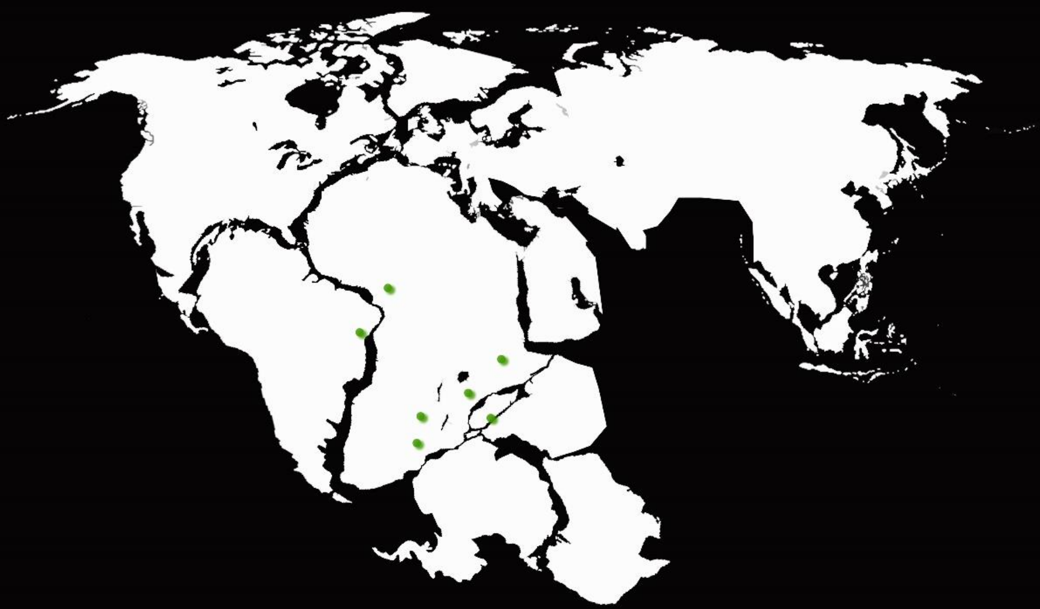
EMERALD

MODERN GEMMOLOGY

DIETMAR SCHWARZ & MARTIAL CURTI

200 MILLION YEARS AGO



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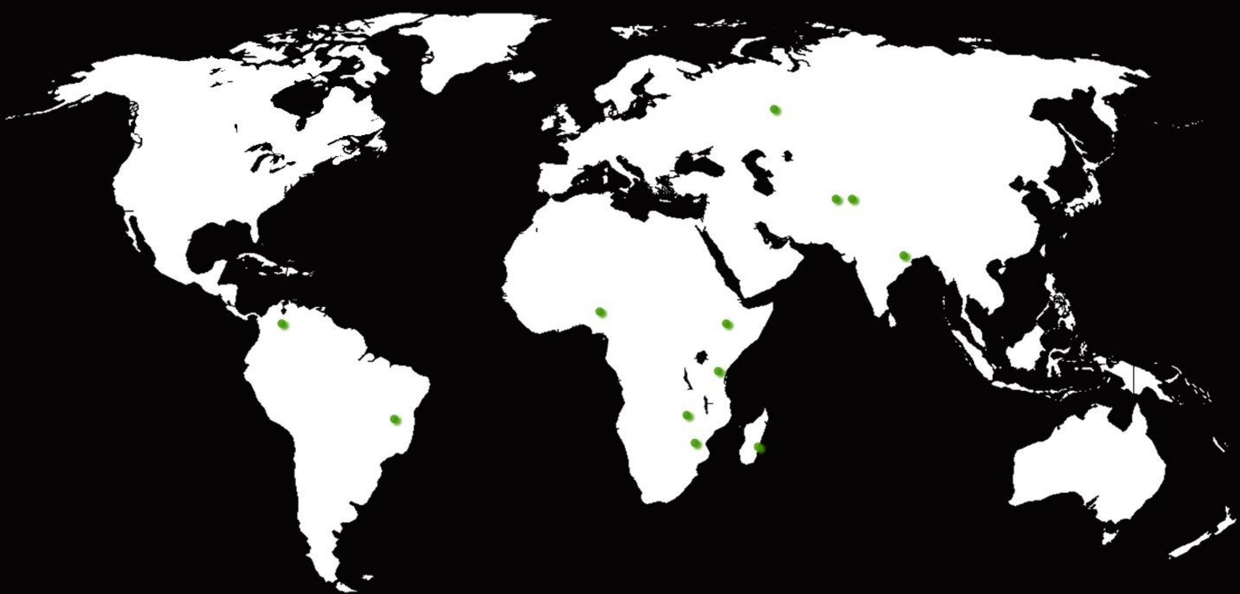

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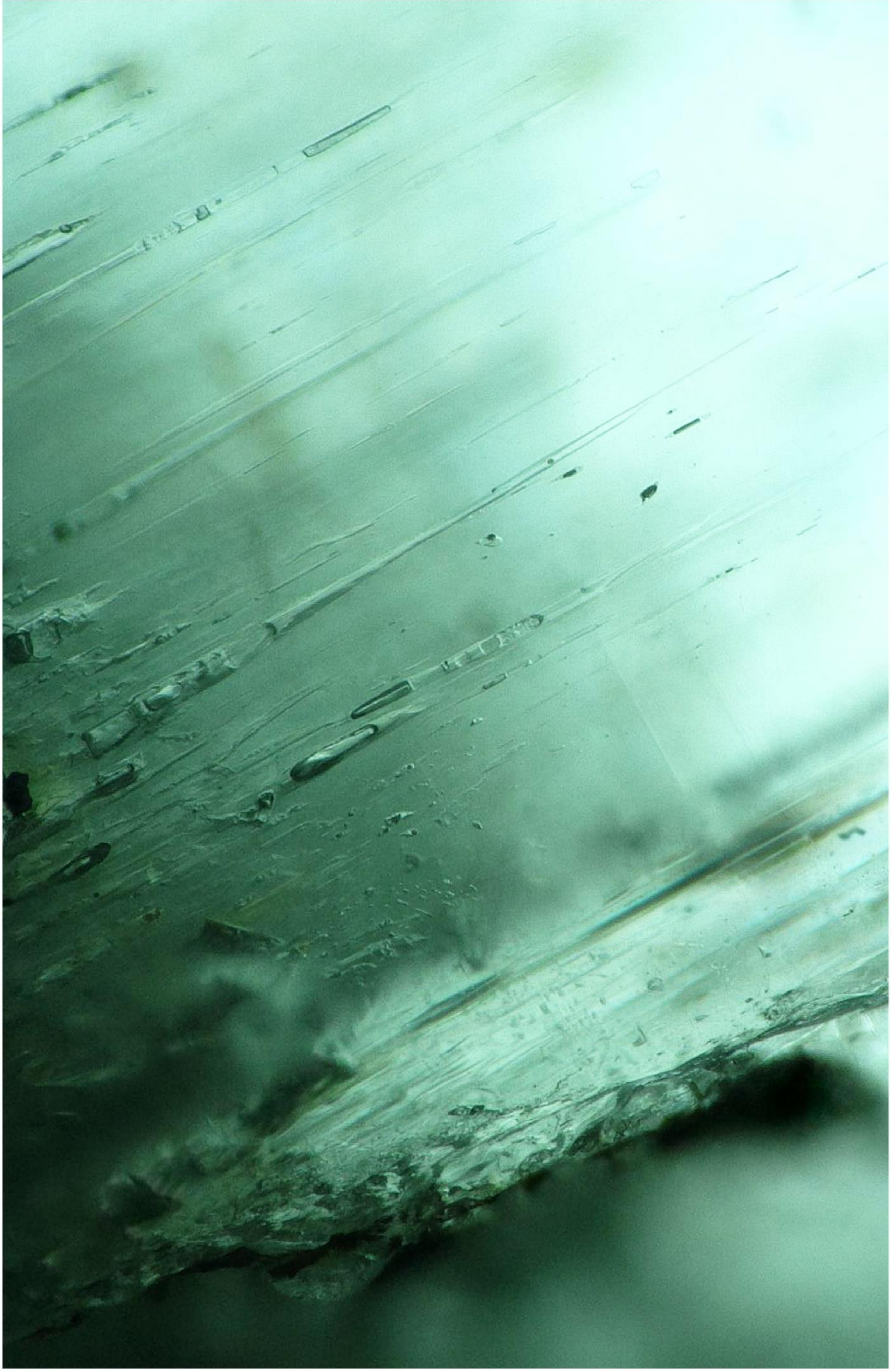


ACKNOWLEDGEMENT | M.P.H. Curti

First and foremost, I would like to express my deepest gratitude to all the past and present gemmologists whose research has created the solid foundation on which we can build greater knowledge and whose invaluable guidance enables us to continue their work, always pushing the boundaries of our understanding and aiming forever higher.

Special thanks also go to my mentors in gemmology who taught me the methodology needed to carry out research, to always question theory, and to present facts as clearly as possible, and who deeply inspired me through their dynamism, vision, sincerity and motivation. It was and is a great privilege and honour to study and work under them and with their guidance.

I am also extremely grateful to the Bellerophon team for their hard work, caring attitude, and sacrifices. Without them, none of this would have been possible. Special and warm thanks go to **Theodore Rozet** for assisting us at every step; to Ben **Ploypailin Chaimart** for all the dedication in her work and for her assistance with photography and photo editing; and to **Sumalee Tapprasert** for her help during the preparation of the samples.

To the Bangrak Gems team, I would like to express my gratitude for their tireless help before and during this research. A special mention must also go to the Director, **Michel Locow**, who shared with us his invaluable comments and suggestions and to gemmologist, **Ben Douciere**, for his technical help during the micro photo session.

I would also like to express my sincere gratitude to the Sukhadia Gemstone team, especially the Directors**, Chiku Sukhadia** & **Kaimesh Sukhadia,** for sharing countless insights and knowledge of Zambian Emeralds.

My special thanks also goes to the 8th Dimensions team, especially the Director, **Jeffery Bergman**, for his regular guidance before and during this research, for his insights and knowledge of Ethiopian emeralds, and for the help and support he has given me from the beginning.

I would also like to express my gratitude to the Crown Color team, especially the Director, **Lewis Allen**, for his insights and knowledge of Colombian emeralds.

For this project, I would also like to express my heartfelt thanks to all the many people who made it possible by being in the right place at the right time and doing the right thing. I am deeply grateful to all those who helped with the mining, buying, referencing, sampling, cutting and more importantly collecting of these 1,026 samples over a period of 40 years.

I would like to say a big thank you to all the people who received us in their countries and shared with us their invaluable information along with their passion for gemstones.

Finally, many thanks to all the peoples not mentioned in this list but who contributed in so many ways.

FOREWORD

MARTIAL
CURTI

This is not the first nor will it be the last book of this genre. The internal features of gemstones are a fascinating world. However, the book you hold is different from other books on this topic in that it aims to display a wide spectrum of facts and evidence on emeralds categorised by their country of origin. This book is intended only to be what it is: a reference collection of data on the internal features of emeralds from different geographical origins.

This book is the culmination of a journey we started 2 years ago. Gemmologist Engineer Master (GEM) is a type of AI/ES that we apply in our research and laboratory work to help and guide us. Based on correlation analysis in the fields of chemistry and spectroscopy, and more importantly, in the recognition of inclusions, this expert system analyses a high volume of data to ensure standard and average deviation, especially in the micro photos, as the core of gemmology is still the visual input from under the microscope.

Pictures speak a thousand words. Many of the common features in gemmology do not benefit from clearly defined nomenclature or a wide terminology. Also, the technology required to identify those features properly is beyond the scope of the current day-to-day practice of gemmology. Addressing these issues is not the purpose of this research. Rather, the growth features, succession, accumulation, and recurrence of inclusions are the subject of this book. As such, these aspects lack scientific terminology and are described instead by more poetic terms, despite the significant role they play in origin determination.

