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INTACT ROCK STRENGTH AND ELASTIC PARAMETERS FOR ROCK TYPES IN KIRUNA AND MALMBERGET MINES

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Abstract

This study aims to analyse the correlation between intact strength and elastic parameters of Kiruna and Malmberget rock masses with their geological and alteration characteristics. Recent geotechnical programs in these mines have identified intact rock strength and elastic parameters for various rock masses. Key rock mass classification systems like IRMR, RMR89, or Q use both subjective assessments (IRS - Intact Rock Strength) and objective point load tests to evaluate intact rock strength. Accurate measurements are essential for estimating in situ geotechnical conditions and stresses in deep mine designs. Ongoing UCS (Unconfined Compressive Strength) and TCS (Triaxial Compressive Strength) campaigns have provided valuable additional data for geotechnical models. Numerous studies have demonstrated that Kiruna rock masses generally exhibit greater strength than Malmberget. This study reveals that Malmberget rock types have intact strengths ranging from 100 to 300 MPa, with various types and intensities of alteration for granites, rhyodacites and trachyandesites sometimes exceeding 300 MPa, while biotite schist and massive magnetite may fall below 90 MPa. In Kiruna, intact strength varies between 100 and 350 MPa, including massive magnetite, with the strongest types such as quartz porphyries and tuff, exceeding 350 MPa. Although alteration settings are observed to have a negligible impact on UCS, however, they play a significant role in influencing the elastic parameters. These findings enhance the geotechnical understanding of these mines and lead to more efficient strategic mine planning.

Key words

Intact rock strength, Elastic parameters, Unconfined compressive strength (UCS), Young’s modulus, Poisson’s ratio, Lithology, Alteration

1. Introduction

Understanding the geotechnical properties of rock masses is critical for the design and safety of deep mining operations. The rock masses in Kiruna and Malmberget mines, the two largest iron ore underground mines in Sweden (Figure 1), present a unique opportunity to study these properties due to their extensive geotechnical programs. In recent years, these programs have focused on identifying the intact rock strength and elastic parameters for various rock types, essential for realistic estimation of in situ geotechnical conditions and stress distribution.

The importance of accurate measurements of intact rock strength and elastic parameters cannot be overstated, particularly in the context of deep mine designs where the structural integrity and stability of rock masses are paramount. Traditional rock mass classification systems, such as the In-situ Rock Mass Rating (IRMR), Rock Mass Rating 1989 (RMR89), and the Q-system (Bieniawski 1985, Laubscher 1990) often rely on subjective assessments of IRS. These assessments can also be complemented by more objective methods, such as point load tests, which provide a more reliable basis for classification and subsequent engineering decisions (ISRM 1985).

Figure 1 A map of Northern Europe showing the Scandinavia peninsula where Kiruna and Malmberget mines in Sweden are spotlighted

Ongoing Uniaxial Compressive Strength (UCS) and Triaxial Compressive Strength (TCS) testing campaigns have been instrumental in yielding valuable data that contribute significantly to geotechnical models (Bieniawski & Bernede 1979, Deere & Miller 1967, Hoek & Brown 2019). This study's comprehensive analysis based on geotechnical borehole logging and laboratory testing not only corroborates previous findings but also provides new insights into the mechanical behaviour of these rock masses. By expanding the geotechnical knowledge base, this research supports the development of more accurate and reliable geotechnical models, ultimately enhancing the safety and efficiency of mining operations in these regions.

This study leverages the latest data from extensive geotechnical investigations conducted in Kiruna and Malmberget mines. By examining the correlation between the intact strength, elastic parameters, and lithological - alteration characteristics, this research aims to enhance the understanding of these rock masses. The findings indicate notable differences between the two regions.

