category 4, but differed in mineral composition and permeability, as identified through the logs. Additionally, Categories 2 and 3 (X's and Y's GMUs) were considered intermediate groups. They had similar permeability values, while Category 3 displayed lower porosity. The distinguishing factor between Categories 3 and 4 was the difference in their porosity. Therefore, five geomechanical units were assumed in this study based on the classification of the plugs and the distribution of log data.

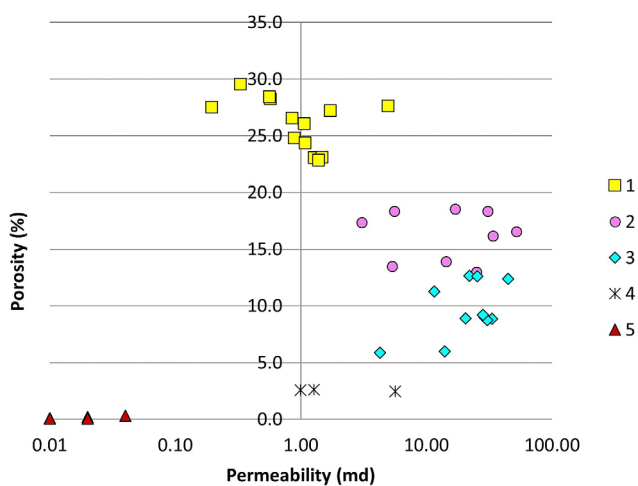


Figure 2. Classification of core plug samples based on measured porosity and permeability

Determining geomechanical units in the wellbore is challenging due to the high volume of petrophysical data and the limited core information. Using clustering algorithms helps reduce engineering and visual interpretation errors. Three clustering methods – hierarchical clustering, density-based clustering, and K-means – were used in this study for GMU clustering. In the hierarchical method, it is necessary to determine the distance be-

tween two data points as well as the distance between two sets (clusters of data). The distance between two data points is evaluated using a distance metric, while the distance between two sets is assessed using a linkage criterion (Abbas, 2008). Euclidean distance that depicts the distance between two points based on the Pythagoras theorem is one of the most utilized algorithms in the cluster investigation (Prakash, 2024). The density-based method defines a cluster as a continuous region in the data space with high point density, separated from other clusters by regions with low point density. Data points in these separating regions, with lower density, are usually considered noise. It requires two input parameters: the neighbourhood radius (rn) and the minimum number of points (MinPts) needed to form a dense region. The K-means method, a popular approach, aims to divide the data into number of clusters, where each data point belongs to the cluster with the nearest mean. A key input parameter is the number of clusters (K), which must be specified in advance (Hasan et al., 2023).

The number of geomechanical units was set to five based on our plug analysis, and this value served as the primary input for methods requiring a predefined cluster count. For the density-based approach, we determined $rn = 0.42$ and $MinPts = 5$ by inspecting k-distance plots to capture the most coherent high-density regions while filtering out noise. In the hierarchical method, various distance metric, including Euclidean distance, squared Euclidean distance, and standardized Euclidean distance, along with different linkage criteria for set distance, such as average, centroid, complete, single, median, Ward's minimum variance algorithm, and weighted averaging. The resulting dendrogram was then cut to yield five final clusters. Finally, for K-means, we set $K = 5$ and ran the algorithm multiple times with different random initial centroids to ensure consistent clustering results.

The best clustering method was determined based on the division of plugs in **Figure 2** and the silhouette index, which ranges from -1 (least match) to +1 (best match). The silhouette score measures how similar an object is to its own cluster (cohesion) compared to other clusters (separation). If most objects have high silhouette values, the clustering structure is appropriate. However, if many points have low or negative values, it indicates that the clustering structure may have too many or too few clusters.

The match between the clustering results and the plug classification, in terms of percentage, as well as the silhouette index for all three clustering methods, is presented in **Table 3**. A higher match percentage between the clustering results and the plug classification indicates a more accurate clustering method, and a higher silhouette index indicates greater precision of the clustering method. The match percentage and silhouette index for hierarchical clustering methods are higher than for the K-means and density-based methods. Additionally, the

Table 3. Percentage of agreement between clustering results and plug classification and silhouette index

Density-based		42%,-0.56						
K-means		79%,0.38						
Hierarchical		Linkage criterion						
		average	centroid	complete	median	single	ward	weight
Metric	Euclidean	76%,0.35	61%,0.48	82%,0.48	76%,0.31	39%,0.21	94%,0.45	85%,0.47
	Squared Euclidean	73%,0.49	85%,0.46	82%,0.48	76%,0.38	39%,0.21	70%,0.49	85%,0.38
	Standardized Euclidean	58%,0.44	79%,0.45	61%,0.41	73%,0.35	39%,0.21	94%,0.48	91%,0.44

Table 4. Average Log Values for the Five Geomechanical Units in the Well

GMU	Lithology	Frequency (%)	PHIE log		E dyn (Gpa)		ν dyn	
			Ave	SD	Ave	SD	Ave	SD
V	Dolomite	22	0.02	0.01	90.1	6.0	0.26	0.01
W	Limestone	15	0.04	0.03	69.0	8.3	0.28	0.03
X	Limestone	14	0.06	0.03	72.4	5.5	0.27	0.03
Y	Dolomite	29	0.12	0.03	53.2	5.8	0.26	0.03
Z	Limestone	20	0.18	0.04	41.2	6.1	0.25	0.02

silhouette index for hierarchical clustering with the linkage criteria “single,” “median,” and “average” is the lowest. The results using the standardized Euclidean distance metric were better compared to the Euclidean and squared Euclidean. The standardized Euclidean method with the Ward linkage algorithm produced the best results and was used in this study.

The frequency of the five geomechanical units along the wellbore and the average log values of porosity, Young’s modulus, and dynamic Poisson’s ratio for each GMU can be observed in **Table 4**. The geomechanical units exhibit differences in various aspects, which validate the significance of the proposed classification. The distribution of geomechanical units in the well, along with the variations in stress parameters, pore pressure, uniaxial compressive strength, internal friction angle, and cohesion, is illustrated in **Figure 3**.

4.3. Rock mass condition

The condition and distribution of discontinuities were evaluated to determine the rock mass condition and assign scores to the classification indices. In order to evaluate the discontinuities within the well, their distribution and density in each GMU, and to apply the results to the Hoek-Brown failure criterion, the discontinuities within the wellbore were identified. The use of image logs for breakout geometry and detecting active faults has also been highlighted in recent studies (**Heydari Gholanlo & Nikkhah, 2023**). The number and types of discontinuities were determined using resistivity image logs. In this method, bright colors in the logs indicate low conductivity and high resistance, which signify low porosity and permeability, while discontinuities are displayed in dark colors. The way the discontinuity plane intersects

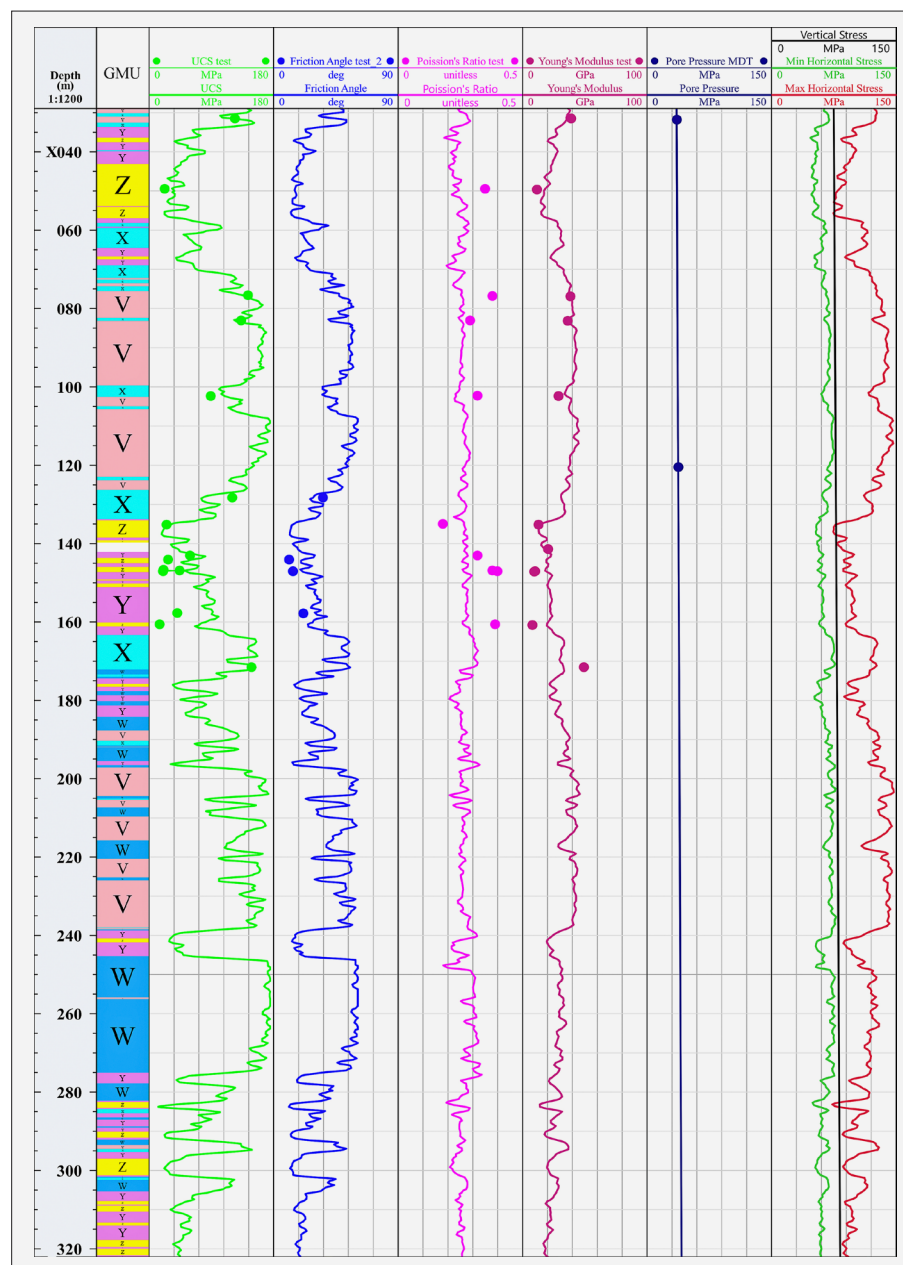
with the wellbore is identified as perpendicular (circular image), angled (elliptical image), or parallel to the wellbore (two parallel lines along the wellbore axis), with the corresponding image appearing as horizontal, sinusoidal, or vertical on the log, as shown in **Figure 4**.

Discontinuities within the wellbore have been categorized for analysis into three groups: primary natural, secondary natural, and failures due to instability. Primary natural discontinuities include bedding planes, which are identified by color changes within the image log and generally exhibit permeability and aperture similar to the host rock. Secondary natural discontinuities include stylolites (serrated, wavy lines), lamination, open fractures, and cracks within the wellbore, which typically have higher permeability compared to the host rock.

The GMU for each data point in the wellbore (approximately every 15 cm) was identified in the previous section, with the total number of data points for each GMU corresponding to its total recognized length. The percentage of natural discontinuities relative to the total data points for each GMU is shown in **Figure 5**. According to this figure, approximately 60% of the length of Z geomechanical unit is associated with discontinuities, while 40% is discontinuity-free. Excluding open fractures, the percentage of discontinuities decreases as the mechanical strength of the geomechanical units increases (from Z to V). Lamination, bedding, and other discontinuities are more prevalent in geomechanical units with weaker mechanical properties. As shown, open fractures have a high percentage in V geomechanical unit, which has higher rock strength. Given the low porosity of this unit, the formation of open fractures was possible. Stylolites are absent in geomechanical units with either very low or very high mechanical strength.

The values of GSI and RMR were used to estimate m and s , which were determined based on the discontinuity

Figure 3. Geomechanical Units and Changes in Geomechanical Parameters Along the Well



conditions evaluated earlier. The GSI value was estimated based on the average spacing of discontinuities and the surface condition index of the discontinuities, following the method provided by **Kang et al. (2017)**. The RMR classification was also calculated RMR modifications (**Hoek & Brown, 1988**) and was based on six parameters: uniaxial compressive strength (UCS), RQD index, discontinuity spacing, discontinuity condition, groundwater, and orientation of discontinuities.

The parameters m and s were estimated based on GSI and RMR values for the entire wellbore and for each geomechanical unit separately, as shown in **Table 5**. As mentioned, the m_i value was determined based on the strength parameters, such as the internal friction angle, and the best-fit failure envelope from laboratory data. The RMR values obtained for the geomechanical units

were generally higher than the GSI values, except in the W geomechanical unit, where GSI was higher. This was due to the sensitivity of the method used, influenced by the spacing of discontinuities and the low number of discontinuities in this unit. Finally, wellbore instability was evaluated using the m and s values obtained from these two rock mass classification systems.

