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The emeralds of the Belmont Mine, Minas Gerais, Brazil

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1. Introduction

Although Brazil was for many years renowned for its agate, tourmaline and aquamarine, emerald can be considered today to be its most important gemstone.

The search for the 'Serra das Esmeraldas', a mythical country in the north-east of present-day Minas Gerais, significantly helped the development of the interior of the country by the Bandeirantes in the sixteenth and seventeenth centuries. The first large discoveries of emerald, however, were not made until 1963, in Bahia. The discovery of further occurrences in the states of Bahia, Goiás and Minas Gerais, has resulted in Brazil becoming one of the leading producers of emerald.

At the present time, emerald mines in production are Carnaíba and Socotó (both in Bahia state), Santa Terezhina (Goiás) and Itabira (Minas Gerais). In addition, there are a number of other occurrences whose yields were never, or only temporarily, of economic significance (Figure 1).

The Belmont mine lies near Oliveira Castro (Itabira district, MG), about 13km south-east of the town of Itabira and 120km north-east of Belo Horizonte, the state capital of Minas Gerais.

The first emeralds were discovered in 1978 at Itabira, near the railway line joining Belo Horizonte with Vitoria. Using primitive tools, garimpeiros set about exploiting an area of about 60 by 120 metres to a depth of 6 metres. From this initial stage of mining, about 40 kg of emeralds were extracted from about 20 000 cubic metres of rock, and marketed.

Since 1981, the workings have been extended using modern machinery. A few hundred metres from the workings is the plant, and within this a water cannon is used to wash away the finer components. Coarser pebbles of waste material are then removed before the remaining material is transported to a large hall by conveyor belt. In this hall the emerald is removed and sorted manually.

The average emerald-content of the biotite schist is 165 s/ton. The Belmont mine is probably the richest emerald occurrence in Brazil so far as emerald-content of the parent rock in relation to the average quality of the emeralds is concerned.

2. Geology

The following remarks concerning the regional and local geology are based on the works of Schorscher (1973), Schorscher and Guimarães (1976) and Schorscher *et al.* (1982) – see Figure 2.

2.1. Regional Geology

The stratigraphy of the Itabira region is characterized by two rock series of Precambrian age: the crystalline basement (after Pfulg, 1968: 'Série pré-Minas'), underlying meta-sediments ('Supergrupo Minas').

The (crystalline) basement is mainly composed of paragneiss and poly-metamorphic migmatites. The rocks, which show a mainly granitic character, are subdivided according to their origin into 'primary' and 'secondary' components (Schorscher *et al.*, 1982).

The 'primary' components comprise mainly meta-tectic gneisses and anatectic migmatites. Granitic intrusions are rare. Amphibolites occur within these and, depending on their origin, are designated either 'basic' or 'ultramafic'. The 'ultramafic' amphibolites are made up of over 95% (vol.) of a green clino-amphibole as well as accessory chromite (further minerals: tremolite, talc, clinozoisite, epidote and magnetite). Two samples analysed by Schorscher *et al.* (1982) exhibit a peridotitic composition with high Cr- and Ni-contents (ca. 2000 ppm Cr and 1500 ppm Ni).

The 'secondary' components mainly comprise metasomatic crystalline rocks, low-grade meta-sediments (serpentinites to chloritites and talc schists) and non-metamorphic rocks. Granitic intrusions are common. Pegmatoids, meta-ultramafites as well as meta-basic and basaltic rocks are

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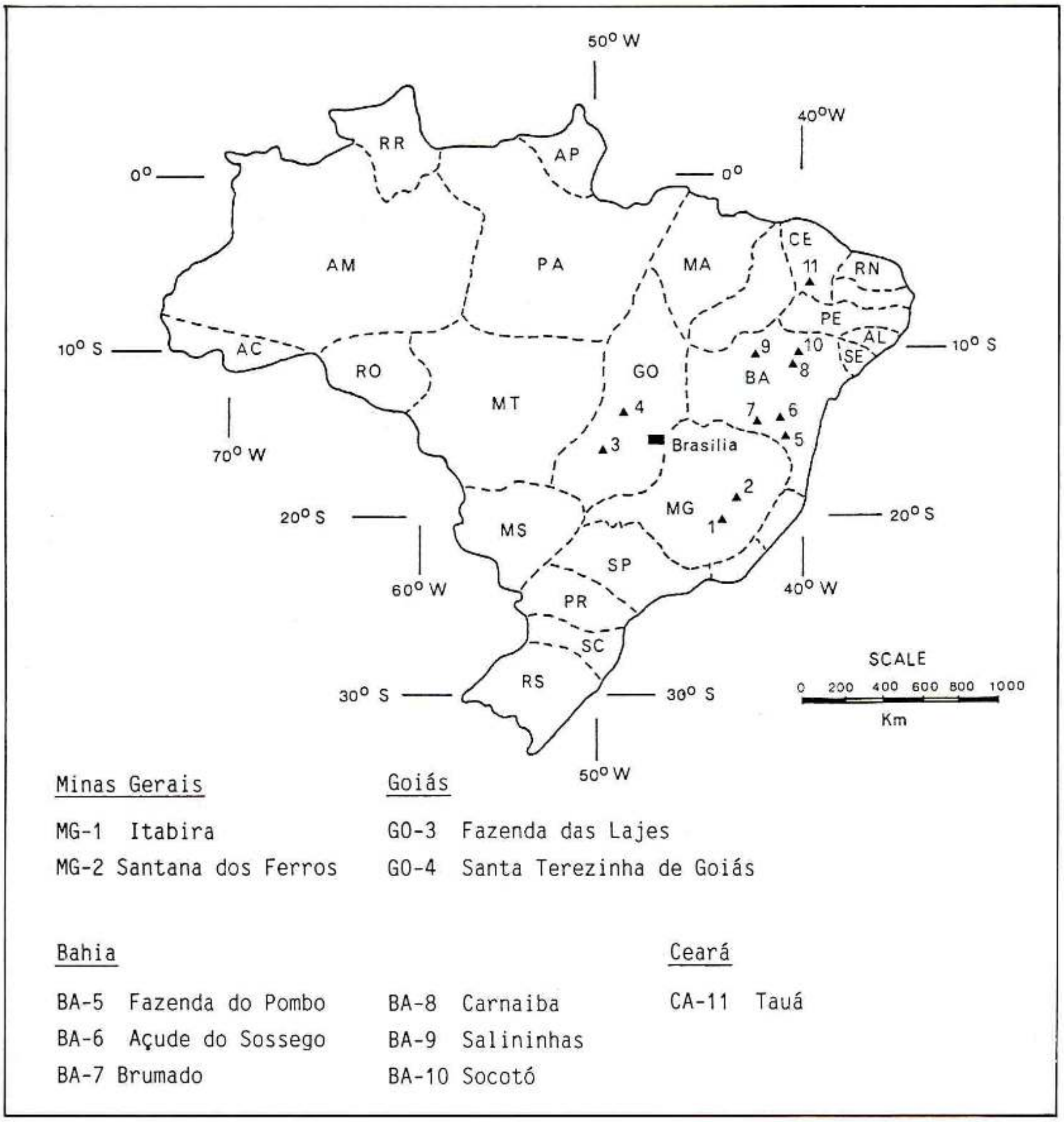

