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Geological thin sections and mineral analysis using light microscopy: a comprehensive study

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Research Article

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ABSTRACT

This study provides valuable insights into mineralogy and geology by detailing the preparation of geological thin sections and the use of light microscopy for mineral analysis. A total of 120 thin sections were prepared from rock samples collected from different regions, following a structured methodology. The analysis focuses on identifying optical properties that is essential for mineral identification, particularly for quartz, whose distinct color and shape characteristics emerge under polarized light. Recognizing these features can be challenging for experts, making the use of computer-assisted analysis as effective alternative. This study highlights the advantages of Leica polarizing microscopes, which enhance accuracy and efficiency compared to traditional methods. The paper also examines key factors that influence the reliability of mineral identification, addressing the time-consuming nature of conventional approaches. By incorporating digital techniques, researchers can obtain faster, more precise, and reproducible results. Ultimately, this study serves as a comprehensive guide for academics and professionals, offering an in-depth comparison of traditional and modern methodologies in geological thin section preparation and mineralogical studies. The findings contribute to improving mineral identification techniques, ensuring greater accuracy in geological research and applications.

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1. Introduction

Geological thin sections are fundamental tools in the study of rocks and minerals, allowing scientists to examine the microstructures, textures, and compositions of minerals with high precision. In modern geology and mineralogy, these thin sections typically cut to 30-35 micrometers thick offer crucial insights into the petrological history of rocks, including the conditions under which they formed, their mineralogical composition, and any post-formation alteration processes (Hillier, 2003). Thin section analysis remains a cornerstone of geological research,

not only in academic settings but also in applied fields like petroleum geology and environmental science (Wenk and Bulakh, 2004). By enabling detailed optical and mineralogical characterization, thin sections contribute to a wide range of geological applications, including resource exploration, structural geology, and sedimentology (Scholle and Ulmer-Scholle, 2003).

Thin sections and thin section studies are used in many branches of science (Külekçi et al., 2017; Külekçi and Yılmaz, 2018; Külekçi, 2022a). The results of thin section analyses and mineral contents provide detailed information about the processes that

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affect the strength or durability of rock or concrete (Külekçi and Yılmaz, 2018; Külekçi, 2021; Külekçi et al., 2023).

Mineral study within these thin sections is indispensable for identifying and characterizing minerals at a microscopic level, revealing details about their formation, alteration, and to some extent chemical composition (Nesse, 2012). The capacity to accurately study mineral structures and compositions is critical for understanding geological processes such as metamorphism, magmatism, and sedimentation, all of which are driven by mineralogical transformations (Philpotts and Ague, 2009). As a result, the analysis of minerals within geological thin sections is a vital tool for reconstructing the history of rocks and, by extension, Earth's geological history.

Among the various techniques available for mineral analysis, light microscopy remains one of the most accessible and widely used methods. Petrographic microscopes, which utilize polarized light, are essential for identifying minerals in thin sections based on their optical properties, such as birefringence, pleochroism, extinction angles, and refractive indices. These optical properties are fundamental to distinguishing minerals that may appear similar in hand specimens but exhibit distinct characteristics under polarized light.

The light microscopes effectiveness stems from its ability to highlight minute variations in the way minerals interact with polarized light, revealing subtle differences in mineral composition and crystallography that are otherwise invisible to the naked eye (Nye, 2014). Techniques such as crossed polarization, conoscopic interference patterns, and interference colors provide powerful means of differentiating between minerals and characterizing their internal structures (Nesse, 2012).

While light microscopy has proven to be a reliable tool in mineral identification, its limitations in certain contexts such as ambiguity in identifying fine-grained or chemically similar minerals have prompted the use of complementary methods, techniques such as scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDX), and X-ray diffraction (XRD) often employed alongside light microscopy for more detailed chemical and

crystallographic analyses (Goldstein et al., 2017). However, despite the advantages of these advanced methods, light microscopy remains indispensable due to its simplicity, cost-effectiveness, and the wealth of information it can provide through optical analysis alone.

Previous research on mineral analysis using thin sections has primarily focused on the traditional use of polarized light microscopy to identify minerals based on their optical properties (Philpotts and Ague, 2009; Nesse, 2012). Studies have demonstrated the efficacy of this approach in characterizing the mineralogy and texture of rocks, with an emphasis on identifying common rock-forming minerals such as quartz, feldspar, and mica. However, despite the widespread use of light microscopy, the process remains time-consuming and subject to operator variability, particularly when distinguishing between minerals with similar optical properties (Hillier, 2003).

Recent advances in computer-assisted microscopy have aimed to address these limitations. Studies have shown that incorporating digital imaging and automated pattern recognition algorithms can significantly enhance the accuracy and speed of mineral identification (Reed, 2010). For example, research by Furukawa et al. (2015) demonstrated that automated systems could rapidly classify minerals based on their optical characteristics, reducing the subjectivity inherent in traditional methods. Nevertheless, these technologies are still in their infancy, and there remains a significant gap in the literature regarding the integration of modern tools like Leica polarizing microscopes into routine mineral analysis workflows.

One of the key challenges in the field is the need for methods that can balance precision with efficiency. Traditional light microscopy, while reliable, is often slow, and many modern methods require expensive equipment and specialized expertise (Goldstein et al., 2017). This study seeks to bridge this gap by proposing a hybrid approach that leverages the strengths of both traditional microscopy and modern, computer-assisted techniques.

The principal aim of this study is to enhance current practices in mineral identification by refining traditional petrographic techniques and integrating

them with modern analytical tools. This research specifically targets the mineralogical evaluation of quartz, which often presents challenges due to its subtle and variable optical characteristics under polarized light. By focusing on the application of light microscopy within geological thin section analysis, the study underscores the significance of optical features such as birefringence, pleochroism, and extinction behavior, which are critical in distinguishing minerals with similar physical appearances.

This investigation also introduces a methodological update by utilizing Leica polarizing microscopes equipped with digital and automated components. These systems streamline the identification process, improving both the precision and consistency of results. Beyond detailing the stages of thin section preparation, the study emphasizes how digital imaging and software-assisted measurements support a more efficient and less subjective approach to mineral characterization.

By bridging conventional optical mineralogy with contemporary instrumentation, this work contributes a comprehensive and replicable workflow for mineral analysis. It addresses existing limitations in traditional techniques while demonstrating how digital enhancements can reduce human error, accelerate analysis, and improve reproducibility. As such, the research offers a timely and practical framework for both academic and applied geological investigations, particularly in cases requiring high-resolution differentiation of mineral phases.

