

Emerald Origin Determination Through Automated Pattern Recognition

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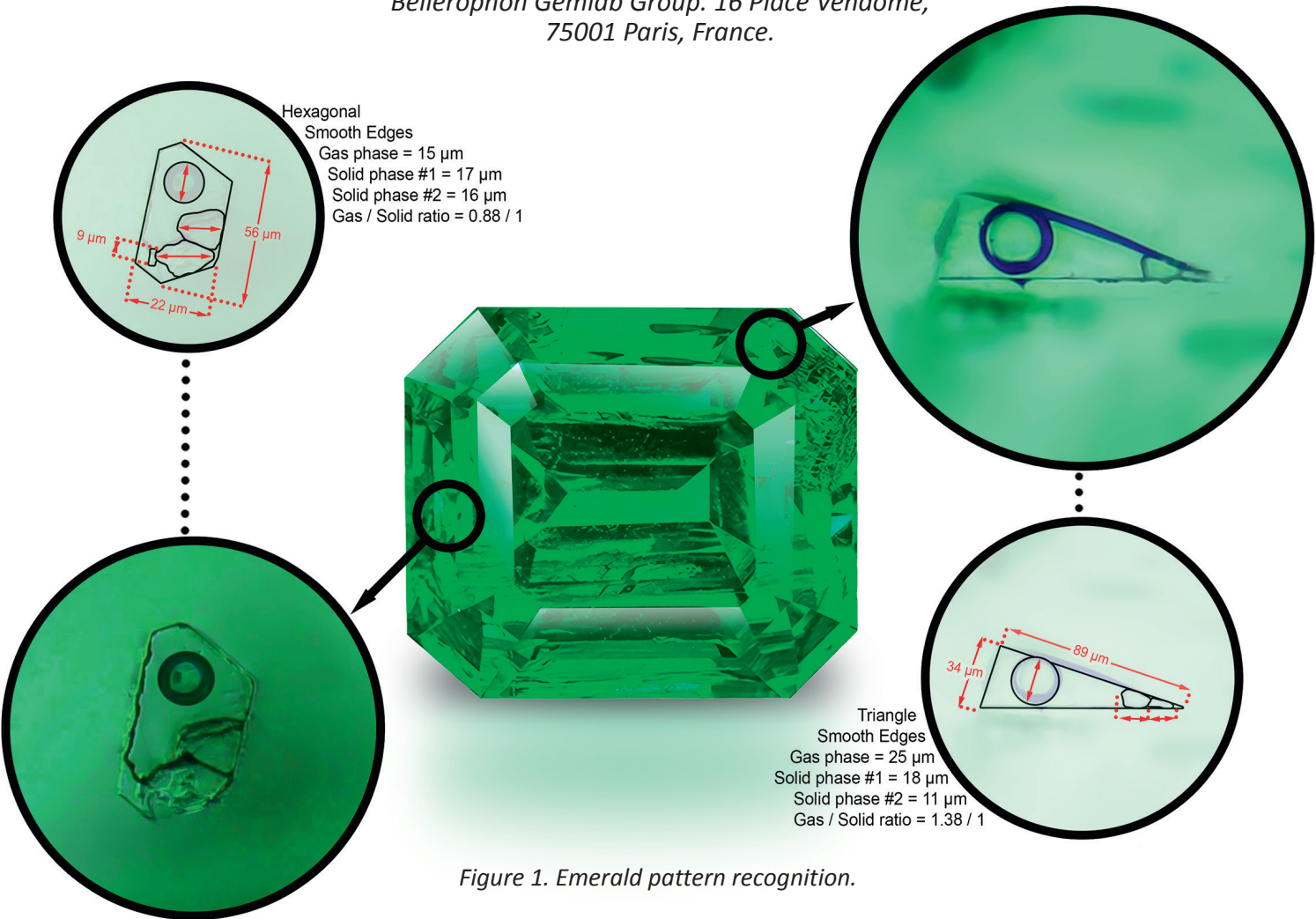


Figure 1. Emerald pattern recognition.

Introduction

The microscope remains one of the most important tools for gemologists, particularly for origin determination. An experienced gemologist, using the microscope, relies on the brain's ability to recognize and compare patterns such as shapes, sizes, and colors of inclusions, as well as the distances, numbers, and relief between internal features. All of this information, coupled with state-of-the-art technologies may support conclusions about a gem's provenance. However, the human factor in pattern recognition is likely the single most significant source of subjective error. Advanced analytical techniques greatly reduce human error, but do not eliminate it entirely. Research aimed at quantifying pattern recognition is not new (Saeseaw

et al., 2014), but the practical, day to day measurement of internal features has only recently become feasible thanks to technological advances in digital microscopy and software. Finally, proper pattern studies offer a much more effective way to transfer knowledge to new generations of gemologists and may also enable artificial intelligence to receive visual data directly from the microscope.

Material and Methods

Seventeen emerald deposits (Table 1) were selected for this study, with 100 samples per origin, except for Australia (Torrington) and Goiás (Brazil), resulting in a

total of 1,535 samples. This provides an average margin of error of less than 10% per origin using the pattern recognition method presented.

All photomicrographs, measurements, and pattern observations were conducted using a Keyence VHX 6000 and/or VHX 7000 digital microscope at the Bellerophon Gemlab laboratories (Figure 2), with magnification ranging from ×30 to ×2500.

Sample sizes ranged from 0.68 to 4.53 carats. The samples included a mix of wafers (polished with two windows), rough stones, and faceted gems. Lighting conditions varied and included darkfield, brightfield, direct illumination, and fiber optic light sources.

Special attention was paid to gemstone temperature during illumination (<29 °C); no halogen or heat emitting lights were used, as even low heat from lighting sources may temporarily alter internal features, particularly the balance between gaseous and liquid phases.

UV-Vis-NIR spectra were also collected at the Bellerophon Gemlab using an Ocean Insight SR-4XR250-50 spectrometer with 500 lines blazed at 250 nm, a 50 μm slit, and coupled with a 10-watt halogen and 1.2-watt xenon light source.

Table 1. Sample reliability used in this study.

EMERALD SAMPLE TRACEABILITY GRADING

	Sample n	Grades			
		AAA	A	B	C
Colombia (Muzo & Chivor)	101	4	78	19	-
Musakashi (Zambia)	100	-	-	82	18
Afghanistan (Panjshir)	100	-	28	66	6
Zambia (Kafubu)	100	-	81	19	-
Ethiopia (Shakiso)	100	-	-	28	72
Madagascar (Mananjary)	100	2	18	-	80
Russia (Malysheva)	100	8	29	-	63
Nigeria (Kaduna)	100	-	-	5	95
Australia (Torrington)	18	-	-	-	18
Swat (Pakistan)	100	-	59	-	41
Chitral (Pakistan)	100	-	82	-	18
Minas Gerais (Brazil)	100	-	78	-	22
Goiás (Brazil)	16	-	16	-	-
Bahia (Brazil)	100	-	69	-	31
India (Rajasthan)	100	-	-	60	40
Tanzania (Manyara)	100	-	12	-	88
Zimbabwe (Sandawana)	100	-	22	-	78

AAA: Extracted the gem from the ground.
A: Got the gem at the mine from the miner.
B: Got the gem from the miner not at the mine.
C: Got the gem from trusted contact in the market.



Figure 2. Emerald pattern recognition.

Methodological Considerations for Measuring Primary Cavities in Emeralds

The definition, qualification, and quantification of internal features, especially primary cavities, which are the primary focus of this study due to their extensive presence in emeralds, present small technical challenges that must be addressed to ensure proper comparisons.

Most internal features are three-dimensional; as such, any measurement is axis dependent. Therefore, it is important to emphasize that measurements are made most often perpendicular to the optical axis.

Primary cavities are aligned along their own axis (which generally follows the host crystal's orientation) to ensure accurate width and length measurements. These features are treated as two-dimensional images (ignoring depth) by ensuring that the entire measurement plane is perpendicular to the lens (in focus), either by adjusting the microscope or the gem's axis.

Additionally, stacked microphotographs are not permitted during measurement, since accurate dimensions are focus dependent. Measuring a feature at twice the distance from the original focal plane could result in an error of measuring it at half its actual size.

Low Iron Type and High Iron Type

Pattern studies are divided into two groups: low iron type and high iron type emeralds, based on the relative Fe²⁺ absorption band at 825 nm in their respective UV-Vis-NIR spectra (Figure 3).

Low iron type deposits include Colombia (Muzo and Chivor), Zambia (Musakashi), and Afghanistan (Panjshir), while high iron type deposits include all other deposits. However, in this article, we have chosen to limit the list of high-iron type deposits to those most relevant in terms of current production, availability, and the statistical likelihood of encountering them in a laboratory, market, or auction context.