Fig. 1. The emerald occurrences in Brazil.

also present, albeit to a lesser degree.

The meta-ultramafites contain high Cr and Ni values (>1000 ppm) and are younger than the 'primary' rocks.

2.2. Local Geology

In the Itabira region (MG), the 'Supergrupo Minas' is made up of the following sub-groups, from the lowest to the uppermost: paragneisses, greenschists, the Caraca group, the Itabira group and the Piracicaba group. The three last-named groups are separated from the basement ('Série pré-Minas') by a structural and metamorphic discontinuity.

The paragneisses were formed through the metamorphism of greywackes and other sandstones. The Caraca group is composed of micaceous quartzites and, to a lesser extent, phyllites. The Itabira group is economically the most important unit of the Minas Series, due to its itabirite- and hematite-iron ore contents. Quartzites, sericites and phyllites dominate the Piracicaba group.

The 'Supergrupo Minas' sequence is structurally characterized by folds with horizontal or nearly

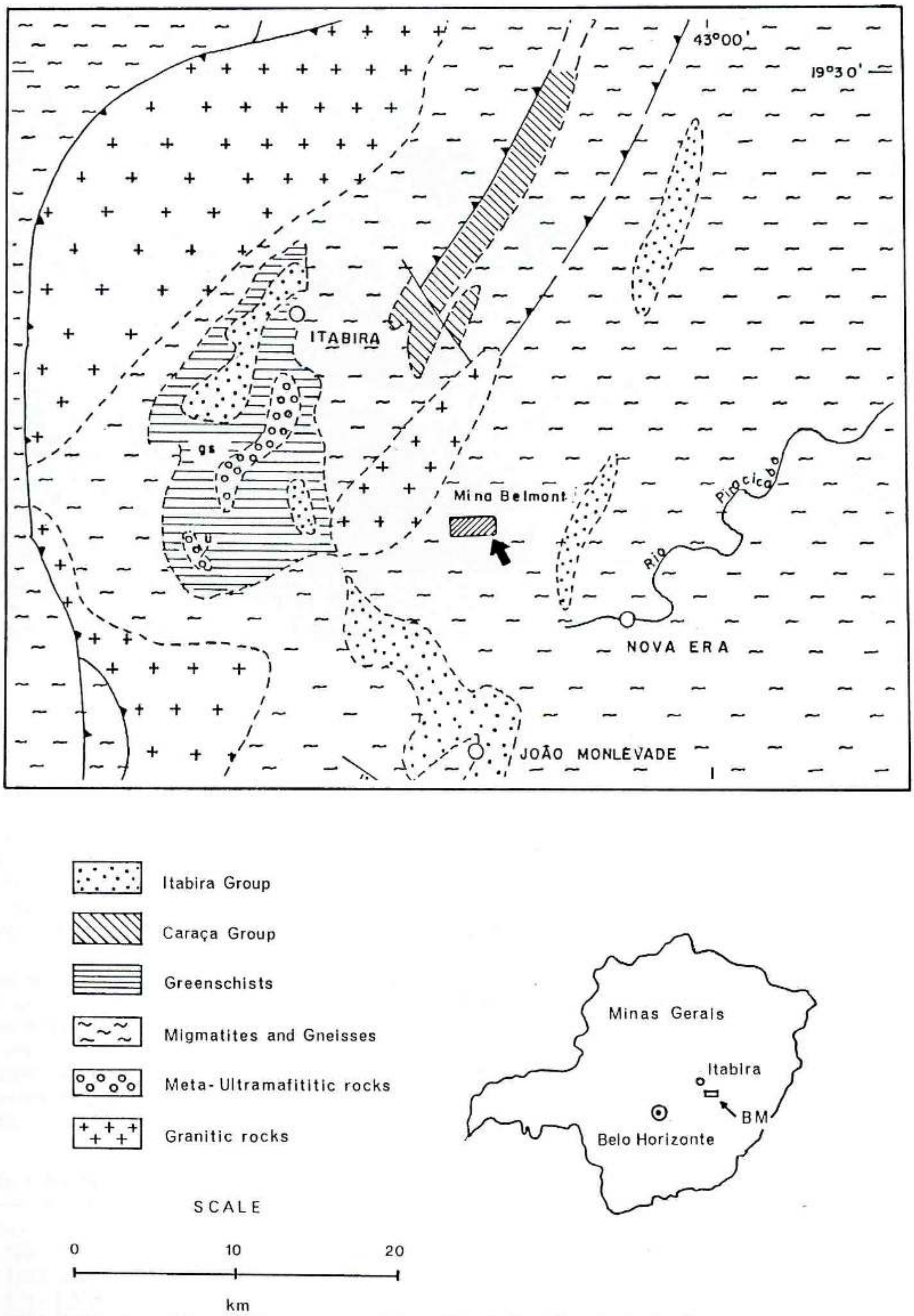

Fig. 2. Regional geology of the emerald occurrences at Belmont Mine, Itabira, Minas Gerais, Brazil.

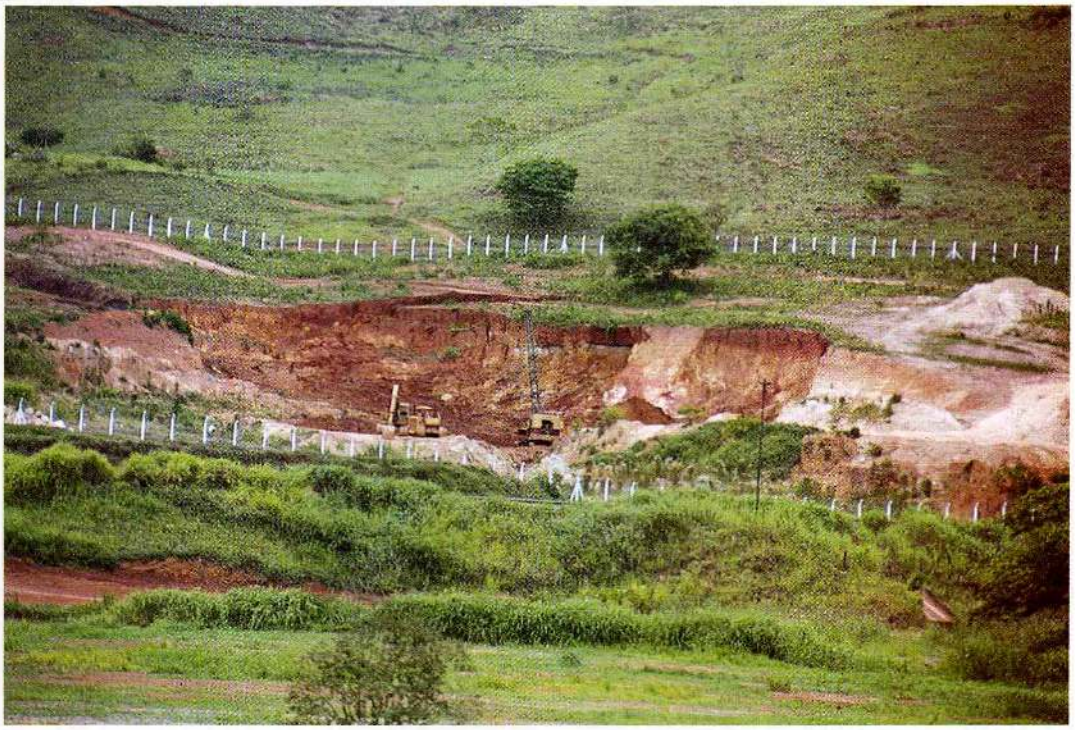

Fig. 3. The present workings of the Belmont Mine in the emerald occurrence near Itabira.

horizontal axes. The whole sequence was subjected to a regional metamorphism.