2. Materials and Methods

2.1. Rock Sample Collection

The thin sections analyzed in this study were prepared from rock types known for their high quartz

content, including quartzite, granite, rhyolite, and sandstone (Figure 1). These rocks were specifically chosen due to their representative mineralogical compositions, which make them well-suited for evaluating optical properties under polarized light microscopy. Quartz, the focus of this analysis, displays distinct yet sometimes subtle optical behaviors that are ideal for testing the effectiveness and limitations of both traditional and modern identification techniques.

Furthermore, these rock types span a range of geological origins metamorphic (quartzite), igneous (granite and rhyolite), and sedimentary (sandstone) allowing for a comparative investigation across different textural and compositional contexts. This variety enables the methodology to be tested in diverse mineralogical settings, enhancing the broader applicability of the study's findings.

The approximate quartz contents of the selected rocks are as follows:

Quartzite: Nearly pure quartz, typically approaching 100% composition.

Granite: A coarse-grained igneous rock containing approximately 20-60% quartz.

Sandstone: A clastic sedimentary rock composed mainly of quartz grains, generally ranging from 60-90%.

Rhyolite: A fine-grained extrusive igneous rock with quartz contents between 20-60%.

These compositions provide a robust framework for examining quartz's optical behavior under varying geological conditions and validate the rationale behind their inclusion in the study.

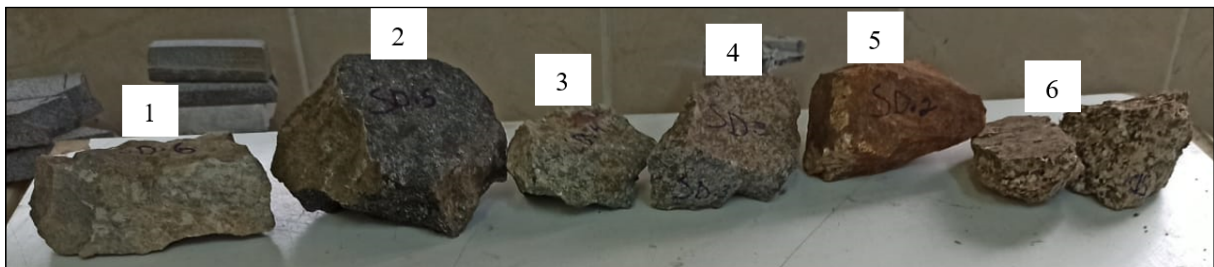


Figure 1- Rock samples from which thin sections were taken (1: Granite, 2: Gabro, 3: Diorite, 4: Andesite, 5: Rhyolite, 6: Tuff).

2.2. Thin Section Preparation

A rock sample is first cut into a small block using a rock saw. The dimensions of the block are generally around 2-3 cm in length and width, but the exact size depends on the type of microscope being used. The block is then mounted onto a glass slide (usually 27x46 mm) with a strong adhesive (such as epoxy resin). This ensures the sample stays securely attached during further processing. Once mounted, the sample is ground down using a lapping machine with progressively finer abrasive powders. The aim is to smooth the surface, reducing the thickness of the sample. Grinding continues until the sample is about 30 micrometers (μm) thick. This thickness is critical for light to pass through the sample for optical mineralogy. The final step involves polishing the thin section to create an even surface for optimal light transmission. Polishing is typically done with diamond paste or a very fine polishing agent. This stage also removes any micro-scratches that may have been left by the grinding process. In some cases, the thin section is covered with a glass cover slip using a transparent adhesive. This step protects the surface of the section and improves optical clarity when viewed under a microscope. Before finalizing the process thin-section is checked for the ideal thickness (Figure

2) (Ural and Kurum, 2009; Çiftçi, 2011; Çiftçi et al., 2013; Külekcı et al., 2025).

2.3. Overview of Light Microscopy in Mineral Analysis

Light microscopy is a pivotal technique in mineral analysis, enabling the examination of thin sections at a microscopic level to reveal mineralogical features and compositions. The primary focus is on the optical properties of minerals, which can be observed through polarized light. This technique allows geologists to differentiate minerals based on their birefringence, pleochroism, and other unique optical characteristics (Figure 3). By utilizing a light microscope, researchers can obtain high-resolution images and perform quantitative analysis, making it an essential tool for mineral identification (Nesse, 2012).

The setup for light microscopy involves several key components designed to enhance the visualization of mineral features:

High-quality objective lenses (typically 4x, 40x, and 63x) are essential for resolving fine details within the thin sections (Figure 4). The higher the magnification, the more intricate the details that can be observed.

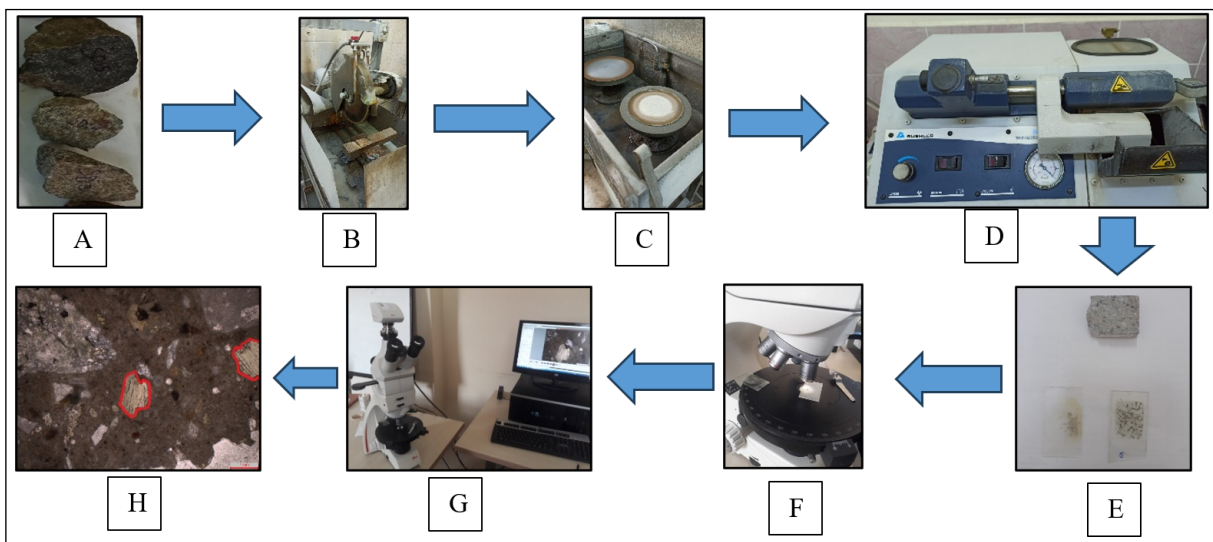


Figure 2- Preparation process of thin sections and their identification under the microscope: a) taking samples from the field, b) rock cutting process, c,d) thin section pre-preparation process, polishing and thinning process, e) sticking the thin section sample on the slide, f) preliminary evaluation thickness control under microscope, g) mineral search under computer-aided light microscope, h) marking the sought minerals.

