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Origin of emerald deposits of Brazil

G. Giuliani[1,2], L. J. H. D. Silva[3] and P. Couto[4]

[1] ORSTOM, Universidade de Brasilia, Brazil
[2] C.R.P.G., 15 Rue N.D. des Pauvres, BP 20, 54501 Vandoeuvre-les Nancy, France
[3] Mineração Caraiba Metais Ltda, Bahia, Brazil
[4] Secretaria das Minas e Energia, C.P.R.M./SGM, Bahia, Brazil

Abstract. Precambrian emerald deposits of Brazil are found in a typical geologic setting with Archean basement and supracrustal, ultramafic, granitoid and rocks. Volcano-sedimentary series occur as imbricated structures or as bodies affected by complex folding and deformation. Emerald mineralization belongs to the classic biotite-schist deposit, which formed by the reaction of pegmatitic veins within ultrabasic rocks. At the same time, pegmatite-free emerald deposits linked to ductile shear zones are also known. Emerald formation is attributed to infiltrational metasomatic processes provoking a K-metasomatism of the ultrabasic rocks and also a desilication of the pegmatites. A new classification based on the geological setting, structural features, and ore paragenesis is proposed.

Gemstone deposits are of great importance in Brazil. Agate, amethyst, tourmaline, and topaz represent the important gemstones in terms of weight while emerald is characterized by its high commercial value and represents the main export as uncut and cut gems.

In 1961, the first economic occurrence of emerald was discovered at Salininha (Bahia State), renewing interest for prospection of this gemstone. After 1963, other important occurrences were located, and Brazil soon became one of the leading world producers of emeralds in terms of both volume and quality. For instance, four economic emerald deposits are in production (Fig. 1): (1) the Carnaíba, (2) Socotó (Bahia State), and (3) Santa Terezinha de Goiás (Goiás State) prospecting pits, called "garimpos", and (4) the Belmont mine (Minas Gerais State).

Schist-beryl-type deposits, which resulted from the chemical interaction between pegmatites and basic-ultrabasic rocks (or their metamorphic equivalents), form the major part of emerald mineralization throughout the world (Smirnov 1977; Van Landingham 1984; Sinkankas and Read 1986). Brazilian emerald deposits belong to this classic type except for the Santa Terezinha de Goiás and Itaberai prospects (Fig. 1), where pegmatite veins are absent. The pegmatites are directly linked to intrusive granitic bodies with limited local extension, or are related to important and extended pegmatite provinces as in Minas Gerais and Ceará (Giuliani and Couto 1988a).

The aim of this paper is to present an overview of the geological setting, structural features, and ore paragene-

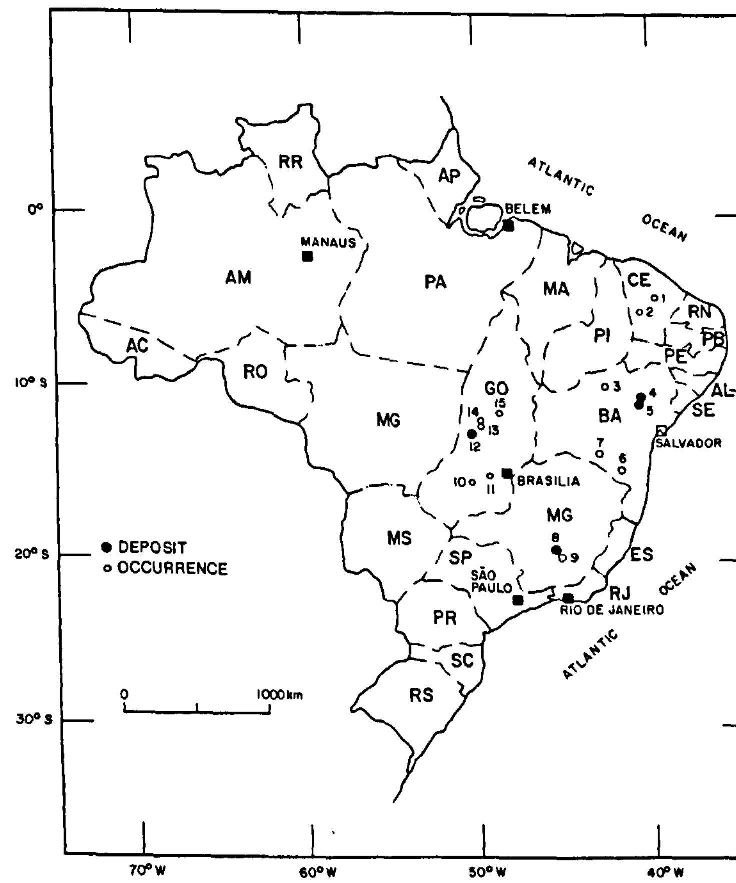

Fig. 1. Geographical distribution of emerald deposits of Brazil. *Ceará State:* 1, Coqui; 2, Tauá. *Bahia State:* 3, Salininha; 4, Socotó; 5, Carnaíba; 6, Anagé; 7, Brumado. *Minas Gerais:* 8, Itabira; 9, Santana dos Ferros. *Goiás State:* 10, Itaberai; 11, Pirénopolis; 12, Santa Terezinha de Goiás; 13, Mara Rosa; 14, Porangatu; 15, Pela Ema-Minaçu