In the area of the emerald occurrence, a belt of schists dominates, stretching in a north to north-easterly direction. The width of the belt varies between 750 and 1200 metres. Leucogneisses occur symmetrically on both sides of this belt. The schist belt, together with the mafic rocks, is stongly folded, with axes generally trending north to north-east.

The gneisses and the schists are riddled with small pegmatite bodies in the form of pockets of quartz and kaolin. These are concentrated between the gneisses and the schist belt. The largest pegmatite body is a vein (ca 10 metres wide) which cross-cuts the gneiss and schist structures at right-angles.

No emeralds are found in the gneisses, although these occasionally contain pegmatites with beryl and/or aquamarine.

Emeralds mined from the present workings (Figure 3) occur in black biotite/phlogopite schists, in green chlorite schists or in kaolin masses (altered pegmatite). They are occasionally accompanied by chrysoberyl or alexandrite. Crystals of lower quality are also found in quartz masses.

3. Optical and chemical properties of Itabira emerald

Optical data of Itabira emerald determined by different authors are presented in Table 1. The measured density values range between 2.72 and 2.74 g/cm^3.

Table 1. Refractive indices and birefringences of Itabira emeralds.

n_e	n_o	Δ_n	References
1.580	1.589	−0.009	Muller-Bastos (1981)
1.580±0.01	1.589±0.01	−0.009	Sauer (1982)
1.574−1.578	1.580−1.583	−0.004−0.006	Schwarz (1986)a
1.581−1.582	1.589−1.590	−0.007−0.008	Schwarz (1986)b

Table 2. Microprobe analyses of Itabira emeralds. Total iron as FeO. CaO-content <0.01 Wt%.