5. Wellbore Instability Analysis

The theoretical analytical model used in this study was solved under the assumption of elasticity, and it does not account for inelastic behaviour or thermo-hydro-mechanical coupling effects. The theoretical analysis of wellbore instability has been conducted using various failure criteria for each data point (every 15 cen-

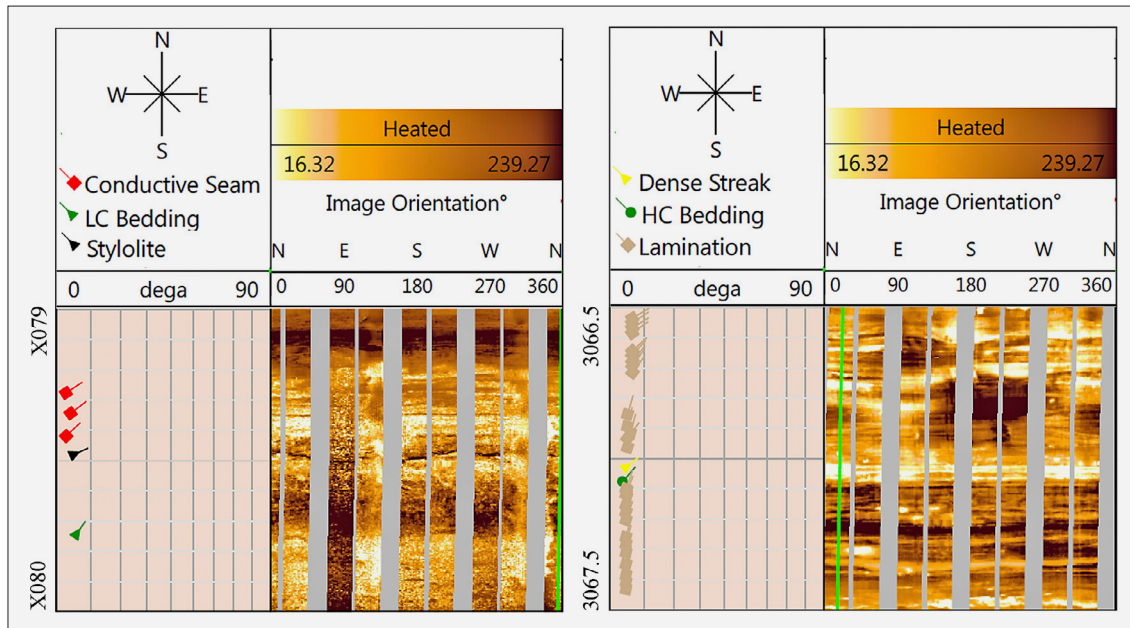


Figure 4. An example of discontinuities observed in the image log

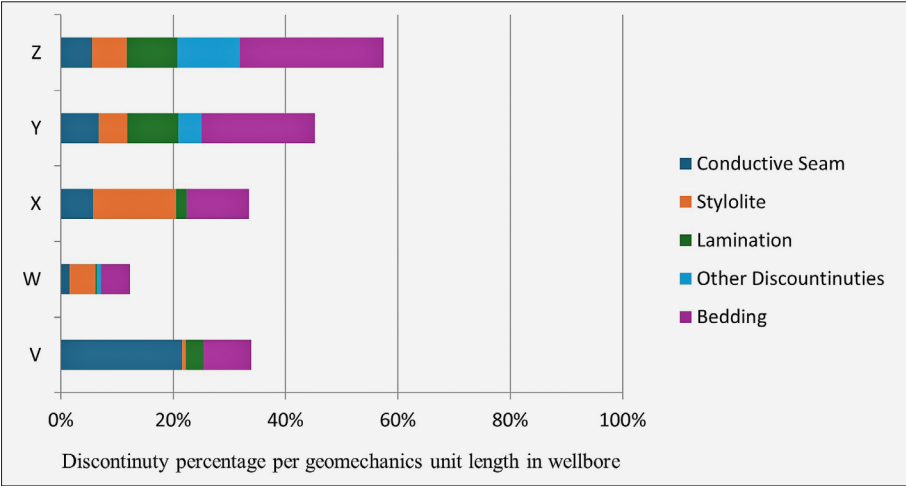


Figure 5. Frequency percent of different types of discontinuities relative to the total length of each GMU

timeters of 290 meters) from the well. In fact, the modeling was performed in two dimensions for each section of the wellbore, where the in-situ stresses were considered anisotropic, while mechanical parameters such as elastic modulus were assumed to be isotropic, which is a common assumption for carbonate formations. The evaluation of wellbore failures was initially conducted using the Hoek-Brown failure criterion, assuming intact rock conditions in the wellbore. The results were then compared with six other criteria: Mohr-Coulomb, Modified Lade, Stassi D’Alia, Mogi-Coulomb, and both the inscribed and circumscribed Drucker-Prager criteria.

The theoretical analysis, based on the outcome of each criterion for each point along the well, compared to the actual wellbore conditions, are shown in **Figure 6**. The theoretical analysis of each data point of the wellbore was predicted as either stable or unstable by each failure criterion, and the results were compared with the

actual conditions in the wellbore (stable or unstable), as shown in the figure. If a point in the wellbore was identified as stable by the theoretical analysis and was also stable based on the image logs, it is displayed in dark green. If a point was identified as unstable by the theoretical analysis and also unstable according to the image

Table 5. Estimation of m and s values for the Hoek-Brown criterion using RMR and GSI

GMU	m_i	RMR	m	s	GSI	m	s
V	44	82	23.3	0.14	76	18.7	0.07
W	40	82	20.8	0.13	85	23.4	0.19
X	35	79	16.3	0.09	73	13.1	0.05
Y	14	74	6.6	0.05	68	5.4	0.03
Z	10	72	4.3	0.04	65	3.4	0.02
Totally (Average)	35	77	13.6	0.08	75	12.6	0.06

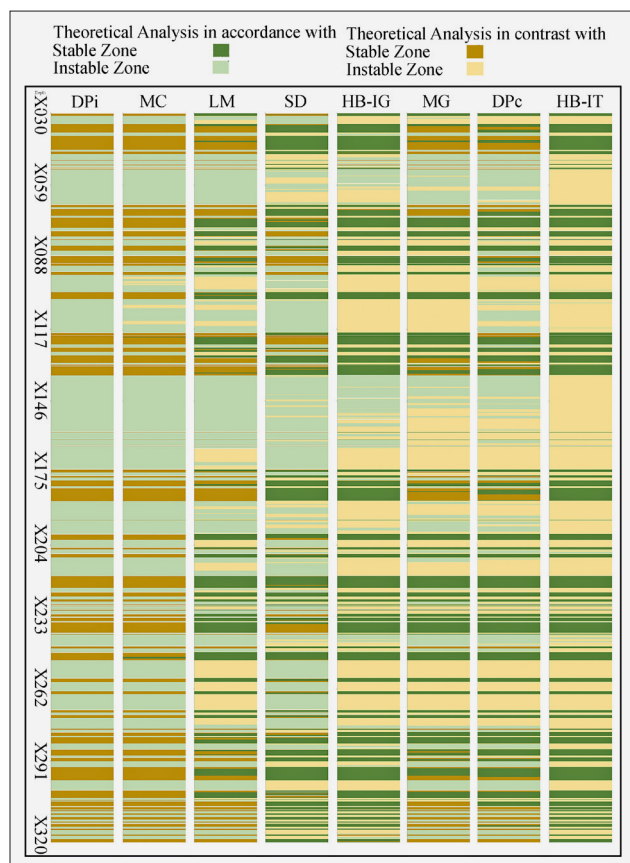


Figure 6. Performance of Failure Criteria Against Observed Conditions in the Well

logs, it is displayed in light green. If a point was identified as stable but predicted as unstable by the theoretical analysis, it is shown in dark gold, and if a point was identified as unstable but predicted as stable by the theoretical analysis, it is shown in light gold.

For example, the theoretical analysis of the Mohr-Coulomb and inscribed Drucker-Prager failure criteria predicted most of the points in the wellbore as unstable, which contrasts with the stable points (dark gold) and aligns with the unstable points in the wellbore (light green). The Stassi D'Alia criterion had the highest alignment with the stable and unstable points in the well, while the inscribed and circumscribed Drucker-Prager criteria acted as upper and lower bounds for predicting wellbore conditions.

6. Results

The use of the Hoek-Brown criterion under intact rock conditions, assuming a single value of m_i for the entire well (HB-IT) and a value of m_i for each geomechanical unit (HB-IG), has led to two different results. As shown in **Figure 7**, under the HB-IT condition, all points in the wellbore were predicted as stable, but when m_i was assigned for each geomechanical unit, the match between the Hoek-Brown failure criterion and the actual wellbore conditions significantly improved. Quantitatively, the percentage of alignment for the HB-IT and HB-IG methods across the entire wellbore (the ratio of green points to total wellbore points) was 37.5% and 49.6%, respectively. As observed, using specific values for each geomechanical unit (HB-IG) improved the accuracy of the Hoek-Brown failure criterion for evaluating wellbore conditions under intact rock.

The evaluation of the results obtained from the analysis of well conditions for different values of m and s in both intact and rock mass scenarios (RMR and GSI) is shown in **Figure 7**. The methods include assumptions of intact rock with uniform parameter values across the entire well (HB-IT), intact rock with parameter values spe-

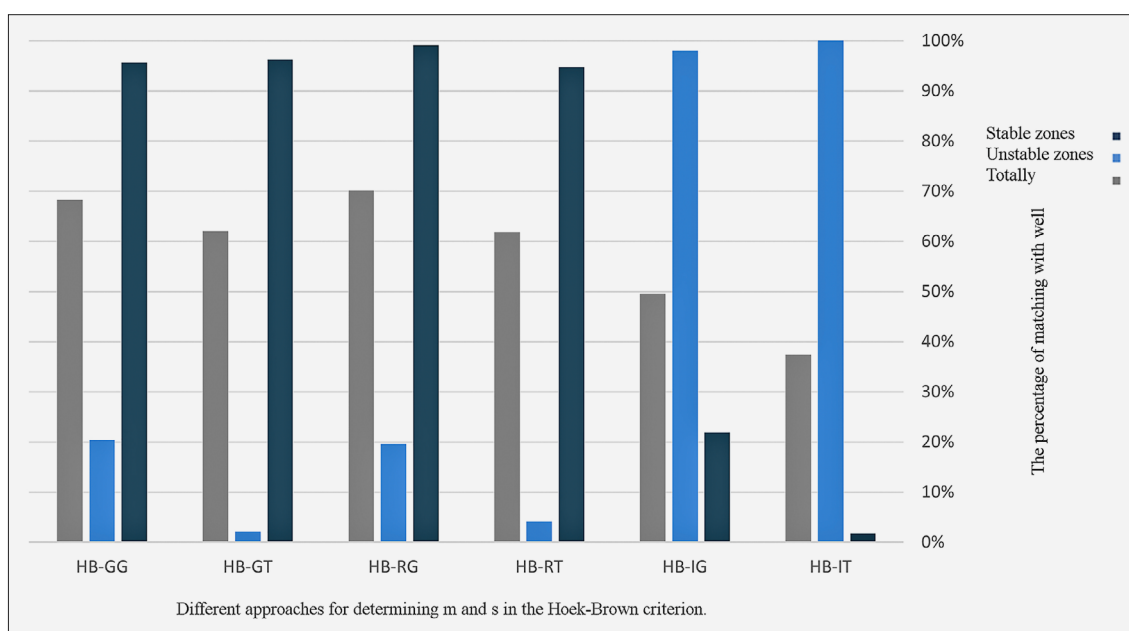


Figure 7. Correspondence between predicted failures and actual in-wellbore conditions for different methods.

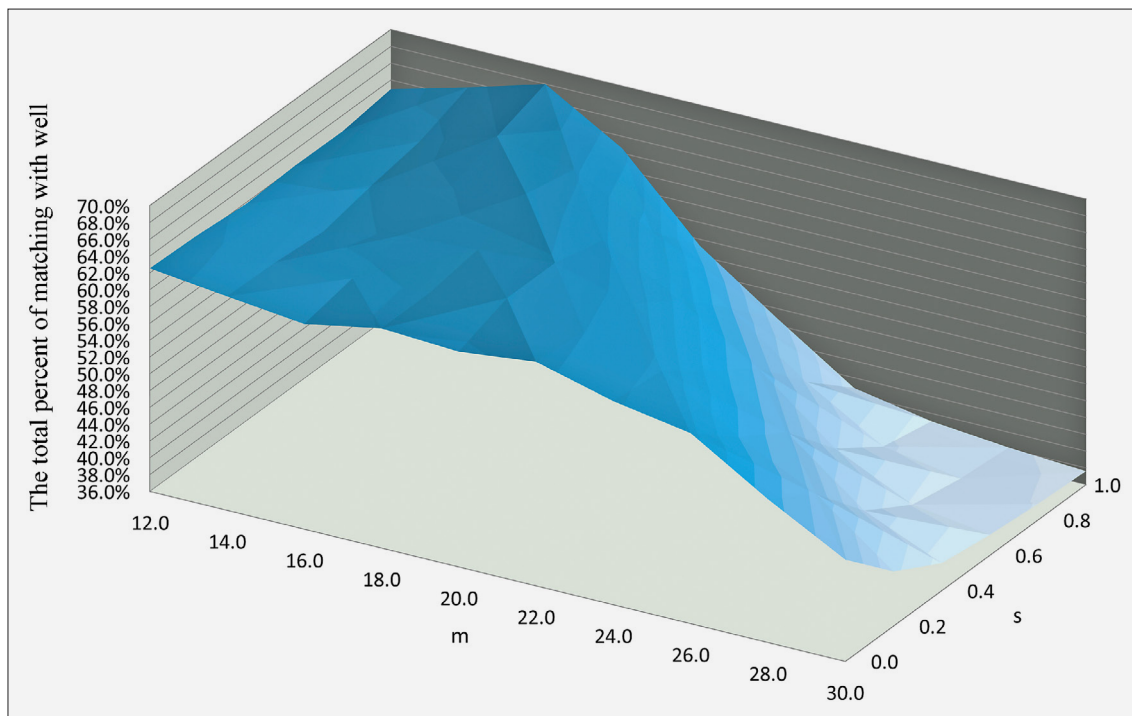


Figure 8. Back analysis for values of m and s based on the percentage of match between predicted conditions and actual in-wellbore observations

cific to each geomechanical unit (HB-IG), rock mass with parameter values from RMR and uniform across the entire well (HB-RT), rock mass with parameter values from RMR and specific to each geomechanical unit (HB-GT), rock mass with parameter values from GSI and uniform across the entire well (HB-GI), and rock mass with parameter values from GSI and specific to each geomechanical unit (HB-GG).