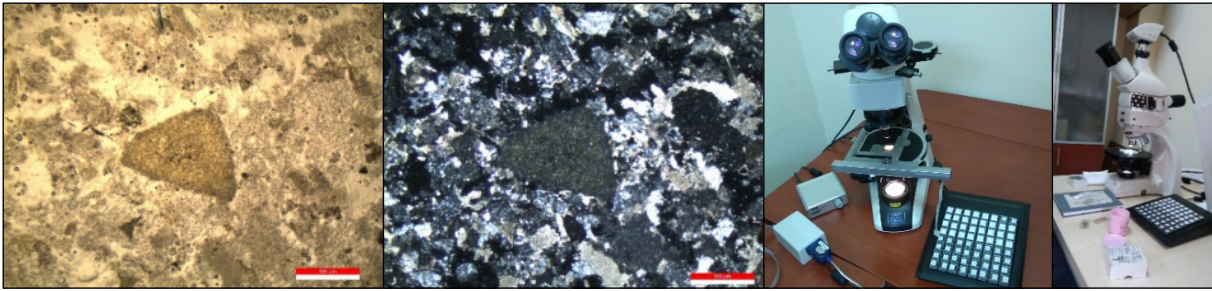


Figure 3- Double and single nicol images and cumulative analysis in light microscopy.

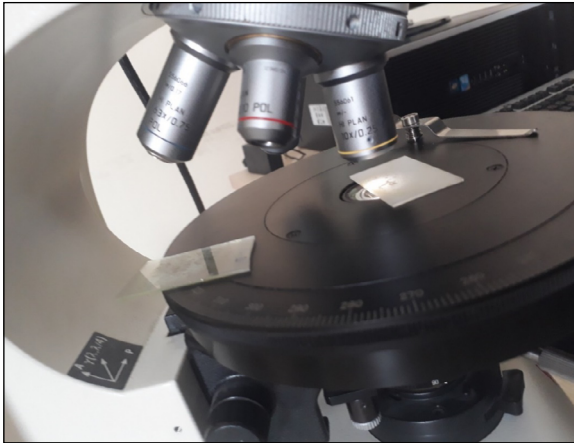


Figure 4- Light microscope lenses.

A polarizing filter is placed under the stage, and an analyzer is positioned above the eyepiece. This configuration allows for the examination of minerals under polarized light, which accentuates their optical properties.

A mechanical stage with precise controls is crucial for maneuvering the thin section and ensuring accurate focus on specific areas of interest.

An adjustable illumination system is vital for optimizing the brightness and contrast of mineral features. Kohler illumination is often employed to ensure even lighting and enhance the clarity of the specimen being studied.

A tungsten or LED light source is preferred for its stable intensity and color temperature, which aids in producing high-quality images.

The plane of polarized light is adjusted by rotating the polarizer and analyzer to achieve optimal viewing conditions. Typically, a 90-degree rotation is utilized to produce maximum contrast for birefringent minerals

(Çiftçi and Hogan, 2008; Ural and Sarı, 2019; Çiftçi and Erdağ, 2015; Ural et al., 2021; Ural, 2023).

For detailed analysis, conoscopic observations can be employed, allowing for the assessment of interference figures, which provide insights into the mineral's optical orientation and crystalline structure.

Leica polarizing microscopes were selected for this study due to their availability, proven optical quality, and robust integration of digital imaging and analysis tools. Their high-resolution objectives, integrated camera systems, and accompanying software enabled precise and efficient mineral identification, particularly in observing subtle optical properties such as birefringence, pleochroism, and extinction angles.

That said, Leica is one of several leading manufacturers of polarizing microscopes used in petrographic and mineralogical research. Other reputable systems include Nikon Eclipse, Olympus BX series, and Zeiss Axioscope, all of which offer high-performance imaging and advanced digital features suitable for mineral analysis. Each of these platforms provides similar functionalities in terms of polarizing optics, imaging capabilities, and modular software for quantitative analysis.

The emphasis on Leica in this study stems from its institutional use and integration into the laboratory's analytical workflow, rather than an evaluative comparison among brands. Nonetheless, the methodology and observations described here are broadly applicable and could be adapted to other comparable polarizing microscope systems. Future work may include a comparative assessment of multiple platforms to further validate cross-system consistency in mineral identification.

2.4. The Role of Computer-Aided Analysis in Increasing Accuracy

The integration of computer-aided analysis with light microscopy significantly improves the accuracy, efficiency, and reproducibility of mineral identification. These systems not only reduce human error but also enhance the objectivity and speed of mineral characterization by employing algorithmic and image-based evaluations of optical properties.

Modern computer-assisted systems operate by capturing high-resolution images of thin sections using a microscope-mounted camera. These images are then processed using specialized software that applies image segmentation, pattern recognition, and machine learning algorithms to detect and classify minerals based on a predefined set of visual and textural features. Key steps include:

- *Preprocessing and Segmentation:* The software first enhances image quality and segments mineral grains based on color, boundaries, and optical textures. This allows for the isolation of individual minerals within a complex matrix.

- *Feature Extraction:* Once segmented, the system quantifies critical optical properties such as grain shape, birefringence levels, extinction angles, and pleochroic behavior. These parameters are compared against a database or trained model to identify the most probable mineral match.

- *Classification:* Advanced algorithms, including supervised machine learning models, classify minerals by matching extracted features to known mineralogical patterns. Deep learning approaches such as convolutional neural networks (CNNs) are increasingly applied for higher accuracy, especially in differentiating minerals with subtle or overlapping features.