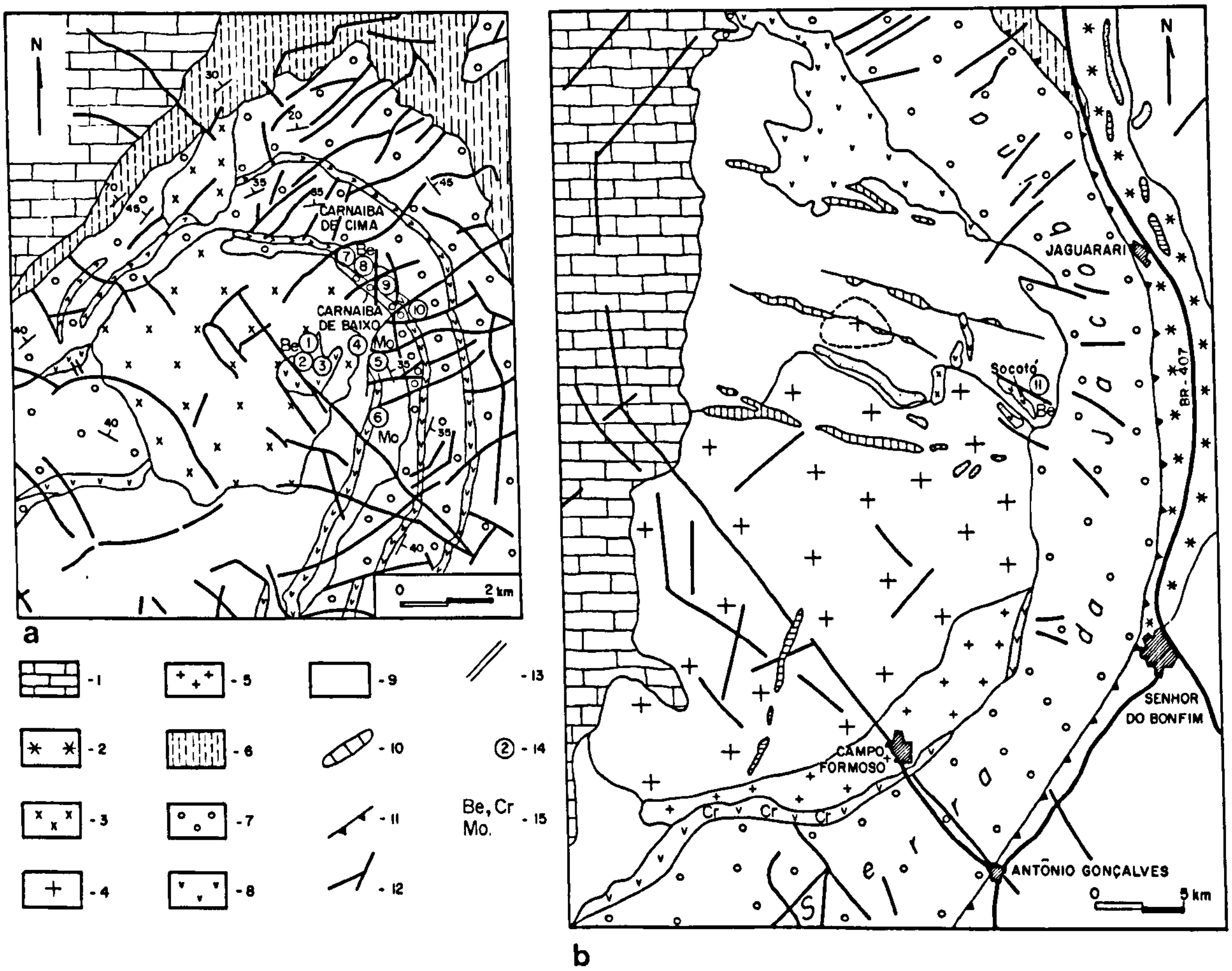

Fig. 2. a Geology of Carnaíba and b Campo Formoso mining districts. 1, carbonate Proterozoic cover; 2, Jaguarari granitoid; 3, Carnaíba leucogranite; 4, two-mica, porphyroid to fine-grained Campo Formoso leucogranite; 5, two-mica, coarse-grained Campo Formoso leucogranite; 6, chlorite schist, phyllites; 7, volcano-sedimentary formations of the Serra da Jacobina; 8, serpentinites; 9, Archean gneisses; 10, silicified zones; 11, thrust fault; 12, faults; 13, roads; 14, prospecting pits (1, Bode; 2, Lagarta; 3, Gavião; 4, Formiga; 5, Braúlia; 6, Marota; 7, Trecho Velho; 8, Trecho Novo; 9, Bica; 10, Cabra; 11, Socotó); 15, Be, green beryl-emerald; Cr, chromite; Mo, molybdenite

sis of the main emerald deposits of Brazil. Therefore, this should contribute to the discussion of the mechanism of ore formation and the main process involved in forming the associated metasomatic rocks. A new classification for these deposits is proposed.

Emerald deposits of Brazil

The emerald deposits are located in rock sequences consisting of Archean basement, Proterozoic volcano-sedimentary series, and granites with their magmatic to late-magmatic equivalents. The basement includes generally tonalitic gneisses, migmatites, diatexites, or granite gneiss. The volcano-sedimentary series are composed of intercalated