The percentage of match between the theoretical wellbore analysis and the actual well conditions for each method is shown in this figure. According to this figure, the match percentage under intact rock conditions for the two cases HB-IT and HB-IG are 37.5% and 49.6%, respectively. This percentage for the values of m and s obtained from RMR in the two cases HB-RT and HB-RG is 61.8% and 70.2%, respectively. Additionally, this percentage for the values of m and s obtained from GSI in the two cases HB-GT and HB-GG is 62% and 68.3%, respectively. As a result, considering parameters for geomechanical units and assuming rock mass conditions improves the accuracy of the analytical model.

A back-analysis was conducted using sensitivity analysis to determine the optimal values for m and s in the Hoek-Brown criterion, aiming to achieve the highest agreement between the results of the theoretical analysis and wellbore observations. The results of the back-analysis for various m and s values are presented in **Figure 8**. The back-analysis indicates that the increase in accuracy and agreement is more dependent on the value of m . The optimal range for m is between 12 and 20, while the optimal value for s is between 0.6 and 1. Choosing the

best values for m and s increases the agreement between predicted and observed wellbore failures to 68%. The corresponding optimal values for m and s are 16 and 1, respectively.

7. Conclusions

In this study, the parameters used in the Hoek-Brown criterion for assessing wellbore instability were examined by identifying wellbore discontinuities and defining geomechanical units. The hierarchical clustering method showed higher accuracy in defining geomechanical units compared to density-based and K-means methods. Among the clustering methods, the least variance method with the standard Euclidean metric had the highest correlation with segmented plugs (94%) and a silhouette index of 0.48. The distribution of discontinuities indicates that lamination, bedding, and fractures were more frequently observed in geomechanical units with weaker mechanical properties. The most open fractures were found in geomechanical unit V, which had higher strength due to its dolomitic structure and low porosity. If mechanical properties of the discontinuity surfaces were available, it would be possible to compare modeling results assuming fractured intact rock or to construct a representative volume for rock mass modelling.

The Hoek-Brown criterion, based on the two parameters m and s , assuming intact rock, was compared to six criteria: Mohr-Coulomb, Modified Lade, Stassi D'Alia, Mogi-Coulomb, and both inscribed and circumscribed Drucker-Prager. The research findings indicated that

theoretical analysis using the Hoek-Brown criterion under intact rock conditions, without considering geomechanical units (HB-IT), behaves similarly to the circumscribed Drucker-Prager criterion. This implies that most points within the well are assessed as stable, whereas in reality, this is not the case. However, the accuracy of the criterion significantly increases when considering intact rock with the distinction of geomechanical units (HB-GT), effectively identifying instability points in line with actual wellbore events.

The RMR and GSI classification indices were used to estimate the values of m and s for rock mass conditions, differentiated for each geomechanical unit based on the characteristics and frequency of discontinuities. The assigned scores for RMR and GSI ranged from 72 to 82 and 65 to 85, respectively, with the RMR value being slightly higher than GSI. Estimating the values of m and s using RMR and GSI resulted in the theoretical analysis of all wellbore points as unstable, enhancing the accuracy of the Hoek-Brown criterion for this well. Furthermore, when the m and s values were differentiated by geomechanical units for the rock mass (in the HB-RG and HB-GG scenarios), the Hoek-Brown criterion also performed in predicting stable points within the wellbore. The results of back-analysis to find the best m and s values show that the accuracy is more influenced by m than by s . The m values estimated through various methods showed a reasonable agreement with the best m value obtained from back-analysis, while the estimated s values had a greater deviation compared to the best s value from the back-analysis.

The research results indicate that the conditions and parameters used in the Hoek-Brown criterion have a significant impact on the conclusions drawn from this criterion. When applying this criterion under intact rock conditions, all points within the wellbore are predicted to be stable, which represents the lower limit for mud weight. Conversely, when assuming rock mass conditions, most points are predicted to be unstable, indicating the upper limit for mud weight. However, by using geomechanical units and differentiating the parameters, a much closer approximation to a mid-range value can be achieved using this criterion.

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SAŽETAK

Analiza stabilnosti kanala bušotine na temelju Hoek-Brownova kriterija loma korištenjem geomehaničkih jedinica i procjene diskontinuiteta

Točnost procjene stabilnosti kanala bušotine postaje pouzdana kada se koristi dovoljno podataka geomehaničkoga modela i odgovarajući kriteriji za predviđanje loma stijena. U analizi stabilnosti kanala bušotine često se koristi Hoek-Brownov kriterij; međutim, malo je pozornosti posvećeno određivanju parametara i specifičnih uvjeta za njegovu primjenu (netaknuta stijena ili stijenska masa) unutar bušotina. U ovome je radu provedena teorijska analiza stabilnosti kanala bušotine primjenom raznih kriterija za predviđanje loma stijena s primarnim fokusom na usporedbu Hoek-Brownova kriterija za uvjete netaknute stijene ili stijenske mase. Razvijen je geomehanički model korištenjem rezultata petrofizičkih svojstava stijena, laboratorijskih testova i karotažnih mjerenja u bušotinama. Geomehaničke jedinice kanala bušotine određene su primjenom klsterskih algoritama, uz podršku sonde u bušotini. Prirodni diskontinuiteti unutar bušotine utvrđeni su snimanjem stijenki kanala bušotine (engl. *image logs*), a njihova je distribucija mapirana za svaku geomehaničku jedinicu. Parametri za netaknutu stijenu u Hoek-Brownovu kriteriju dobiveni su iz rezultata laboratorijskih testova, dok su oni za uvjete stijenske mase određeni pomoću RMR klasifikacije stijenske mase (engl. *rock mass rating*, RMR) i geološkoga indeksa čvrstoće (GSI). Rezultati pokazuju da primjena Hoek-Brownova kriterija uz pretpostavku netaknute stijene ne pruža pouzdanu procjenu stabilnosti kanala bušotine. Međutim, korištenjem toga kriterija u uvjetima stijenske mase mogu se točno predvidjeti nestabilnosti kanala bušotine s obzirom na uvjete u bušotini. Osim toga, procjena uvjeta u bušotini na temelju geomehaničkih jedinica poboljšava točnost teorijske analize i omogućava identifikaciju stabilnih i nestabilnih zona.

Ključne riječi:

Hoek-Brownov kriterij, geomehanička jedinica, klasifikacija stijenske mase, stabilnost kanala bušotine

Author's contribution

Mohamadali Chamanzad (PhD candidate): data curation, formal analysis, investigation, resources, software, writing – original draft and writing – review & editing. **M. Nikkhah** (Associate Professor at the Faculty of Engineering): conceptualization, formal analysis, methodology, project administration, resources, supervision, validation, visualization and writing – review & editing. **A. Ramezanzadeh** (Professor at the Faculty of Engineering): conceptualization, supervision, validation, visualization, review and editing. **Misha Pezeshki** (Senior Staff of Pars Oil and Gas Company): data curation, supervision, validation, visualization, and review. **Imandokht Mostafavi** (Senior Staff of Pars Oil and Gas Company): data curation, supervision, validation, visualization, and review.

All authors have read and agreed to the published version of the manuscript.

A review on recent studies in the area of conjugate heat transfer modelling in transformers

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Review scientific paper



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Abstract

The exact position and the value of the hot-spot temperature in a transformer could be estimated by calculation using computational fluid dynamics. However, this approach requires the usage of significant computational resources. In this paper, a review on some recent investigations on this topic is made, focusing thereby primarily on the investigation in which the field distribution of the dependent variables is taken into consideration in a conjugate heat transfer problem. Still, the determination of the hot-spot temperature in the transformer is an open problem. Furthermore, a review on some fundamental aspects related to the heat transfer in the transformer was made, and some new approaches for the calculation of heat transfer in the transformer were proposed: smoothed-particle hydrodynamics, two-fluid model and the application of T-Flows computational software. Thus, the smoothed-particle hydrodynamics is found as a convenient approach, since it is traditionally related to laminar flow, that is present in the transformer; the two-fluid model significantly saves the computational resources, while the application of the computational software T-Flows is free and extremely powerful for computation of conjugate heat transfer and parallel computation. The conducted research defined the guidelines for the future work in numerical modelling of heat transfer in transformers.

Keywords:

transformer; conjugate heat transfer; computational fluid dynamics; hot-spot temperature

1. Introduction

The computational fluid dynamics (CFD) analysis of electric transformers, such as the ones produced in Končar D&ST, a renowned Croatian transformer manufacturer with internationally recognized high-quality of its devices, requires high computational power and significant time consumption. The slow convergence rates of the CFD algorithms and application of multigrid approach for its enhancement is outlined in Volkov (2024) and references therein.

The reason for conducting such a computational demanding analysis is the information about location and value of the hot-spot temperature of the transformer winding, since if this temperature exceeds a certain limit, the aging of the insulation material is much more pronounced and, hence, the safe operation of the device becomes questionable. Other electric equipment is also the subject of active research in the scientific community using CFD techniques, such as the recent investigation of thermal and flow fields in an electric motor (Iacovano

et al., 2024), but would not be further investigated within the scope of the present paper.

In doing so, the practitioners in industry mostly use standard CFD models that are available in the commercial CFD packages and that mostly require many computational cells that, in turn, necessitate the usage of the aforementioned high computational power and consume significant time. The same holds for other areas of industrial importance, such as aerodynamics (Liu et al., 2023; Qin et al. 2024) or naval hydrodynamics (Tezdogan et al., 2015; Kim and Tezdogan, 2022), where detailed computational meshes composed of millions of cells are also used to obtain the field distributions of the dependent variables. Please note that in both cases, aerodynamics and naval hydrodynamics, a single set of governing equations is used.

However, due to the averaging procedure applied in derivation of two-fluid model and corresponding source terms responsible for interphase transport across the interface, the exact information about the interface is lost and the interface could not be tracked explicitly. To mitigate this, several approaches were proposed in the past, all of them being addressed in the introductory part in Mer et al. (2018).

Among the approaches mentioned therein, we shall outline the work of Štrubelj et al. (2009), where the be-

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haviour of the single-fluid model is established by proper modelling of interphase drag term in the momentum equation that leads to equalisation of the velocities at the interface. By having equal velocities at the interface, the two-fluid model behaves as a single-fluid method, preserving the features of the single-fluid methods, while being computationally less expensive. Another approach that belongs to this group of models is the large-bubble model (LBM), presented in **Denèfle et al. (2015)**, where the momentum transport is established within the same phase, but of different size. This is actually an argument for further exploration of the possibility to apply the two-fluid model in practice in the case of oil flow in a transformer.

More recently, in **Cukrov et al. (2023)** the two-fluid VOF method has been used together with an approach termed “frozen turbulence” has been proposed to solve the transient temperature evolution in a solid during the film boiling phase. In this approach the turbulent kinetic energy (TKE) value is prescribed in the domain but differing in the near wall region from the far field. Hence, the wall adjacent cells possess $k = 0 \text{ m}^2/\text{s}^2$, indicating the laminar flow, while outside of this zone the non-zero TKE value is prescribed.

This is in line with **Uruba (2012)**, where it is stated that the dominant turbulence generation is accomplished within the first 5% of the boundary layer. Being around boundary layer theory, in **Dedov et al. (2010)** the jet theory is applied to study liquid-vapor behaviour during a pipe flow. In addition, the two-fluid model has been found as a promising turbulence modelling approach in **Malikov (2020); Malikov (2021); Malikov (2022)**. An example of a two-fluid model algorithm could be found in the recent study by **Li et al. (2024)**.

The study reviews heat transfer modelling options of mostly power transformers and is organised as follows. In Chapter 2, a literature survey has been made, starting from seminal work by **Torriano et al. (2010)** and more focusing on the recent progress in the field. Some other works published in the meantime have been also covered in this chapter. In Chapter 3, a discussion of some aspects presented in the studied literature has been made and important features of the models were addressed. Furthermore, the relationships with other fields were made and some fundamental topics that were not covered in the studied literature were pointed out. Additionally, a software recommendation was made and the steps for future industrial collaborations were stressed. The paper ends with conclusions, Chapter 4, where important items from the work are briefly summarized and the steps for future investigations were proposed.

2. Literature review

A disc-type power transformer winding has been comprehensively studied by usage of CFD technique by **Torriano et al. (2010)**. The generated heat is a conse-

quence of ohmic and eddy losses in the transformer's windings. The authors examined six different cases involving isothermal flow, prescribed heat flux value, assumption of homogeneity of the disc structure (that the disc is completely made of copper instead of its composition, copper and paper insulation), without buoyancy, and buoyancy modelled using Boussinesq assumption.