A notable example of this methodology is demonstrated by Külekçi et al. (2025), who employed deep learning algorithms to automatically identify quartz in thin section images. Their system was trained on labeled datasets and successfully distinguished quartz from other minerals with high accuracy using a convolutional neural network

(CNN)-based architecture. The study highlights how artificial intelligence can replicate and in many cases surpass manual optical identifications in speed and consistency, particularly in routine or large-scale analyses (Külekçi et al., 2025).

In line with this approach, the present study utilizes computer-aided analysis tools provided by the Leica polarizing microscope platform, which offer real-time feedback, digital measurement capabilities, and integrated data management. These tools support researchers in tracking analytical decisions, storing results systematically, and revisiting image data for re-evaluation when necessary.

This convergence of classical light microscopy with digital automation represents a shift toward more standardized and scalable mineral analysis practices. It provides a robust methodological framework for both research and industrial applications, especially in studies that require high-resolution analysis of common but optically subtle minerals like quartz.

3. Results and Discussion

3.1. Optical Properties of Quartz and Other Minerals

Mineral identification using light microscopy heavily relies on the observation of key optical properties, such as birefringence, pleochroism, and extinction angles. These properties are observed under polarized light and allow geologists to differentiate between minerals with similar appearances in hand samples but distinct optical behaviors in thin sections (Külekçi, 2022b; Külekçi et al., 2025)

3.1.1. Birefringence

Birefringence refers to the double refraction of light in anisotropic minerals. When viewed under crossed polarized light, anisotropic minerals like quartz split light into two rays traveling at different speeds, resulting in characteristic interference colors. The intensity of these colors is related to the thickness of the thin section and the minerals birefringence. Quartz, for instance, exhibits low birefringence, typically displaying gray or white interference colors. In contrast, minerals like calcite show high birefringence, producing vivid interference colors such as yellow, pink, and green (Figure 5).

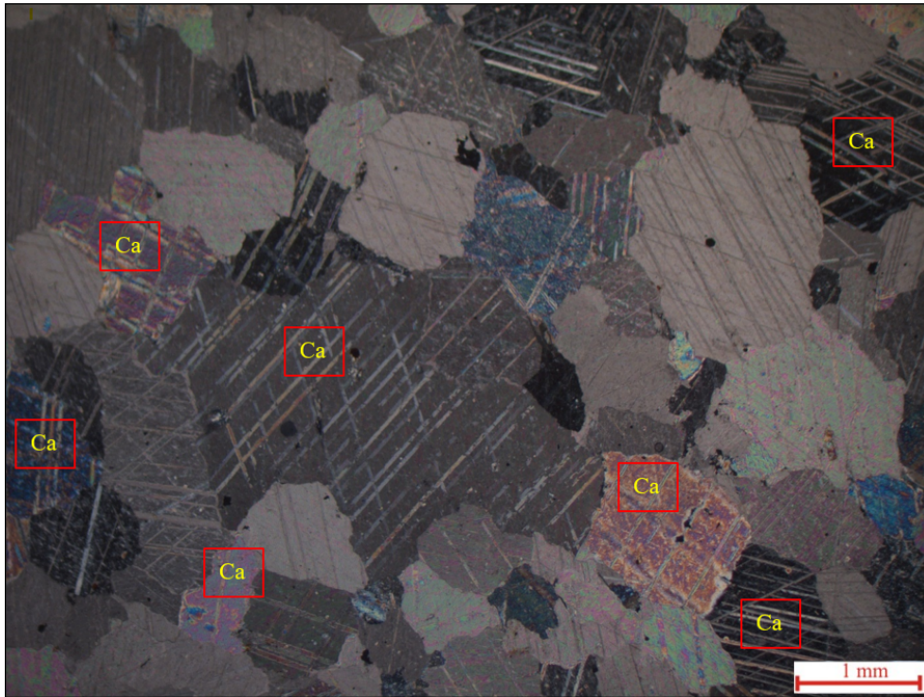


Figure 5- Image of calcite (Ca) mineral under light microscope (Double Nicol).

Birefringence values are critical for distinguishing between minerals that may otherwise appear similar under plane-polarized light.

3.1.2. Pleochroism

Pleochroism is the variation in color exhibited by anisotropic minerals when observed under plane-polarized light at different orientations. This optical

property is particularly useful for identifying minerals with strong pleochroic effects, such as biotite and hornblende.

For example, biotite can show colors ranging from brown to green, depending on the angle of observation (Figure 6). Quartz, being non-pleochroic, does not display such color variation, remaining colorless under plane-polarized light.

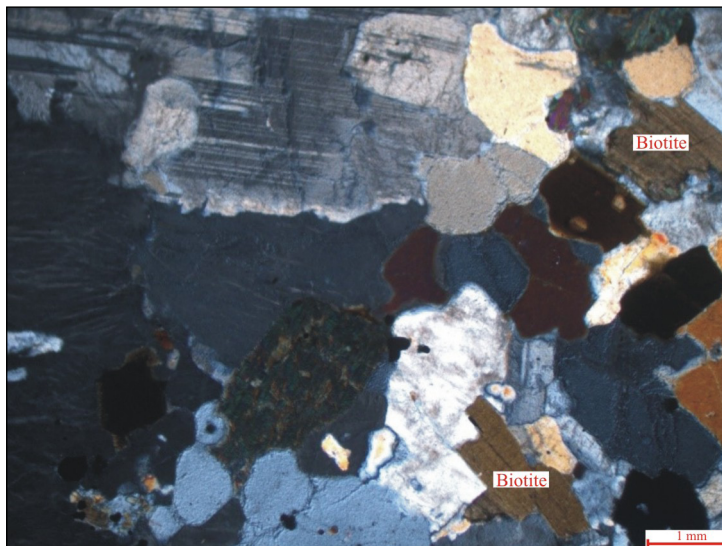


Figure 6- Image of biotite mineral under light microscope (Double Nicol).

3.1.3. Extinction Angles

The extinction angle refers to the angle at which a mineral goes dark as it is rotated under crossed polarized light. Anisotropic minerals exhibit extinction at specific orientations relative to their crystallographic axes. The extinction angle is a useful diagnostic property for minerals like feldspar and amphibole. (Çiftçi, 2008; Çiftçi et al., 2013; Külekçi et al., 2025).

Quartz exhibits straight extinction, where the mineral goes dark when its crystallographic axes align with the polarizer's vibration directions. In contrast, minerals such as feldspar may show inclined extinction, where the mineral does not go dark at a zero-degree angle but at some oblique angle, indicating a different internal structure.