iron formations, acid and basic-ultrabasic horizons, cherts, and quartzites, which sometimes belong to a greenstone belt sequence (as in Santa Terezinha de Goiás) and occur as imbricated structures (Socotó) or are affected by complex folding and deformation (Carnaíba).

The Carnaiba and Socotó emerald prospecting pits (Bahia State)

These deposits are associated with two Proterozoic leucogranite massifs intruding the Serra da Jacobina volcano-sedimentary series and older gneissic-migmatitic Archean basement (Santana 1981; Rudowski et al. 1987; Rudowski and Fonteilles 1988; Rudowski 1989).

The Carnaíba prospecting pits (Fig. 2a) are found around the Carnaíba granite and are divided into two main districts (Couto and Almeida 1982; Moreira and Santana 1982), i.e., Carnaíba de Cima, including the Trecho Velho, Trecho Novo, Bica, and Cabra pits, located 1000 m above sea level, and Carnaíba de Baixo, displaying pits developed in serpentinite roof pendants in granite (Bode, Gravião, Lagarta, and Formiga) or mined in country rock terranes (Marota, Braúlia).

The emerald mineralization is related to intrusive albitic (albite-oligoclase) or quartz-albitic pegmatoids (Brazilian name corresponding to desilicified pegmatites), or quartz veins crosscutting the serpentinites. Two kinds of veins are distinguished: (1) fracture veins