1.1. Geological settings of Kiruna mine

The Kiruna iron ore deposit, one of the largest and most significant in the world, is an apatite iron oxide deposit formed around 1.9 billion years ago during the Precambrian era (Hallberg et al. 2012). The iron ore is hosted within a sequence of metavolcanics and metasedimentary rock, known as Porphyry Group. The primary minerals in the Kiruna deposit are magnetite and hematite (less abundant), with significant amounts of apatite (a calcium phosphate mineral) and minor amounts of other minerals such as actinolite, albite, scapolite, quartz and carbonates. The ore body is generally steeply dipping and tabular to lens-shaped, extending for almost 5 kilometres along strike, up to 100 m thick and more than 1300 m down dip. The surrounding rocks have experienced extensive hydrothermal alteration, including albitisation, silicification, sericitization, and the introduction of various hydrothermal minerals (Bergman et al. 2001). The origin of the Kiruna ore is debateable, linked to either direct magmatic activity lead crystallization of iron minerals or hydrothermal processes that concentrated the iron and phosphate minerals (Geijer 1910, Troll et al. 2019). The mine operates primarily as an underground mine using sublevel caving, a method well-suited to the steeply dipping and extensive ore bodies of the Kiruna deposit.

1.2. Geological settings of Malmberget mine

The Malmberget iron ore deposit, located in the Gällivare municipality in northern Sweden, is an important iron oxide-apatite (IOA) type ore body, similar to the Kiruna deposit. Formed around 1.9 billion years ago during the Precambrian era, the iron ore is hosted within a sequence of felsic and mafic metavolcanic and metasedimentary rocks, predominantly of volcanic origin, which have undergone significant metamorphism and deformation (Bergman et al. 2001, Hallberg et al. 2012, Sarlus et al. 2020). The primary minerals in the Malmberget deposit are magnetite and hematite, with significant amounts of apatite and other accessory minerals such as amphiboles, pyroxenes, quartz, and feldspar. The ore structure is complex compared to Kiruna, consisting of multiple steeply dipping ore bodies in a fold structure that vary significantly in size and shape, extending for almost 5 kilometres along strike, more than 1800 m down dip while thickness varies between 30 to 200 m depending on the ore zone. The surrounding rocks have experienced extensive hydrothermal alteration, including silicification, chloritization, and the introduction of various hydrothermal minerals. The origin of the Malmberget ore is linked to volcanic activity, with iron-rich sediments being deposited on the sea floor and later concentrated by hydrothermal processes. The mine operates primarily as an underground mine using sublevel caving and sublevel stopping methods, which are well-suited to the complex and extensive ore bodies of the Malmberget deposit.

2 Methods

This study employed a comprehensive approach to present and analyse the intact strength and elastic parameters of rock material for the Kiruna and Malmberget mines, with geotechnical laboratory testing being the primary methodology. Samples from various rock types were collected through drilling campaigns and subjected to Uniaxial Compressive Strength (UCS) tests to determine the maximum axial compressive stress they could withstand before failure. Additionally, Triaxial Compressive Strength (TCS) tests were conducted to assess the rock's strength under confining pressure, simulating in situ stress conditions and providing insights into the rock's behaviour under different stress regimes. Secant elastic parameters such as Young's modulus and Poisson's ratio were measured using strain gauges during UCS and TCS tests, which are crucial for understanding the deformation characteristics of the rock masses. Point load tests were also performed as a supplementary method to quickly estimate the intact rock strength. Alongside laboratory testing, geotechnical borehole logging was conducted to gather continuous records of rock properties along the drilled holes, including Rock Quality Designation (RQD), and detailed geological characterization such as RMR89, IRMR and Q.

The data collected from laboratory tests and borehole logging were systematically analysed to establish correlations between intact rock strength, elastic parameters, and geological characteristics. Statistical methods were used to evaluate the distribution of strength and elastic parameters, investigate the influence of lithology and alteration on rock behaviour, and compare the geotechnical properties of Kiruna and Malmberget rock material. This methodological framework ensured a robust and comprehensive assessment, contributing significantly to the geotechnical understanding necessary for safe and efficient deep mining operations in these regions.