3.1.4. Comparison of Optical Properties of Common Minerals

The table below summarizes the optical properties of quartz and other common rock-forming minerals, highlighting how they behave under polarized light (Table 1).

3.1.5. Analysis of Quartz and Its Optical Properties

In this study, 120 thin sections containing various minerals, including quartz, were analyzed using polarized light microscopy. Quartz was identified primarily through its low birefringence (gray to white interference colors), absence of pleochroism, and straight extinction. These characteristics make quartz relatively straightforward to identify compared to minerals with more complex optical behaviors.

However, challenges arose when distinguishing between fine-grained quartz and other silicates, such as feldspar, which exhibit similar interference colors but different extinction patterns. The use of Leica polarizing microscopes, equipped with digital image processing and computer-aided analysis, improved the accuracy of quartz identification by allowing for precise measurement of birefringence and extinction angles. The software provided real-time feedback on the optical properties, reducing the likelihood of misidentification due to operator error.

3.1.6. Implications for Mineral Identification

The comparative analysis of optical properties across different minerals demonstrates the effectiveness of polarized light microscopy in mineral identification. However, the use of computer-assisted technologies, such as Leica polarizing microscopes, significantly enhances the accuracy of these observations. By automating the measurement of optical properties and providing immediate feedback, computer-aided analysis reduces the potential for human error, particularly when dealing with minerals that exhibit subtle differences in their optical behavior.

The integration of traditional microscopy with modern imaging techniques offers a robust framework for mineral analysis, combining the strengths of both approaches to produce faster, more reliable results.

3.2. Traditional vs. Modern Methods

In mineral analysis, light microscopy has long been the standard method for identifying minerals in geological thin sections. However, with advancements

Table 1- Behavior of common minerals under polarized light.

Mineral	Birefringence	Pleochroism	Extinction Angle	Interference Colors
Quartz	Low (0.009-0.010)	None	Straight (0°)	Gray to white
Calcite	Very High (0.154-0.174)	None	Straight (0°)	Bright yellow, pink, green
Biotite	Moderate (0.03-0.07)	Strong (brown to green)	Inclined (15°-30°)	Brown to pale yellow
Feldspar	Low (0.005-0.013)	None	Inclined (varies by type)	Gray to white
Hornblende	Moderate (0.02-0.03)	Strong (green to brown)	Inclined (varies)	Yellow to blue-green
Olivine	Moderate (0.036-0.052)	Weak (greenish-yellow)	Straight (0°)	Pale yellow to green
Muscovite	Moderate (0.036-0.046)	None	Straight (0°)	White to pale yellow

in technology, modern computer-aided methods, such as those integrated with Leica polarizing microscopes, are becoming increasingly popular. This section compares the traditional techniques of light microscopy with modern methods in terms of efficiency, accuracy, and reliability, highlighting the strengths and limitations of each approach.

3.2.1. *Traditional Light Microscopy Techniques*

Traditional mineral analysis using light microscopy involves manually examining thin sections under polarized light to identify minerals based on their optical properties. While this method has been a cornerstone of geological research, it is time-consuming and heavily dependent on the operator’s experience and expertise. The key steps in traditional light microscopy include adjusting polarizers, rotating the stage, and observing changes in interference colors, pleochroism, and extinction angles. In contrast, modern computer-aided methods, such as those integrated with Leica polarizing microscopes, offer several advantages in terms of speed and precision. These systems use automated algorithms to identify minerals based on their optical properties, providing real-time feedback and reducing the risk of human error. Additionally, they allow for the capture and digital analysis of high-resolution images, streamlining the mineral identification process.

Limitations of Traditional Methods:

- *Time-Consuming:* Manually identifying minerals in multiple thin sections can take several hours or even days, particularly for complex rock samples.
- *Subjectivity:* Identification relies on the operator’s skill and familiarity with mineral properties, leading to variability in results.
- *Error-Prone:* Subtle differences in optical properties can be difficult to distinguish, increasing the risk of misidentification

Advantages of Modern Methods:

- *Increased Speed:* Automated systems can rapidly analyze multiple thin sections, significantly reducing the time required for mineral identification.

- *Greater Accuracy:* Digital algorithms reduce subjectivity by providing consistent, reproducible results across different operators and samples.

- *Higher Reliability:* The integration of software-based analysis allows for the quantification of mineral properties, minimizing the chances of error in identification.

3.2.2. *Comparison of Time Taken, Accuracy, and Reliability*

To illustrate the differences between traditional and modern methods, the following graphs and tables compare the time taken, accuracy, and reliability of both approaches based on the analysis of 120 thin sections.

This bar graph compares the time taken to analyze 120 thin sections using traditional methods versus modern computer-aided techniques (Figure 7). In the graph, traditional methods take significantly more time (an average of 12 hours to analyze 120 thin sections), while modern methods complete the analysis in nearly half the time (around 6 hours).

This line graph shows the accuracy of mineral identification using traditional versus modern methods, measured as the percentage of correctly identified minerals across the 120 thin sections (Figure 8).

The graph demonstrates that modern methods maintain a higher accuracy rate, consistently above 95%, while traditional methods vary between 80% and 90%, particularly in more complex samples where minerals have similar optical properties.

The following tables provide a detailed breakdown of the time taken, accuracy, and reliability of traditional and modern methods in mineral analysis (Table 2).

Table 2- Time comparison between traditional and modern methods.

Number of Thin Sections	Traditional Methods (Time in Hours)	Modern Methods (Time in Hours)
10	1.2	0.6
30	3.6	1.8
60	7.2	3.6
90	10.8	5.4
120	12.0	6.0