The validation case in **Torriano et al. (2010)** (full scale, the last case) involved all the necessary features, with the disc being modelled as a continuum with space dependent physical properties (density, specific heat capacity and thermal conductivity), thus alleviating the need for modelling of a small scale interfaces between the paper insulation and copper blocks that would further increase the computational effort. However, the distinction between the fluid and solid domain has been established by the application of generalised grid interface (GGI) procedure, that is common for moving boundary solutions in turbomachinery (**Yang et al., 2024**). The procedure used to solve the CHT problem may be found, for example, in **Cukrov et al. (2025)**.

It was noted by **Torriano et al. (2010)** that a hot spot temperature could be efficiently estimated both by using the full scale simulation and the one with Boussinesq approximation for buoyant flow; the Boussinesq approximation refers to linear dependence of density with respect to the fluid temperature in the buoyancy term of momentum equation, while the density is kept constant in other terms. Due to low velocities of oil flow, the flow is considered as laminar. The heat source is determined from the electromagnetic theory. The influence of mass flow rate of dielectric fluid, that is, oil, has been justified, showing better performance when higher dielectric fluid's mass flow rates were applied.

The correlations for calculation of Nusselt numbers, that are relevant for heat transfer analysis of a power transformer, are given in **Gościński et al. (2016)**. The authors have conducted the CFD simulation of the power transformer using a commercial CFD package ANSYS CFX and have obtained the maximum temperature that is below the limit proposed by the standard in the field.

A thermal-hydraulic code for estimation of hot-spot temperature has been proposed in **Jaramillo (2020)**. The authors verified the proposed approach by comparison of the simulation results with the ones obtained using commercial CFD code ANSYS Fluent. In the numerical simulation conducted by the author, a conformal computational mesh has been chosen at the solid-liquid interface. Thus, the need for GGI is alleviated. The studied cases involve the solution in orthogonal and cylindrical coordinates, that is, the arrangement of power transformer's windings in a plane or in an axisymmetric domain. The volumetric heat source in both cases, planar and axisymmetric, has been set based on the study by **Torriano et al. (2010)**, where it was determined from electromagnetic theory that has not been presented in their work.

The detailed CFD model of the power transformer's radiator has been proposed in the study by **Zhao (2022)**. The author has considered all heat transfer modes, namely the heat conduction in the radiator's wall, the convection of the fluid medium and to the ambient air and the radiation heat transfer from the outer surfaces of the device to the surrounding surfaces that participate in this mode of the heat transfer. The computational model is validated against experiments for seven different cases. The difference is based on different input parameters: top liquid temperature, ambient temperature and liquid flow rate at the top of the radiator. The outputs, bottom liquid temperature and total heat dissipation, were compared to the experimental data.

A comprehensive review on power transformer's conjugate heat transfer processes is given in **Smolyanov et al. (2024)**. As a main source of thermal energy losses the high and low voltage windings were identified, contributing, as per authors, 97% in total thermal energy losses. The authors address relevant methodologies in the investigation of heat transfer in a power transformer, thus noting the electric circuit analogy, thermal network model, and CFD models, the latter being in the focus in the present paper. In solving electromagnetism, the authors emphasise the role of finite element method (FEM) in performing this task. This may be explained with the fact that structural modelling, in which the FEM is usually used, is similar to electromagnetism in a sense that there is no viscosity, and hence no advection that is usually solved using finite volume method (FVM).

The possibility of solving the heat transfer within power transformer winding using correlations for heat transfer coefficient has been also outlined in the work by **Smolyanov et al. (2024)**. Thus, one alleviates the need to solve the liquid part of the domain, which may lead to discrepancies in the simulation result. In addition, the role of the Richardson number in determination of hot-spot temperature has been also outlined. Furthermore, the different correlations for the estimation of the Nusselt number were shown, being divided in one suitable for a large-scale domain, i.e. the large transformer, that are derived from boundary layer theory for flat plates, and those appropriate for small-scale domains. Some of these correlations slightly differ from those mentioned in the work by **Gościński et al. (2016)**.

The influence of uneven distribution of electromagnetic losses on the temperature field in a dry-type iron-core reactor has been studied in **Liao et al. (2024)**. A multiphysics simulation has been carried out for a 10 kV reactor in a coupled electromagnetic, thermal and flow field simulation. Firstly, an electromagnetic simulation has been carried out, and the orders of eddy and ohmic losses were determined. This result is further transferred for the purposes of the thermal simulation in which the temperature field has been obtained. Then, a fluid flow field has been solved and the vice versa approach has been utilized. The natural convection cooling is estab-

lished within an enclosed space, thus simulating, at least to a certain extent, the real situation in which this type of reactor is usually placed.

The reduced order modelling (ROM) influenced by a full order model (FOM) in estimation of 3D temperature field within transformer winding is presented in **Liu et al. (2024)**. The validation of the approach has been conducted using CFD and measurement data on a 35 kV power transformer winding immersed in oil, and the significant time savings were reported in obtaining the temperature field.

A detailed analysis of a power transformer using wedge-type geometry is conducted in **Wang et al. (2024)**. In the study, a hex-dominant computational mesh composed of 24 million cells is used and all the heat transfer modes were taken into consideration. The tank with corrugated wall surface, that is difficult to handle with thermal-hydraulic models (THM), has been studied using CFD technique.

The CFD analysis aimed at determining a hot-spot temperature in an oil cooled power transformer has been carried out using computational software ANSYS Fluent in **Taghikhani (2024)**. In addition, the spatial distribution of the magnetic field has been obtained. Furthermore, within the CFD study, the author has conducted a mesh sensitivity check, and the comprehensive CFD simulation using the computational mesh composed of several million cells. The results were compared with the grey wolf optimisation (GWO) algorithm proposed by the author, and a close correspondence with the CFD result has been achieved. In the conducted CFD simulation the heat transfer coefficient has been prescribed at the outer walls of the tank.

The dynamic heat transfer coefficient approach has been used in study by **Xiao et al. (2024)**. The heat transfer coefficient was determined using a classical approach. The infrared thermography has been applied to determine the dynamic heat transfer coefficients that were used to obtain the exact heat transfer coefficient. A 3D numerical simulation has also been carried out with detailed insight in the flow and thermal fields.

This review is completed with the recent work by **Lin et al. (2025)**, who have reviewed the techniques for determination of the hot spot temperature in an oil-immersed power transformer. In their study, firstly three different losses that lead to heat generation (iron-core, winding and stray losses) were identified, and methods for their calculation were discussed. Then, the problem of hot-spot temperature estimation has been tackled from the viewpoint of two distinct approaches: measurement and calculation. In the latter approach, four different calculation methods were identified: empirical calculation, thermal circuit modelling, numerical simulations and artificial intelligence (AI).

In their work, **Lin et al. (2025)**, the presentation of hot-spot temperature dependency on the transformer height is conducted by a linear function and is identified

as transformer type dependent. Among the calculation methods for estimation of hot-spot temperature, numerical simulations and AI were identified as the ones that can accurately estimate the location of the hot-spot temperature.

However, as per **Lin et al. (2025)**, the numerical simulations are considered very slow and computational demanding, while AI techniques depend on training of the model. Furthermore, the features of oil flow were related to the hot-spot temperature. For example, it was found that the increased oil flow rate at the inlet influences the decrease in the hot-spot temperature. The number of baffles, furthermore, has to be specified with care since its increase results in a decrease of the hot-spot temperature to a certain level. After this level is reached, further addition of baffles would yield an increase in the hot-spot temperature.

3. Discussion

In this section, the studied literature is further discussed and the relations with other fields were made. Furthermore, some aspects that were not found in the studied literature were identified and discussed. Possibilities for industrial cooperation based on findings is given at the end of this chapter.

3.1. Discussion on the studied literature with the relations to other fields

Since the seminal work of **Torriano et al. (2010)** the classical computational strategies were, to the authors' knowledge, found as the ones that are used mostly to determine the location of the hot-spot temperature in the windings of the oil-immersed power transformer in application of CFD techniques. This refers to mesh based CFD methods using standard continuum mechanics features. Furthermore, the work by **Torriano et al. (2010)**, in which the winding temperature distribution has been successfully estimated using the Boussinesq approach, may be, at least to a certain extent, related to the work by **Dović (2005)**, who has investigated the flow behaviour in a solar collector. In his study, the author has applied the Boussinesq model to solve the buoyancy driven flow in the device.

The idea of prescription of the heat transfer coefficient at the domain's boundaries in order to avoid modelling of the fluid medium is shown in **Smolyanov et al. (2024)**, referring to the work by **Doolgindachbaporn et al. (2022)**. This approach is, however, used in numerical modelling of heat treatment, e.g. quenching, where the CFD-determined heat transfer coefficient is used for further analyses within material in the recent article by **Gamidi and Passam (2024)**.

The natural convection cooling of a dry-type iron-core transformer reported in **Liao et al. (2024)** follows similar trends as in the case of natural convection around

a square shown in the work by **Savio et al. (2022)**. In addition, the natural convection around a differentially oriented square has been studied in **De and Dalal (2006)**. In both cases one may note the increased velocity at the upper parts of the object in a buoyancy driven flow. In the area of determination of eddy current losses, that were determined together with ohmic losses to determine the temperature field, we may also outline the recent work by **Frlić (2023)**. The author has conducted the estimation of the eddy current losses using finite element method.

It is interesting to note that in the studied literature it was found that the problem of natural convection in enclosures with differentially heated walls has not been tackled in sufficient detail. The conceptual sketch of this problem is shown in the left part of **Figure 1**. It is about the buoyancy driven flow induced by the different temperatures of side walls as shown, for example in **Wu (2015)**.

A comprehensive review on natural convection in enclosures is given in **Miroshnichenko and Sheremet (2018)**, while a more recent review by **Rashid et al. (2022)** also includes the presence of nanofluids in the flow. A theoretical treatise on the subject, together with correlations for the calculation of the Nusselt number is given in **Abramov et al. (2020)**, while the further enhancement of the topic by consideration of conjugate heat transfer could be found, for example, in **Bilgen (2009)** and is schematically shown in the right part of **Figure 1**.

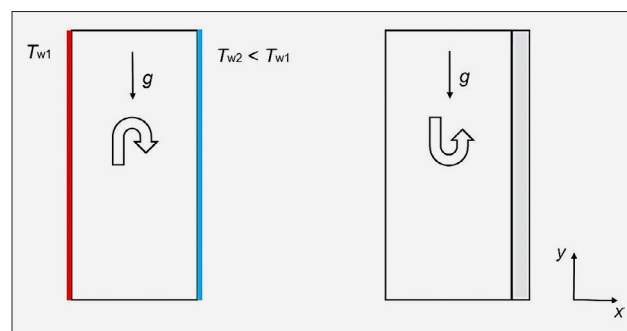


Figure 1. A conceptual sketch of natural convection in cavity: (a) without conjugate heat transfer; (b) with conjugate heat transfer. Image enhanced using PhotoGrid software (<https://www.photogrid.app/en/>)

The radial basis function (RBF) technique, that is used in conjunction with neural network (NN) in an RB-FNN approach, mentioned in **Liu et al. (2024)**, is also an acknowledged approach in handling complex mesh motion in CFD modelling. See **Niu et al. (2017)** for more details on the approach. Other examples of usage of this technique in mesh deformation handling are available in **de Boer et al. (2007)**. The RBF, furthermore, is mentioned as one of the relevant metamodels in the recent study on aerodynamics shape optimization in **Zhang et al. (2024)**.

The application of optimisation algorithms to reduce the consumption of computational resources, such as in the case of GWO algorithm usage in **Taghikhani (2024)**, could be related to weather forecast, where AI could be used to estimate the weather conditions, shown in the lecture by **Güttler (2024)**. However, although faster, it is significantly less accurate since the accuracy, as noted by the author, lies in the physics.

In the conducted literature survey, one may note that following topics were not addressed by the authors so far and that would be discussed in more detail in the following text.

- The application of particle based smoothed-particle hydrodynamics (SPH) approach that, at present, is applied in the automotive industry for solving complex tasks.
- The application of the two-fluid model has not been found.
- The application of T-Flows, an open-source CFD software capable for flow modelling including heat transfer, has not been used by any author in the studied literature.

The engineering application of the discussion outcomes is discussed later, after the above three items are presented in more detail.

3.2. The application of SPH

In SPH, the continuum is discretized using a finite number of particles (Lagrangian approach) instead of computational cells (Eulerian approach) used in mesh based CFD. The brief exposition of the method fundamentals could be found, for example, in recent works (**Pozorski and Olejnik, 2024; Sigalotti and Vargas, 2025; Le Touzé and Colagrossi, 2025**). The method has difficulties with boundary handling, turbulent flow modelling and requires huge computational resources. An approach for handling boundaries is recently proposed in **Kim and Torrens (2024)**.

The other issue is tensile instability that could be remedied using the energy stable schemes, as presented in **Zhu (2024)**. However, it has shown great potential for handling complex geometries, such as those in the automotive industry where the lubrication flow together with conjugate heat transfer (CHT) is solved in **Klos et al. (2024)**. In their presentation, the fluid flow is modelled using SPH, while the coupling with commercial CFD software is made for purposes of solving the heat conduction equation in the solid part of the domain.