Sample number:	1	2	3	4	5	6	7	8	9
SiO_2	64.00	67.58	65.46	66.00	65.59	66.99	66.48	66.35	68.05
Al_2O_3	15.83	17.79	18.25	18.25	18.42	16.66	16.21	16.09	18.92
Cr_2O_3	0.39	0.20	0.00	0.05	0.18	0.91	0.07	0.08	0.06
V_2O_3	0.00	0.11	0.00	0.02	0.00	0.07	0.02	0.00	0.00
FeO	0.98	0.33	0.40	0.32	0.19	0.76	0.64	0.62	0.43
MnO	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.07	0.08
MgO	1.86	0.56	0.66	0.62	0.52	1.69	1.84	1.79	0.97
Na_2O	1.29	0.29	0.40	0.34	0.26	0.99	1.18	1.18	0.37
Total	84.35	86.86	85.17	85.60	85.16	88.07	86.47	86.18	88.88
Chemical formula (normalized: Si = 6)									
Si	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000
Al	1.749	1.862	1.972	1.956	1.986	1.759	1.724	1.715	1.966
Cr	0.029	0.014	0.000	0.004	0.013	0.064	0.005	0.006	0.004
V+	0.000	0.008	0.000	0.001	0.000	0.005	0.001	0.000	0.000
Fe++	0.077	0.024	0.031	0.024	0.015	0.057	0.048	0.047	0.032
Mn	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.005	0.006
Mg	0.260	0.074	0.090	0.084	0.071	0.226	0.248	0.241	0.127
Na	0.234	0.050	0.071	0.060	0.046	0.172	0.206	0.207	0.063
Total	8.349	8.032	8.164	8.129	8.124	8.283	8.234	8.221	8.198

The microprobe analyses (Table 2) were carried out using an ARL-SEMQ instrument, with wavelength dispersive (WD) spectrometers and an energy dispersive system (EDS, TN 2000) (Schwander and Gloor, 1980). Beam diameter was 2 microns, accelerating voltage 15 kV and specimen current 30 mA. Standards used for the analyses comprised synthetic oxides and some simple silicate minerals.

Franz *et al.* (1986), in their work on beryl in regionally metamorphosed rocks, discussed in detail the problems which may arise during the calculation of the beryl formula. For this reason, the emerald analyses given in Table 2 were normalized both cationically (Si = 6) and anionically (O = 15); as the lighter elements such as Be or Li cannot be analysed with the microprobe, 3BeO was not taken into consideration during the anionical normalization.

Both methods of normalization resulted in virtually identical chemical formulae.

Structural and chemical considerations indicate that the following substitutions in the Itabira emeralds could be applicable:

(a) Al^{3+} (octahedral) = $(Mg,Fe)^{2+}$ + Na^+ (channel site).

(b) Al^{3+} (octahedral) = $(Cr,Fe,V)^{3+}$.

The mineral formulae calculations (Table 2) indicate substitution type (a) is mainly present. Through this substitution, channel positions are also occupied and the difference in charge between Mg^{2+} and Fe^{2+} versus Al^{3+} is compensated for by Na^+.

Figure 4, showing a gradient of less than 1, demonstrates a slight excess of (Mg+Fe) over Na. This can be explained by a small amount of Fe^{3+}, which is not compensated charge-wise by Na^+.

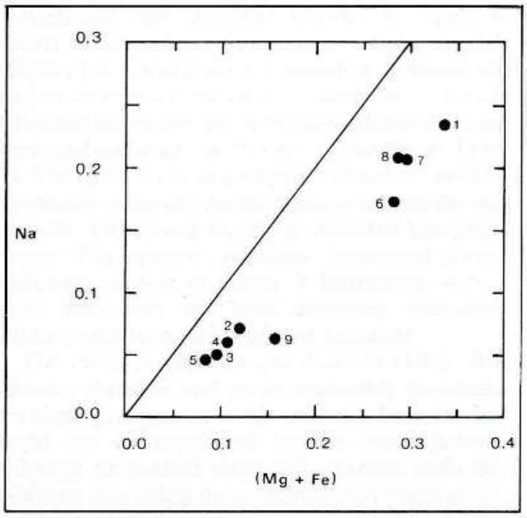

Fig. 4. Plot of (Mg + Fe) v. Na for the Itabira emeralds showing the slight excess of (Mg + Fe) over Na. Numbers refer to analysis numbers in Table 2.

According to (b), Cr^{3+} is accommodated into the lattice at the same time (the analyses show Cr_2O_3-values from 0.00 to 0.91).

The emerald analyses show relatively low values for FeO, MgO and Na_2O when compared with similar material from biotite schists (Hänni 1982, Hänni and Klein, 1982, Hänni and Kerez, 1983).

4. Inclusions

In general, emeralds from the Belmont mine at Itabira, Minas Gerais, can be easily distinguished from those from Santa Terezinha, Goiás, Carnaiba, Bahia, and Socoto, Bahia, on the basis of inclusion studies.

Under the optical microscope Itabira emeralds are found to contain relatively few inclusions. By far the most common inclusions are of mica, which occurs in a diversity of form and colour.

Not only does the colour of the mica inclusions vary from emerald to emerald, but also within the same gemstone itself. The colour is mainly various shades of brown, from a yellowish brown through grey-brown to nearly black. Greenish shades also occur, albeit seldom.