As such, the high iron type group includes: Australia (Torrington), Brazil (Minas Gerais, Bahia, Goias), Ethiopia (Shakiso), India (Rajasthan), Madagascar (Mananjary),

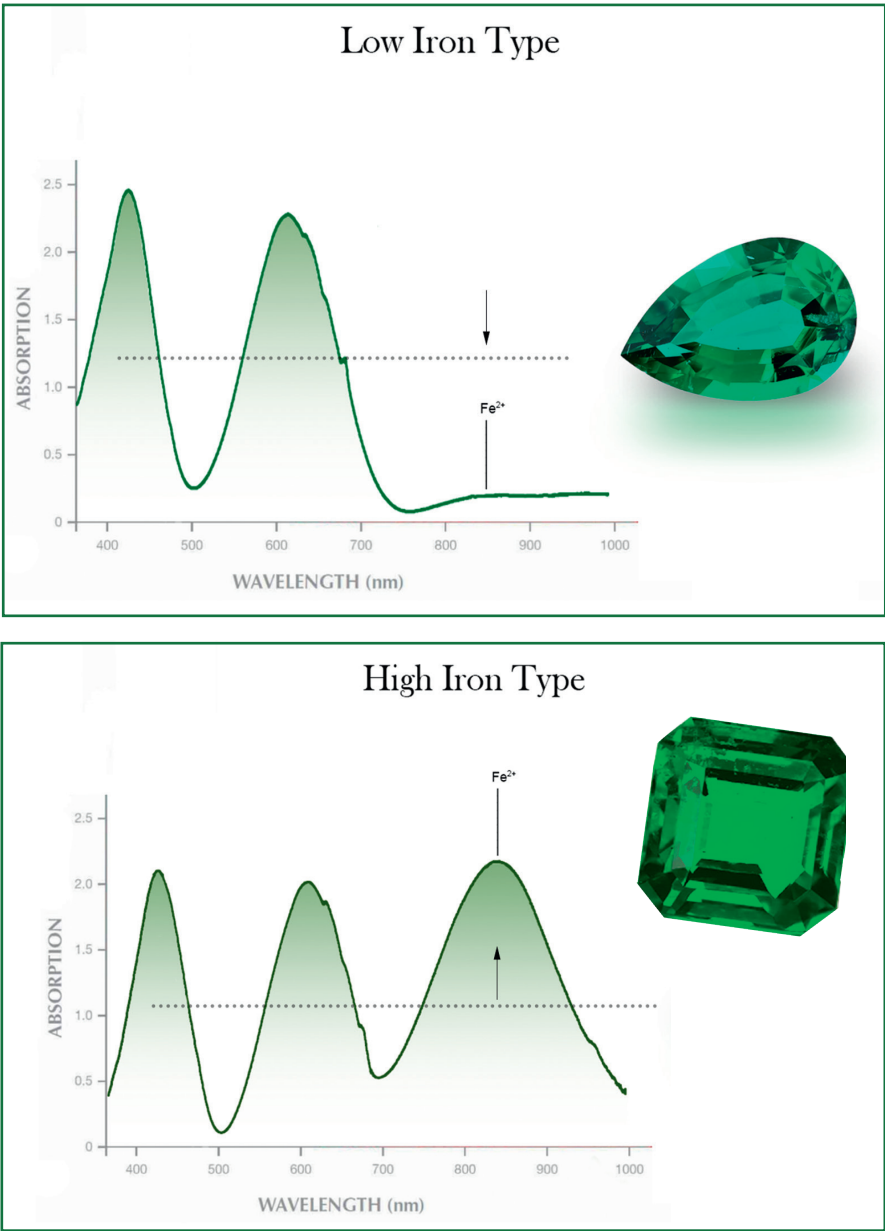


Figure 3. UV-Vis-NIR low iron and high iron types of emerald groups.

Nigeria (Jos Plateau), Pakistan (Chitral and Swat), Russia (Malysheva), Tanzania (Lake Manyara), Zambia (Kafubu) and Zimbabwe (Sandawana).

Nomenclature

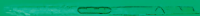
A clear definition with set boundaries is the most important first step in making comparisons. Accordingly, we first classify the overall shape of the cavity, and secondly its edges (Tables 2a and 2b).

The *shape* is defined as the overall external 2D form or outline of a cavity, while the *edge* refers to the boundary

IDEALISED NOMENCLATURE					
SHAPES	EDGES				
		Irregular	Irregular blocky	Serrated	Smooth edge
	Square				
	Rectangle				
	Elongated Rectangle				
	Hexagonal				
	Triangle				
Irregular					

SHAPES	EDGES		
	Jagged	Pointy one side	Pointy two side
Irregular			

Table 2a. Nomenclature and combination used in this study.

REAL NOMENCLATURE					
EDGES					
	Irregular	Irregular blocky	Serrated	Smooth edge	
SHAPES	Square		-	-	
	Rectangle				
	Elongated Rectangle	-	-	-	
	Hexagonal		-	-	
	Triangle	-	-	-	
	Irregular				

EDGES				
	Jagged	Pointy one side	Pointy two side	
SHAPES	Irregular			

Table 2b. Nomenclature and combination used in this study.

where the cavity meets the emerald host, closer to a one-dimensional feature or contour. This classification yielded six shapes and seven edge types.

Not all theoretical combinations were observed in the emeralds studied, however, 17 combinations were identified and compared. Some shapes and edges were not observed in this study, but we do not exclude the possibility that they may exist in other samples.

The use of specific patterns for origin determination in emeralds is not new, for example, the well-known three-phase jagged inclusion in Colombian emeralds. It is also known that this pattern occurs in other deposits as well (Saeseaw et al., 2014). However, to the authors’ knowledge, no complete synthesized qualitative analysis of this pattern exists across most emerald deposits, let alone a quantitative study of its frequency or a systematic classification of other primary cavity types.

Definition of Shapes

Square: Quadrilateral with four equal sides and four right angles, with a length/width ratio <1.15/1. Angles are approximately 90° with a tolerance of ±9° accepted.

Rectangle: Quadrilateral with four equal sides and four approximate right angles, with a length/width ratio >1.15/1 and <15/1.

Elongated Rectangle: Quadrilateral with four equal sides and four approximate right angles, with a length/width ratio >15/1.

Hexagonal: Polygon with six angles and, consequently, six sides.

Triangular: A triangle is a polygon with three corners and three sides. Most triangles have three sides of different lengths.

Irregular: Any shape that does not fit in the above description, and which cannot be described by any geometric form.

Definition of Edges

Smooth: The edges of the fluid cavity are regular and slightly curved, with no distinctive markings. The lines may show a few bumps or pronounced curvatures, but the edges have a certain regularity.

Serrated: Serrated edges may be present all around the cavity or only on one or more faces. They must present

a repetition of at least four small sharp *triangles* of similar size, with a tolerance below twice the height of the average *triangles*. Beyond this, the edge of the cavity will be considered *jagged*.

Jagged: Jagged edges may be present all around the cavity or only on one or more faces. They must exhibit a repetition of at least two long, sharp tips, unlike serrated edges, which are smaller and more regular.

Irregular Blocky: Cube-like angular edges may be present all around the inclusion or only on one or more faces. They present right and/or pseudo-right angles that are often repeated in a stair-step pattern.

Pointy One Side: Sharp tips are described as being present at one end of the cavity. They should consist of a single, long, sharp tip, unlike jagged inclusions, which display at least two sharp tips on the same face.

Pointy Two Sides: Sharp tips are described as being present at both ends of the cavity. Each end should display a single, long, sharp tip, unlike jagged inclusions, which show at least two sharp tips on the same face.

Irregular: Any edge that does not fit in with the above description.

Results and Discussion

Pressure, temperature, the alkalinity of the mineralizing fluids, as well as chemistry, growth rates, and growth events all play important roles in the formation of patterns observed in cavities. Using only the nomenclature defined above to qualitatively classify cavities yields impressive results (Table 3).

Qualitative referencing of cavities in emeralds already allows for significant differentiation between various deposits. However, statistical quantitative analysis provides a much clearer picture of the likelihood of encountering a particular cavity feature in relation to origin determination (Table 4).

Three main groups emerge from the statistical occurrence of specific cavity types associated with different deposits. Group I is dominated by irregular, jagged cavities, representing nearly 50% of all cavities in Afghan and Colombian emeralds.