Other applications in the automotive sector include the sensor pollution simulation, presented in **Kleineberg and Singh (2024)** and car motion through liquid-water (motion through deep water and fast motion through water), shown in **Posch (2024)**. From the scientific point of view, we may outline the complex fluid-structure interaction (FSI) problem in a shock-wave induced load on a structure, presented in **Chen et al. (2024)**. The authors

model the fluid part using the finite-difference method (FDM), since it is more suitable for modelling the compressible flow features studied in the paper, while the motion of the solid part is modelled using the SPH.

The coupling between FDM and SPH, shown in **Chen et al. (2024)** is established using the immersed boundary method (IBM), which is also an approach in conjugate heat transfer analysis of metal quenching in **Kosseifi (2012)**. Since the flow in the transformer is considered as laminar (**Zhao, 2022**), the difficulty in handling turbulent motion associated with the method, may not be regarded as a problem. The application of SPH in solving natural convection in a differentially heated square cavity is presented in **Yang et al. (2021)**.

3.3. The application of two-fluid model

In the application of the large bubble model (LBM), described in **Denèfle et al. (2015)**, the interfacial momentum transfer is accomplished within the same phase, but with a different size of the interface. Thus, one may model various scales in a two-fluid four field approach, which leads to reasonable consumption of computational time (**Gauss et al., 2016**) and explicitly stated in **Pointer and Liu (2017)**.

Using the two-fluid VOF model in conjunction with frozen turbulence model is applied to solve the conjugate heat transfer during film boiling around a silver cylinder in **Cukrov et al. (2023)** and the method for estimation of the turbulent kinetic energy estimation based on Kelvin-Helmholtz instability (KHI) theory model proposed in **Hillier et al. (2020)** has been proposed.

The foundations of the approach proposed in **Cukrov et al. (2023)** is depicted in **Figure 2** and the underlying modelling approach is described in **Cukrov et al. (2021)**, while its application in temperature and heat flux estimation during the quenching process is demonstrated in **Cukrov et al. (2023a)** and **Cukrov et al. (2024)**, respectively. The complete development of the method is presented in **Cukrov et al. (2025a)**.

Regarding the KHI, it is a flow mode that appears in a single-phase flow, such as the jet flow where the shear is induced by different velocities of the jet issuing from the nozzle and the quiescent surrounding medium. In addition, the phenomenon may also be induced in a two-phase flow, where the phases flow with different velocities and thus induce the shear if the relative velocity exceeds a certain velocity limit described in a recent study by **Krpan et al. (2023)**.

By involving turbulent kinetic energy value using KHI, we follow the so-called “physics informed” approach, but with a difference from the standard one in which the information is gathered from the comprehensive set of data, we close the modelling approach using the data obtained from theory. This was recently applied in a study by **Jang et al. (2024)** where a Timoshenko beam theory has been involved in structural analysis using discrete element method (DEM).

The involvement of the dispersed formulation of a realizable k - ε turbulence model within a two-fluid VOF model available in ANSYS Fluent allows for definition of laminar zone in the vicinity of solid surface (laminar zone in the left part of **Figure 2**) with $k \cong 0 \text{ m}^2/\text{s}^2$, while the remainder of the domain is filled with a finite value of turbulent kinetic energy, i.e. $k > 0 \text{ m}^2/\text{s}^2$.

As the flow evolves, as shown in the right part of **Figure 2**, the laminar zone is preserved while the turbulent zone is present only outside the jet structure since the turbulent viscosity is a function of strain rate tensor and, hence, the turbulence occurs on the interface between the zones and in the complete liquid phase. This could be related to the assumption in the work of **Dedov et al. (2010)**, where jet theory is used to this end, but with the difference that in their work, a pipe flow is considered.

An analogy with the jet flow could be made because in this type of flow, the maximum turbulence intensities are on the outer surfaces of the jet, as shown in the experimental work by **Philip (1972)**. Hence, even in the single-phase flow, we may apply this approach by assigning the zero turbulent kinetic energy value in the vicinity of the stationary walls, while keeping it non-zero out of this area.

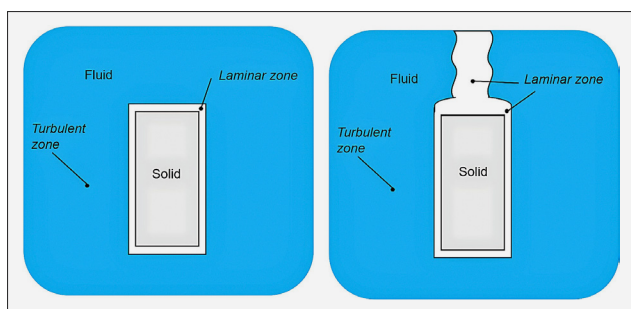


Figure 2. The proposed two-fluid VOF modelling concept: (a) initial state; (b) evolved flow. Image enhanced using PhotoGrid software (<https://www.photogrid.app/en/>).

3.4. The application of T-Flows open-source CFD code

T-Flows is an open-source computational software capable for parallel computation of heat transfer and fluid flow, and is proposed in **Ničeno (2001)**. Furthermore, the software also covers advanced flow modelling; the software tutorial is available at **Sayed (2024)**. Its convenience in solving environmental aerodynamics problems has been shown in **Hadžiabdić et al. (2022)**. In doing so, an automatic mesh generation procedure using GMSH (**Geuzaine and Remacle, 2009**), an open-source mesh generator, has been proposed.

Furthermore, it was also successfully applied in solving the Rayleigh-Bernard convection in an enclosure (**Hadžiabdić et al., 2021**). The advanced turbulence modelling options were demonstrated in heat transfer and fluid flow modelling in **Palkin et al. (2021)**; **Palkin**

et al. (2016); **Palkin et al. (2018)**; **Palkin and Mullyadzhanov (2019)**. The application of this software in the transformer modelling has a great potential since the software is freely available and has parallel computation capabilities between any header of different ranks.

3.5. The possibilities for application of two-fluid model in product development sector of Končar D&ST

The high visibility of Končar D&ST products worldwide stems from the high-quality engineering that is incorporated in the R&D sector of the company. The advanced approaches applied to this end may be tracked from works (**Marković and Čučić, 2018**; **Meško et al., 2020**; **Čučić et al., 2014**). Within the modelling and simulation group of the company, highly skilled professionals (**Kovačević et al., 2024**) with a strong background in thermodynamics, fluid mechanics and heat transfer (the thermofluids) conduct the temperature and flow field analyses of a transformer as well as the electromagnetic analysis.

This work serves as a basis for future work on application of the two-fluid model in transformer development, established between Končar D&ST and University of Zagreb's Faculty of Mechanical Engineering and Naval Architecture. The reason for this is the great potential of the method that has been recognized in the research and development team in Končar D&ST.

4. Conclusions

The hot-spot temperature in a transformer is to appear at the top part of the device and was successfully determined by using computational techniques by the scholars whose publications were studied within this research. Furthermore, the relations with other areas are made and some aspects that were not found in the studied literature were revealed, and the following conclusions may be drawn.

- The full order models of the transformers yield accurate results, but at a high computational cost and significant time consumption.
- The usage of optimisation techniques may lead to the achievement of accurate results without significant time consumption; however, the inexistence of underlying continuum mechanics fundamentals in such approaches may be found as a loss of generality of such approaches.
- AI algorithms produce faster solutions, but since the true accuracy stems from the appropriate modelling of underlying physics, should be used with care.
- Although very popular in the automotive industry, the application of SPH may yield some other problems, such as boundary handling and high computational cost.

- The application of novel approaches, in particular the two-fluid VOF method, may lead to a significant decrease in the consumption of computational resources and time.
- The strong parallel computation capabilities of the open-source CFD software T-Flows may be applied for future calculations of the hot-spot temperatures in the transformers.
- The engineering practitioners in industry have recognized the potential of application of the two-fluid modelling in the case of single-phase flow using theory based turbulence assumptions.

Finally, we can conclude that still more work has to be carried out in order to minimise the computational effort required for determination of the hot-spot temperature. The future steps include fundamental research on the two-fluid modelling of single-phase flow using frozen turbulence approach. Hence, the turbulence (or the laminar flow) quantities should stem from careful theoretical reasoning rather than statistics.

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SAŽETAK

Pregled recentnih istraživanja na području modeliranja spregnutoga prijenosa topline u transformatorima

Točan položaj i iznos najviše temperature materijala izolacije unutar transformatora proračunski se može utvrditi korištenjem računalne dinamike fluida. Međutim, ovaj pristup zahtijeva korištenje znatnih računalnih resursa. U ovome radu napravljen je pregled nekih nedavnih istraživanja na ovu temu fokusirajući se pritom ponajprije na istraživanja u kojima je u obzir uzeta prostorna distribucija zavisnih varijabli u problemu spregnutoga prijenosa topline. Određivanje najviše temperature izolacije unutar transformatora još uvijek je otvoreno pitanje. Nadalje, napravljen je osvrt na fundamentalne aspekte vezane uz prijenos topline unutar transformatora te su predloženi neki novi pristupi za proračun prijenosa topline transformatora: ugađena hidrodinamika čestica, dvofluidni model i primjena računalnoga programa T-Flows. Tako se ugađena hidrodinamika čestica pokazala prikladnim pristupom jer je tradicionalno vezana uz laminarno strujanje kakvo se pojavljuje unutar transformatora; dvofluidni model znatno štedi računalne resurse, dok je primjena računalnoga programa T-Flows besplatna, a izrazito snažna za proračun spregnutoga prijenosa topline i paralelno računanje. Provedenim se istraživanjem definiraju smjernice za daljnji rad na području numeričkoga modeliranja prijenosa topline unutar transformatora.

Ključne riječi:

transformator, spregnuti prijenos topline, računalna dinamika fluida, najviša temperatura izolacije

Author's contribution

Alen Cukrov (senior assistant, PhD, mechanical engineering) contributed with the paper conceptualization, investigation, writing - original draft and visualization. **Ivanka Boras** (full professor tenure, PhD, mechanical engineering) contributed with supervision and funding acquisition. **Martin Jurina** (MSc of Mechanical Engineering, thermodynamics development engineer at Končar D&ST) contributed to project administration. **Dino Kovačević** (MSc of Mechanical Engineering, thermal engineer at Končar D&ST) contributed to review and editing. **Branimir Čučić** (PhD, Department Head at Končar D&ST) contributed to conceptualization and supervision of the project. All authors have read and agreed to the published version of the manuscript.

Detrital Zircon U-Pb Geochronology Reveals Sediment Pathways and Depositional Systems for Lower Miocene Reservoirs, Cuu Long Basin, Vietnam

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Abstract

The oil and gas industry faces increasing challenges in replenishing reserves. Enhancing exploration efficiency requires the integration of diverse datasets to build robust geological models. This study investigates the provenance and depositional systems of Lower Miocene sandstone reservoirs in the Cuu Long Basin (CLB), offshore Vietnam. We integrate 3D seismic, wireline log, conventional core, and detrital zircon U-Pb geochronological data to build a comprehensive source-to-sink model. Our findings reveal that the clastic components of the Lower Miocene sandstones (formations BI.1 and BI.2) predominantly originate from Cretaceous (ca. 105–108 Ma) magmatic rocks of the adjacent Dalat Zone on the Vietnamese mainland, with minor contributions from recycled older crustal sources. Seismic and well data show deposition occurred in environments ranging from alluvial-fluvial plains to more marine-influenced deltaic and coastal plain settings. This work provides new, high-resolution constraints on the provenance, depositional systems, and tectonic controls that influenced reservoir development in the Early Miocene CLB, offering crucial insight for future hydrocarbon exploration in the region.

Keywords:

Cuu Long Basin; Lower Miocene; U-Pb zircon; provenance; tectonic evolution

1. Introduction

Determining the provenance and depositional controls of sedimentary sequences, particularly in complex offshore basins, presents significant challenges (Dung et al., 2018; Breiffeld et al., 2022). Factors influencing sediment generation, transport, deposition, and diagenesis are numerous and intertwined (Ta et al., 2021; Thanh et al., 2021). Identifying the source of clastic minerals within sedimentary rocks provides crucial insight into paleogeography, erosion patterns, and sediment routing pathways (Tran et al., 2007; Breiffeld et al., 2020). Understanding the relationship between origin of the material and reservoir characteristics necessitates a multi-faceted approach, combining geophysical, sedimentological, and geochemical methods (Shellnutt et al., 2013; Liu et al., 2020).

The CLB offshore southeast Vietnam is a significant Cenozoic hydrocarbon reservoir (Breiffeld et al., 2022; Hieu, 2015). Although studies have established a gen-

eral stratigraphic framework and identified key petroleum systems (e.g. Dung et al., 2018; Ta et al., 2021; Hennig-Breiffeld et al., 2021), the specific provenance and depositional controls on the economically important Lower Miocene sandstone reservoirs (formations BI.1 and BI.2) remain debated. Accurate knowledge of the characters of these reservoirs, including their geometry, petrophysical properties, and compositional variability, is critical for optimizing ongoing exploration and production (Faure et al., 2018; Nguyen et al., 2019). Isotopic dating techniques, such as U-Pb geochronology on detrital zircons, offer powerful tools for tracing sediment provenance and correlating strata (Boehnke et al., 2013; Hieu et al., 2017; Tod et al., 2021; Pham et al., 2022). Previous studies (Hieu et al., 2022; Pham et al., 2022; Shellnutt et al., 2013) have documented that the Cretaceous magmatism in potential source regions like the Dalat Zone (e.g. 107–75 Ma, Tod et al., 2021; 91 Ma, Pham et al., 2022), might provide significant detritus of the Lower Miocene sandstone. However, a dedicated study integrating detailed core analysis, well log stratigraphy, seismic interpretation, and detrital zircon U-Pb is still lacking, specifically for the Lower Miocene reservoir intervals across the northwestern and central CLB.