In this study, only the uniaxial compressive strength (UCS) results for Kiruna and Malmberget mines are presented accompanied with core logging characteristics including lithology and alteration. The triaxial compressive strength (TCS) results are excluded due to their complexity, necessitating a more detailed and comprehensive analysis, which will be addressed in a subsequent study. In Table 1 an inventory of the samples used is presented and in **Error! Reference source not found.** the geospatial distribution of the samples is visualised in plan view perspective for both sites. As becomes prominent in Figure 2, the geospatial distribution of testes samples is notably sparse, particularly in Kiruna region. Consequently, further sampling is required to enhance the geotechnical investigation in subsequent studies.

Table 1 Inventory about the type, amount and date for the samples used for both sites

				Testing date	
Test type	**Site**	**Samples**	**Boreholes**	**From**	**To**
UCS	Kiruna	192	21	Sep-23	Feb-24
UCS	Malmberget	218	21	Oct-22	Nov-23
Total		**410**	**42**		

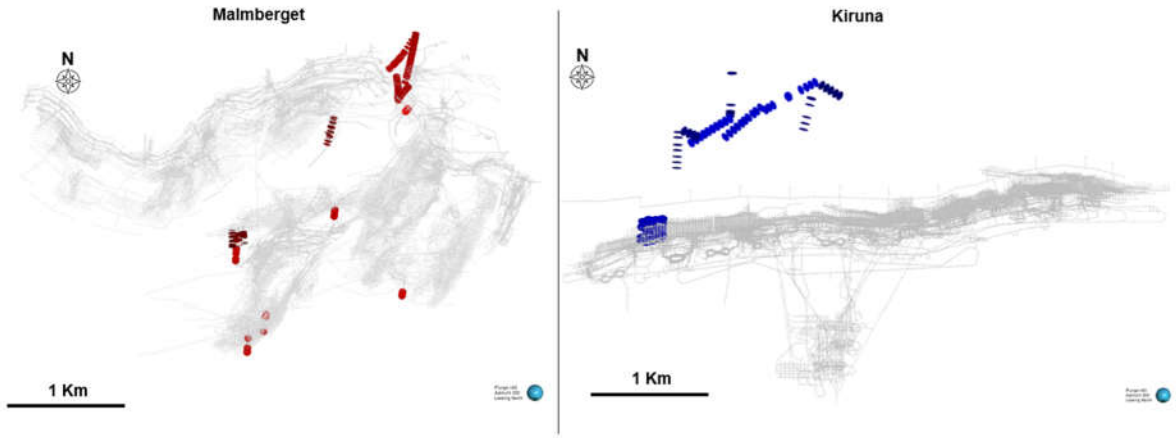

Figure 2 The geospatial distribution of UCS samples used in the present study is presented in a plan view perspective for Malmberget and Kiruna sites, looking north with a plunge of +60°. The mine layouts are presented in grey colour.

3 Results

The results of this study provide a detailed understanding of the intact strength and elastic parameters of rock material from the Kiruna and Malmberget mines. The findings are based on extensive geotechnical laboratory testing, supplemented by borehole logging. Here, we present the key results for each mine and discuss their implications.

A comparative analysis of the two mining regions revealed distinct differences in geotechnical properties, which correlate with their geological characteristics. In Figure 3, the overall distribution of all tested samples for UCS, Young's modulus and Poisson's ratio is presented in box plot form. Although in Kiruna the highest concentration of data is lower than in Malmberget, strength results are obtained above 300 MPa and greater Young's modulus is observed which highlights that more competent rocks are present in Kiruna than in Malmberget. Moreover, in Kiruna, higher elastic modulus is attributed due to the predominance of syenite and quartz porphyry and massive magnetite, which are less altered and more structurally competent. Conversely, the higher elasticity of Malmberget rocks is associated with the presence of more altered rock types and the existence of biotite schist and the high concentration of biotite mineral in the matrix of rocks.