Each locality has its own unique history, geography, geology, and gemmology. The link between each part of the bigger picture is unbreakable. The country of origin that we use to categorise a gemstone may be a man-made geopolitical construct, but the borders of many of those countries are formed by geographical features, designed by geological events.

While gemstones are often created in the stresses and fractures resulting from the formation of mountains, they may be carried away by rivers, taking them across great natural geopolitical borders. As the Earth's plates are constantly moving, countries that are geographically far apart today and even separated by great oceans might have shared common borders in a distant past, their deposits created by the same event that results in them sharing a common chemistry and internal features despite their geographical distance.

This second great journey we are now embarking upon, the one we are sharing with you through this book, is one of curiosity. Gemmology is a journey to the centre of a gemstone. Like detectives, we must collect facts and evidence to reach conclusions about the nature of a gemstone.

We can spend hours travelling in a tiny crystal back and forth, like an astronaut with a microscope as our spaceship, wandering in a different universe, one that is microscopic and crystalline.

Gemmology today | **Dietmar Schwarz**

The main task of a high-level gemmological laboratory today is to offer a service that comprises the issuing of a piece of paper stating the geographic provenance of a gemstone, the "Country of Origin Report". This paper, of course, will also address the presence/absence of treatments.

The so-called "geographic origin determination" requires a laboratory infra-structure that can be explained using the tripod scheme. The three "gemmological legs" are: [1a] physical space/premises, [1b] administrative infra-structure, and [1c] specific gemmological equipment/instrumentation; [2] qualified staff members (different levels: operator, analyst, scientist); and [3] a complete reference collection comprising samples of the coloured gemstones that are relevant for the geographic origin determination.

The handling of item 1 of the geographic origin determination process depends mainly on the financial background situation of the lab. If enough money is available, the renting of physical space, the acquisition of equipment and the employment of administrative staff are easy and fast. However, the creation of an appropriate employee infra-structure in the technical sector [item 2] depends not only on financial conditions. In general, the main constraint here is the availability of qualified professionals in national and international markets. In practice, this may cause serious restrictions in terms of time planning/time management and with regard to the desired/requested professional level of the lab.

When going back to our "tripod scheme", we must remember that a tripod is only stable if its three legs are of comparable length and strength. For the "laboratory tripod", this means that the three sectors – instrumentation, staff qualification and reference collection/data base – should all be on the same (high) level. It is not enough, for example, to have only high-level instrumentation and highly qualified professionals.

For item 3 – the reference collection and factors related to it – a comprehensive database is equally important. Surprisingly, the importance of this aspect of the geographic origin determination process is often undervalued when discussing the basic prerequisites that have to be satisfied for a geographic origin laboratory to deliver a high-level service. In fact, fixing the third laboratory leg is probably the most difficult to achieve. Not only does it require a substantial financial input, but it also takes considerable time to assemble a sufficiently complete reference collection on which a comprehensive database can be built. This includes the collection, evaluation/processing and interpretation of the data which represent the cornerstone for the everyday activities of the lab gemmologists.

The geographic origin determination of coloured gemstones has its beginnings in Europe. The systematic characterization of gem deposits was started in the early 1950s by Dr. Eduard Gübelin, who is considered the pioneer in this area. His work paved the way for additional gemmological information: the country of origin. At the beginning, the labs applied the 'classic approach' to geographic origin determination. This consisted of trying to find properties in an unknown gemstone that were considered locality-specific (this means identifying properties that are typical of a certain geographic region). Traditionally, the testing procedure in the lab focused mainly on the study of the inclusion features through a gemmological microscope. For example, the "classic" 's-l-g' three-phase inclusions have been considered for a long time as locality-specific for emeralds from the Colombian Cordillera Oriental.

Today, the high-level geographic origin laboratories follow the 'modern approach', whereby geographic origin determination is based on the full documentation of an unknown gemstone. This means all relevant data for an unknown gemstone are collected during the testing procedure in the laboratory. After the complete documentation of the unknown stone is collected, a comparison of its data set with properties of samples from a precisely documented and interpreted reference collection is performed. Based on this evaluation, the unknown stone can be related to a specific geological-genetic environment and, finally, to a certain geographic location.

My first experience with collecting mineral specimens goes back to my time as student of mineralogy-gemmology at the Johannes Gutenberg University in Mainz Germany. During my first field trips as a student to the emerald mine of Mjøsa in Norway (in 1978) and to the gem fields in Sri Lanka (1980), I already realised the need for a personal reference collection. Today, after four decades and innumerable field trips, my collection comprises several thousand well-documented samples of different coloured gemstones.

The first big step towards building a high-level reference collection was taken during my time as scientific lecturer of the German Academic Exchange Service (DAAD) at the Federal University of Ouro Preto in Minas Gerais Brazil during the period from 1983–1991. As professor of mineralogy and gemmology, I realised the necessity for sample material to be used for training and teaching purposes in the gemmological laboratory of the university. Thanks to the geographic location of Ouro Preto in the centre of the mining region for imperial topaz and because of the easy access to the gemstone mines in the entire State of Minas Gerais, the setup and upgrading of the collection progressed steadily. The main focus at that time was on samples from the imperial topaz mines around Ouro Preto; the minerals from the Pegmatite Province in the states of Minas Gerais, Espirito Santo and Bahia; and, last but not least, the different emerald mines in Brazil: Itabira–Nova Era mining region in Minas Gerais, Carnaíba–Socotó mining area in Bahia, the Santa Terezinha (Campos Verdes) mining area in Goiás (as well as the deposits of Itaberaí and Pirenópolis in the same state), Tauá in Ceará State, and, during a later period, Caiçara do Rio dos Ventos/RN.

Back in Germany, at the beginning of the 1990s, I had the chance to execute several research projects on emerald at my home university, the Johannes Gutenberg University in Mainz. These projects were supported by the German Research Foundation (DFG) and gave me the possibility to visit a large number of emerald mines all over the world, e.g. in the Cordillera Oriental (Colombia), the Ndola Rural Emerald Restricted Area with the Miku–Kafubu mining field (Zambia), the Sandawana-Machingwe mining area (Zimbabwe), the Mananjary area (Madagascar), the Eastern Desert (Egypt), Leydsdorp in South Africa, the Swat Valley (Pakistan), and the Ural Mountains (Russia). During my time as research manager at the renowned Gübelin Gem Laboratory in Lucerne, Switzerland (1993–2013), the focus of my research activities changed towards ruby and sapphire.

Besides my jobs in different gem laboratories (starting in 1993 at the GGL lab), I have been involved in various teaching and training activities in collaboration with many government institutions in different countries, e.g. DNPM and CAPES-CNPq in Brazil, ECOMINAS in Colombia, CRPG/CNRS/IRD in France, GSP in Pakistan, and NGTC in China. In addition, I have conducted research and academic projects at numerous universities in Brazil and Thailand, as well as in Colombia (Universidad Nacional de Colombia in Bogota), Portugal (University of Porto), Kenya (University of Nairobi), Tanzania (University of Dar-es-Salaam), and Madagascar (University of Antananarivo). I took the roles of guest lecturer at the China University of Geosciences (CUGB) in Wuhan (China) and in Beijing (China), and part-time Professor of Gemmology at Tongji University in Shanghai (China). I also participated in many international conferences, scientific meetings, committees, etc. I have been a co-ordinator and/or lecturer in several gemmological courses/seminars/workshops in many countries, and author of a significant number of articles published in the most important gemmological magazines and journals.

- PREFACE

Coloured gemstones

“The first objects that we picked up and said ‘this has value for no other reason than its beauty’, it was not a food, not a fuel, not a medicine; these were Coloured Gems”

-Unknown

[...]

CHAPTER I

EMERALD

$Be_3 Al_2[Si_6O_{18}]$ +Cr,V, Fe, Mn, Mg, Na, Cs, Rb, Li, ...

"Emerald is a transparent bright green chromium and/or vanadium-rich variety of beryl."

Emerald – a member of the beryl family – is a beryllium-aluminium-silicate built of ring-shaped units. The crystal structure shows a channel-like arrangement of silicon-oxygen ring units along the c-axis (Figure 1.1). These structural channels play an essential role in incorporating those ions that do not necessarily fit into the beryl lattice. Foreign ions such as sodium and caesium that, because of their size, cannot occupy normal lattice positions can be accommodated in the structural channels. These also play an important role in the integration of entire molecules such as water or carbon dioxide.

Beryl is an allochromatic mineral; chemically pure beryl is colourless. The colour range of beryl varieties (aquamarine, morganite, heliodor, etc.) is determined by those foreign elements that are built into the lattice. The most important of these are iron (for blue, green, and yellow), manganese (for pink and red), chromium and vanadium (both for green). The dominant colourant of most emeralds is chromium although almost identical colour shades are produced by vanadium. The incorporation of variable amounts of ferric and ferrous iron adds the so-called aquamarine component to the emerald colour and leads to an undesirable blue tint.

Other elements, such as magnesium and sodium, can also be present in emerald while not impacting its colour. Their presence is highly variable and can reach several weight percentages. High magnesium content indicates that the crystal formed in metamorphic schist. Sodium is an essential partner to magnesium, as together they constitute a coupled isomorphic replacement of aluminium. When a magnesium ion with a valence of plus two replaces an aluminium ion with a valence of plus three in an octahedral position, one positive charge unit is missing in the mineral's structure. This is balanced by incorporating an atom with the valence of plus one (e.g. sodium, lithium, or caesium) within the structural channel, usually along with one or two water molecules. The substitution of Al^{3+} by bivalent ions such as Mg^{2+} and/or Fe^{2+} requires a coupled substitution to maintain a neutral charge balance, normally with Na^{1+} in the following way:

$$Al^{3+,VI} = Mg^{2+,VI} + Na^{1+(channel)} \quad \text{or} \quad Al^{3+,VI} = Fe^{2+,VI} + Na^{1+(channel)}$$