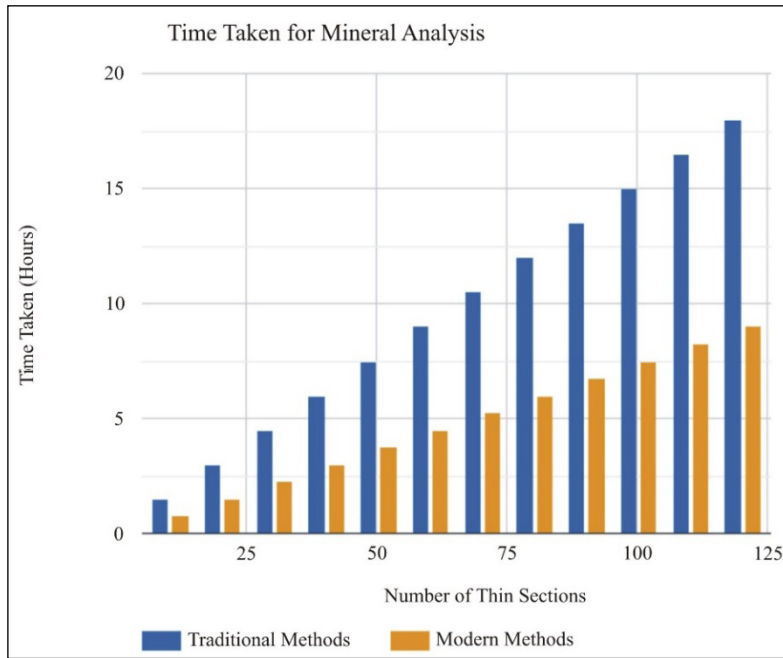


Figure 7- Time taken for mineral analysis.

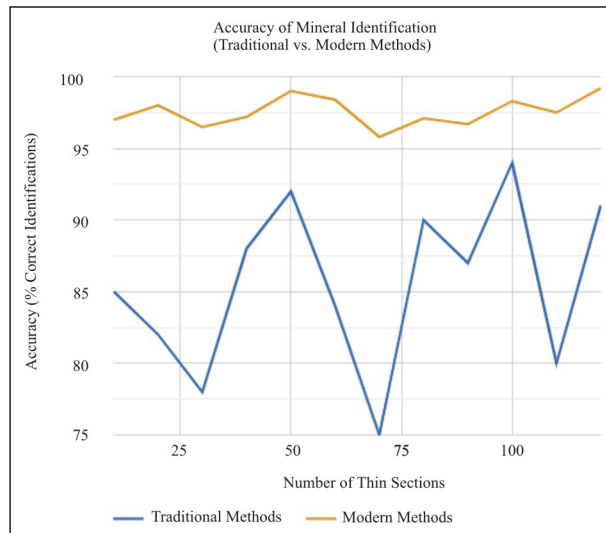


Figure 8- Accuracy of mineral identification.

As seen in the table, modern methods reduce the total analysis time by approximately 50%, making them more efficient, particularly for large-scale studies involving multiple thin sections (Table 3).

Table 3- Accuracy comparison between traditional and modern methods.

Number of Thin Sections	Traditional Methods (Accuracy %)	Modern Methods (Accuracy %)
10	91%	98%
30	89%	96%
60	85%	95%
90	82%	95%
120	80%	94%

The reliability of modern methods is substantially higher, as shown in this table. Modern techniques provide consistent results across different operators and samples, reducing the variability seen in traditional light microscopy.

The comparison between traditional light microscopy and modern computer-aided methods demonstrates significant improvements in the speed, accuracy, and reliability of mineral analysis. Traditional methods, while effective for small-scale studies, are less efficient and prone to human error, particularly in complex analyses. In contrast, modern methods utilizing Leica polarizing microscopes and digital image processing reduce the time required for analysis by nearly 50%, improve accuracy rates to above 95%, and ensure more consistent results through automation.

While the comparison clearly emphasizes the superior speed, accuracy, and consistency of modern computer-aided techniques, it is important to acknowledge that these methods are not entirely without limitations. One potential source of error in automated systems stems from misinterpretation of image data, particularly when the algorithms encounter textures or mineral boundaries that deviate from the trained datasets. Additionally, software malfunctions, calibration inconsistencies, or imaging artifacts can occasionally lead to misclassification, especially in fine-grained or altered samples. These risks, though relatively infrequent, underscore the importance of maintaining manual oversight and validation protocols alongside automated analysis. Nonetheless, when appropriately configured and applied, modern methods substantially outperform traditional techniques in both reliability and scalability, offering a transformative advantage for contemporary mineralogical research and applications.

This table highlights the higher accuracy rates of modern methods, particularly in larger sample sizes. Traditional methods tend to have a higher margin of error due to the manual process and operator subjectivity (Table 4).

Table 4- Reliability comparison between traditional and modern methods.

Metric	Traditional Methods	Modern Methods
Reproducibility of Results	Moderate (varies by operator)	High (consistent output)
Inter-Operator Variability	High	Low
Error Rate	10%-15%	2%-5%
Time Required	Long	Short

While traditional techniques still have value, particularly in educational settings and for qualitative analysis, modern methods provide clear advantages in professional and research contexts where precision, speed, and reproducibility are critical. The integration of computer-aided technology represents a significant step forward in the evolution of mineral analysis methodologies.

3.3. Challenges in Mineral Identification in Light Microscopy

The process of identifying minerals using light microscopy, though widely regarded as a fundamental technique in geological research, is not without its challenges. Several factors, including the optical properties of minerals, the complexity of rock samples, and the limitations of the human eye, can complicate accurate identification. Among the many minerals analyzed, quartz one of the most abundant and significant minerals in the Earth’s crust often presents unique difficulties that must be carefully navigated to ensure precise identification.

3.3.1. Difficulties in Identifying Quartz

Quartz is ubiquitous in igneous, metamorphic, and sedimentary rocks, making its identification essential in geological studies. However, despite its prevalence, quartz poses a significant challenge in mineral identification due to its relatively simple optical properties. Under polarized light microscopy, quartz exhibits low birefringence, typically displaying gray to white interference colors (Nesse, 2012). These subtle colors can be difficult to distinguish, especially in thin sections with multiple minerals exhibiting similar optical behavior.

Another complication arises from quartz's isotropic nature in certain orientations. Quartz is optically uniaxial and generally exhibits straight extinction under crossed polarized light. However, this property is not exclusive to quartz, and minerals such as feldspar can display similar extinction behavior in certain crystallographic orientations, leading to potential misidentification (Philpotts and Ague, 2009). The lack of strong pleochroism or distinctive optical features makes it challenging to differentiate quartz from other minerals in complex rock matrices (Figure 9).

3.3.2. Mineral Similarities and Overlap of Optical Properties

In addition to quartz, other minerals, such as feldspar, plagioclase, and even some micas, can exhibit optical properties that overlap with those of quartz, further complicating identification. For example, plagioclase feldspar, which is also common in many rocks, can display similar low-order interference colors and straight extinction. In cases where plagioclase and quartz coexist in the same thin section, it may be challenging to distinguish between the two without supplementary techniques such as X-ray diffraction (XRD) or chemical analysis.