Group II is characterized by square and rectangular cavities with smooth edges commonly referred to as *blocky* in the gemological literature (Saeseaw et al., 2019), with an average occurrence of 52% across emeralds from Brazil (Goiás and Minas Gerais), Ethiopia

Qualitative Occurrence per Deposit					
SHAPES	EDGES				
		Irregular	Irregular blocky	Serrated	Smooth edge
	Square	India Zimbabwe	-	-	Zambia (Kafubu); Nigeria Ethiopia; Pakistan Madagascar; Brazil Russia; India Tanzania; Zimbabwe
	Rectangle	Chitral (Pakistan) Bahia (Brazil) India; Tanzania Zimbabwe	Zimbabwe	Minas Gerais	Afghanistan; Zambia Ethiopia; Madagascar Russia; Nigeria Pakistan; Brazil India; Tanzania Zimbabwe
	Elongated Rectangle	-	-	-	Afghanistan; Zambia Ethiopia; Madagascar Australia; Nigeria Pakistan; Bahia India; Zimbabwe
	Hexagonal	Madagascar Russia	-	-	Zambia (Kafubu); Ethiopia Madagascar; Russia Australia; Swat Minas Gerais
	Triangle	-	-	-	Russia Nigeria Swat (Pakistan)
	Irregular	Afghanistan; Kafubu Ethiopia; Russia; Swat Chitral; Minas Gerais Bahia; Zimbabwe Tanzania; India	Zambia (Kafubu) Chitral (Pakistan) Bahia; India Zimbabwe	Colombia; Musakashi Ethiopia; Swat Minas Gerais; Bahia India	*ALL* Exept Goias

SHAPES	EDGES			
		Jagged	Pointy one side	Pointy two side
				
	Irregular 	Colombia; Musakashi Afghanistan; Nigeria Chitral; India Zimbabwe	Colombia; Musakashi; Afghanistan Zambia; Ethiopia; Madagascar Russia; Nigeria; Australia Chitral; India; Tanzania	Colombia; Musakashi; Afghanistan Russia; Nigeria; Australia Swat; Chitral; Minas Gerais India

Table 3. Qualitative analysis of cavity shapes and edges with corresponding deposits.

(Shakiso), India (Rajasthan), Madagascar (Mananjary), Pakistan (Chitral), Tanzania (Lake Manyara), and Zambia (Kafubu).

Finally, Group III shows a high occurrence, averaging 60% of irregular cavities with smooth edges, and includes emeralds from Australia (Torrington), Brazil (Bahia), Nigeria (Jos Plateau), Pakistan (Swat), Russia (Malysheva), and Zambia (Musakashi).

Zimbabwe stands out as an outlier, being the only deposit dominated by cavities with both irregular shapes and irregular edges. One important point not directly evident from this study is the lack or statistical absence of fluid inclusions in some emeralds, which warrants further research.

Nevertheless, it is already apparent that emeralds from Santa Terezinha De Goias (Brazil) and Zimbabwe contain an extremely low number of fluid inclusions. Combining the different cavity types with their group occurrences yields interesting results. Statistical patterns alone do not provide a clear distinction between low iron type emeralds.

As shown in Table 4, low iron type emeralds are predominantly characterized by irregular shaped cavities with either jagged or smooth edges. However, not all cavities are equal. Their absolute length and width, as well as their relative ratios, provide valuable information for origin determination (Table 5).

Colombian irregular jagged cavities tend to be significantly larger, with an average length of 256 µm. They also cluster around a width to length ratio of 1:1 to 1:5. In contrast, Afghan irregular jagged cavities are much more delicate in terms of width, usually below 10 µm, and display extremely elongated ratios, reaching up to 12 times their width.

The average ratio of irregular cavities with smooth edges also varies between deposits. Musakashi shows ratios closest to 1:1, while Afghanistan remains the most elongated, with an average ratio near 1:4 and a cluster of widths below 10 µm.

High iron type emeralds are dominated by two groups of cavity features: rectangular smooth edged cavities and irregular smooth edged cavities.

Madagascar and Minas Gerais exhibit a very blocky (square smooth edged) structure, with a width to length ratio close to 1:1 (almost square), while Swat (Pakistan) shows an average ratio of five times the length to the

width. Zambia (Kafubu) and Ethiopia display much longer cavities, with average lengths of 115 µm and 105 µm, respectively (Table 6).

In contrast, cavities from Swat and Madagascar are significantly smaller, averaging 35 µm and 56 µm. Within the irregular smooth edged group of high iron type emeralds, Swat clearly stands out from the other deposits by cavity size, with an average width of 15 µm, and no other origin shows cavities with widths below the 10 µm mark.

Solid Phase: Daughter Crystals

Primary and secondary cavities may contain solid phase inclusions. The crystals trapped within these cavities (Figure 4), their statistical occurrences, sizes, and numbers provide important clues to the geographical provenance of an emerald.

Daughter crystals have been divided into two groups. The first group consists of transparent, angular, cubic like minerals, mostly halite and sylvite (halides), or dolomite, calcite, and magnesite (carbonates), among others (Qin et al., 2022).

The second group includes all other solid phases, typically irregular, black or brownish, mostly opaque, rounded and/or forming agglomerates. These include scheelite, sphalerite, pyrite, and chalcopyrite, among others (Qin et al., 2022; Gaudfrin Arboleda, 2019). When more than two solid phases of the same state are found within a cavity, they are referenced from the largest (n¹) to the smallest (n^x).

Angular Transparent Daughter Crystals

The occurrence of angular transparent daughter crystals within cavities in low iron type emeralds is nearly universal, with 99% of cavities in Musakashi emeralds containing at least one crystal, 95% in Colombian emeralds, and 87% in those from Panjshir, Afghanistan (Table 7).

Counting the number of daughter crystals also reveals a noticeable trend: there is an increasing probability of finding multiple crystals within a single cavity in Afghan emeralds, and a decreasing one in Colombian samples. No more than four daughter crystals were observed in any of the 201 Colombian and Musakashi samples. However, cavities in Afghan emeralds may contain up to ten angular transparent daughter crystals.

EMERALD PATTERN RECOGNITION OCCURENCE PER DEPOSITS														
n= % of n samples with the pattern.														
	Colombia	Musakashi	Afghanistan	Zambia (Katubvu)	Ethiopia	Madagascar	Russia	Nigeria	Australia	Swat	Chitral	Minas Gerais	Gosau	Bahia
Square	Irregular	-	-	-	-	-	-	-	-	-	-	-	-	1%
	Smooth edge	-	-	7%	12%	17%	1%	3%	-	2%	6%	4%	19%	3%
Rectangle	Irregular	-	-	-	-	-	-	-	-	-	3%	-	-	3%
	Irregular blocky	-	-	-	-	-	-	-	-	-	-	-	-	-
	Smooth edge	-	-	4%	57%	45%	7%	1%	-	2%	37%	51%	81%	24%
	Serrated	-	-	-	-	-	-	-	-	-	-	3%	-	-
Elongated Rectangle	Smooth edge	-	-	2%	8%	20%	2%	2%	22%	9%	1%	-	-	1%
	Irregular	-	-	-	-	1%	1%	-	-	-	-	-	-	-
Hexagonal	Smooth edge	-	-	-	1%	10%	1%	-	6%	2%	-	8%	-	-
	Smooth edge	-	-	-	-	-	-	-	-	-	-	-	-	-
Triangle	Smooth edge	-	1%	-	-	-	1%	1%	-	1%	-	-	-	-
	Jagged	50%	6%	45%	-	-	-	15%	-	-	4%	-	-	10%
Irregular	Ponty one side	11%	7%	7%	1%	1%	3%	15%	16%	-	10%	-	-	12%
	Ponty two sides	8%	1%	5%	-	-	5%	20%	16%	1%	5%	1%	-	5%
	Irregular	3%	-	6%	10%	4%	15%	5%	-	3%	13%	10%	-	12%
	Irregular blocky	-	-	-	5%	1%	-	-	-	-	4%	-	-	8%
	Serrated	5%	11%	1%	-	2%	-	-	-	1%	-	-	-	2%
	Smooth edge	24%	74%	30%	11%	14%	6%	38%	38%	79%	17%	23%	-	19%

	Tanzania	Zimbabwe
	-	2%
	5%	-
	1%	1%
	-	2%
	60%	11%
	-	-
	-	-
	1%	1%
	20%	24%

Table 4. Quantitative distribution of cavity shapes and edges by deposit.