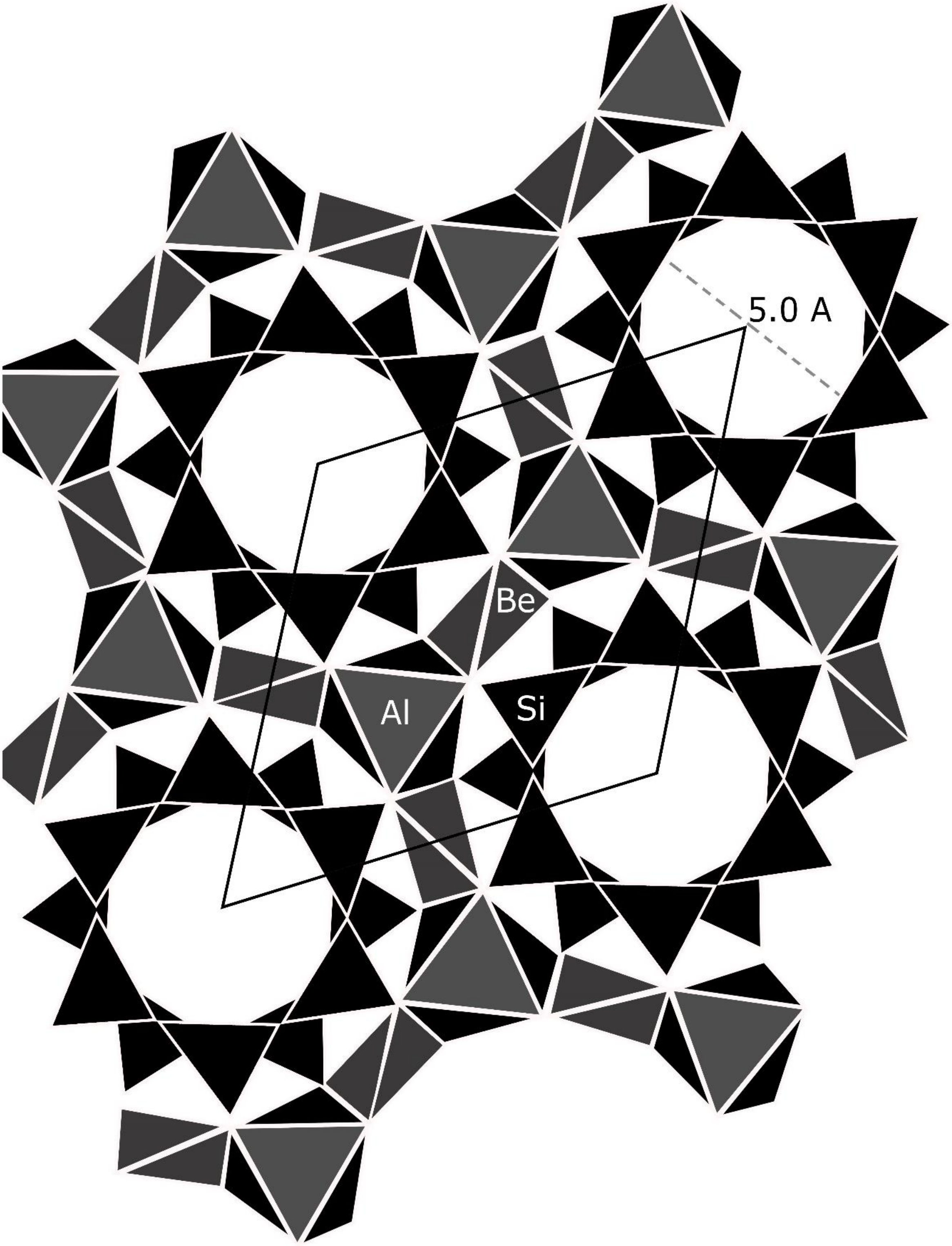


Figure 1.1: Crystal structure of beryl (001) plane.

Like any other gemstone mineral, emerald can be characterised using the following mineralogical-gemmological criteria:

[1] Internal features.

[2] Chemical fingerprinting.

[3] Spectral fingerprinting - UV-vis-NIR.

[4] Vibrational fingerprinting: FTIR and Raman.

[5] Isotopic fingerprinting.

[6] Physical-Optical characteristics.

From these criteria, the internal features, the chemical fingerprinting and, to a lesser extent, the spectral fingerprinting in the UV-vis-NIR region and the vibrational fingerprinting (FTIR and Raman range) are the most valuable characteristics for the 'gemmological description' of emerald. The determination of isotope ratios in faceted gemstones is still not considered a routine analytical procedure in the lab industry. Chemical fingerprinting using L.A.-I.C.P.-M.S. (laser ablation-inductively coupled plasma-mass spectrometry) is considered 'quasi non-destructive' because a tiny crater is burnt by the laser at the surface of the gemstone (generally in the girdle area).

[1] Internal features

The documentation, description and interpretation of the inclusion scenarios observed in natural emeralds from the most important locations all over the world are discussed in detail in Chapter II of this book.

[2] Chemical fingerprinting

The chemical fingerprint of an emerald reflects the geological-mineralogical environment (composition of mineralising fluids, host rock composition, temperature, and pressure conditions) at the time of its formation. For example, emeralds from the Pakistani Swat Valley and the Santa Terezinha mining area in Brazil (both originating from iron- and magnesium-rich talc-carbonate schists) show foreign element contents, which are among the highest found in emeralds. In contrast, emeralds originating from the black shales of the Cordillera Oriental in Colombia are characterised by a very low concentration of foreign elements.

Because of the presence of the channels that are oriented parallel to the c-axis, the beryl/emerald structure can be considered an 'open' structure that allows the incorporation of many foreign elements. On one hand, this makes the crystal chemistry of emerald quite complex while, on the other hand, the resulting chemical fingerprinting becomes a strong tool for the lab gemmologist when trying to assign a geographic (genetic) origin to an unknown emerald.

The replacement of Al^{3+} by trivalent ions and by bivalent ions such as Mg and/or Fe are the most common exchange reactions in natural emerald. The substitution of Al^{3+} in octahedral lattice sites by trivalent ions does not need a charge compensation:

$$Al^{3+(oct)} \rightarrow [V, Cr, Mn, Fe]^{3+(oct)}$$

[...]

CHAPTER II

INTERNAL FEATURE CLASSIFICATION

Among the properties used for the characterisation of coloured gemstones, the interpretation of the internal features is – in general – still the most common and most important routine examination for the gemmologist in the laboratory.

The precise description and the identification of inclusions in emeralds is an important tool in distinguishing between genuine and synthetic emeralds as well as in determining the geographic origin of natural emeralds. The study and documentation of the inclusion phenomena under the gemmological microscope are essential and an integral part of the testing procedure for a coloured gemstone. Solid inclusions, cavities with diverse types of fluid fillings, growth structures as well as the partially healed and unhealed fissures are addressed during the microscopic examination.

The intimate relationship between the genetic environment in which emeralds grow in nature and their ‘mineralogical-gemmological outfit’ is clearly shown by their inclusion scenarios. The so-called ‘internal mineral association’ (meaning the entire suite of minerals/host rock particles) observed in emeralds originating from different geological environments is generally a perfect reflection of the mineralisation that hosts an emerald in nature (‘external mineral association’).

Classification of the internal characteristics observed in coloured gemstones

The internal characteristics (solid inclusions, cavities containing fluid fillings and growth features) of coloured gemstones can be classified in different manners, as follows:

[A] The genetic classification is based on the time of formation with regard to the gemstone host ('matrix'); it is the appropriate method for the discussion of genetic aspects of emerald growth. In this classification, the inclusions can be addressed as protogenetic, syngenetic, or epigenetic. Fluid inclusions are designated as primary, secondary or pseudo-secondary (see below).

Protogenetic: formed before the growth of the host emerald started (generally under different genetic conditions); trapped 'accidentally' by the growing emerald; in general, protogenetic inclusions do not show a crystallographic orientation in the host emerald, e.g. black spinel grains or colourless talc flakes in emeralds from Santa Terezinha.

Syngenetic: formed simultaneously during the growth of the host emerald (under the same genetic conditions); often have a crystallographic orientation in the host emerald, e.g. parallel to the basal pinacoid or parallel to the emerald's c-axis.

Epigenetic: formed after the growth of the host emerald had definitely ended. Epigenetic fluid inclusions form when xeno-physical solutions penetrate into open fissures and fractures where they crystallise or just dry out (→ pseudo-healing = mechanical filling of a fissure by infiltration of foreign substance, e.g. the formation of dendritic patterns).

[B] The phenomenological classification is more useful for the description and interpretation of the internal features when dealing with the separation of synthetic and natural emeralds, and also for the characterisation of natural emeralds originating from different genetic environments (e.g. the Colombian deposits related to black shales or the many deposits that are related to metamorphic schists).

The inclusion types to be considered in the phenomenological classification are:

[1] Solid inclusions: (normally crystals or crystal aggregates; more rarely amorphous substance).

[2] Cavities containing fluid fillings or melt fillings: (this type shows a great variability regarding size, shape, and filling combinations).

[3] Primary and secondary growth features: growth tubes; negative crystals; zonal structures (including colour zoning and uneven colour distribution); twin lamellae; partitioning/cleavage planes; intersection tubules; structural textures (e.g., growth planes); fissures and fractures (the most important ones, from a diagnostic standpoint, are the so-called 'partially healed fissures').

[1] Solid inclusions

Solid inclusions are among the most common internal features in emeralds. They show an enormous diversity of colour, transparency, shape and size. Synthetic emerald can also host solid inclusions (e.g., crystals of phenakite, chrysoberyl, etc.), but these do not exhibit nearly as wide a variety as those in natural stones. The solid inclusions in natural emeralds (internal mineral association) reflect the nature and composition of the emerald's host rock (external mineral association). Among natural stones, emeralds from metamorphic schists are significantly rich in solid inclusions. Unable to grow freely in open cavities in the same way as, for example, Colombian or Nigerian emeralds, schist-type emeralds supplant the host rock's minerals in a solid state.

Along with the other characteristics, solid inclusions have great diagnostic value in distinguishing natural from synthetic emeralds; they are also essential indicators of a stone's paragenetic environment and eventually its geographic origin. The majority of the world's emerald deposits are hosted in different types of metamorphic schists. The most common host rocks of emerald are mica-schists, which, in general, show a biotite-phlogopite composition. Consequently, it is no surprise that mica crystals of the biotite-phlogopite series are, by far, the most frequent mineral inclusions in emeralds. The appearance, i.e. shape, colour, and size of the mica inclusions may show an enormous variability. Mica inclusions will prove the natural origin of an emerald but, in general, they do not give an indication of the exact provenance. Therefore, they do not have a locality-specific diagnostic value (Figures 2.1 to 2.5).

In many cases, the schist-type host rock shows variations in its mineral composition. For example, mica-schists may contain variable amounts of amphibole minerals (mostly actinolite-tremolite) or they may gradually pass into almost pure amphibole schists. In emeralds originating from such schists, the amount of amphibole inclusions will also increase, and this mineral will become the dominant inclusion mineral (Figures 2.3 and 2.4).

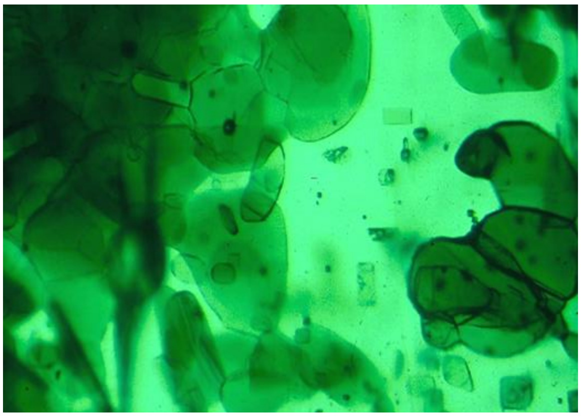


Figure 2.1: Biotite-phlogopite inclusions in a Madagascar emerald. The micas are of protogenetic formation. Immersion, x 50.

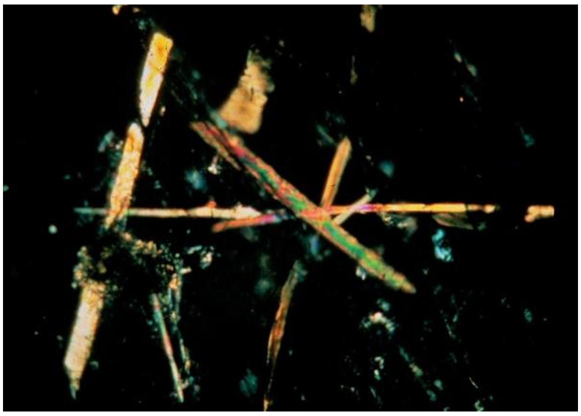


Figure 2.2: Biotite-phlogopite inclusions in an emerald from the Carnaíba-Socotó mining area in Bahia/Brazil. The micas are of protogenetic formation and show unusual, lath-like shapes. Crossed polariser, x 70.

The most frequent inclusion minerals in emerald are those that are the main components of the surrounding host rock (meaning those that belong to the 'external mineral association'). Micas of the biotite/phlogopite series are the dominant mineral inclusions in emeralds from the following occurrences: Carnaíba-Socotó in Bahia State (Brazil); Itabira-Nova Era region in Minas Gerais (Brazil); Ndola Rural District in Zambia; Mananjary region in Madagascar; Transvaal (South Africa); Lake Manyara (Tanzania); Ural Mountains (Russia); Eastern Desert (Egypt); Habachtal (Austria) and Shakiso in the Seba Boru district (Ethiopia).