The mica flakes are usually strongly rounded or irregular (Figures 5, 6), although elongated forms or nearly ideal pseudo-hexagonal crystals (Figure 7) can be observed. Two generations can be seen, the first indicating formation before that of the emerald (protogenetic), and the second indicating formation at the same time as that of the host crystal (syngenetic). The protogenetic micas exhibit irregular, or strongly rounded forms, and usually possess a deep brown colour. This colour can be so deep that platelets thick enough may appear opaque. These inclusions are irregularly distributed within the emeralds and show no preferred orientation (Figure 5). The syngenetic micas on the other hand, are thin, transparent flakes which either are elongated or partly exhibit a distorted pseudo-hexagonal shape (Figure 7). These flakes usually show a preferred orientation within the emerald: the elongated crystals lie sub-parallel to the *c*-axis, and the pseudo-hexagonal sections lie parallel to the basal plane.

Microprobe analyses have shown that these micas are members of the biotite-phlogopite series. The fluorine-contents of these micas are about 2–3 wt% (Table 3). This indicates that complex fluorine phases played a role during the formation of the emeralds, especially during the formation of ion complexes capable of migration.

Apart from intergrowth of mica crystals with other mineral inclusions (Figure 8), interesting phenomena can be observed, apparently related to dissolution and re-crystallization processes. Figure 9 shows a mica crystal whose narrower end has been either partly dissolved or altered to another mineral species. At the other end, apart from signs of resolution, the 'birth' of a (new?) mineral can be observed in the form of dendrites.

Table 3. Microprobe analyses of some mineral inclusions in Itabira emeralds.

	Andesine	Biotite/ Phlogopite	Fe-Dolomite
SiO_2	59.95	38.15	0.12
TiO_2	0.00	0.86	0.00
Al_2O_3	25.64	15.01	0.00
Cr_2O_3	0.00	0.35	0.00
FeO	0.06	9.26	6.32
MnO	0.00	0.11	0.69
MgO	0.20	16.65	16.62
CaO	7.99	0.10	33.40
Na_2O	7.35	0.35	0.00
K_2O	0.14	9.15	0.01
F	0.00	3.09	0.00
Total	101.33	93.08	57.16
	An 37.2% Ab 62.0% Or 0.8% Andesine		

As mentioned above, inclusions other than mica in the Itabira emeralds are much less abundant. Apart from an opaque mineral (hematite or molybdenite), the following minerals have been identified using either X-ray diffraction or micro-X-ray spectroscopy techniques: quartz, tremolite, dolomite, andesine and apatite.

Andesine (see chemical analyses in Table 3) occurs as colourless, transparent, tabular crystals (Figure 10). Quartz occurs colourless to brownish, mainly as crystals rounded by corrosion. Similarly corroded forms are also normally exhibited by the beryl and carbonate inclusions (Fe-dolomite: Table 3). The latter occur in groups of colourless crystals. Tremolite generally forms transparent needle-like crystals, and apatite occurs as rounded hexagonal forms. The opaque (?pseudo-) hexagonal crystal inclusions shown in Figure 8 intergrown with a mica flake have not been positively identified. These could be molybdenite or hematite.

The claim of Gübelin and Koivula (1986) that 'biotite, chromite and pyrite preferably determine the inner paragenesis of the emeralds from Itabira' could not be confirmed by our investigations, although we studied about 300 emeralds from this location, also using the gemmological microscope.

The very commonly-occurring growth tubes in the Itabira emeralds are of greater diagnostic value than the mineral inclusions. These tubes are tiny

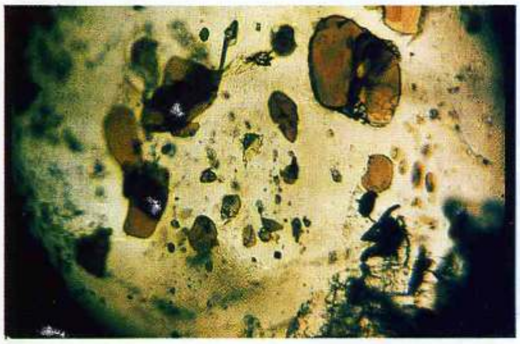

Fig. 5. Protogenetic mica inclusions (biotite/phlogopite) with irregular/rounded outlines. These crystals possess no preferred orientation to the host crystal. 20x. (Note: all photographs were taken using immersion liquids).

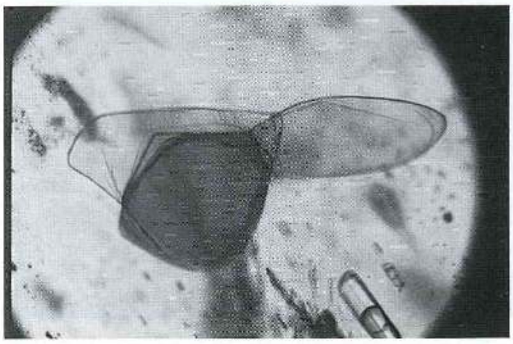

Fig. 6. Biotite/phlogopite inclusions with a protogenetic origin. The crystals exhibit rounded forms and their colour varies from light to dark brown. 100x.

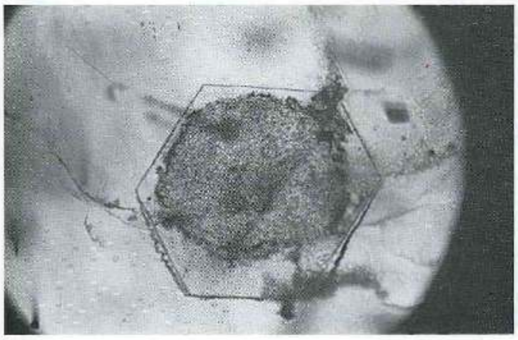

Fig. 7. Mica flakes with a syngenetic origin showing nearly ideally-formed pseudo-hexagonal shapes. Orientation parallel to the basal plane of the emerald host crystal. Partly corroded surface. 100x.