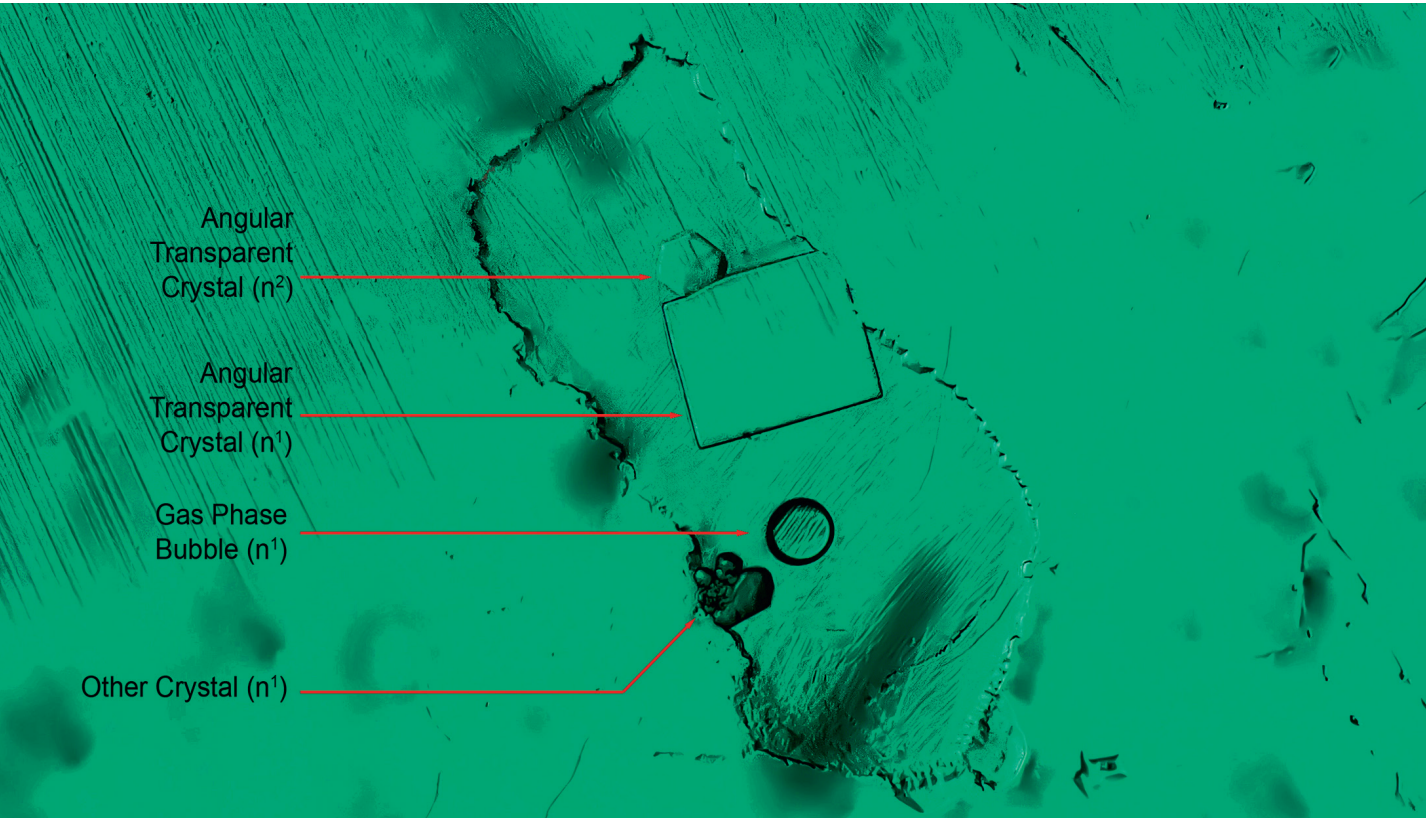


Figure 4. Daughter crystals present within a cavity in an emerald.

Gas (and/or Liquid) Phase

The occurrence of at least two phases (gas, liquid) in primary cavities is extremely common in emeralds (Giuliani et al., 2019), so common that it is observed in nearly all cavities across all deposits analyzed.

However, the presence of a second gas phase offers additional insights for certain deposits. It remains unclear whether these two gas phases are of the same nature or different (e.g., CO₂ and CH₄), depending on the origin. Questions also remain regarding the role of cavity shape in splitting a single bubble into two, and the critical size at which a bubble's surface tension is no longer sufficient to keep it intact. Correlations between Raman micro-spectrometry, bubble sizes, and cavity shapes did not yield conclusive results and are therefore not detailed here.

It is important to note that identifying gas phases presents significant challenges. For example, a cavity may contain a gas phase within a liquid phase, itself surrounded by another liquid (e.g., CO₂ gas trapped in CO₂ liquid, surrounded by H₂O). In such cases, the term *gas phase* may be semantically inaccurate and might be more appropriately referred to as the *bubble phase*.

For the purposes of this section, all bubbles, whether gas or liquid, are treated equally, not by their physical state or chemical nature, but as purely visual features.

Nevertheless, these features may provide useful information about the provenance of the host emerald. In low iron type emeralds, gas phase distribution within cavities is relatively homogeneous (Table 8), with Afghan emeralds showing the highest statistical occurrence of two bubble phases, believed to be of the same nature (CO₂), but split due to the high elongation ratios of their cavities.

Bubble sizes are also generally homogeneous, with Afghan emeralds again standing out, likely due to their narrower average cavity widths. The average size of the second bubble phase (n²) may exceed that of the first (n¹), owing to the low overall probability of observing two gas phases in a single cavity and the tendency for larger first bubbles to increase the likelihood of a second. Thus, a second gas phase of the same nature is typically observed only in larger cavities.

The high-iron type group shows the same correlation between average bubble phase sizes and average cavity sizes, with Swat (Pakistan) having the smallest bubbles

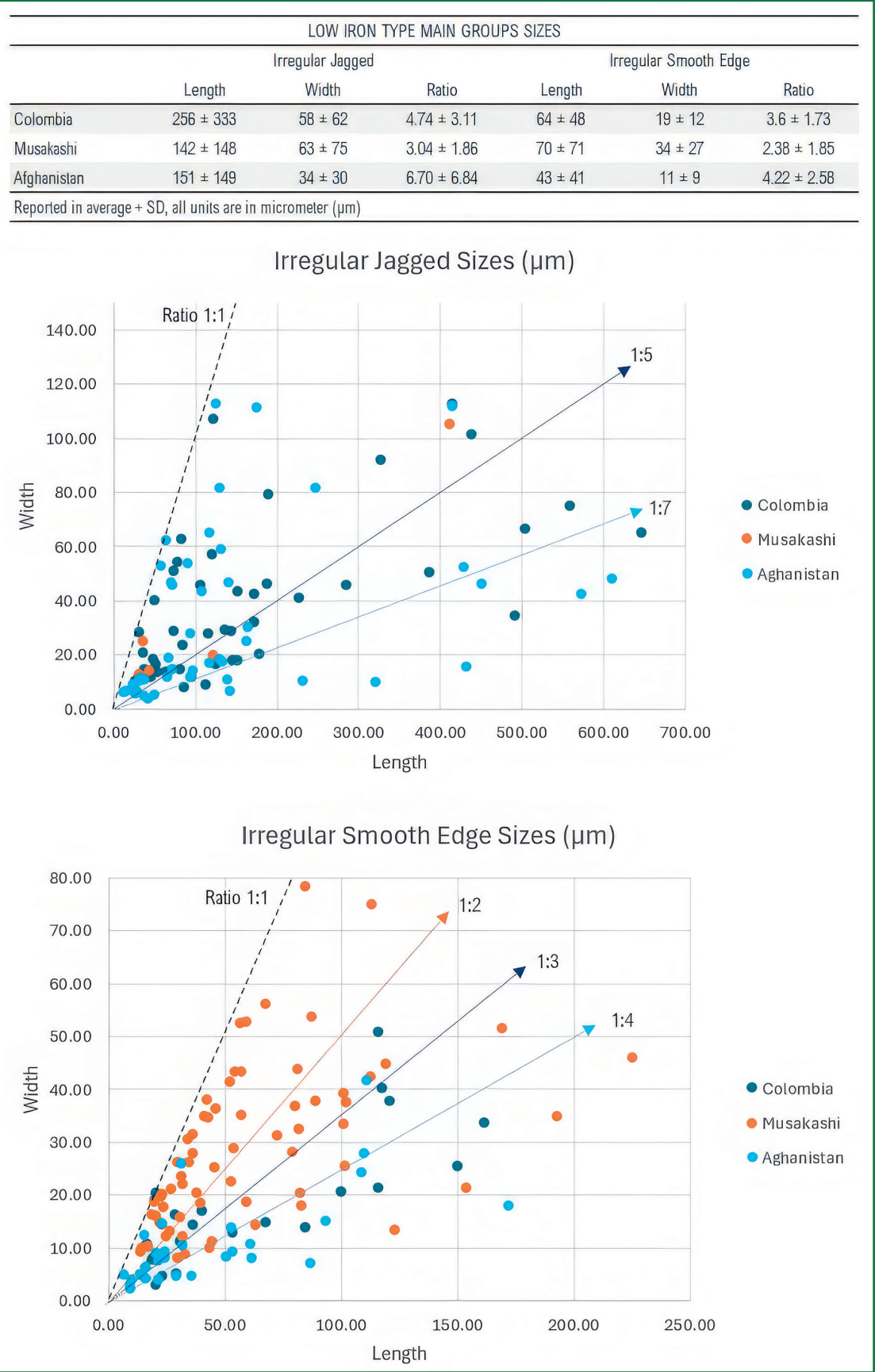


Table 5. Size comparison of irregular jagged and irregular smooth-edged cavities in low iron type emeralds.