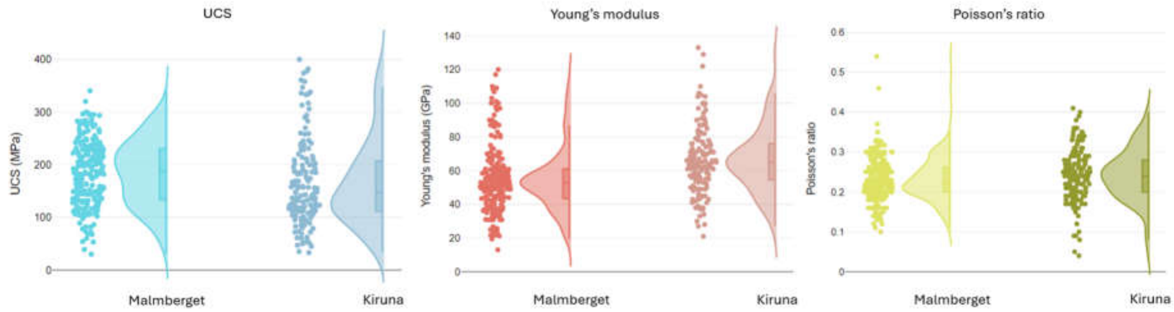

Figure 3 Summarised distribution of all tested samples for UCS, Young's modulus and Poisson's ratio.

In Kiruna site the lithologies analysed encompasses syenite porphyry, magnetite, quartz porphyry, tuff, and dyke porphyry. In contrast, Malmberget site includes trachyandesite, rhyodacite, trachybasalt, pegmatite, granite, magnetite, and biotite schist. It is noteworthy that the lithologies of Malmberget are identified by local names, which are extensively used by mine geologists and engineers and are based on colour. The correspondence is the following: Trachyandesite is known as grey-red leptite (GRL), rhyodacite as red-grey leptite (RGL) and trachybasalt as grey leptite (GLE). Also, magnetite is considered an alteration for Malmberget by the means of magnetite minerals enrichment in the hanging and footwall wall rock masses due to hydrothermal fluids. Figures included in the following subchapters 3.1 and 3.2, present statistical analyses using box plots to compare UCS (Figure 4, Figure 7), Young's modulus (Figure 5, Figure 8), and Poisson's ratio (Figure 6, Figure 9) across different lithologies and alteration states for the Kiruna and Malmberget sites. It should be noted that the black boxes appearing in the box plots serve two purposes: they either delineate areas of denser distribution for different alterations within the same lithology or highlight multiple data concentrations for the same lithology and alteration.

3.1 Kiruna rock mass

The geotechnical laboratory tests revealed that the intact rock strength in the Kiruna mine exhibits significant variability depending on the rock type. Kiruna rock material exhibit UCS values ranging from 50 to nearly 400 MPa, with most values falling between 100 and 270 MPa. Notably, magnetite shows UCS values from 100 to 200 MPa, whereas higher values are observed for quartz porphyry and tuffs. The lithology of tuff material warrants further analysis due to the variability observed in its uniaxial compressive strength (UCS) results. For a total of 55 UCS tests conducted on tuff with a quartz porphyry matrix, the values range from 50 to 400 MPa, with a denser distribution between 100 and 250 MPa. Young's modulus generally ranges between 40 and 80 GPa, except for magnetite, which varies from 40 to 120 GPa, with some extreme values exceeding 120 GPa or falling below 40 GPa. The high elastic modulus reflects the rocks' ability to withstand significant stress without deforming, which impacts stability in deep mining operations. Similarly, Poisson's ratio ranges from 0.15 to 0.3, with magnetite displaying a broader range of 0.15 to 0.4, and occasional extreme values above 0.4 or below 0.15. The primary alteration observed in Kiruna is the "pervasive albite with hematite staining," which appears to impact nearly all the tested lithologies. In this context, several alterations specifically affect magnetite and quartz porphyry. Actinolite mineral significantly influences both lithologies by generally increasing their strength, whereas chlorite exclusively affects quartz porphyry by reducing its strength. Regarding elastic parameters, a more pronounced influence is obvious. Specifically, actinolite and calcium minerals increase Young's modulus in magnetite, whereas apatite enrichment decreases it.

Chlorite minerals, on the other hand, tend to lower Poisson's ratio in quartz porphyry.