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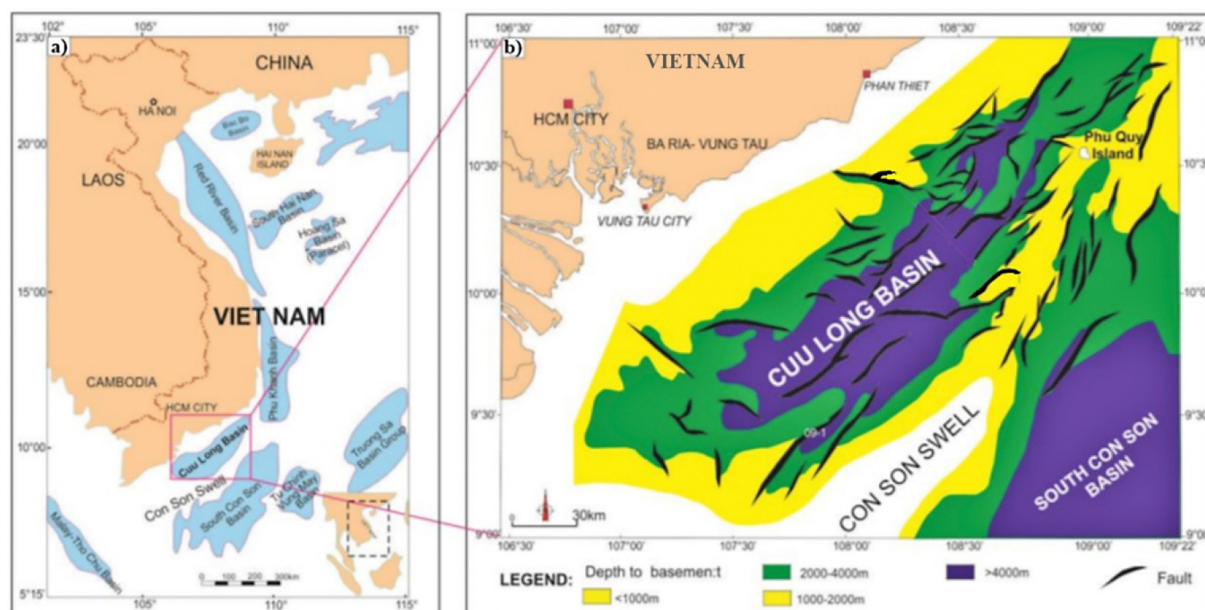


Figure 1. Location map of the Cuu Long Basin. (a) Regional map of Southeast Asia showing the location of the Cuu Long Basin (CLB). (b) Detailed map of the CLB showing major structural elements, the study area, the locations of key wells used in this study (including WT10 and WT19 for U-Pb dating), and the location of the collected samples as shown in **Figure 3**. (Modified from VNOGG, 2019; Breitfeld et al., 2022).

This study aims to fill this gap by providing a comprehensive analysis to determine the provenance, depositional processes, and tectonic context controlling the formation of the Lower Miocene (BI.1 and BI.2) sandstone reservoirs in the CLB. The objectives of this research are: (1) To refine the seismic stratigraphic framework for the Lower Miocene section; (2) To characterize the lithological and petrophysical properties of the reservoir intervals using well log and core data; (3) To determine the provenance of the reservoir sandstones using detrital zircon U-Pb geochronology; and (4) To synthesize these datasets to interpret the depositional environments and assess the influence of regional tectonics on reservoir development. The novelty of this research lies in its integrated approach, providing new, high-resolution U-Pb zircon age constraints directly from the reservoir units. These new data explicitly link to seismic and well log data to build a coherent tectono-sedimentary model for the Early Miocene evolution of the CLB.

2. Geological Background

The Cuu Long Basin (CLB) is a major Cenozoic rift basin located on the southern continental shelf of Vietnam, extending partially onto the Mekong Delta (**Thanh et al., 2021**). It is one of the most prolific hydrocarbon areas in Southeast Asia, with significant oil and gas accumulations primarily within Oligocene to Miocene clastic reservoirs and fractured granitic basement. The basin exhibits an oval shape, arching southeastward, and lies between 9°00'N and 11°00'N and 106°30'E to 109°00'E (see **Figure 1**). It is bounded by the coast to

the northwest, the Con Son uplift zone (separating it from the Nam Con Son Basin) to the southeast, the Tuy Hoa fault zone (separating it from the Phu Khanh Basin) to the northeast, and the Khorat-Natuna uplift zone to the southwest (**Hieu, 2015**).

The tectonic evolution of the CLB is characterized by several major phases:

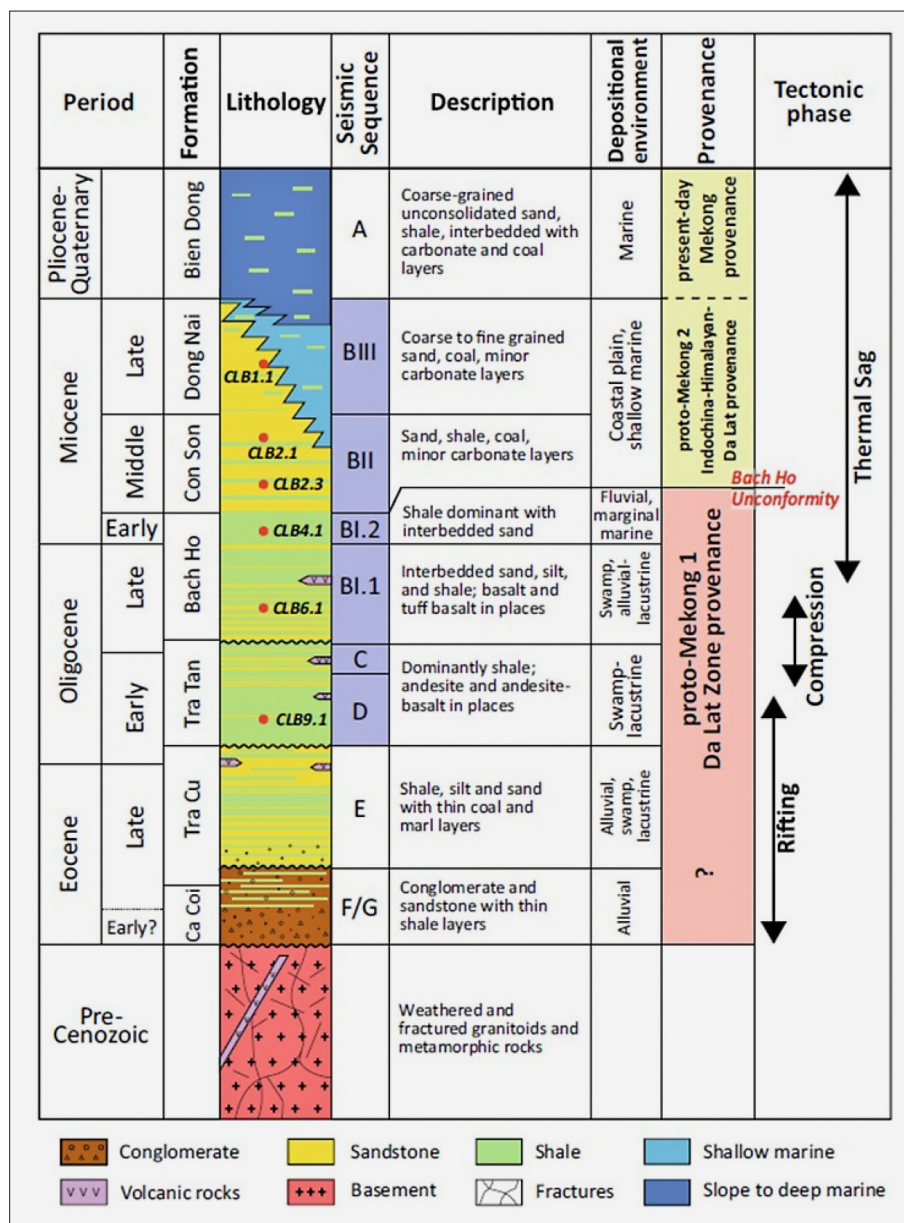
Pre-rift phase (Pre-Cenozoic Basement): The basement largely comprises fractured granitoids and metamorphic rocks, which are important hydrocarbon reservoirs in some fields (**Tran et al., 2007**).

Syn-rift phase (Oligocene to Early Miocene): This phase involved extensive rifting, driven by the collision between the Indian and Eurasian plates. This led to the formation of numerous horst and graben structures, which controlled initial sediment deposition. Sedimentary infill during this phase includes coarse clastics (conglomerates, sandstones) and shales, often with volcanic interbeds (see **Figure 2**).

Post-rift thermal sag phase (Early Miocene to Quaternary): Following rifting, the basin underwent thermal subsidence, leading to the deposition of a thick Cenozoic sedimentary succession. This phase is characterized by a transition from continental to marine-influenced environments.

Exploration in the CLB commenced in 1967, with the first wildcat well drilled in 1974 (Bach Ho structure), providing foundational geological data (**Dung et al., 2018; Breitfeld et al., 2022**). The general stratigraphic column (see **Figure 2**) comprises a pre-Cenozoic basement overlain by a Cenozoic sedimentary succession punctuated by several volcanic events. This study fo-

Figure 2. Generalized stratigraphic column for the Cuu Long Basin, showing key formations, seismic sequences, depositional environments, tectonic phases, and interpreted provenance signatures. The Lower Miocene interval of interest (BI.1 and BI.2) is highlighted. (Modified from Breitfeld et al., 2022).



cuses on the Lower Miocene sedimentary section, specifically the BI.1 and BI.2 sequences (see **Figure 2**), which are well known for significant hydrocarbon accumulations. These formations represent key targets for exploration and production, and understanding their provenance and depositional history is critical for optimizing resource recovery.

3. Methods

We integrated various datasets to investigate the Lower Miocene reservoirs.

3.1. Seismic and Well Data

Approximately 2,000 km of 2D and 4,800 km² of 3D seismic reflection data across the northwestern and central CLB were utilized. We performed sequence strati-

graphic analysis by identifying and mapping key sequence boundaries (specifically SH-5 and SH-7, which bound the Lower Miocene). Seismic facies distributions were mapped based on reflection characteristics (amplitude, continuity, configuration) and calibrated by tying seismic data to 32 well locations. Well log interpretation (**Rider, 1996**) and conventional core data provided direct lithological and environmental information, allowing us to ground-truth the interpretation of seismic patterns (e.g. chaotic, high-amplitude reflections corresponding to channelized sandstones).

3.2. Core and Petrographic Analysis

Two conventional cores from the Lower Miocene section in wells WT10 (sample BK03) and WT19 (sample BK04) were strategically chosen for U-Pb dating to represent different positions within the basin. An additional

200 thin sections from various wells were analyzed for petrography. This involved point counting (minimum 300 points per slide) to determine mineralogical composition. To aid in provenance interpretation, modal compositions from the petrographic dataset (N=200) were plotted on a Quartz-Feldspar-Lithic fragment (QFL) ternary diagram following the methodology of Dickinson (1985).

3.3. Detrital Zircon U-Pb Geochronology

Zircon grains were separated from the two core samples (BK03, BK04) using standard heavy liquid and magnetic techniques. Cathodoluminescence (CL) imaging was performed to reveal internal structures and guide laser spot placement. U-Pb isotopic analyses were conducted in-situ using Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS), following procedures described by Hieu et al. (2013). Raw data were processed using GLITTER software (Griffin et al., 2008). Analytical results exhibiting discordance greater than 10% were excluded from the final geological interpretation to ensure data robustness. For zircons <1000 Ma, the $^{206}\text{Pb}/^{238}\text{U}$ age is used; for grains >1000 Ma, the $^{207}\text{Pb}/^{206}\text{Pb}$ age is preferred. Age distributions were plotted as probability density plots (PDPs) with kernel density estimates (KDE) using IsoplotR (Vermeesch, 2018). Age peaks were statistically identified from the maximum on the generated KDE curves.

4. Results

4.1. Seismic Stratigraphy and Facies

The Lower Miocene interval is clearly bounded by regional seismic horizons SH-5 (base) and SH-7 (top) and comprises two main sequences, BI.1 and BI.2 (see Figure 3). An illustrative seismic line shows the typical basin architecture, with fault-bounded horst and graben structures inherited from earlier rifting phases. Seismic facies analysis reveals significant lateral variations. In the northwestern part of the study area, the BI.1 and BI.2 intervals are often characterized by discontinuous, chaotic to sub-parallel, moderate-to-high amplitude reflections (see Figure 4). Tying these facies to wells reveals they correspond to sections with blocky, sand-prone log signatures, interpreted as channelized fluvial and distributary channel systems. Towards the east and south-east, these facies transition into more continuous, parallel to sub-parallel, lower-amplitude reflections, which correspond to more heterolithic log signatures, interpreted as lower-energy coastal plain, floodplain, or distal deltaic deposits as illustrated on the seismic profile (see Figure 3) and paleo-environmental maps (see Figure 4).