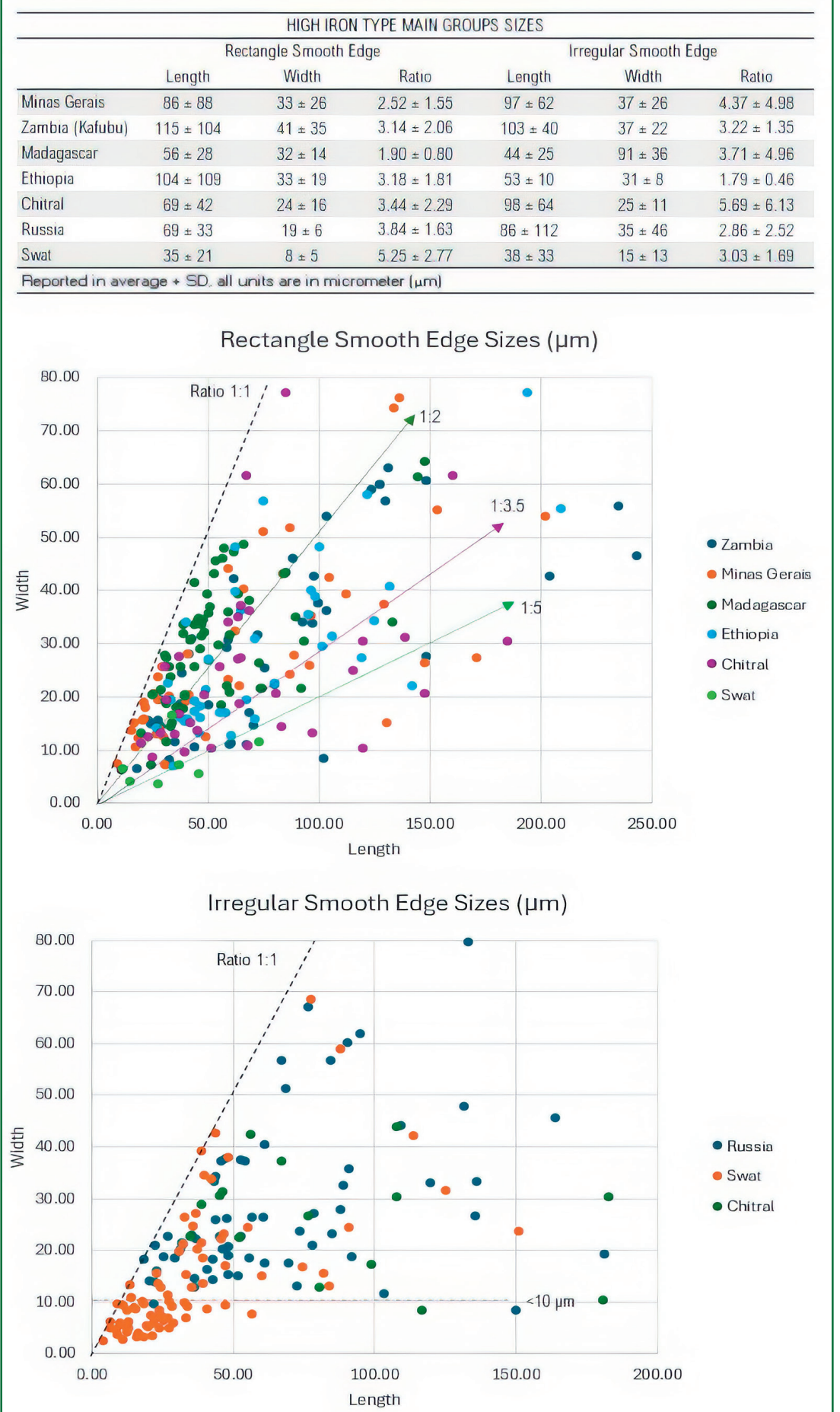


Table 6. Sizes comparison of rectangle smooth edges and irregular smooth edges cavities in high iron type emerald.

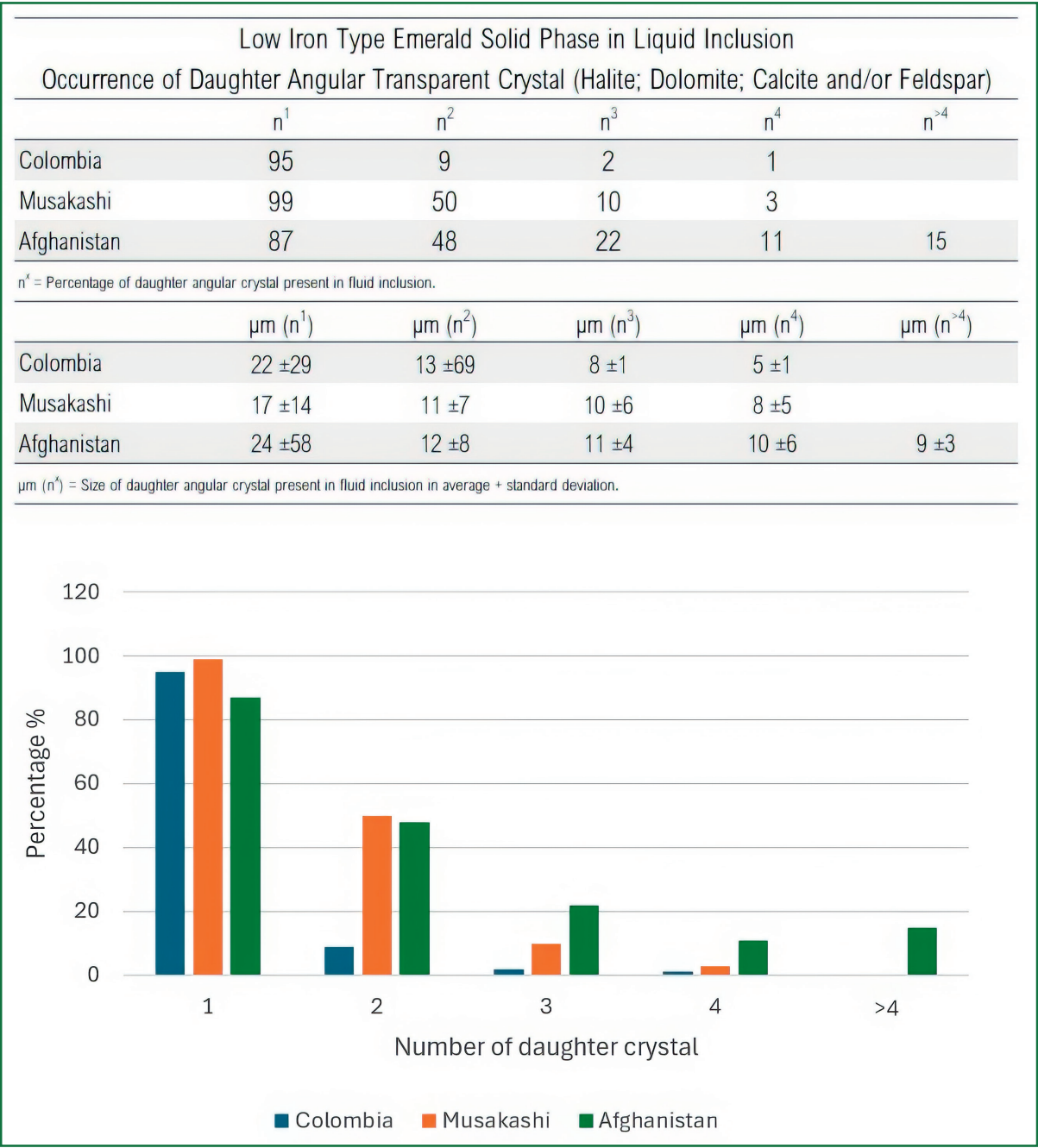


Table 7. Statistical occurrence of angular transparent crystals in low iron type emeralds.