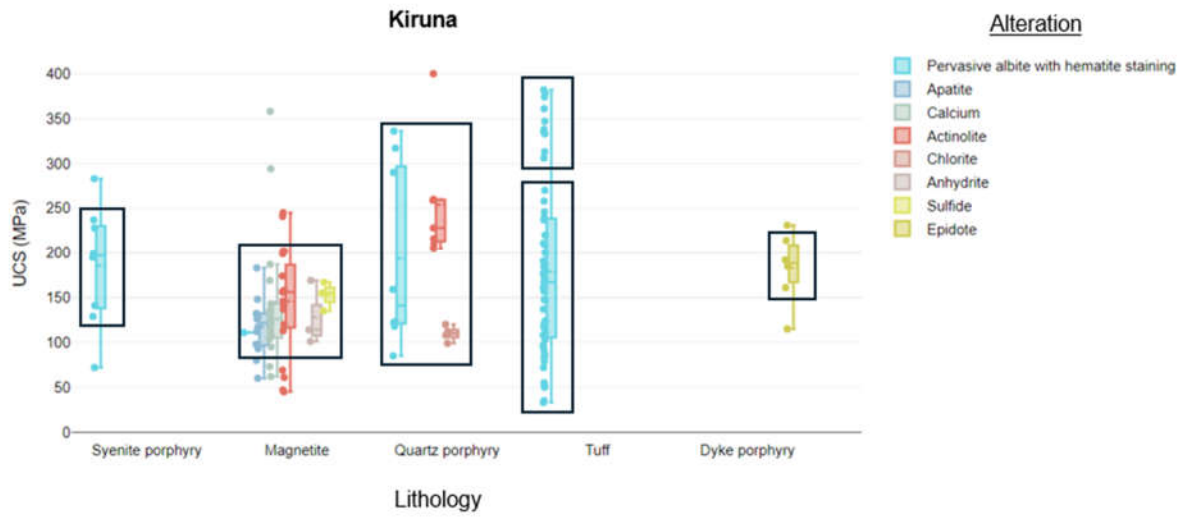

Figure 4 UCS visualization for Kiruna in comparison with Lithology and Alteration units.

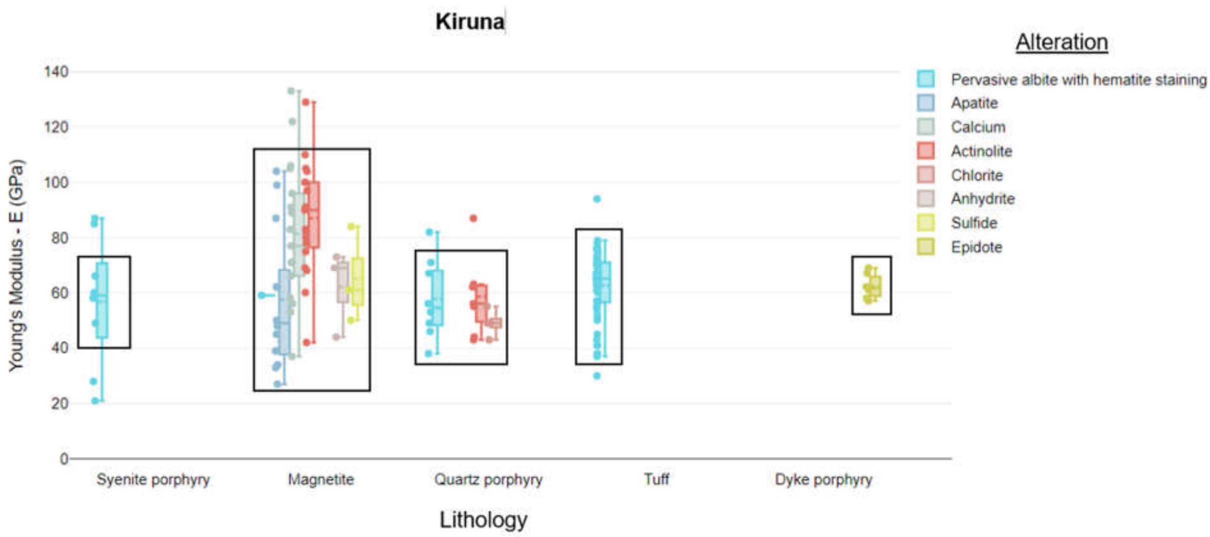

Figure 5 Young's Modulus visualization for Kiruna in comparison with Lithology and Alteration units.