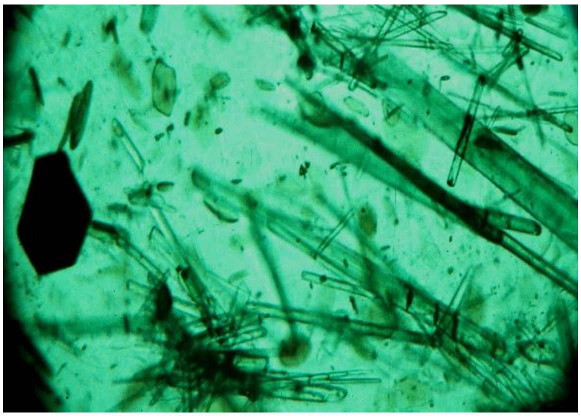


Figure 2.3: Emerald from the Tauá occurrence in Ceará State (Brazil). These emeralds have formed in a biotite/phlogopite-amphibole mica schist. As a consequence, their inclusion scenario is dominated by the presence of mica and amphibole inclusions (also present is a well-developed, black-opaque, six-sided molybdenite platelet).

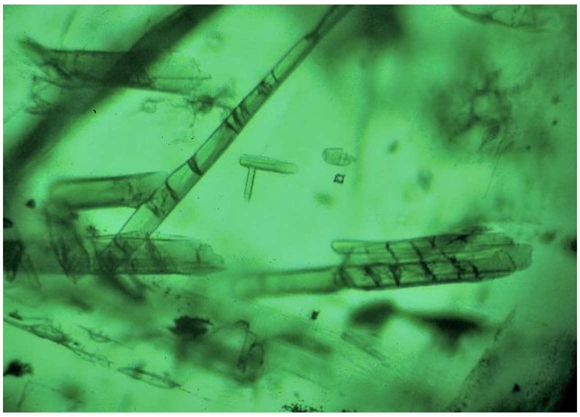


Figure 2.4: Emerald from the Mananjary mining area in Madagascar. The emerald host rocks are mica-amphibole schists of variable composition. The internal mineral association contains both biotite/phlogopite and amphibole as the dominant inclusions.

Emeralds from the Kaduna/Plateau States in central Nigeria show a unique and locality-specific internal mineral association, including some quite 'exotic' minerals: different fluorides + Fe-rich micas + albite + ilmenite + monazite. Its dark-brown, Fe-rich mica crystals are most likely in the compositional range of annite-siderophyllite or zinnwaldite. Their presence reflects the special genetic environment for these emeralds that have been formed in greisen associations of Mesozoic alkali granite ring complexes (Schwarz et al., 1996), (Figure 2.5).

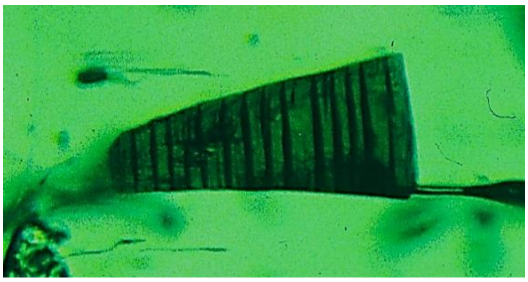


Figure 2.5: Emeralds from the Nigerian Kaduna State were formed in a unique geological setting. Consequently, the internal mineral association of the Nigerian emeralds is also unique. Whereas the mica inclusions in emeralds from 'classic' schist-type deposits are generally biotites/phlogopites, the mica inclusions in the Nigerian emeralds belong to an iron-rich variety (most likely in the compositional range of annite-siderophyllite or zinnwaldite).

[...]

CHAPTER III

GEOLOGICAL-GENETIC CONSIDERATIONS

Emerald is a rare mineral of the beryl family. Emerald's rarity comes from that fact that its chromophore elements – chromium and vanadium – are geochemically not related to beryllium, which is one of the main components of beryl. The limiting factor in the formation of emerald is the requirement of geological conditions that result in an environment rich in both beryllium and chromium and/or vanadium. With beryllium concentrated in the Earth's continental crust and chromium/vanadium concentrated deeper in the upper mantle, unusual geologic and geochemical conditions are required for chromium and/or vanadium to encounter beryllium. There are a few deposits in which the circulation processes inside one geological unit are sufficient for emerald formation (e.g., the black shales of Colombia), but in general, the source rocks for the different elements must first be brought together (during small-scale or large-scale geological events) and then channels must be opened to permit the circulation of the fluids and the mobilisation of the elements that are necessary for emerald formation.

This happens mostly through the action of plate tectonics. The tectonic events related to the movements of the crustal plates result in the formation of folds and faults which mobilise fluids that move along the newly created fractures. These fluids can then dissolve and transport the required elements. Once the essential elements are brought together, emeralds can crystallise in diverse geologic environments. Most common among these are emerald deposits in biotite-phlogopite schists (e.g. 'the schist-type deposits' in Africa, Brazil, and Russia).

Emerald is trapped in different structures (shear zones, faults, veins, breccias, pockets, lens-shaped cavities, etc.), or it is disseminated in the infiltrated rocks. Its deposition is a function of [a] mechanical effects due to brecciation, geometry of the vein wall-rock, etc. and [b] chemical aspects like the effect of fluid-rock interactions on the solubility of Be, Al, and Si; the mobility of these elements within an alteration zone; and the activity coefficients of Be, Si, Al in the fluid and within each of the infiltrated zones (Schwarz and Giuliani, 2001).

Geological timescale and formation of emerald deposits/occurences

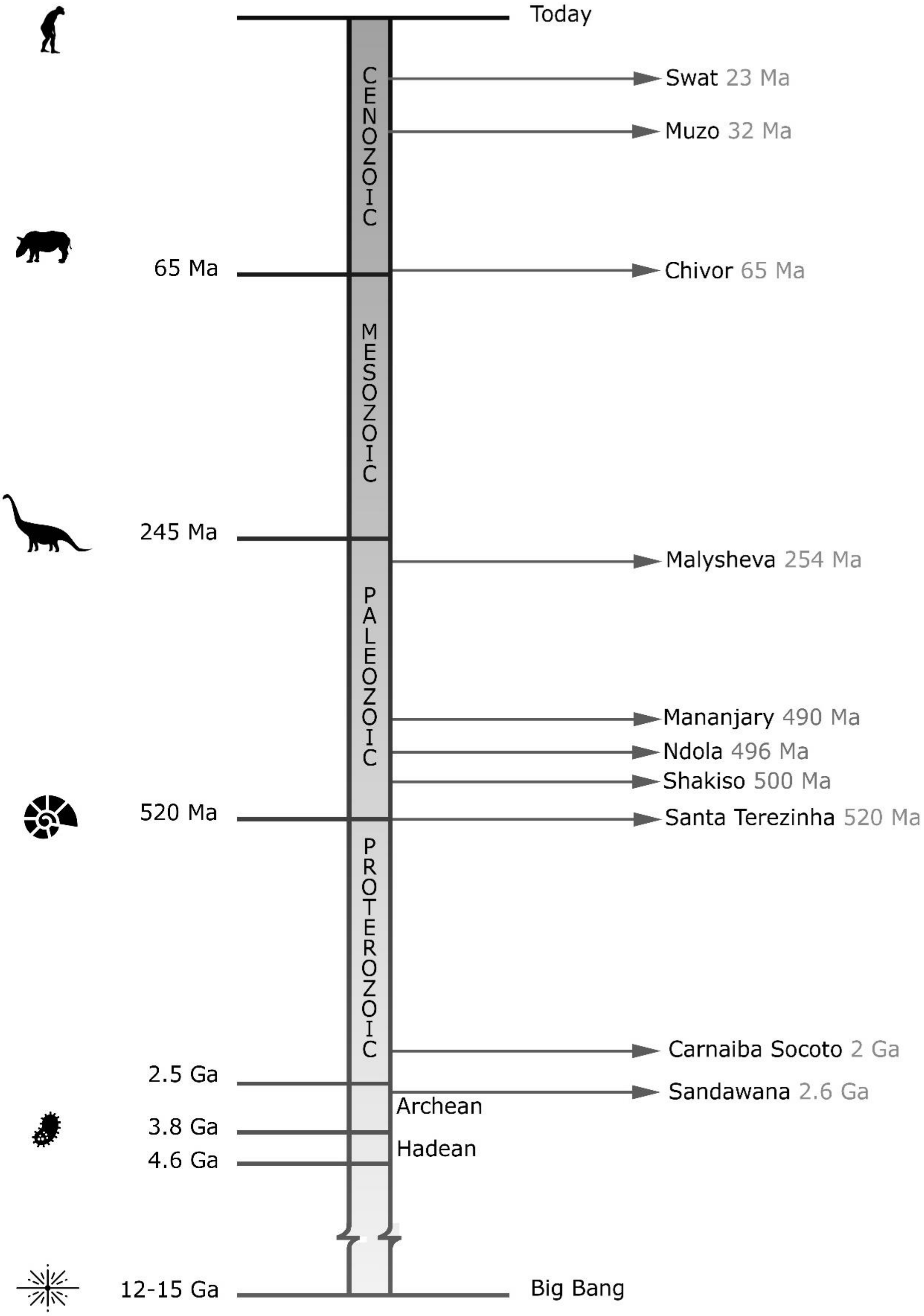


Figure 3.1: Formation of emerald deposits/occurrences.

Emerald growth always results from fluid-rock interactions. The infiltrating fluids interact with the emerald's parent rocks and along their contact zones, for example, between a pegmatite vein and a mafic-ultramafic rock ('metasomatic alteration'). Chemical exchanges occur along closely-spaced fractures. The infiltrated rocks are hydrothermally altered, and chemical components (Al, Si, K, Be, F, Cl, B, Li, Rb, Nb, Ta, Mo, ...) carried by fluids or leached (Si, Mg, Na, Fe, Ca, Cr, V, Sc) from the parent rocks combine to form emeralds within the alteration zone, at pressure and temperature (P-T) conditions controlled by the fluid circulation processes (Schwarz and Giuliani, 2001).

While aquamarine and other pegmatite minerals develop in relatively steady and smooth environments which allow for continuous crystal growth without strong perturbations, emeralds are formed in geologic environments characterised by abrupt changes and by the influence of mechanical stress. Smaller crystals with considerable internal defects such as fissures, fractures or foreign solid inclusions are consequences of the formation in a 'chaotic' mineralogical-geologic environment, and partially-healed or unhealed fissures and fractures are quite common. The presence of such defects lowers a crystal's mechanical resistance. Unable to withstand the stress of river transport, emerald is only very rarely found in secondary deposits.

Emerald deposits are known from five continents, with South America, for many years, being the world's most important emerald producer. The most intense emerald formation occurred during the continental collisions which gave rise to large mountain complexes, extended fault zones, regional metamorphic overprints and eventually to further uplift and erosion. All these events favour the formation of emerald deposits. Emerald can, therefore, take its place among the oldest gemstones in the Earth's crust.

Many published proposals have attempted to classify and categorise the different types of emerald mineralisation. Historically, emerald deposits have been classified into three broad types.

The first and most abundant deposit type, in terms of production, is the desilicated pegmatite-related type that formed via the interaction of metasomatic fluids with beryllium-rich pegmatites, or similar granitic bodies, that intruded into chromium- or vanadium-rich rocks, such as ultramafic and volcanic rocks, or shales derived from those rocks. A second deposit type, accounting for most of the emerald of gem quality, is the sedimentary type, which generally involves the interaction, along faults and fractures, of upper level crustal brines rich in Be from evaporite interaction with shales and other Cr- and/or V-bearing sedimentary rocks. The third, and comparatively rarest, deposit type is the metamorphic-metasomatic deposit. In this deposit model, deeper crustal fluids circulate along faults or shear zones and interact with metamorphosed shales, carbonates, and ultramafic rocks; Be and Cr (±V) may either be transported to the deposition site via the fluids or already be present in the host metamorphic rocks intersected by the faults or shear zones. All three emerald deposit models require some level of tectonic activity, and continued tectonic activity can often result in the metamorphism of an existing sedimentary or magmatic type deposit (Giuliani et al., 2019).