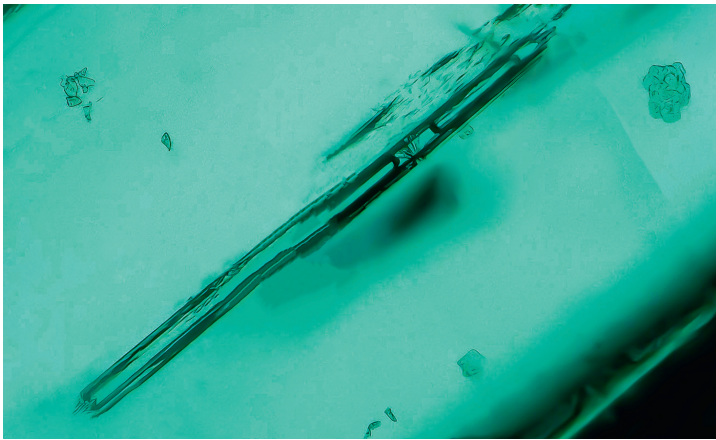
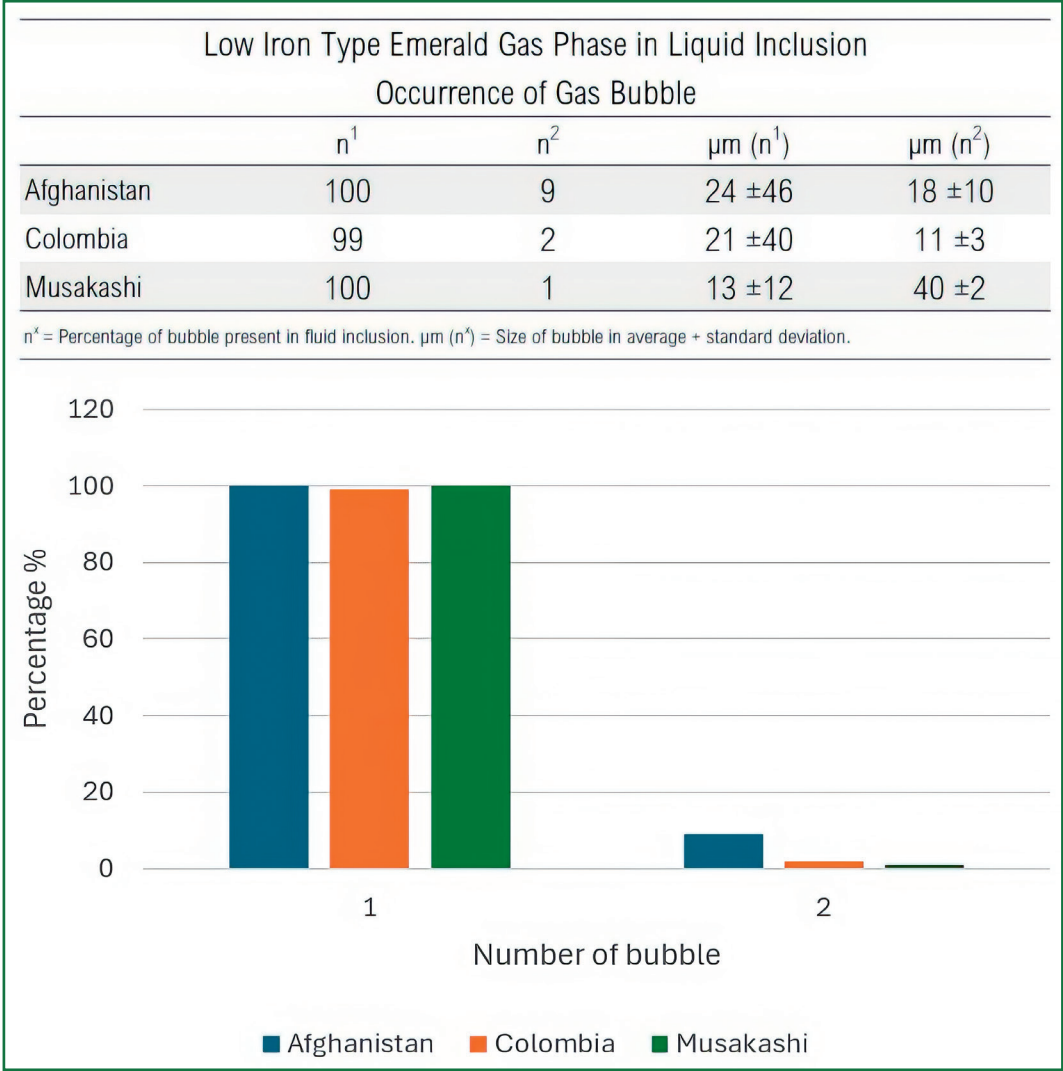


Table 8. Statistical occurrence of 'bubble' phase in low iron type.

High Iron Type Emerald Gas Phase in Liquid Inclusion
Occurrence of Gas Bubble

	n ¹	n ²	µm (n ¹)	µm (n ²)
Minas Gerais	100	54	38 ±30	20 ±22
Madagascar	100	26	31 ±29	16 ±7
Ethiopia	100	4	49 ±64	60 ±56
Zambia (Kafubu)	100	-	42 ±43	-
Chitral	100	-	28 ±20	-
Russia	100	-	25 ±29	-
Swat	100	-	13 ±15	-

n¹ = Percentage of bubble present in fluid inclusion. µm (n¹) = Size of bubble in average + standard deviation.