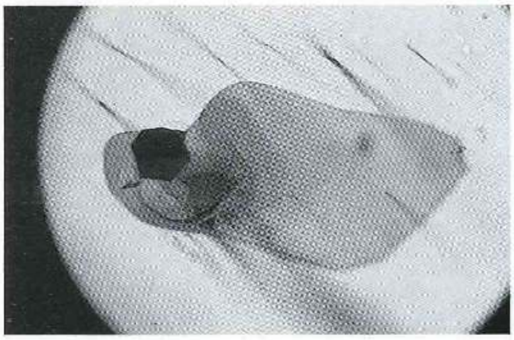

Fig. 8. Intergrowth of a mica crystal with an opaque mineral platelet, which possesses a (pseudo-) hexagonal form (probably hematite or molybdenite). 70x.

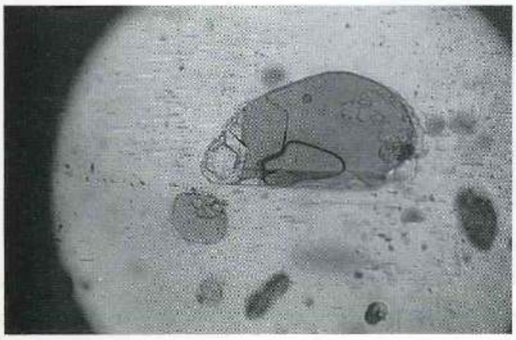

Fig. 9. Mica flake exhibiting solution and recrystallization phenomena. 100x.

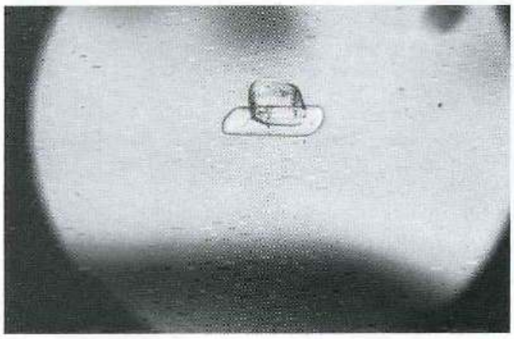

Fig. 10. Colourless, transparent, tabular crystal inclusion (andesine). The other inclusions could not be identified due to their loss during preparation. 70x.

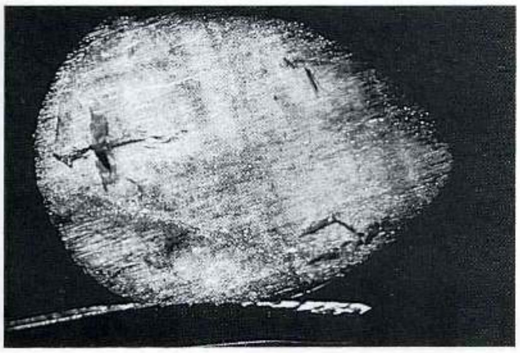

Fig. 11. Itabira emeralds containing numerous fine growth tubes, and exhibiting a slightly turbid, silken appearance. 20x.

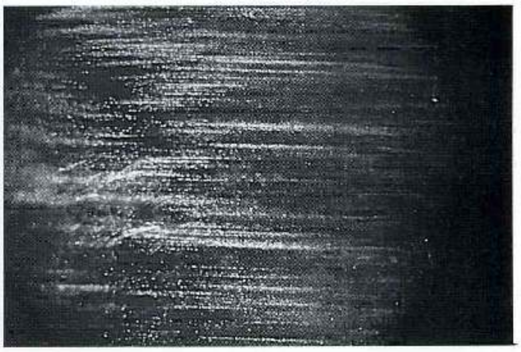

Fig. 12. Growth tubes are often arranged in parallel strings which produces the so-called 'Rain Effect' leading to chatoyancy. 35x.

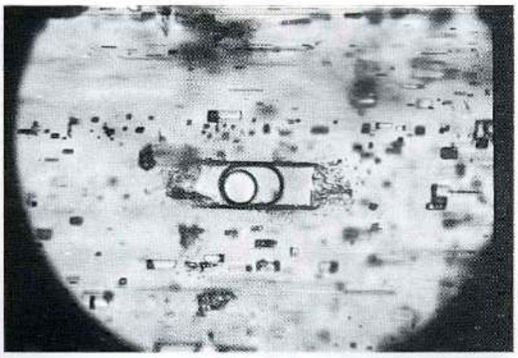

Fig. 13. Rectangular cavity oriented in the direction of the *c*-axis, with a fluid three-phase filling of the type liquid/liquid/gas ('l-l-g'). 70x.

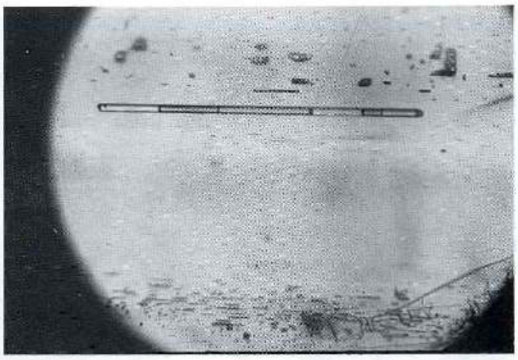

Fig. 15. Elongated cavity oriented parallel to the *c*-axis, with an interesting filling: the phase sequence from left to right is: l_1-g-l_2-l_1-g-l_2. 70x.