Because of the exceptional circumstances required for chromium and/or vanadium to encounter beryllium, emerald deposits tend to be complex, and the sources of their key elements and how they were transported are not always obvious. General classification schemes have been built on certain specific aspects of the deposits' genetic histories and they may take into consideration, for example: (a) the origin of the elements Be and Cr/V and the source of the parental fluids; (b) the petrologic and tectonic associations encountered in the mining areas; and (c) geochemical data, especially the types of hydrothermally altered rocks which are found worldwide in emerald deposits.

Schwarz and Giuliani (2001 a, b) recognised two main types of emerald deposits: those related to granitic intrusions (Type I) and those where mineralisation is mainly controlled by tectonic structures, such as a fault or a shear zone (Type II). Most emerald deposits fall into the first category and are subdivided based on the presence or absence of biotite schist at the contact. Type II deposits are subdivided into schist without pegmatite and black shale with veins and breccia. However, a number of emerald deposits of Type I have been influenced by syntectonic events, such as Carnaíba (Brazil), Poona (Australia) or Sandawana (Zimbabwe), or remain unclassified, such as the Gravelotte (Leydsdorp) deposit in South Africa (Schwarz et al., 2001 a).

Schwarz et al. (2002) classified emerald deposits based upon their appearance in the field following several sketched geological profiles drawn by Grundmann (2002), (see sketches in Chapters VI, VII, X, XI, XII): (1) pegmatite without phlogopite schist; (2) pegmatite and greisen with phlogopite schist; (3) schist without pegmatite with (3a) phlogopite schists, (3b) carbonate-talc schist and quartz lens, or (3c) phlogopite schist and carbonate-talc schist; and (4) black shale with breccia and veins.

Giuliani et al. (2015) classified emerald deposits into three broad types based on worldwide production in 2005: (1) magmatic-metasomatic type (Ma), accounting for about 65% of production; and (2) sedimentary-metasomatic (Se) and metamorphic metasomatic (Me) types, accounting for 28% and 7%, respectively.

Marshall et al. (2016) proposed an enhanced classification for emerald deposits based on the Me, Ma, and Se models, but also including the temperature at formation. They examined the possibility, at deeper crustal levels and with high-grade metamorphism, of the possible remobilisation of previous beryl or emerald occurrences and partial melting of metamorphic rocks blurring the distinction between Me and Ma types.

Finally, Giuliani et al. (2019) presented “A Review and Enhanced Classification” of emerald deposits. In this work, the authors proposed classifying emerald occurrences into two main types (Table 3.1):

[Type I] Tectonic magmatic-related with sub-types hosted in:
- [Type IA] Mafic-ultramafic rocks (Brazil, Zambia, Russia, and others);
- [Type IB] Sedimentary rocks (China, Canada, Norway, Kazakhstan, Australia);
- [Type IC] Granitic rocks (Nigeria).

[Type II] Tectonic metamorphic-related with sub-types hosted in:
- [Type IIA] M-UMR (Brazil, Austria);
- [Type IIB] Sedimentary rocks-black shale (Colombia, Canada, USA);
- [Type IIC] Metamorphic rocks (China, Afghanistan, USA);
- [Type IID] Metamorphosed Type I deposits or hidden-granitic intrusion-related (Austria, Egypt, Australia, Pakistan), and some unclassified deposits.

This enhanced classification for emerald deposits is based on (1) the geological environment, i.e., magmatic or metamorphic; (2) host rock type, i.e., mafic-ultramafic rocks, sedimentary rocks or granitoids; (3) degree of metamorphism; (4) styles of mineralisation, i.e., veins, pods, metasomatites or shear zone; and (5) types of fluid and their temperature, pressure and composition. The new classification takes into account the multi-stage formation of the deposits and ages of formation, as well as probable remobilisation of previous beryllium mineralisation, such as pegmatite intrusions in mafic-ultramafic rocks. Such new considerations use the concept of genetic models based on studies employing chemical, geochemical, radiogenic, and stable isotope, and fluid and solid inclusion fingerprints.

[...]

CHAPTER IV

GEOGRAPHIC ORIGIN DETERMINATION

The determination of the geographic origin of coloured gemstones has its beginnings in Europe in the 1950s, with the first gem labs offering this service being Gübelin (GGL) and SSEF, both based in Switzerland. Since the beginning, the determination of geographic origin has been a controversial topic in the trade, with strong supporters and critical opponents. At the outset, the need for origin reports was restricted to a few kinds of gemstones and a small group of highly reputed deposits, especially rubies from Mogok (Burma) and sapphires from Sumjam, Kashmir (India). Today, however, some labs are also offering determination of origin services for emerald, alexandrite, spinel, and garnet (demantoid; tsavorite).

Criteria for the determination of geographic origin of coloured gemstones

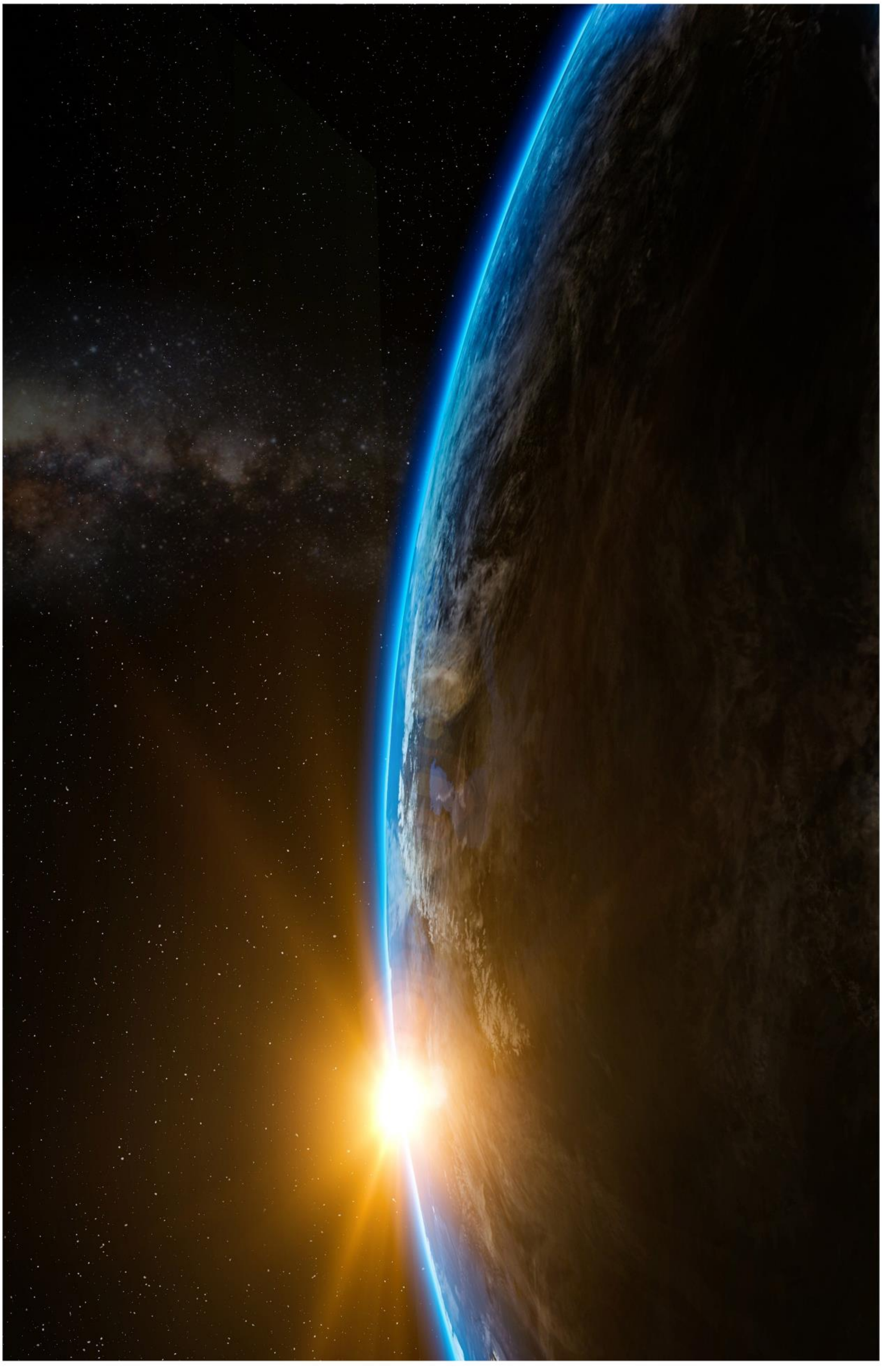
When talking about the determination of geographic origin of gemstones (including emerald), three questions are of central importance:

[1] How is it possible to determine the geographic origin of an unknown emerald?

[2] How is geographic origin determination performed in a laboratory?

[3] What are the limitations of determining the geographic origin of gemstones?

Emeralds, like all coloured gemstones, can be characterised by a series of gemmological-mineralogical criteria. The gemmological properties of an emerald directly depend on the set-up of the geological-mineralogical environment in which it has formed. These properties always reflect the growth conditions that prevailed during the formation of the emerald crystals in their natural setting. The determination of geographic origin is possible because there is a close relationship between the genetic environment, especially the natural environment including the mineralogical composition of the host rock, and the mineralogical-gemmological properties of the emeralds, and this relationship can be studied by gemmologists in the lab.



The 'classic approach' to the determination of geographic origin involved trying to find properties in an unknown gemstone that were considered locality-specific (this means typical for a certain geographic region). Traditionally, the testing procedure in the lab focused mainly on the study of the inclusion features through the gemmological microscope. For example, for a long time, the presence of the 'classic rutile silk scenario' was considered typical for Burmese rubies from the Mogok area; in the same way, the so-called 'three-phase inclusions' – especially when hosted by cavities with jagged outlines – were considered a locality-specific scenario for emeralds originating from the deposits in the Colombian Cordillera Oriental (Figure 2.13).

With the 'modern approach', the determination of geographic origin is based on the full documentation of an unknown gemstone. This means that all relevant data for this gemstone are collected during the testing procedure in the laboratory. In general, this is the combination of inclusion scenario + chemical fingerprinting + spectral fingerprinting (UV-vis-NIR/FTIR/RAMAN). After the complete documentation of the unknown stone has been collected, a comparison of its data set with properties of samples from a precisely documented and interpreted reference collection is carried out. The interpretation of the mineralogical-gemmological properties collected during the testing allows the correlation of these data with a specific environment in nature. Finally, this specific geological-genetic environment can be related to certain geographic locations.

The most relevant factors controlling the genetic environment in which a gemstone is formed are: the nature of the host rock; 'interactive events' between the host rock and the neighbouring rock units (e.g. exchange reactions involving the migration of fluids, thus introducing or taking away chemical components necessary or unwanted for the growth of a gemstone); pressure and temperature conditions; and the composition and nature of solutions/liquids that are responsible for the dissolution, transport and precipitation of the (chemical) components involved in the growth of a gem crystal.

The criteria/analytical methods used for the mineralogical-gemmological characterisation of a gemstone are:

[1] Study of the inclusion scenario*, using

[1a] Optical microscopy for the phenomenological description and

[1b] RAMAN micro-spectroscopy and SEM (scanning electron microscopy) for the identification of solid inclusions.

**Totality of the features observed in the interior of a gemstone: solid inclusions, cavities containing fluid fillings, primary and secondary growth features.*

[2] Chemical fingerprinting, using EDXRF - X-ray spectroscopy or L.A.-I.C.P.-M.S.

(chemical data such as absolute element concentrations; concentration ranges; element ratios or correlation diagrams; trace-element patterns).

[3] Spectral fingerprinting in the UV-vis-NIR range.