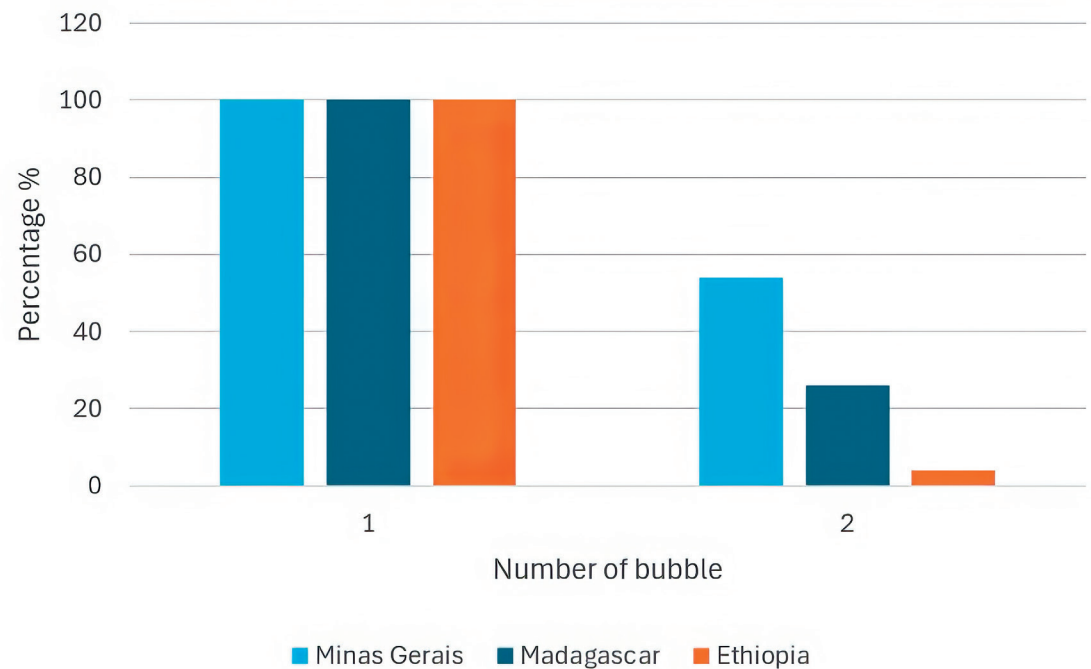


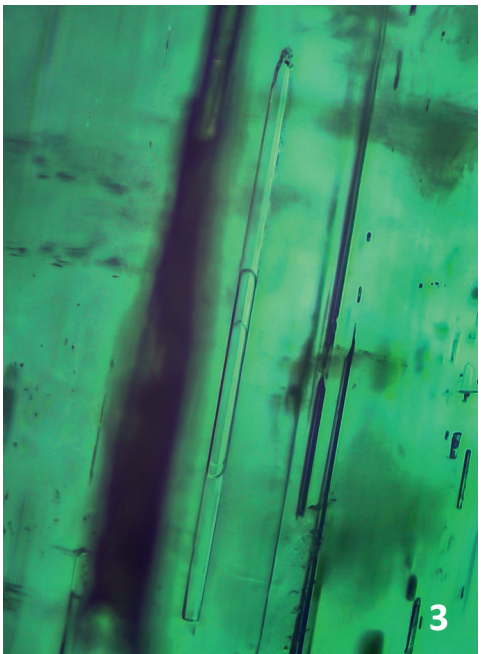
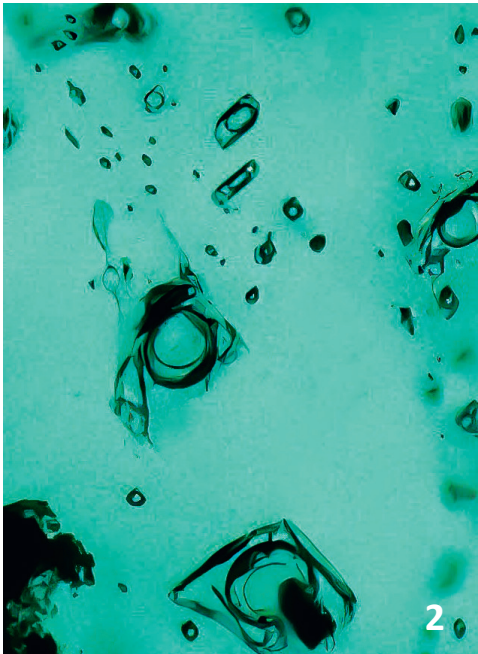
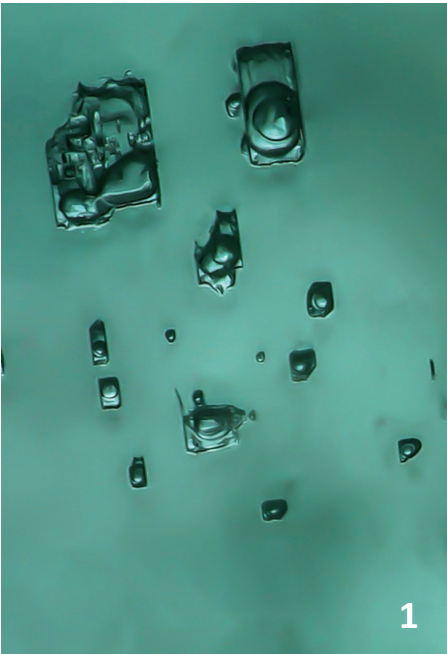
Table 9. Statistical occurrence of the 'bubble' phase in high iron type emeralds.

Figure 6. Inclusions composed of two bubbles nested within one another.

Photo 1. Origin Brazil, FOV: 1.981 mm.

Photo 2. Origin Madagascar, FOV: 1.483 mm.

Photo 3. Origin Ethiopia, FOV: 2.149 mm.



within its cavities. Only three deposits exhibit the presence of two nested bubble phases. Cavities from Minas Gerais (Brazil) show a 54% occurrence of two bubble phases, Madagascar 26%, and Ethiopia only 4% (Table 9 and Figure 6).

No other high iron type origin showed a second bubble phase in any of their cavities. Above 29 °C, the two gas bubbles nested within one another homogenize. It is therefore crucial to keep the laboratory temperature below this threshold, as valuable information may be lost beyond that point.

Solid vs Gas Phase

Interestingly, comparing the size of the first angular transparent daughter crystal within a deposit to its corresponding bubble phase yields relevant information. These comparisons are based on origin and

are not limited to three-phase inclusions. As such, we measured all bubble sizes and all angular transparent daughter crystals within an emerald and compared them with each other. Therefore, we may compare a bubble from one part of the crystal host with a halite inclusion in another cavity located farther away within the same host.

Quantifying these differences provides potential indirect insights into the composition and molar mass of the mineralizer, as well as the composition and molar mass of the primary fluids, combined with the pressure, temperature, and cooling rate of the host emerald.

In low iron type emeralds, the ratio of solid to bubble phases shows a wide variation in Colombian samples. Interestingly, Musakashi (Zambia) and Afghanistan can be distinguished by the dominant phase size. In Musakashi (Zambia) emeralds, the solid phase is almost always larger than the bubble phase, on average about

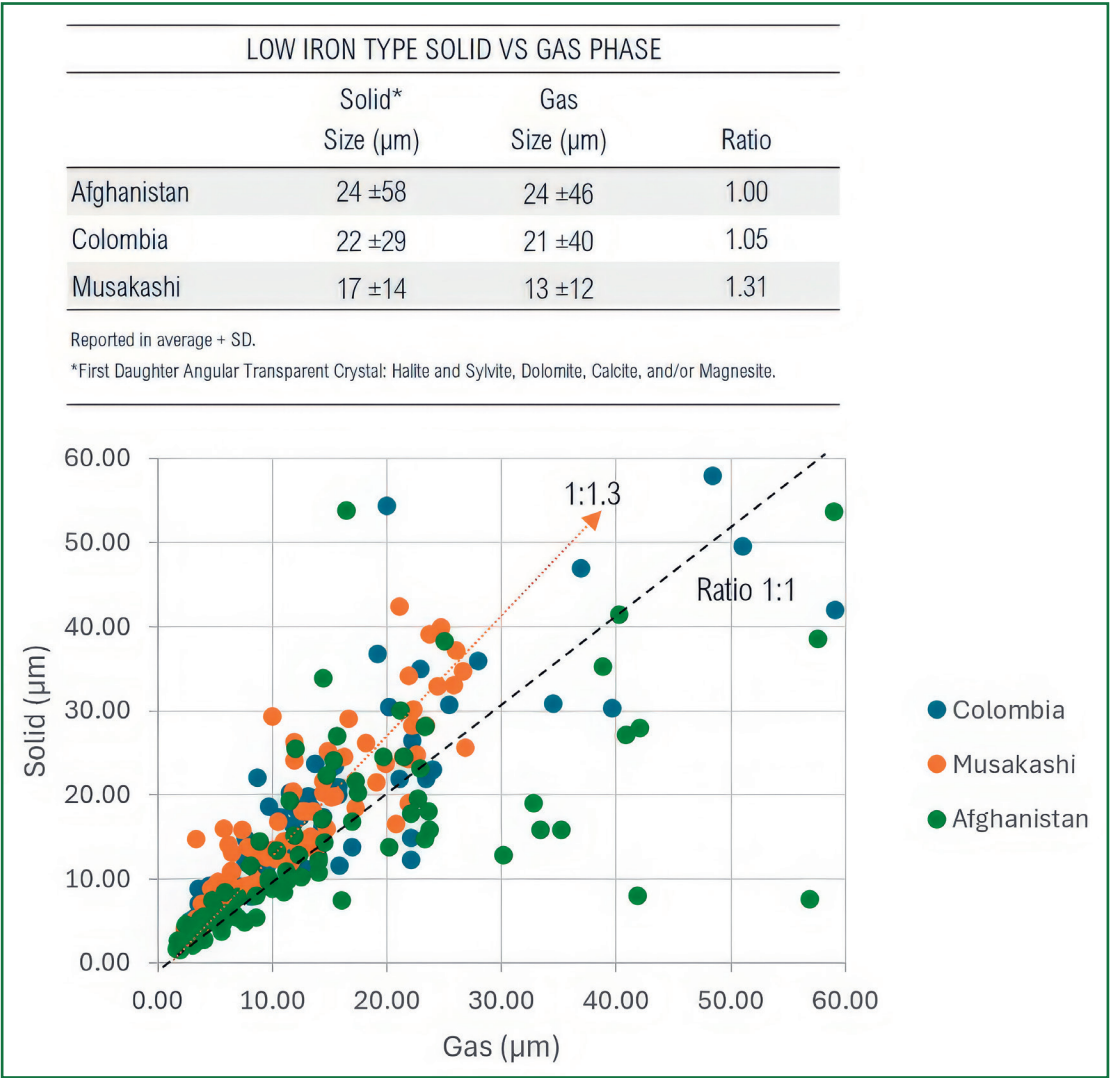


Table 10. Ratio and sizes of 'bubble' phase versus solid phase in low iron type emeralds.

30% larger. Afghanistan shows the lowest ratio, with a near-perfect 1:1 average (Table 10).

Therefore, a ratio below 1:1, where the bubble phase is significantly larger than the angular transparent daughter crystal, is strongly indicative of an Afghan origin and argues against a Musakashi (Zambia) provenance.