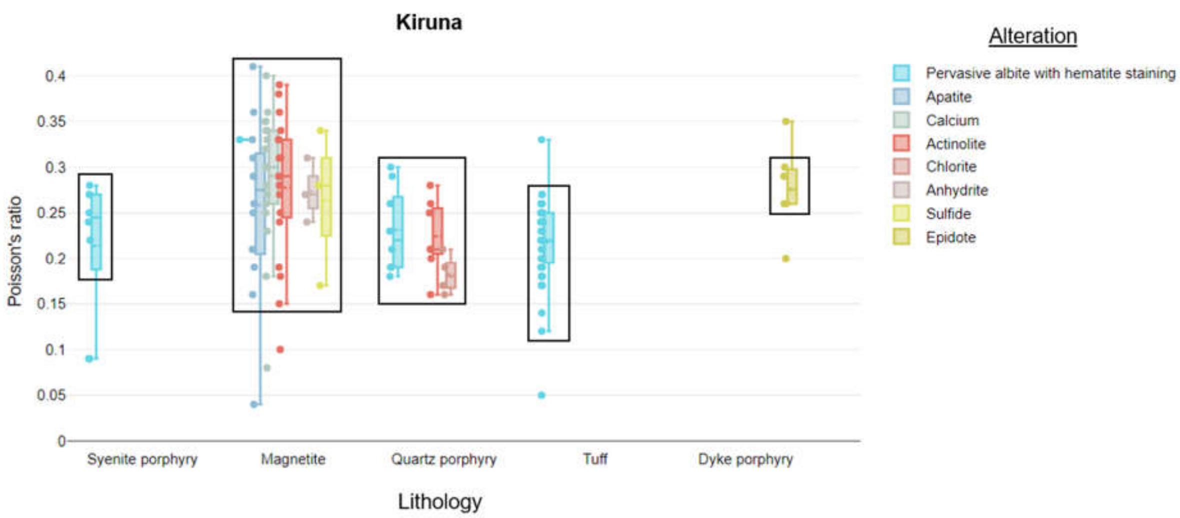

Figure 6 Poisson's ratio visualization for Kiruna in comparison with Lithology and Alteration units.

3.2 Malmberget rock mass

For the Malmberget mine, UCS values range between 70 and 300 MPa, with some extreme cases exceeding 300 MPa. Notably, rhyodacite, trachyandesite and granite exhibit higher UCS values, often surpassing 200 MPa, whereas biotite schist records the lowest values, typically under 90 MPa. Magnetite demonstrates UCS values ranging from 75 to 150 MPa, with the majority clustering around 100 MPa. Further sampling is required to establish reliable UCS data for pegmatite. As there is not an official scale for Young's modulus, the presented results could be categorized into four observed classes: 20-40 GPa, 40-80 GPa, 80-100 GPa, and above 120 GPa, with most test results falling between 40-80 GPa. Magnetite generally exhibits Young's modulus values above 80 GPa, regardless of skarn or apatite alteration, although some specific readings fall below 40 GPa, warranting further investigation. For biotite schist, Young's modulus is consistently below 60 GPa. Poisson's ratio generally ranges from 0.15 to 0.3, with a few samples, including magnetite, exceeding 0.3 or dropping below 0.15. Alteration minerals do not significantly impact UCS results as they do Young's modulus and Poisson's ratio. Biotite alteration notably reduces Young's modulus in trachyandesite and trachybasalt, whereas magnetite enrichment increases it, except in rhyodacite where it decreases. Additionally, biotite alteration raises the Poisson's ratio in trachyandesite, while magnetite enrichment lowers it. This lower Poisson's ratio indicates a higher propensity for deformation under stress, which must be accounted for in geotechnical analysis. Unaltered granite shows a higher Poisson's ratio, and magnetite exhibits two distinct groups, with most values around 0.2.