Ultraviolet-visible-near infrared spectroscopy (UV-vis-NIR or UV/Vis/NIR) refers to absorption spectroscopy or reflectance spectroscopy in the ultraviolet-visible-near infrared spectral region. In this region of the electromagnetic spectrum, molecules undergo electronic transitions.

[…]

CHAPTER V

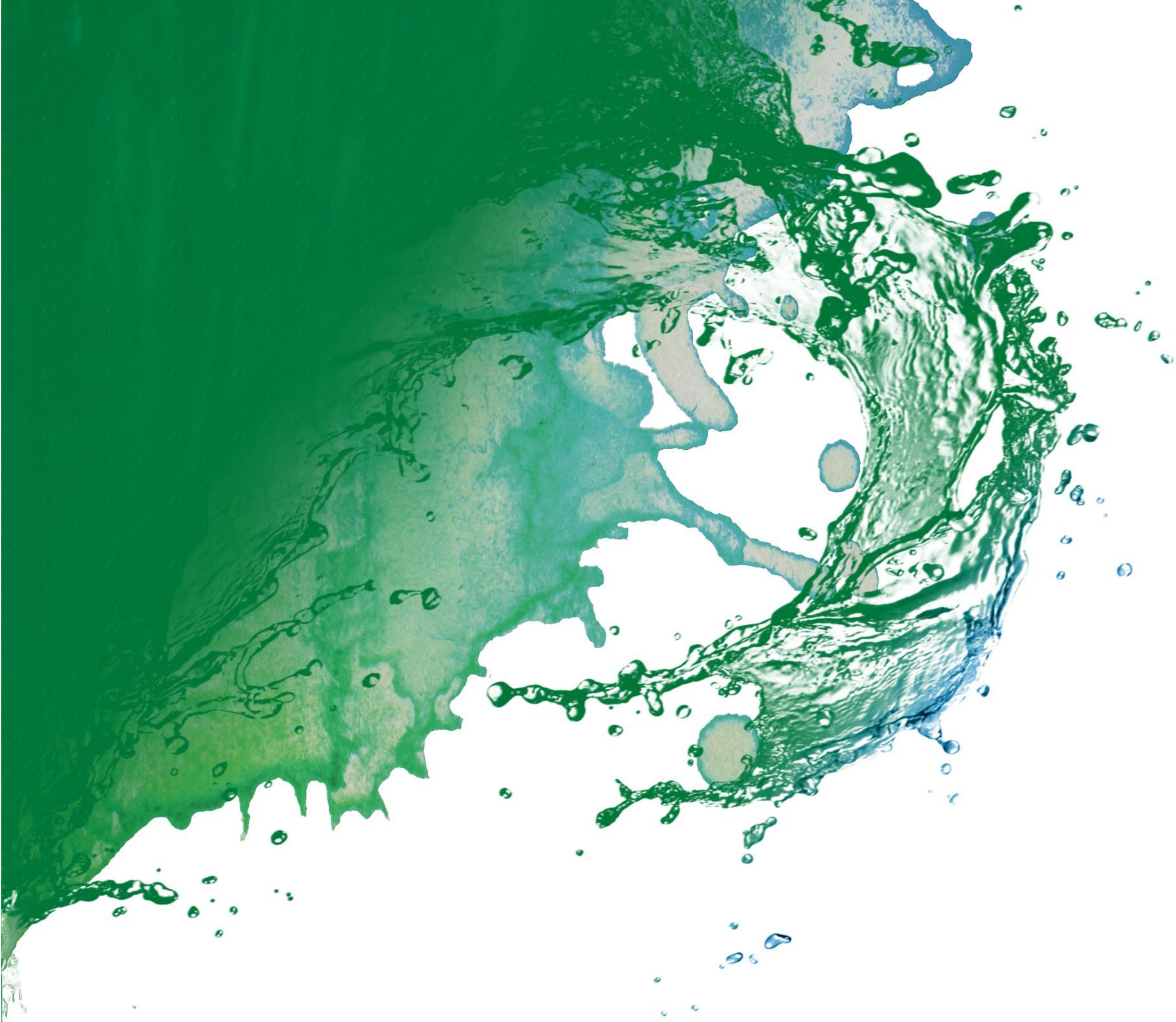
AFGHANISTAN

History

In his 1st century AD account entitled 'Natural History', Pliny mentions "*smaragdus*" from Bactria, an area that includes present-day Iran and Afghanistan. Although emeralds have been reported from this region for literally thousands of years, the Panjshir Valley of Afghanistan has produced commercial amounts of emerald only since the decades of the 1970s and 1980s (Bowersox et al., 1991). Today, it is widely accepted that the so-called Bactrian emeralds from old Hindu treasures (dating back as early as 1000 AD) may have originated from old mines in Afghanistan and Pakistan.

Russian geologists reportedly found emerald deposits during a systematic campaign in the early 1970s; however, analyses of historic emeralds indicate that some of the 'old mine emeralds' in Indian jewellery are in fact from Afghanistan. It is not known when the Panjshir deposits were first mined, but there are indications that mining began not later than the 18th century (Giuliani et al., 2000).

The Panjshir Valley is home to Afghanistan's largest concentration of ethnic Tajiks. It was used by Commander Ahmad Shah Massoud (the 'Lion of Panjshir') as the base for his Northern Alliance during the 1979-1989 Soviet war in Afghanistan. The Panjshir Valley was the only part of Afghanistan which successfully resisted Soviet control. After 1996, when the Taliban took over power in Afghanistan, the Panjshir Valley became an important point of resistance and the stronghold of rebel leader Ahmad Shah Massoud. It was said that Massoud financed his military activities, in part, through the sale of Panjshir emeralds. The emerald production from the area increased in 1999, although the trade route shifted from Pakistan to Tajikistan. The Afghani emerald mines have always been controlled by Tajik Panjshir, who are enemies of the Taliban.



Bowersox et al. (2015) give the following summary of the recent history of the emerald mines of Afghanistan. Commercial production in Afghanistan's Panjshir Valley only commenced in the early 1980s and has primarily been conducted by Afghan enterprises and individuals, with much of this activity based on historic customary, tribal, and family-based operations. Large, dark green crystals have been discovered by local Afghans in hundreds of tunnels and shafts throughout the valley. Informal removal and sale of these emeralds provided financial support for the activities of the Mujahideen ('freedom fighters') during the Soviet occupation of Afghanistan (1979-89). Since that time, the emeralds mined there have continued to provide an informal, if not exactly lucrative, business opportunity for local Afghans. Emerald mining in Afghanistan has never been formalised; no legal licensing of emerald mines is known to be in place. Nonetheless, emerald production conducted by local Afghans generates an estimated $10 million each year, with the revenues generated here not formally taxed.

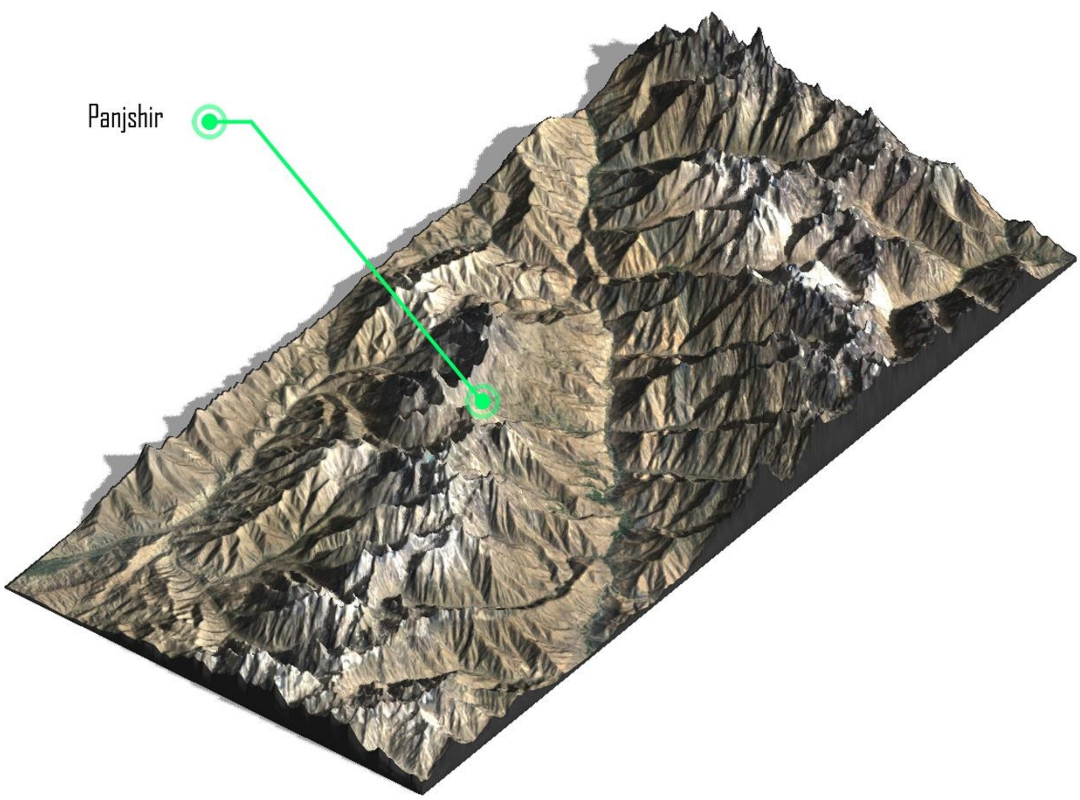
The emerald mines of Afghanistan are located approximately 70 miles (113 km) northeast of Kabul and extend from the village of Khenj to Dest-e-Rewat. The known elevations of the emerald deposits range from ca. 2,135 – 4,270 metres amidst mountainous terrain on the eastern side of the Panjshir Valley.

AFGHANISTAN

Geological and Genetic Aspects

Fragments of Gondwana, an ancient supercontinent that began to drift apart about 200 Ma, collided with, and sutured to, ancestral Asia, thereby creating the Himalaya Mountains. These bits and pieces form a geologic mosaic that is now Afghanistan.

The Panjshir Valley is a major fault zone between two of two crustal plates: the ancestral Asian plate to the northwest and the microcontinental fragment known as Cimmeria to the southeast. The Panjshir Valley marks the location of the closure of a major ocean known as the Paleotethys.



The Afghan emerald deposits belong to the Sub-Type IIC (tectonic metamorphic-related emerald deposits hosted in metamorphic rocks other than M-UMR and black shales). This sub-type includes emerald-bearing quartz vein and veinlet deposits located in medium pressure metamorphic rocks, ranging from greenschist to granulite facies.

The Panjshir emerald deposits in Afghanistan are in the Herat-Panjshir suture zone along the Panjshir Valley. The suture zone, which marks the collision of the Indo-Pakistan plate with the Kohistan arc sequence, contains a number of faults, such as the Herat-Panjshir strike-slip fault, which was mainly active during the Oligocene-Miocene. The emerald deposits lie southeast of the Herat-Panjshir Fault in the Khendj, Saifitchir, and Dest-e-Rewat Valleys. They are hosted by metamorphic schists that have been affected by intense fracturing, fluid circulation, and hydrothermal alteration, resulting in intense albitisation and muscovite-tourmaline replacements.

Emerald is found in vugs and quartz veins associated with muscovite, tourmaline, albite, pyrite, rutile, dolomite, and Cl-apatite. Ar-Ar dating on a muscovite from the emerald-bearing quartz veins at the Khendj mine gave an Oligocene age of 23 ± 1 Ma. At present, the sources of Cr and Be remain unclear (Giuliani et al., 2019).