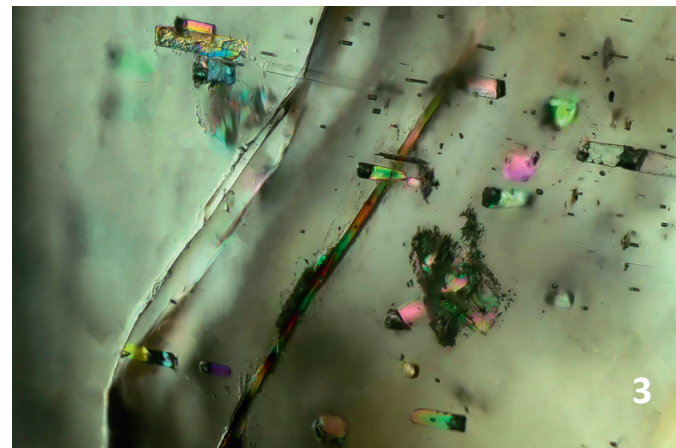
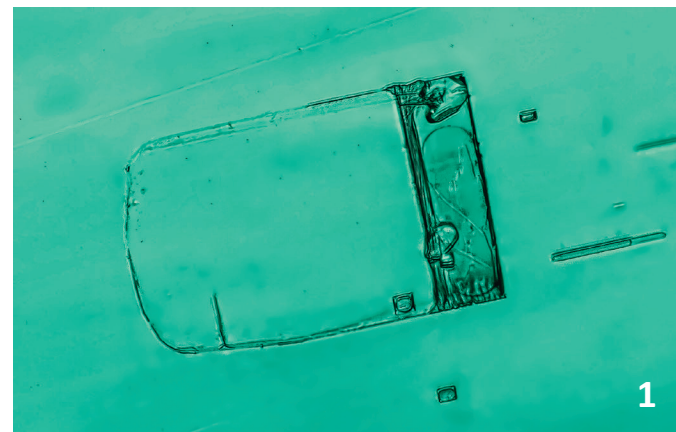


Figure 7. Tongue-shaped inclusions in high iron type emeralds.

Photo 1. Origin Brazil (Minas Gerais), FOV: 0.989 mm.

Photo 2. Origin Madagascar (Mananjary), FOV: 1.483 mm.

Photo 3. Origin Ethiopia, FOV: 1.981 mm.

Characterization of Tongue-Like Fluid-Solid Inclusions in High Iron Emeralds

The study of fluid inclusions in high iron type emeralds revealed the presence of distinctive tongue-shaped inclusions (Figure 7). These consist of a fluid-filled cavity with a rectangular shape and smooth edges, extended by a rounded, tongue-like projection. This *tongue* is solid, and exhibits marked birefringence. When observed between polarizers, it displays a range of interference colors.

This type of inclusion, combining a fluid phase with a solid phase, has been identified in emeralds from three distinct origins: Brazil (Minas Gerais), Madagascar (Mananjary), and Russia (Malysheva).

They can also be present, although rarely, in emeralds from the Santa Terezinha de Goiás and Bahia deposits in Brazil. Owing to their shape, optical properties, and composition, these inclusions represent a significant marker for geographic origin determination (Schwarz & Curti, 2021).

Conclusion

Pattern recognition in gemology has always been at the forefront of gemological science, used for identification, understanding genesis, detecting treatments, and determining origin. It remains the primary and most widely used tool in all gemological laboratories to this day.

Many gemologists speak of a *feeling* when observing the internal features of a stone. This *feeling* is often described as the result of years of experience, having examined thousands of gemstones.

The authors suggest that this *feeling* or *experience* is actually the cumulative pattern recognition developed by the gemologist's brain through exposure to thousands of visual inputs throughout their career.

These patterns have historically been difficult to describe, categorize, and transmit through gemological literature, often using poetic terms for internal features such as *snowflakes* and *streamers* (Palke et al., 2019), accompanied by photomicrographs and subjective descriptors like *short* or *long* features. The advent of digital microscopy now allows laboratories to go far beyond traditional optical microscopes, offering magnification up to 2500x, combined with software capable of analyzing length, width, shape, and ratios within seconds (Figure 8).

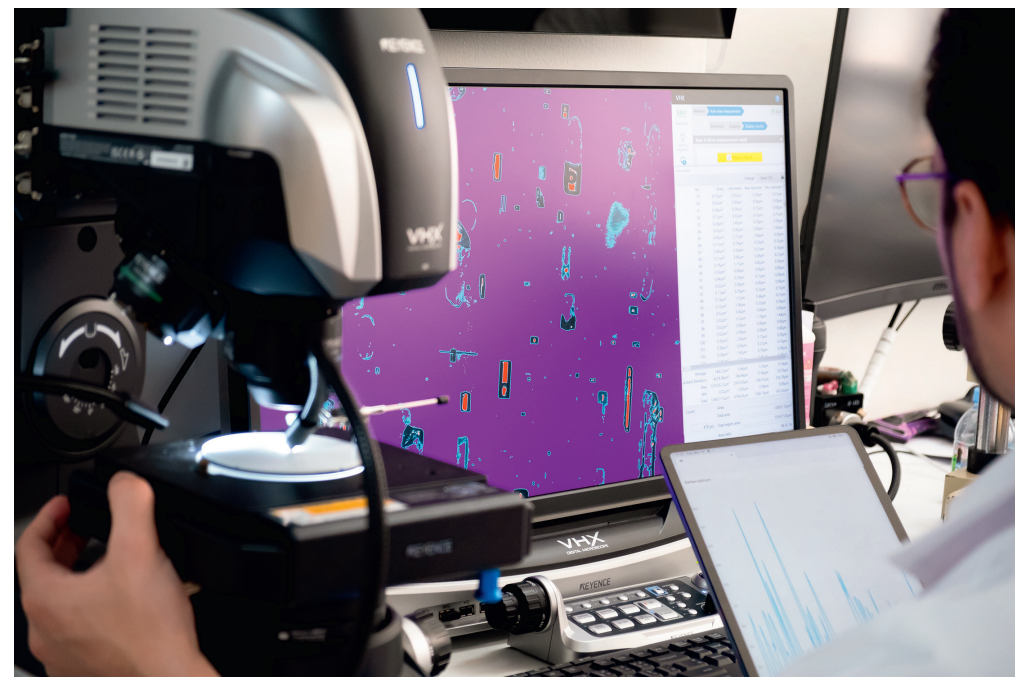


Figure 8. Internal feature analysis using one of our Keyence digital microscopes at Bellerophon Gemlab. A 1.5-mm field of view is analyzed within seconds by V. Fejoz, with automated pattern recognition, and the width, length, and ratio data exported to an Excel file.

This technology opens up a new world within gemstones, offering tremendous potential. The systematic categorization of internal features, including their length, width, ratio, shapes, edges, frequency, and spatial distribution, may fundamentally redefine the internal gemological landscape.

It not only supports gemologists in their daily analyses but also greatly enhances both the quality and efficiency of their work. For example, the ability to zoom up to 2500 times into cavities allows for the routine observation of diaspore fibers within CO₂-filled negative crystals in corundum within minutes, providing invaluable insight into the absence of low-temperature heat treatment, which cannot be detected using Raman microspectrometry or FTIR.

Discussion

The combination of greatly enhanced magnification alone within gemological laboratories should be enough to demonstrate the incredible power a digital microscope brings to the precision of gem analysis.

When combined with pattern recognition software and state-of-the-art technologies such as EDXRF, LA-ICP-MS, LIBS, Raman microspectrometry, photoluminescence, and an optical microscope with a trained gemologist, its full potential is truly remarkable.

The study of primary cavities indirectly brings a faceted mineral habitus back to life, along with all the wealth of information it holds. Lastly, to the best of the authors' knowledge, no gemologist would tell you otherwise: *the microscope is the backbone of our science*. As such, no other equipment within a laboratory should deserve more attention.

Further Research

Models are currently being tested for corundum. Potential applications of fluorescence spectroscopy and birefringence microscopy are also under investigation.

Bibliography

Gaudfrin Arboleda, N. (2019). *Les inclusions triphasées des émeraude de Colombie* (Diplôme d'université en gemmologie). Université de Nantes, U.F.R. des Sciences et des Techniques, Département des Sciences de la Terre et de l'Univers. Soutenu publiquement le 8 mars 2019.

Giuliani, G., Groat, L. A., Marshall, D., Fallick, A. E., & Branquet, Y. (2019). Emerald deposits: A review and enhanced classification. *Minerals*, 9(2), 105–168.

Palke, A. C., Saeseaw, S., Renfro, N. D., Sun, Z., & McClure, S. F. (2019). Geographic origin determination of ruby. *Gems & Gemology*, 55(4), [page numbers not provided].

Saeseaw, S., Pardieu, V., & Sangsawong, S. (n.d.). Three-phase inclusions in emerald and their impact on origin determination.

Saeseaw, S., Renfro, N. D., Palke, A. C., Sun, Z., & McClure, S. F. (2019). Geographic origin determination of emerald. *Gems & Gemology*, 55(4), [page numbers not provided].

Qin, L.-J., Yu, X.-Y., & Guo, H.-S. (2022, May 20). Fluid inclusion and chemical composition characteristics of emeralds from Rajasthan area, India. *Minerals*, 12(5).

Schwarz, D. T., & Curti, M. (2021). *Emerald: Modern Gemmology*. Bellerophon Gemlab. ♦