4.2. Well Log Characteristics and Reservoir Properties

Well log correlation across the study area shows that the Lower Miocene interval generally thickens from

west to east (see Figure 5). The BI.2 reservoir interval ranges from 250 m to over 600 m thick. In the SD field, petrophysical analysis indicates good reservoir quality with porosity (ϕ) from 17% to 27% and net-to-gross (NTG) from 28% to 61.5%. The underlying BI.1 reservoir varies from 110 m to over 650 m thick. In the HS area, it exhibits porosities of 19–22% and NTG of 55–70% (see Table 1).

4.3. Core Lithology and Sandstone Composition

Core observations from the BI.1 and BI.2 intervals show light- to dark-gray, fine- to medium-grained sandstones with features including cross-bedding, laminations, and fining-upward trends (see Figure 6). Petrographic analysis reveals the sandstones are predominantly Arkose and Lithic Arkose. They are compositionally immature, containing abundant feldspar (32–34%, mostly K-feldspar) and lithic fragments (2–8%, mostly volcanic and granitoid), in addition to quartz (30–33%) (see Table 2). The modal composition data, when plotted on a Dickinson (1985) QFL diagram, falls overwhelmingly in the “Dissected Arc” and “Transitional Arc” provenance fields (see Figure 7). This strongly indicates that the sediment was derived from the erosion of a magmatic arc terrane.

4.4. Detrital Zircon U-Pb Geochronology

The U-Pb dating results from both samples (BK03 and BK04) are strikingly similar (see Figure 8). Sample BK03-WT10 yielded a dominant Cretaceous age population (63.3% of grains) with a prominent peak at ca. 108 Ma. Sample BK04-WT19 also yielded a dominant Cretaceous age population (67.4% of grains) with a prominent peak at ca. 105 Ma. Both samples also contain subordinate populations of older, likely recycled zircons, including Permian-Triassic (ca. 210–280 Ma), Ordovician-Silurian (ca. 440–460 Ma), and Precambrian grains. The Cretaceous zircons are typically euhedral to subhedral with clear oscillatory zoning, indicative of a magmatic origin and relatively short transport (see Figure 9).

5. Discussion

5.1. Provenance of Lower Miocene Sediments

The detrital zircon U-Pb age data provide robust, quantitative evidence for the primary sediment source. The overwhelming predominance of Cretaceous zircons (ca. 105–108 Ma) in both samples points unequivocally to the Dalat Zone on the adjacent Vietnamese mainland as the principal source terrane (see Figure 8). This age range correlates perfectly with the well-documented Cretaceous granitoid intrusions and volcanic rocks of the Dalat Zone (Shellnutt et al., 2013; Hieu et al., 2017; Tod et al., 2021). This interpretation is strongly supported by the petrographic data, as the arkosic composition classifies the sandstones within the “Dissected Arc” field on the QFL diagram (see Figure 7), a classic

Figure 3. The map shows key sequence boundaries SH-3 (top) and SH-7 (base) bounding the Lower Miocene formations BL.1 and BL.2. Note the underlying horst-and-graben basement structure. The seismic facies transition from chaotic/sub-parallel in the west (interpreted as fluvial/proximal deltaic) to more parallel/continuous in the east (interpreted as distal deltaic/coastal plain) is highlighted. The “collected sampling area” refers to the region where core samples for U-Pb dating were acquired.

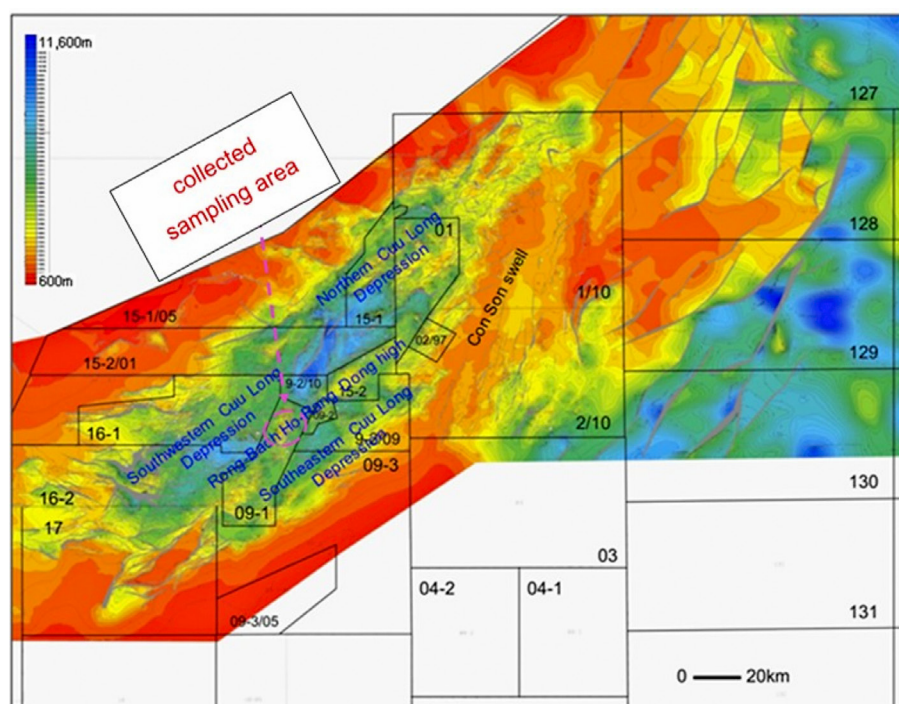
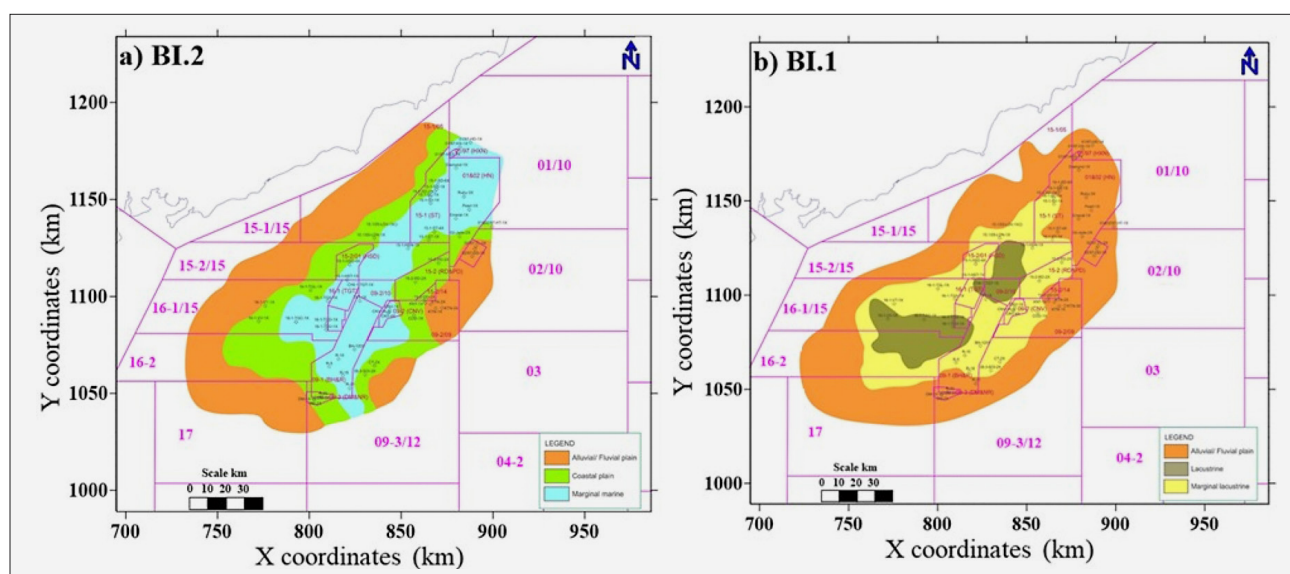


Figure 4. Interpreted paleo-environmental maps for the Lower Miocene sequences a) BL.1 and b) BL.2 based on seismic facies analysis calibrated to well data. The maps illustrate the distribution of depositional systems, transitioning from fluvial-dominated in the west to more deltaic/marine-influenced in the east.

signature of sediment derived from an eroded granitic-volcanic arc. The euhedral to subhedral morphology of the Cretaceous zircons (see **Figure 6**) suggests relatively short transport distances, consistent with derivation from the adjacent mainland.

Our results provide the first direct geochronological confirmation for the provenance of these specific reservoir units. While previous studies (e.g. **Breitfeld et al., 2022**) inferred a Dalat Zone source, our data quantify its dominance (~65%). Furthermore, the lack of a significant Permian-Triassic zircon peak, which is characteris-

tic of the Mekong River system, suggests that a “Proto-Mekong” source had minimal to no influence on deposition in the northwestern CLB during the Early Miocene. The subordinate older zircon populations were likely recycled from Paleozoic-Mesozoic sedimentary cover rocks or basement terranes exposed within the Dalat Zone’s eroding hinterland.

5.2. Depositional Environments and Pathways

Integrating core, well log, and seismic data allows for a refined interpretation of depositional environments.

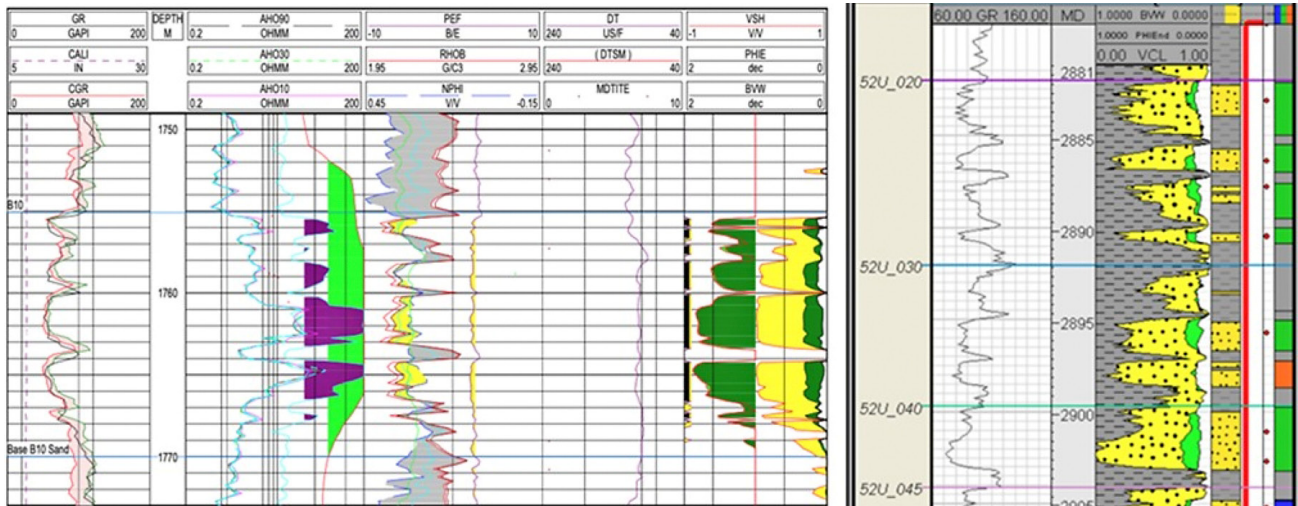


Figure 5. The map shows well logs from two different wells. Gamma Ray (GR) and Resistivity (RES) logs are displayed. Low GR (yellow) indicates sand-prone intervals, while high GR (green/gray) indicates shale-prone intervals (Modified from Tran and Phung, 2007).

Table 1. Summary of Reservoir Properties for BL.1 and BL.2 Formations.

Formation/Area	Average Porosity (%)	Average Water Saturation (%)	Average Net-to-Gross (%)	Depositional Environment
BL.2 (HS Field)	19	45	62	Delta Front / Distributary Channel
BL.2 (SD Field)	16	65	35	Lower Delta Plain / Interdistributary Bay
BL.1 (Central Area)	22	40	70	Fluvial Channel Belt (Braided/Meandering)
BL.1 (Basin Margin)	15	55	45	Alluvial Plain / Floodplain

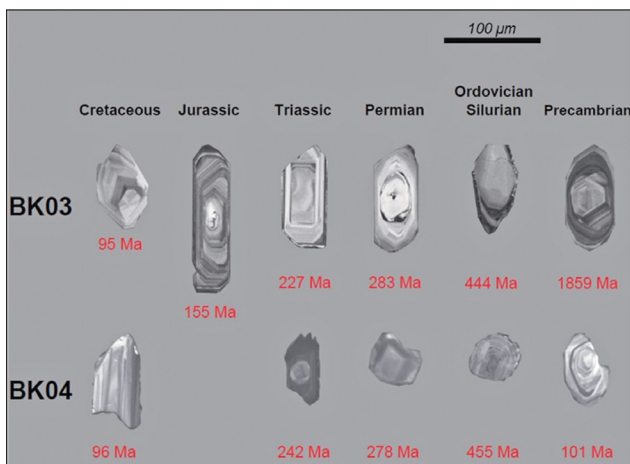


Figure 6. Cathodoluminescence image of pre-Cambrian zircon grains and cathodoluminescence image of ordovician-silurian zircon grains in core samples BK03 and BK04.

The Lower Miocene succession records a transition from terrestrial to marine-influenced settings.