AFGHANISTAN

GEMMOLOGY

Emerald Panjshir 4.88 ct
Bellerophon Gemlab Collection

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Emeralds from the Panjshir Valley (Afghanistan)

Internal features

[1] Solid inclusions (see inclusion gallery, photos AFG-01 to 05)

Not much information is available regarding the solid inclusions in Panjshir emeralds. Bowersox (1991) mentioned limonite, beryl, pyrite, rhombohedra of a carbonate and feldspar. Moroz and Eliezri (1999) identified only Fe-Cr oxide and beryl as solid inclusions. Sabot et al. (2001) described natural organic compounds and graphite inclusions (linked with the thermochemical reduction of sulphate by organic matter). The most frequent inclusion minerals in Panjshir emeralds found by Schwarz and Pardieu (2006) were carbonate(s), quartz, pyrite, and tourmaline. The reported 'internal mineral association' is in accordance with the nature of the emerald host rocks in the Panjshir Valley.

Hereinafter, the results of a detailed microscopic examination of more than 200 Panjshir emeralds is presented (Schwarz, 2018/2019). The 'internal mineral association' is described in detail as follows:

- Colourless-transparent, short- to long-prismatic beryl/emerald crystals. These may be difficult to see in transmitted light; however, when using crossed polarisers, they become visible, because their position of extinction is different from that of the host emerald.
- Colourless-transparent, irregularly shaped (rounded) or well-developed (rhombohedral) carbonate crystals. The carbonates have strong contours in the host emerald. They do not show a preferred orientation. They are of proto-genetic formation.
- Proto-genetic pyrite crystals of variable size. The pyrites are mostly irregularly rounded; often, they show many (slightly rounded) faces. When using fibre optics illumination, the pyrite inclusions display a typical brass-like metallic lustre.
- Tourmaline inclusions in the form of greenish brown, transparent, short- or long-prismatic crystals of proto-genetic nature (Figure 5.1).
- Black-opaque mineral inclusions; these are present as:

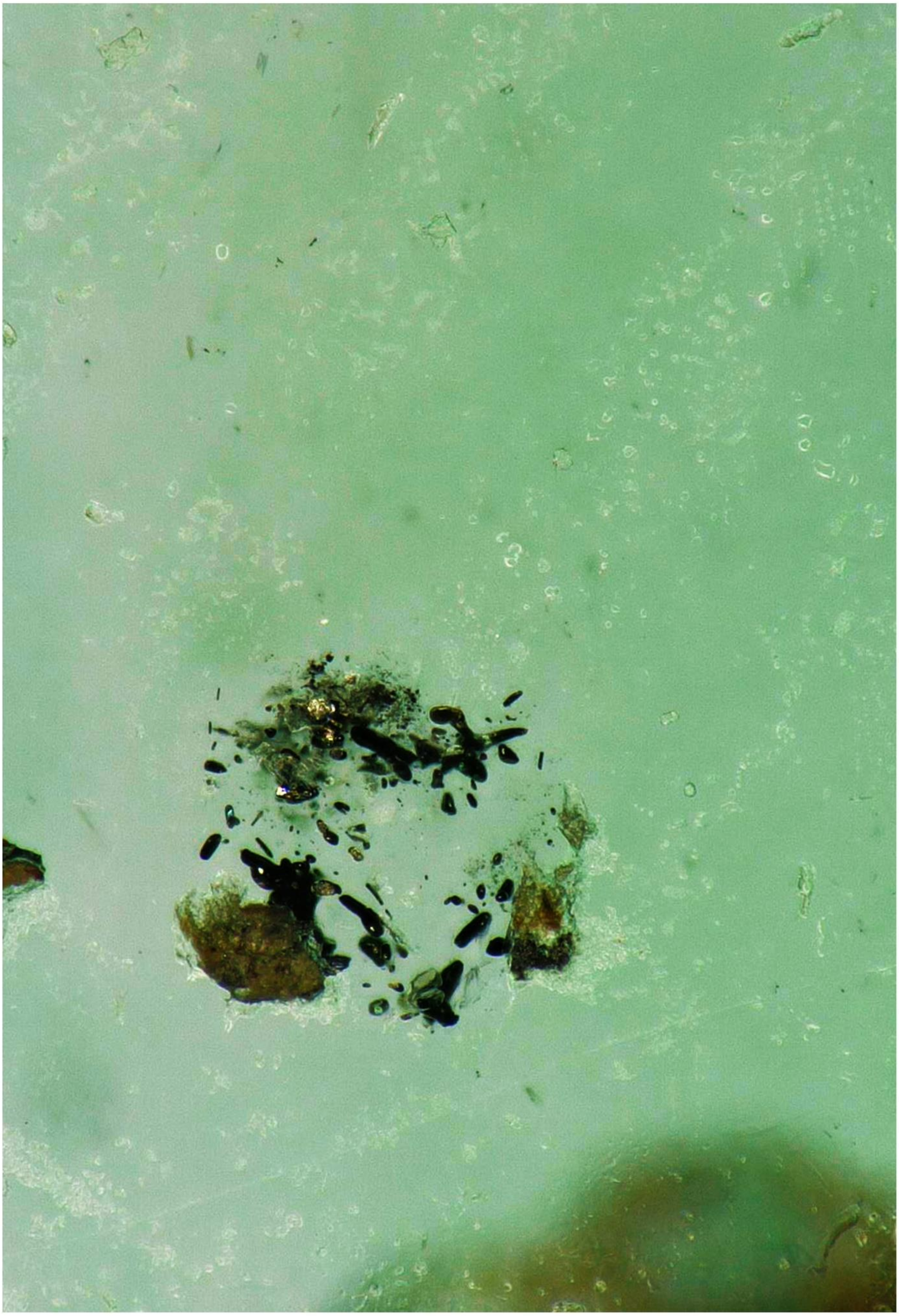
  (1) irregularly rounded crystals showing a 'rough' surface; or

  (2) small, angular crystals that display a strong 'sub-metallic' lustre when cut at the surface (graphite?).
- Colourless mineral inclusions are common in Panjshir emeralds; they belong to different species (carbonate, quartz, feldspar, and undefined crystals). These display a large variation with respect to transparency (transparent to greyish white), size (mostly small, sometimes sugar grain-like), shape (irregularly rounded to angular; rarely well-developed) and the strength of their contours in the host emerald (weak to strong). Mostly, these crystals occur in isolation (single); in part, they are arranged in cluster-like formations or in compact agglomerations.
- Brownish to orange-brown, transparent-to-translucent, irregularly shaped (angular) crystals of unknown nature.
- The only mineral inclusion found until now exclusively in Panjshir emeralds is a phosphate mineral for which Raman analysis gave two options: monazite or eosphorite (Schwarz and Pardieu, 2009), (Figure 5.2).

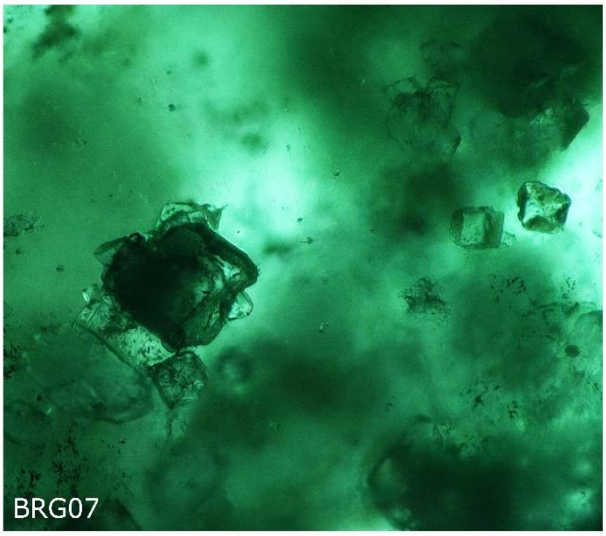
[...]

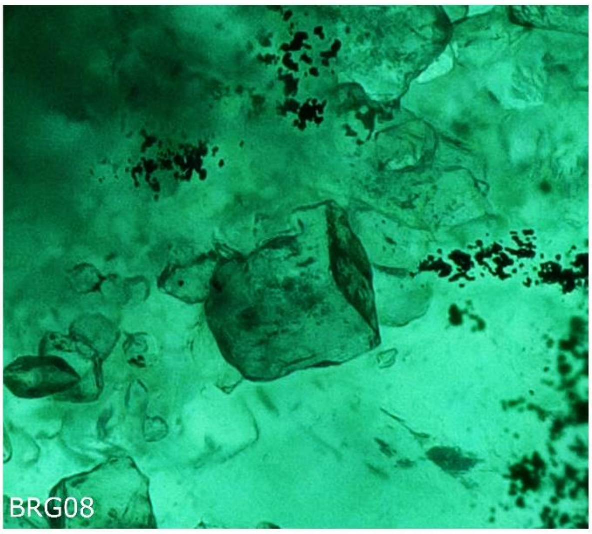
INCLUSIONS GALLERY

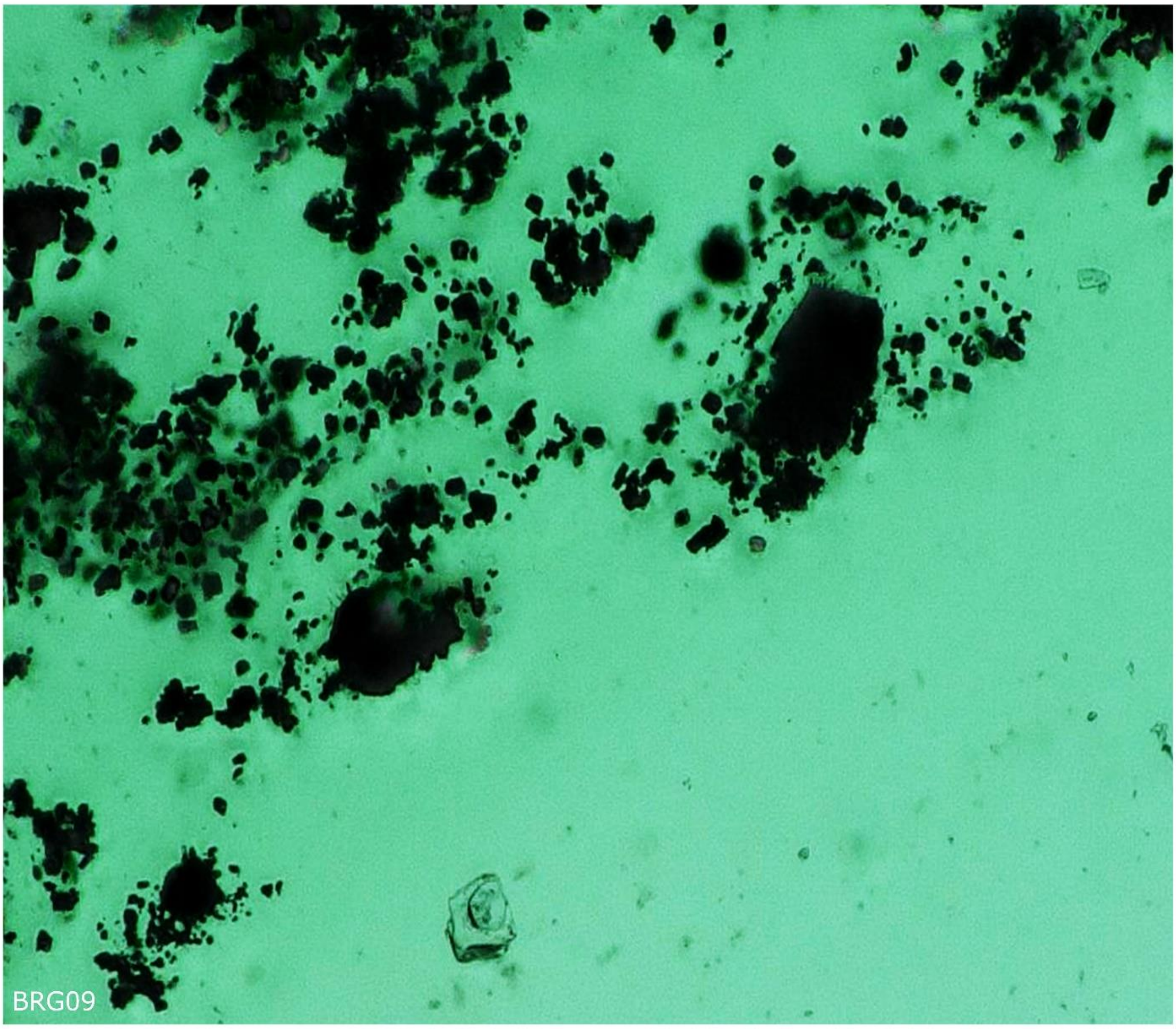
Brazil Goias



BRG01: Agglomeration of different protogenetic mineral inclusions.