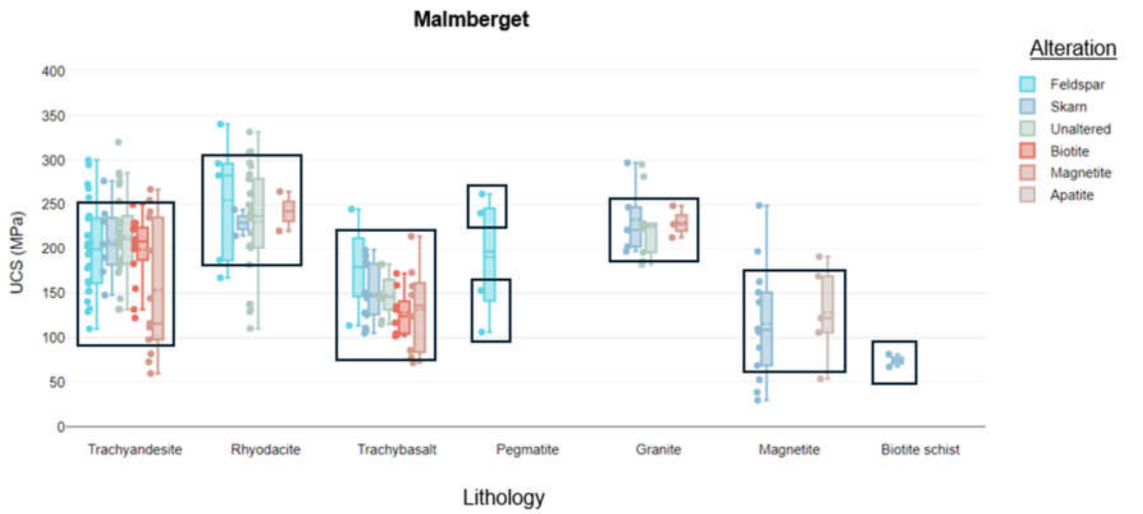

Figure 7 UCS visualization for Malmberget in comparison with Lithology and Alteration units.

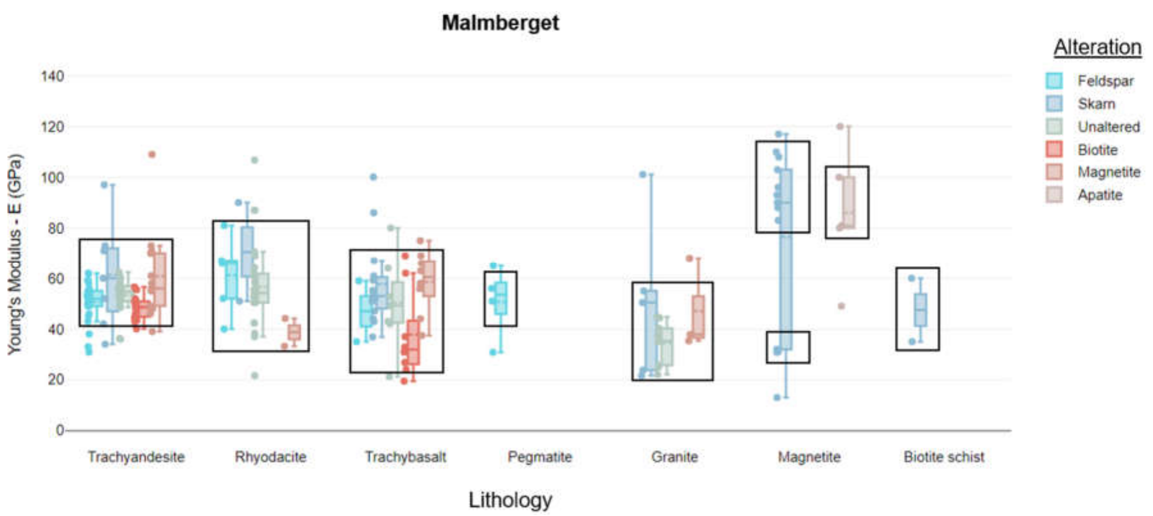

Figure 8 Young's Modulus visualization for Malmberget in comparison with Lithology and Alteration units.