Formation BL.1 is interpreted as being deposited primarily in alluvial and upper delta plain environments. The blocky, sand-prone seismic and well-log facies represent fluvial channel belts.

Formation BL.2 represents a landward shift of environments, with deposition occurring in lower delta plain to coastal plain and marginal marine settings. The inter-

Table 2. Summary of Petrographic Modal Data for Lower Miocene Sandstones.

Component (%)	Sample BK03	Sample BK04	Range (N=200)
Framework Grains			
Monocrystalline Quartz	30.5	28.6	25-35
Polycrystalline Quartz	2.2	3.7	1-5
K-Feldspar	32.1	30.3	28-35
Plagioclase Feldspar	1.8	3.1	1-4
Volcanic Lithic Fragments	2.5	8.1	2-10
Granitoid Lithic Fragments	1.0	1.5	< 2
Matrix (Detrital Clay)			
Cement (Authigenic)	13.2	7.5	5-15
Provenance Classification	Lithic Arkose	Feldspathic Litharenite	Arkose / Lithic Arkose

bedded nature of sands and shales reflects deposition in distributary channels, mouth bars, and adjacent lower-energy interdistributary bays or floodplains.

The overall sediment transport pathway was from the uplifted Dalat Zone in the northwest towards the subsiding basin center in the southeast. Reservoir quality is

highest in the sandstone facies associated with higher-energy channel axes (see **Table 1**).

5.3. Tectonic Controls on Sedimentation

Early Miocene sedimentation occurred during the post-rift thermal sag phase of the CLB's evolution. The primary control on sediment supply was the significant uplift and erosion of the Dalat Zone magmatic arc. This uplift was likely driven by a combination of regional tectonic forces, including post-rift thermal doming and far-field stresses related to the ongoing India-Asia collision (Hieu, 2015; Breithfeld et al., 2022). The creation of accommodation space was controlled by regional thermal

subsidence, while the distribution of depositional systems was heavily influenced by the underlying basement topography of horsts and grabens, which focused sediment fairways into structural lows. The overall landward-to-seaward transition from BI.1 to BI.2 reflects a relative sea-level rise, consistent with a long-term transgressive-to-highstand sequence set. The stacking patterns observed on seismic data, with fluvial systems (BI.1) overlain by more widespread deltaic/coastal systems (BI.2), are consistent with a long-term transgressive-to-highstand sequence set (see **Figure 3**).

5.4. Implications and Limitations

This integrated study provides a robust source-to-sink model for the Lower Miocene reservoirs in the CLB. The confirmation of a proximal, stable Dalat Zone source and the delineation of depositional fairways controlled by basement structure are critical for predicting reservoir distribution and quality in less explored parts of the basin. The provenance conclusions are based on two sample locations, and while their consistency provides confidence, further spatial variability could exist. Similarly, the density of well and core data limits the resolution of paleo-environmental mapping. Future research could expand the detrital zircon dataset to other parts of the basin to test for spatial or temporal changes in provenance and further refine sequence stratigraphic models.

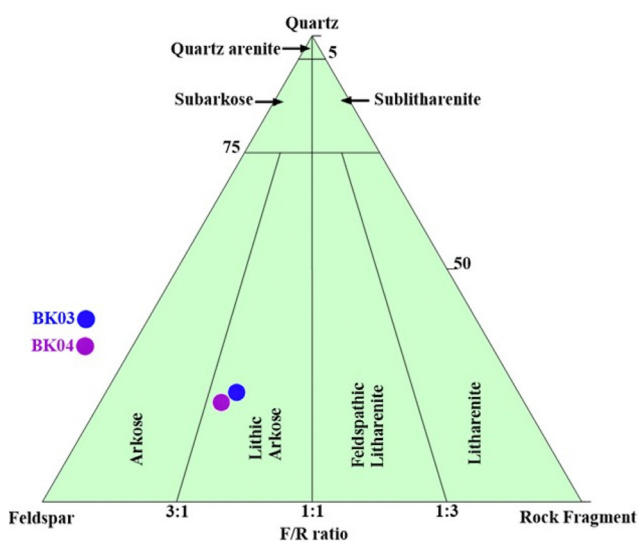


Figure 7. Quartz-Feldspar-Lithic (QFL) fragment ternary diagram for sandstone classification. The diagram is plotted using modal composition data from 200 thin sections across the study area.

6. Conclusions

This integrated study of the Lower Miocene reservoirs in the Cuu Long Basin provides significant new insight into their origin and distribution. Our key conclusions are:

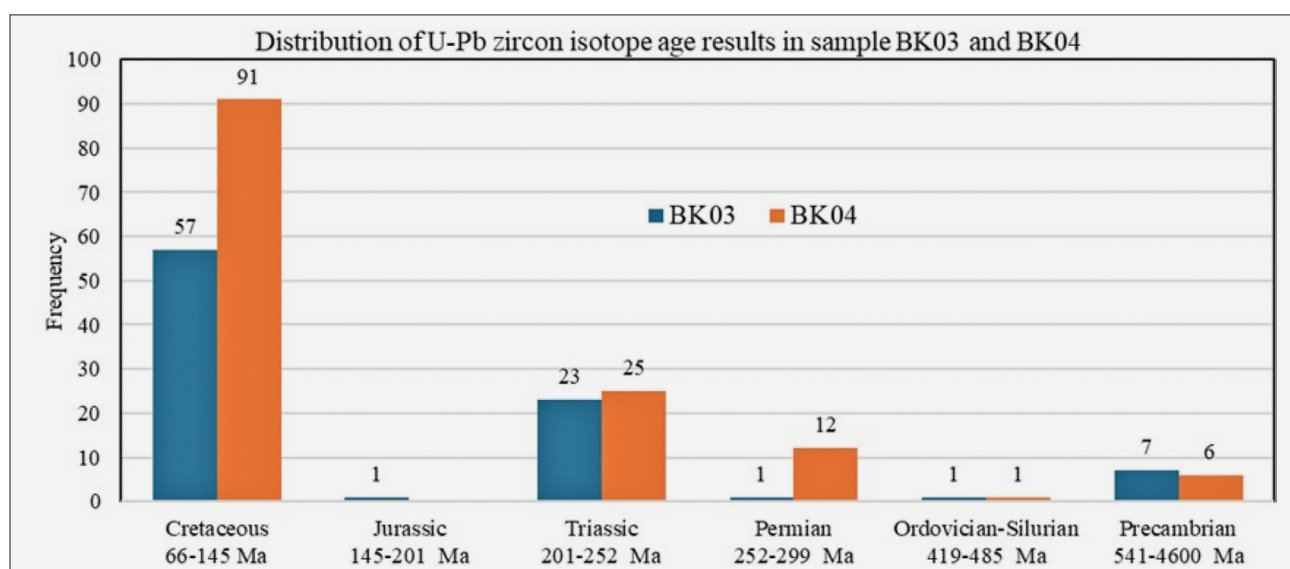


Figure 8. Probability Density Plots (PDP) of detrital zircon U-Pb ages for Lower Miocene sandstone samples from the Cuu Long Basin with sample BK03-WT10 (n=90) and sample BK04-WT19 (n=135). Both samples are dominated by Cretaceous age peak between 100-110 Ma.

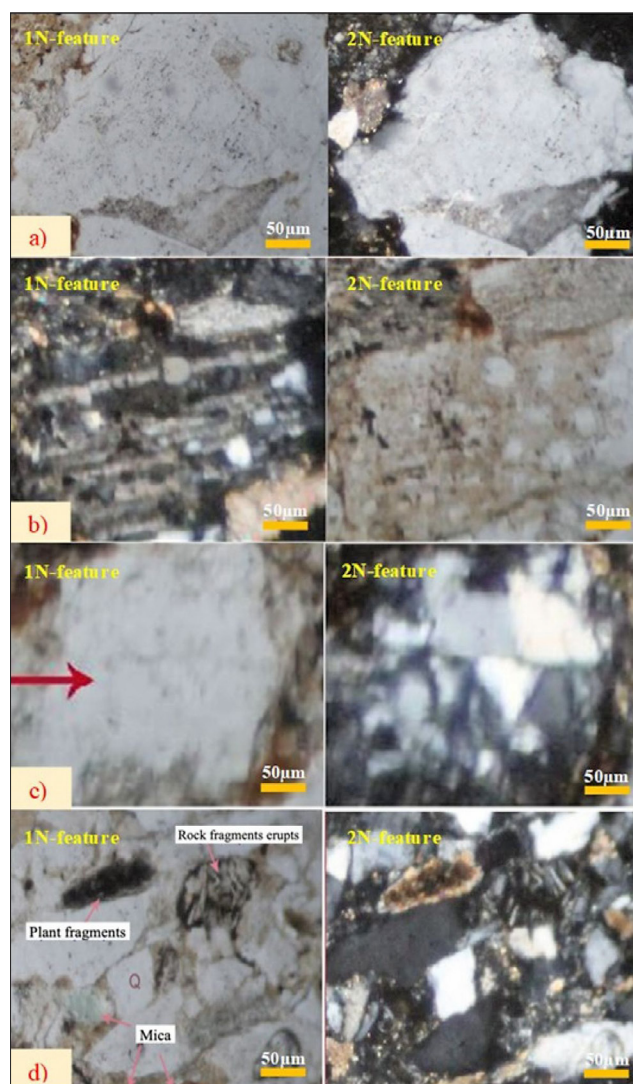


Figure 9. Photomicrographs of Lower Miocene sandstones from the Cuu Long Basin. Granite rock fragment composed of a) multiple feldspar minerals b) plagioclase with albite twinning, c) Poly quartz fragment and thin section photomicrograph BKO3 under polarizing microscope d) plant debris, volcanic rock fragments, mica fragments, quartz (Q).

Primary Provenance Confirmed: Detrital zircon U-Pb geochronology definitively establishes the Cretaceous (ca. 105-108 Ma) magmatic rocks of the Dalat Zone as the primary sediment source for the BI.1 and BI.2 sandstone reservoirs. Contributions from other sources, such as a Proto-Mekong River, were negligible in the study area.

Depositional Systems Delineated: Sedimentation occurred in a range of environments transitioning from alluvial/fluvial plains (predominantly BI.1) to deltaic and coastal plain settings (predominantly BI.2), with sediment transport directed from northwest to southeast. Reservoir heterogeneity is directly linked to these depositional sub-environments.

Tectono-Sedimentary Model Refined: Early Miocene sedimentation was controlled by the interplay of

tectonic uplift of the source terrane, post-rift thermal subsidence creating accommodation space, and underlying basement structures influencing sediment pathways.

Ultimately, this study provides a robust, integrated geological framework that reduces exploration risk by improving predictions of reservoir presence and quality. The methodologies and findings presented here are not only crucial for the Cuu Long Basin but also serve as a valuable case study for hydrocarbon exploration in other tectonically complex rift basins in Southeast Asia.

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SAŽETAK

Interpretacija taložnih sustava i izvorišta materijala donjomiocenskih naslaga u bazenu Cuu Longa, Vijetnam, na temelju U-Pb geokronologije detritičnih zrna cirkona

Naftna i plinska industrija suočava se sa sve većim izazovima u obnavljanju rezervi ležišta. Povećanje učinkovitosti istraživanja zahtijeva integraciju različitih skupova podataka kako bi se izgradili pouzdani geološki modeli. Ova studija istražuje podrijetlo i sustave taloženja ležišta donjomiocenskih pješčenjaka u bazenu Cuu Longa (CLB) na obali Vijetnama. U okviru rada integrirani su 3D seizmički, karotažni te konvencionalni podatci iz jezgara uz analize detritičnih zrna cirkona U-Pb metodom za utvrđivanje starosti. Provedena analiza načinjena je u svrhu izrade modela transporta od izvora do taložnoga prostora. Rezultati su pokazali da klastične komponente donjomiocenskih pješčenjaka (formacije BI.1 i BI.2) pretežno potječu iz magmatskih stijena kredne starosti (otprilike 105 do 108 milijuna godina) koje se nalaze u susjednoj Dalat Zoni na vijetnamskome kopnu, uz manji broj starijih, višestruko resedimentiranih zrna. Seizmički i bušotinski podatci pokazuju da se taloženje događalo u raznim okolišima, od aluvijalno-fluvijalnih ravnica do deltskih i obalnih ravnica koje su bile pod većim utjecajem mora. Ovaj rad pruža nove, vrlo precizne informacije o podrijetlu, taložnim sustavima i tektonskim značajkama koje su utjecale na razvoj ležišta u donjomiocenskim naslagama CLB-a, nudeći ključne uvide za buduća istraživanja ugljikovodika u regiji.

Ključne riječi:

bazen Cuu Longa, donji miocen, U-Pb datiranje cirkona, podrijetlo, tektonska evolucija

Author's contribution

Quoc T. Truong (PhD), characterized the samples, and contributed to the process. **Nguyen Tuan** (PhD), **Quoc T. Truong** (PhD), **Huu X. Mai** (PhD) and **Huynh T. Nguyen** (PhD) contributed to laboratory analyses, analyses result processes, and described the characterization and evaluation of the final products. **Xuan K. Nguyen** (PhD) and **Van X. Tran** (Assoc. Prof.) evaluated the results, reviewed the draft manuscript, and provided technical suggestions. **Van X. Tran** (Assoc. Prof) and **Truong A. Dang** (Assoc. Prof.) edited the entire draft. The entire work was written collaboratively by all the authors.

All authors have read and agreed to the published version of the manuscript.

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