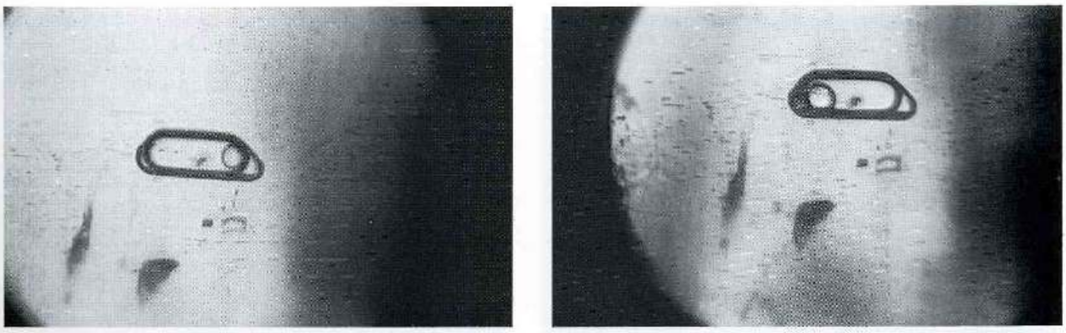

Fig. 14. Negative crystal with an 'l-l-g' three-phase filling. Note the mobile gas bubble seen once on the right-hand side of the cavity. 70x.

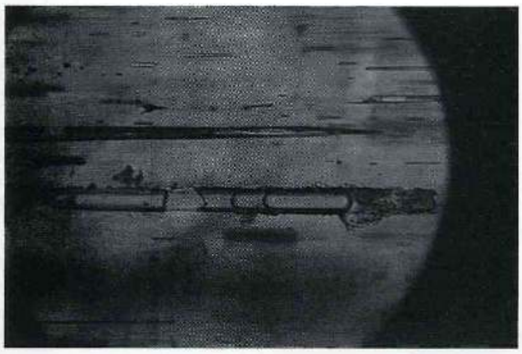

Fig. 16. Elongated multiphase inclusion, oriented parallel to the *c*-axis of the emerald. 100x.

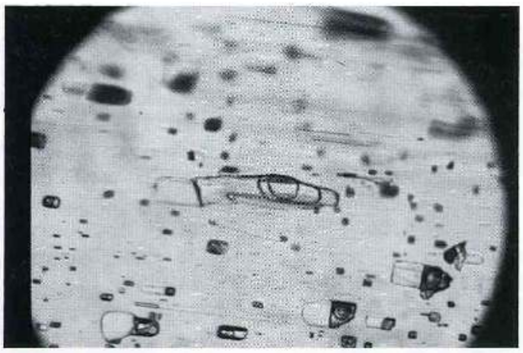

Fig. 17. Common and characteristic inclusion type in the Itabira emerald: birefringent crystals accompanied by cavities containing a variety of fillings (i.e. various fluid inclusions). 100x.

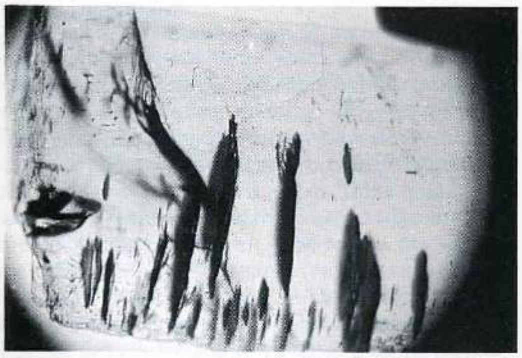

Fig. 18. Cluster of unhealed fissures, parallel to the basal plane. 20x.

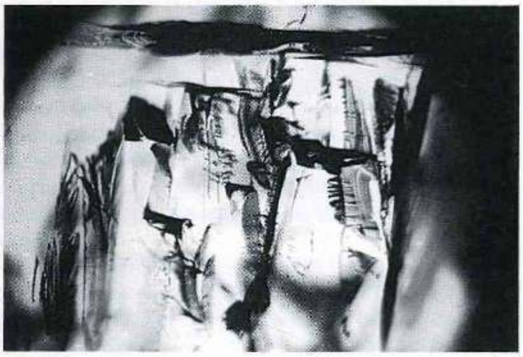

Fig. 19. Unoriented unhealed fissures. 20x.

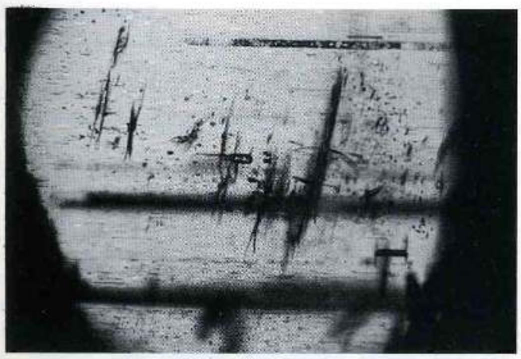

Fig. 20. Disc-like fissures are characteristic of the Itabira emeralds. Their centres usually possess a cavity containing a variety of fillings (Fig. 19). 70x.