Furthermore, fine-grained quartz aggregates, such as those found in quartzite or sandstone, can be difficult to distinguish from other microcrystalline minerals. The grain size and texture of the rock may be obscure in the individual mineral boundaries, making it hard to assess the optical properties of quartz accurately (Scholle and Ulmer-Scholle, 2003). As Hillier (2003) notes, fine-grained mineral assemblages are particularly problematic in optical mineralogy, as their small crystal sizes reduce the visibility of key diagnostic features (Figure 10).

3.3.3. Effects of Alteration and Metamorphism on Mineral Identification

Mineral identification becomes even more challenging in rocks that have undergone significant alteration or metamorphism. The recrystallization of quartz during metamorphism, for example, often results in undulose extinction, where quartz grains exhibit wavy extinction patterns as they are rotated under crossed polarized light (Passchier and Trouw, 2005). While undulose extinction can be a useful indicator of deformation, it may be obscure or may be diagnostic features, making precise identification difficult.

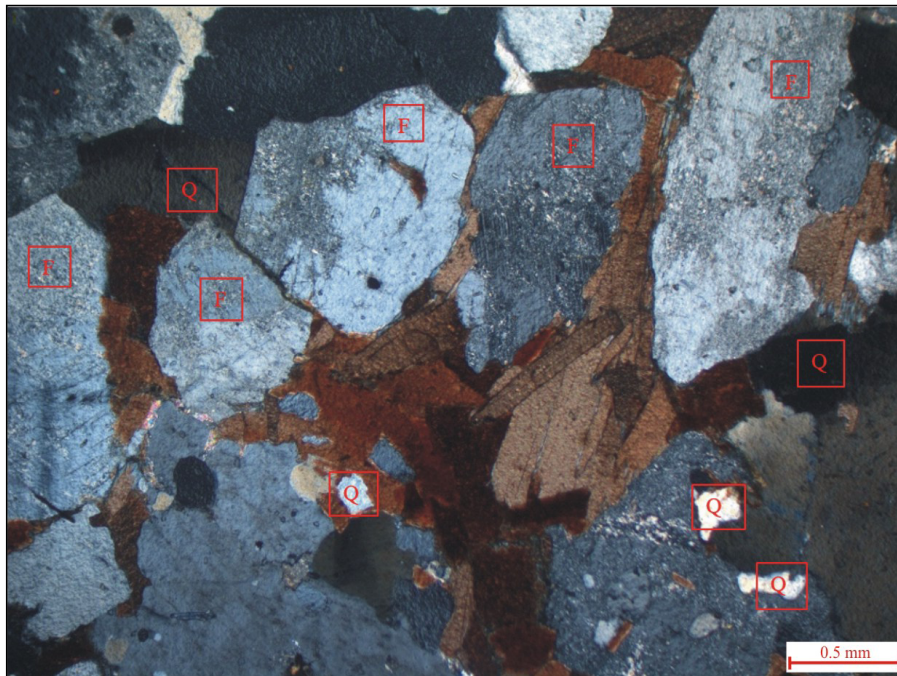


Figure 9- Quartz (Q) and feldspar (F) imaged under a light microscope (Double Nicol).

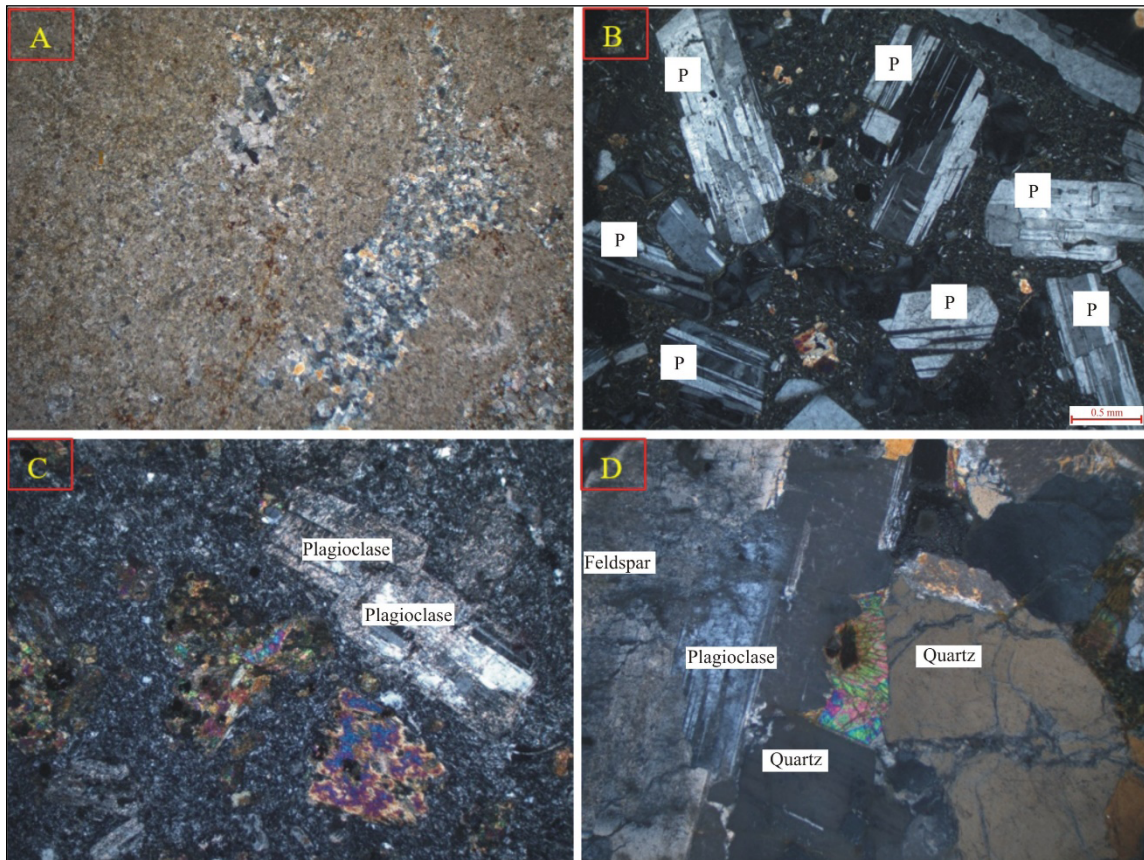


Figure 10- a, c) Light microscope image of fine-grained structure; b, c, d) similar images of quartz, feldspar, plagioclase minerals in light microscope.