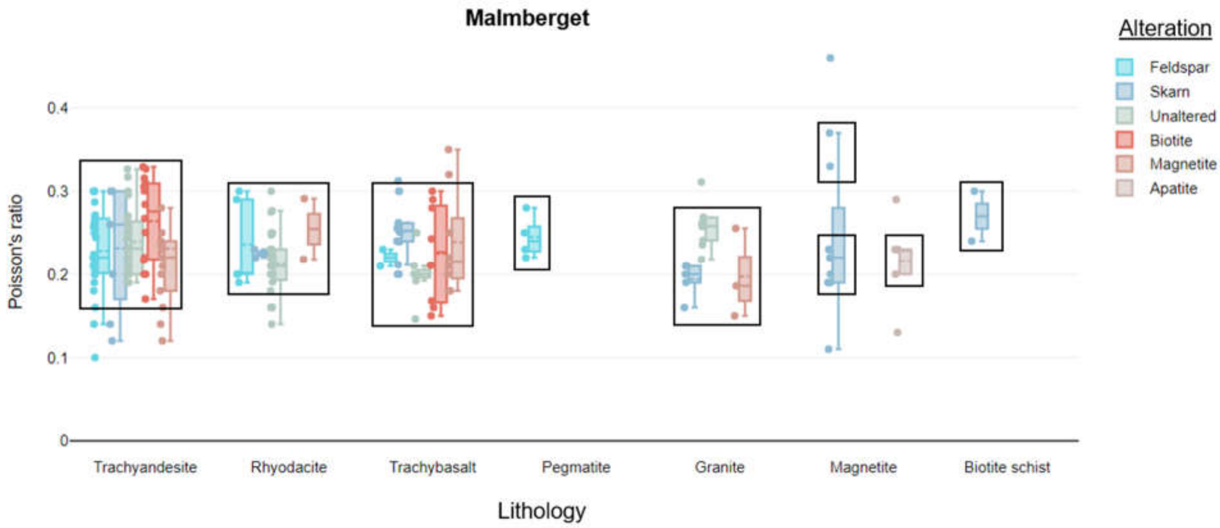

Figure 9 Poisson's ratio visualization for Malmberget in comparison with Lithology and Alteration units.

4 Conclusion

This study has provided a statistical analysis of the intact strength and elastic parameters of rock material in the Kiruna and Malmberget mines, offering a comprehensive understanding of their correlation with geological and alteration characteristics. The current study demonstrates that alteration minerals significantly impact the elastic parameters more than the intact strength, and this must be considered during geotechnical analysis. Through extensive geotechnical programs, including borehole logging and laboratory testing, we have established significant differences in the mechanical properties of the rock types in these regions.

Moreover, the study underscores the necessity of accurate and objective measurements of intact rock strength and elastic parameters for the realistic estimation of in situ geotechnical conditions. The findings highlight the limitations of relying solely on traditional rock mass classification systems that depend on subjective assessments. Instead, integrating objective test results, such as those from point load, UCS, and TCS tests, enhances the reliability of geotechnical models.

The results of this study have important implications for the design and safety of mining operations in Kiruna and Malmberget. The higher strength and stiffness of Kiruna rocks (especially magnetite) suggest that different strategy on support systems may be required compared to Malmberget, where lower strength and higher deformability necessitate more robust support measures. These findings highlight the need for region-specific geotechnical models that account for the unique properties of the rock material in each mine.

To enhance the reliability of the results and comparability of the mines, a greater number of samples must be collected from both sites, particularly in Kiruna, where the geospatial distribution of the data is currently limited. Overall, this study enhances the geotechnical knowledge base for Kiruna and Malmberget, providing valuable data for improving mine design, safety, and efficiency in these significant mining regions.

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