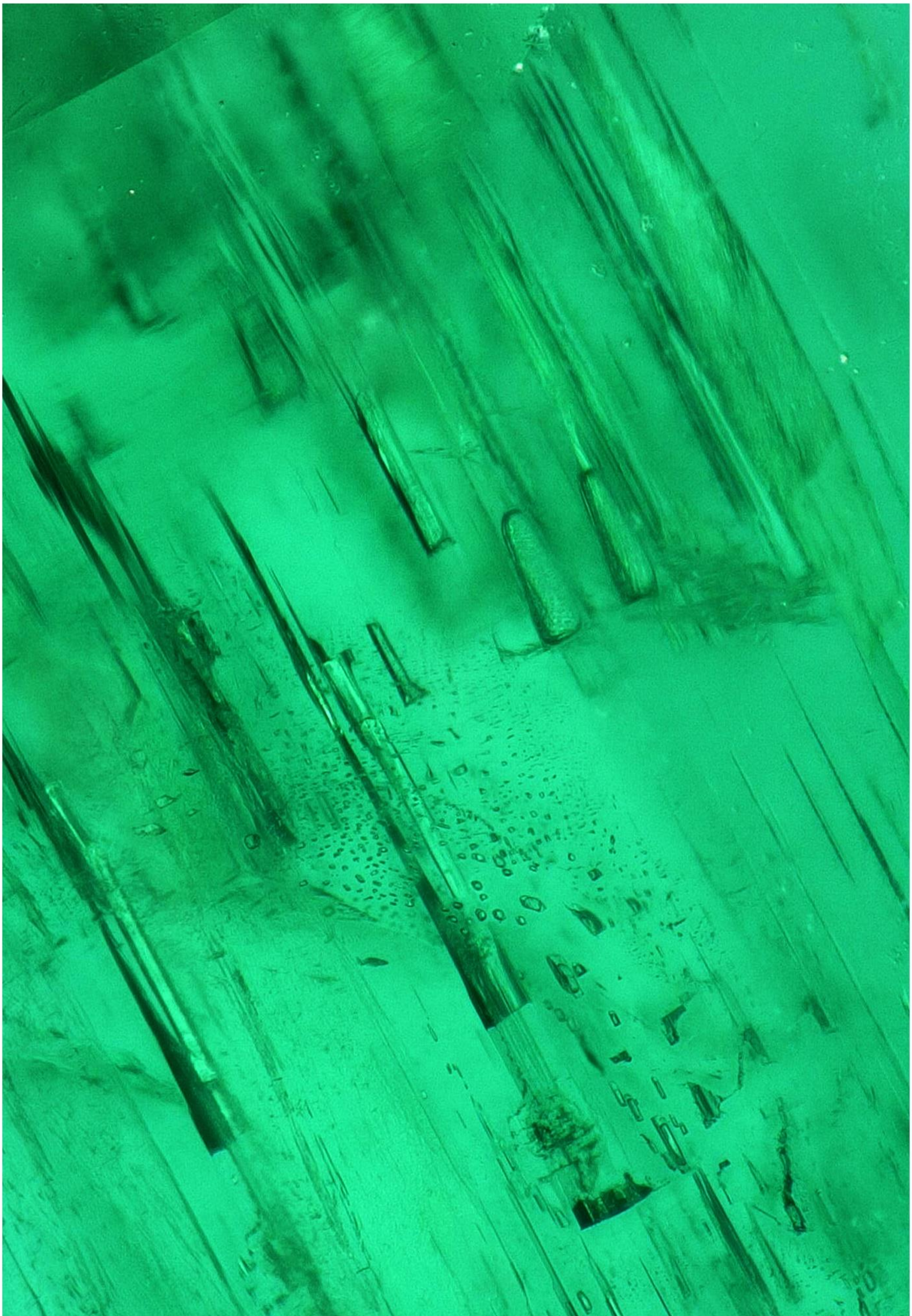




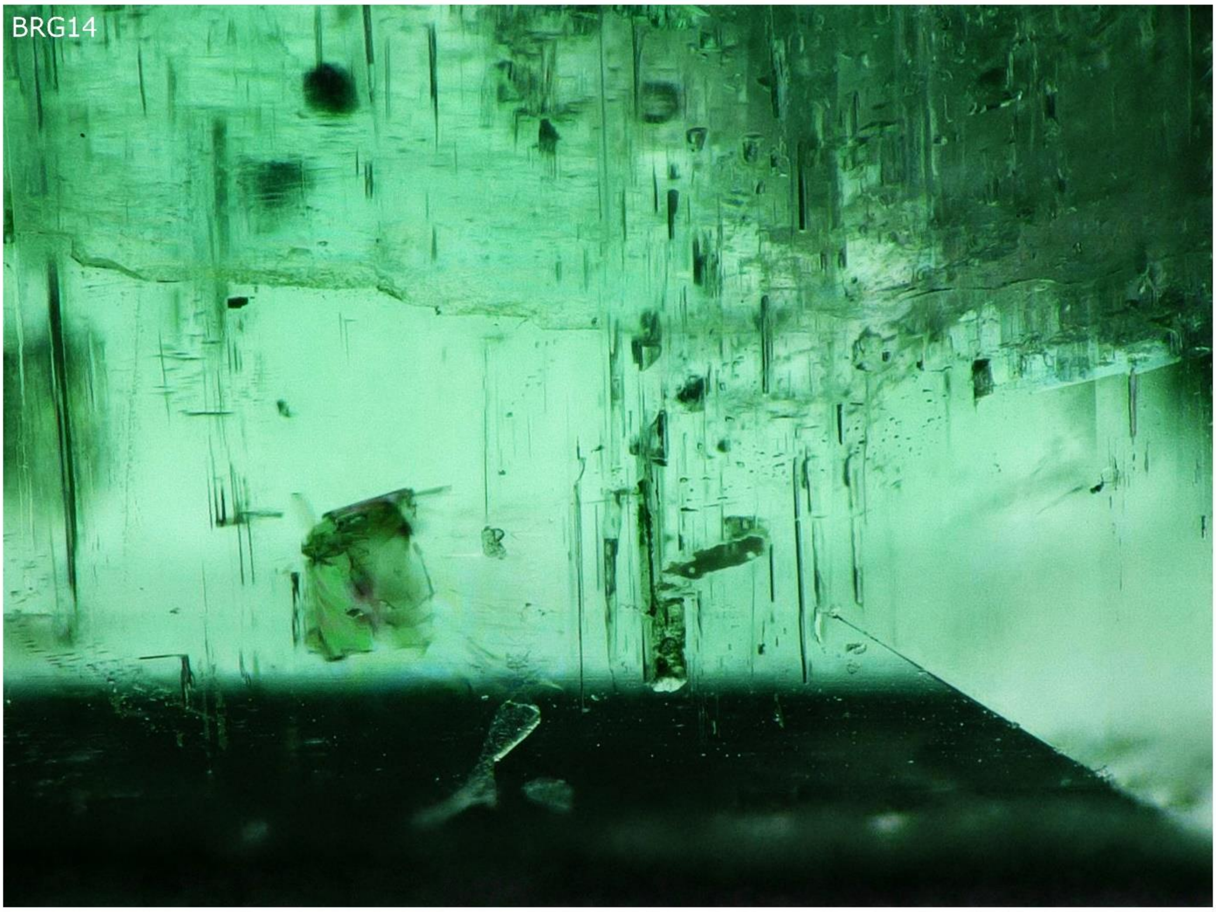
BRG07: Irregularly shaped crystal with carbonate.

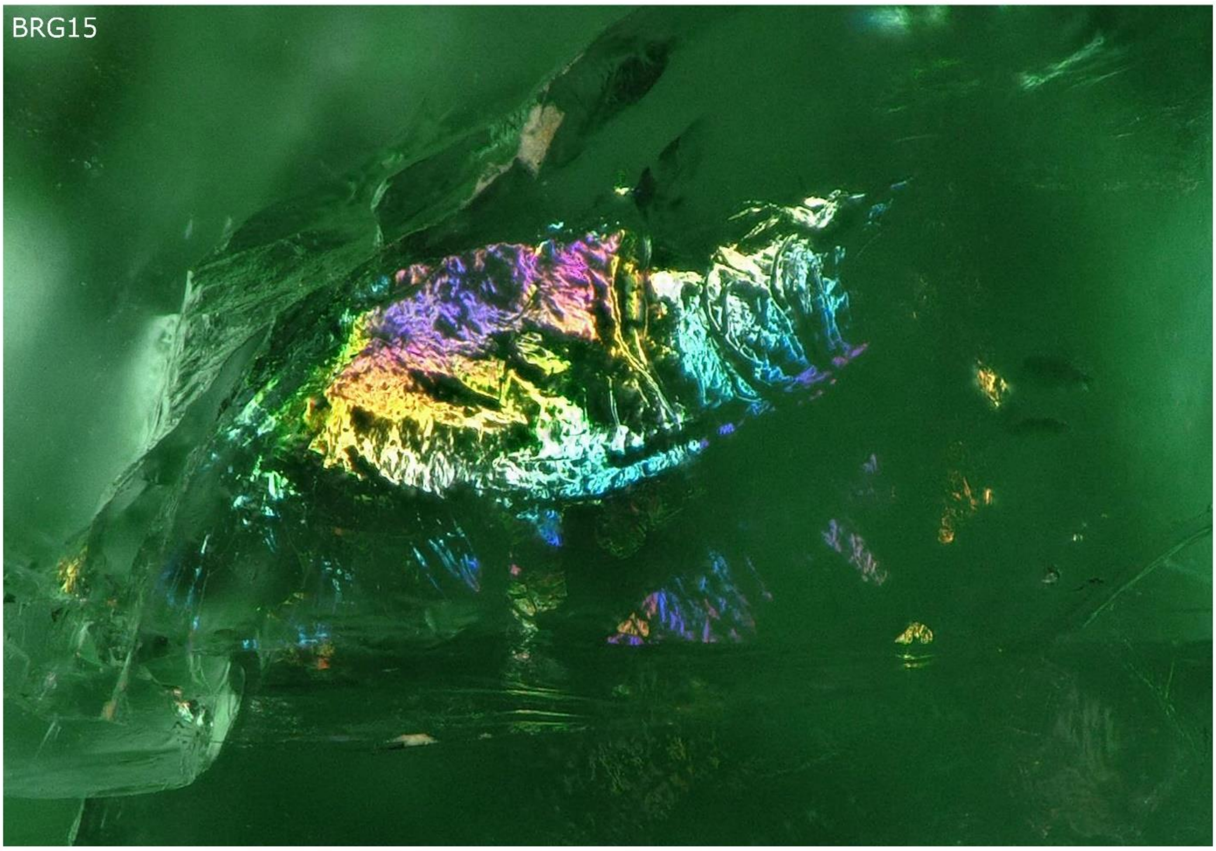
BRG08: Corroded rhombohedron-like crystal surrounded by agglomeration of black opaque spinels.

BRG09: Numerous black opaque spinels.



BRG13: primary cavities in the form of growth tubes oriented parallel to the c axis





BRG14: Growth tubes oriented parallel to the c-axis, and brownish irregularly shaped mica crystals.
BRG15: Tension fissure showing vivid interferences colours.

[...]