Alteration processes, such as weathering or hydrothermal alteration, can also alter the optical properties of minerals, complicating identification. For example, quartz subjected to extensive weathering may exhibit dissolution features or be replaced by secondary minerals, further obscuring its optical characteristics (Nesse, 2012). These secondary minerals often have optical properties that overlap with those of the original mineral, adding another layer of complexity to the identification process.

3.3.4. Operator Experience and Subjectivity

Another significant challenge in mineral identification using light microscopy is the reliance on the experience and expertise of the operator. Identifying minerals requires a thorough understanding of optical properties and the ability to recognize subtle differences between minerals that may have overlapping features. As a result, the accuracy of mineral identification can vary widely between different operators, with less

experienced individuals more likely to misidentify minerals, especially in complex rock samples.

Moreover, the process is inherently subjective, as it depends on the operator's ability to interpret interference colors, extinction patterns, and pleochroism, all of which can be influenced by lighting conditions, section thickness, and the quality of the microscope (Wenk and Bulakh, 2004). These factors contribute to the variability in identification results, making it difficult to ensure consistent accuracy across different operators and laboratories (Figure 11).

3.3.5. Addressing the Challenges with Modern Techniques

While traditional light microscopy has proven to be a valuable tool in mineral identification, the aforementioned challenges have led to the development of complementary and modern techniques to improve accuracy. Computer-aided methods, such as those

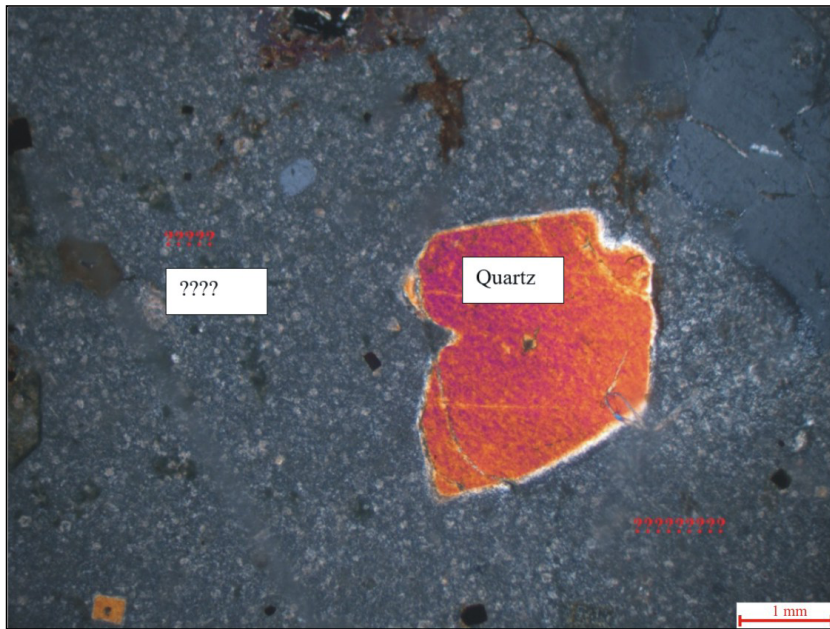


Figure 11- Unidentified minerals and quartz image in thick sections under light microscope (???)

offered by Leica polarizing microscopes, can mitigate some of the subjectivity and operator variability associated with traditional microscopy. These systems use digital imaging and automated algorithms to analyze optical properties, providing more consistent results across different samples and operators (Furukawa et al., 2015).

Advanced methods, such as scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS), are also commonly used alongside light microscopy to improve mineral identification. These techniques allow for chemical and crystallographic analysis, helping to confirm mineral identities when optical properties alone are insufficient (Goldstein et al., 2017). However, these methods are often more expensive and require specialized equipment, limiting their accessibility in routine geological studies.

Despite its long-standing use in mineral analysis, light microscopy presents several challenges in the accurate identification of minerals, especially quartz. The subtle optical properties of quartz, the overlap with other minerals, and the reliance on operator expertise all contribute to the difficulty of mineral identification. While modern techniques such as computer-aided analysis and complementary methods

like SEM and EDS can help address some of these challenges, they come with their own limitations. A thorough understanding of both traditional and modern approaches is essential for geologists aiming to achieve accurate and reliable mineral identification in a variety of geological contexts.

4. Conclusion

This study has demonstrated a comprehensive and methodologically robust approach to mineral identification through the integration of traditional thin section petrography and modern computer-aided microscopy. The research underscores the importance of optical mineralogy as a foundational technique in geology while also addressing its limitations when applied in isolation. Through the detailed analysis of quartz-rich rock samples including quartzite, granite, rhyolite, and sandstone this work has highlighted both the diagnostic strengths and interpretive challenges associated with birefringence, pleochroism, and extinction angle observations under polarized light.

By incorporating digital tools and Leica polarizing microscope systems, the study provides strong evidence for the advantages of computer-assisted analysis in improving identification accuracy, reducing analysis time, and minimizing inter-operator variability. Quantitative measurements, real-time

feedback, and image processing capabilities offer significant improvements over manual techniques, particularly when applied to minerals with subtle or ambiguous optical properties.

Nevertheless, the research also acknowledges that modern technologies introduce new considerations, such as the potential for algorithmic misclassification, software limitations, and the need for continuous validation against expert judgment. These challenges do not diminish the value of digital methods but instead emphasize the need for a hybrid analytical model one in which automated processes are guided and cross-verified by experienced mineralogists.

The broader implications of this study extend to various fields within geology and applied mineralogy. In research environments, this dual-method approach enhances the rigor and reproducibility of petrographic studies. In applied contexts such as resource exploration, sedimentology, or environmental geology, the increased speed and reliability of mineral analysis can significantly improve decision-making processes.

Looking forward, further development of automated thin section preparation techniques, expansion of machine learning models for mineral classification, and inter-system comparisons between microscope platforms represent promising avenues for extending this research. Standardizing hybrid workflows across laboratories could not only increase analytical consistency but also support large-scale, high-throughput studies in academic and industrial settings.

In conclusion, this study offers a relevant contribution to modern mineralogical practices by reaffirming the utility of light microscopy while advocating for its evolution through digital integration. It provides a framework that bridges the gap between conventional methods and the emerging analytical landscape, ultimately fostering a more efficient and accurate approach to mineral identification.

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