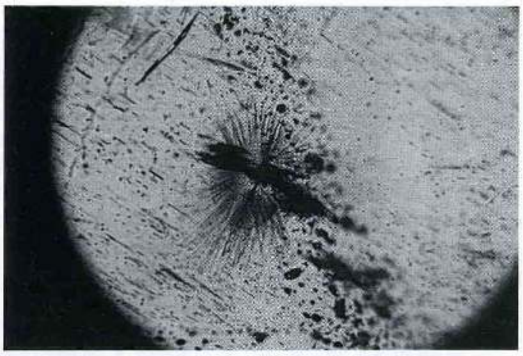

Fig. 21. The fissures shown in Figure 19 often form swarms more or less parallel to the basal plane. 35x.

channels oriented parallel to the *c*-axis of the emerald and are filled with a variety of material. These tiny tubes are sometimes so abundant that they impart a turbid appearance to the emerald or a nearly silken lustre (Figure 10). Their arrangement in parallel strings gives rise to the so-called 'Rain Effect', which has also been observed in many Brazilian aquamarines (Figure 12).

The tiny growth tubes are often concentrated in planes or layers which run parallel to the basal plane of the emerald. These growth tubes could have formed in the crystallization 'shadow' of extremely fine particles of other minerals on the basal plane. These growth tubes are often accompanied by a large number of much larger tubes or channels which can contain various fillings: one or two liquids, possibly combined with a gas bubble and/or a solid phase (see below). When an abundance of fine growth tubes is present, the gemstones, when cut as cabochons, will display the cat's-eye effect termed chatoyancy.

The most abundant group of inclusions in the Itabira emeralds are those with two-, three- and multi-phase inclusions, and these exhibit an extraordinarily large variety of forms (Figures 13–17). This indicates a complex and multiphase formation history of the emeralds. Apart from their occurrence in the various-sized growth tubes, these inclusions can be observed in irregular or regular/rectangular-bordered cavities (Figure 13), as well as in more or less perfectly-formed negative crystals (Figure 14). Analogous to the 'classical' solid/liquid/gas (s-l-g) three-phase inclusions in the Colombian emeralds, they can be sub-divided by virtue of their formation history into primary and secondary inclusions, originations as residues from the mother liquid. The 's-l-g' three-phase inclusions can be observed occasionally, while liquid-gas inclusions (i.e. l-g two-phase inclusions at room temeprature) also occur widely distributed. Other phase combinations, however, are more interesting and of greater diagnostic value.

1. Cavities containing two immiscible liquids (fluid 'l-l two-phase inclusions).
2. Cavities containing two immiscible liquids and a gas bubble (fluid 'l-l-g' three-phase inclusions; Figure 13)
3. Cavities containing two immiscible liquids, a gas bubble and a crystal (fluid 's-l-l-g' four-phase or multi-phase inclusions)

Typical inclusions in the Itabira emeralds are composed of white, birefringent crystals usually associated with a rectangular cavity (Figure 17). The cavity filling can be variable (mainly 'l-g' or 'l-l-g' type). The crystal inclusions could not be positively identified. They normally have short- to long-prismatic forms and seem to show a hexagonal symmetry (apatite?). These inclusions are often abundant, normally oriented parallel to the *c*-axis of the emerald (with primary cavities), but also in healed fractures.

The final types of inclusion to be described from the Itabira emeralds are the various fissure types. Of special note is the relatively large number of unhealed fissure planes (Figures 18, 19). This indicates that these fissures have an epigenetic origin and were only formed after the emerald crystal had finished growing, when it was no longer in contact with any mother liquid. For this reason, the fissures and cracks were often filled with other solutions (mainly water containing Fe or Mn). The relatively fast rate of crystallization resulted in the formation of skeletal or dendritic crystals. In contrast, the 'healing' of a fissure takes place through the crystallization within it of material similar to that of the host crystal. The mother solution generally possesses a complex chemical composition and it contains additional components which are not needed for the formation of further host crystal. These remaining components normally concentrate in small cavities. They seldom form single-phase fluid inclusions, and two-, three- or multi-phase inclusions are more common. The healed fissures so formed have a characteristic appearance and play an important role in the discrimination between natural and synthetic gemstones.

Another type of inclusion, which has not yet been observed in other Brazilian occurrences and which is thus specific to Itabira emeralds, occurs in disc-like stress fissures. Generally, these contain a cavity in the centre with a variable filling (Figures 20, 21). These small fissures mostly occur in swarms, are parallel to each other and also run parallel to the basal cleavage face of the emerald.

5. Formation Conditions

Genetically, the emerald occurrence at Itabira is linked to the association between mafic-ultamafic rocks (or their metamorphic derivatives) and pegmatites. The pegmatites provide the beryllium, and the (ultra-) mafites the Cr and Fe necessary for the green colour of the emerald. Vanadium (stemming from the metasediments) could also contribute to this colour. On the basis of the inclusion-type specific to the Itabira emeralds, this deposit may be regarded as a specific sub-type when considering the occurrence of emerald systematically (Schwarz, 1986).

On the basis of microthermometric determinations on a chosen sample containing 25 four-phase inclusions, a minimum formation temperature of 380°C and a minimum formation pressure of 1400 bars has been calculated (Mullis, 1979). The pressure was calculated on the basis of the temperature of homogenization, with the aid of the PVT data relating to the system H_2O-CO_2-NaCl, after Bowers and Helgeson (1983).

The Itabira deposit is unique in the apparently low conditions of formation (P,T) when compared with other emerald occurrences associated with metamorphic schists. These low conditions are probably responsible for the inclusion and chemical characteristics of the emeralds.

The formation of the Itabira emeralds cannot be directly connected to the intrusion of the pergmatite masses. The emeralds are more likely to have been formed as a result of a later metamorphic or retrograde episode.

The occurrence of various types of gas-liquid inclusion within the same crystal indicates a complex formation history involving more than one event.

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