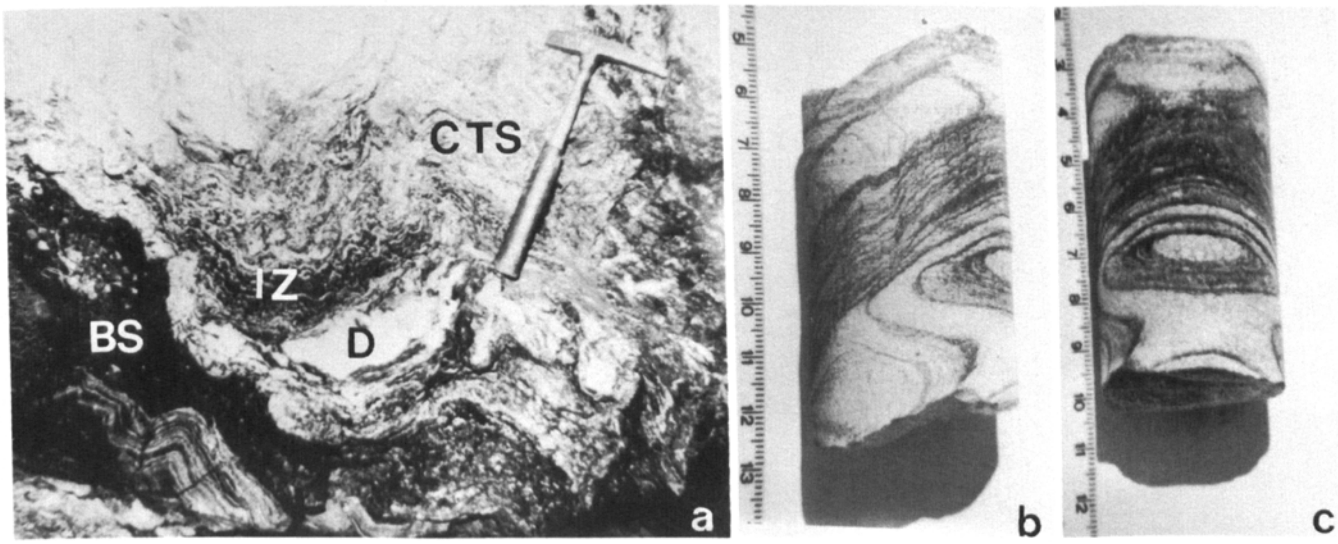

Fig. 3a–c. Santa Terezinha de Goiás deposit. Trecho Novo prospecting pits (167 galleries). **a** Aspect of the biotite schist (BS) which illustrates the circulation of fluids along lithologic contact between carbonate-talcschist (CTS) and pockets of dolomite (D). A successon of small infiltrated zones (IZ) corresponding to a bed-by-bed fluid injection and circulation may be observed. The major "biotite" layer is pyrite-rich; emerald is well developed in (D) and (CTS). **b, c** Typical sheath fold from Santa Terezinha de Goiás affecting chlorite-quartz schists. Drilling hole of Trecho Damiaõ prospecting pit

called "frinchas" and (2) contact veins called "esteiras", which are developed along the contact of quartzites and intercalated serpentinites (Trecho Novo, Cabra, and Bica pits). The frincha veins are generally vertical with an average width of 0.5 m, producing emeralds of good quality. Molybdenite mineralization is intense at Trecho Velho. It is an important feature of the Carnaíba de Baixo district accounting for a production of 135 tons between 1970 and 1986 (Giuliani and Fernandés 1988).

At Marota, the emerald production is insignificant. The pits are deep (80–100 m) and show evidence of numerous coarse- to fine-grained albitic pegmatoid dikes with important molybdenite disseminations. These pegmatoids had caused the formation of a monomineralic, F-rich, biotite-rich zone, developed symmetrically on each flank of one vein. The metasomatic zoning is characterized by a regular succession of zones, each limit corresponding to sharp replacement fronts having different mineralogies. Emerald is intimately associated with the biotite-rich zone and sometimes is found within the vein. The paragenesis of the pegmatoid also includes molybdenite, pyrite, apatite, and alexandrite (Bode pits). Disseminations of scheelite are found in biotite-tremolitic schists of the Marota and Braúlia pits.

The Socotó prospecting pits are located in the northern part of the Campo Formoso granite (Fig. 2b) in serpentinites occurring as imbricated structures in the Archean basement. The ultrabasic horizon is intruded by coarse-grained albitic and/or tourmalinic pegmatoids bearing minor quartz, or quartz with or without plagioclase-tourmaline veins. The pegmatoids, which consist of a successive swarm of parallel veins, developed a metasomatic zoning similar to that observed in Carnaíba. Scheelite, molybdenite, pyrite, phenakite, and apatite complete the paragenesis of the veins.

The Santa Terezinha de Goiás emerald deposit (Goiás State)

The Santa Terezinha de Goiás mining area (Fig. 1) is located in the northern part of the Crixas greenstone belt. Its lithological sequence composed of schists, quartzites with basic-ultrabasic intercalations, and acid sills belongs to the Pilar de Goiás Group (1600–1100 Ma). During the Uruçuano orogeny (1200–1100 Ma) regional metamorphism and deformation had resulted in NS-trending folds, the formation of talc-chlorite-carbonated schists, quartz-sericite schists, metacherts, ferruginous quartzites, metamarl intercalations, and the intrusion of the São José de Alegre granitoid (Costa 1986).

In the Santa Terezinha de Goiás mining galleries pegmatoid veins are absent and emerald mineralization is located in biotite schists, e.g., "biotitites" (also called "phlogopitites" due to the phlogopite composition of the mica), biotite-talc-carbonate and carbonate-biotite schists. The biotitites are the product of a metasomatic process which acted within the Santa Terezinha sequence; their thickness ranges from one centimeter to half a meter. They are parallel to the other lithological contacts but a clear fluid infiltrational process is responsible for their formation (Fig. 3a). Small biotitite fingers cut the contacts at low or high angles everywhere. K-metasomatism is accompanied by intense pyritization.

The Santa Terezinha region experienced strong tangential stresses resulting in thrusting (Silva and Giuliani 1988), on the average from 345° to 165°. These movements formed a first set of recumbent to inclined folds affecting all the lithologies, including the biotitites and the biotite-carbonate-talc schists. The axial plane foliation is well defined and the original orientation of the axial plane of the folds could probably have been 340°–330°/15°–20°, as deduced from the trend of the rock units and the regional foliation. Talc-rich lithotypes pro-

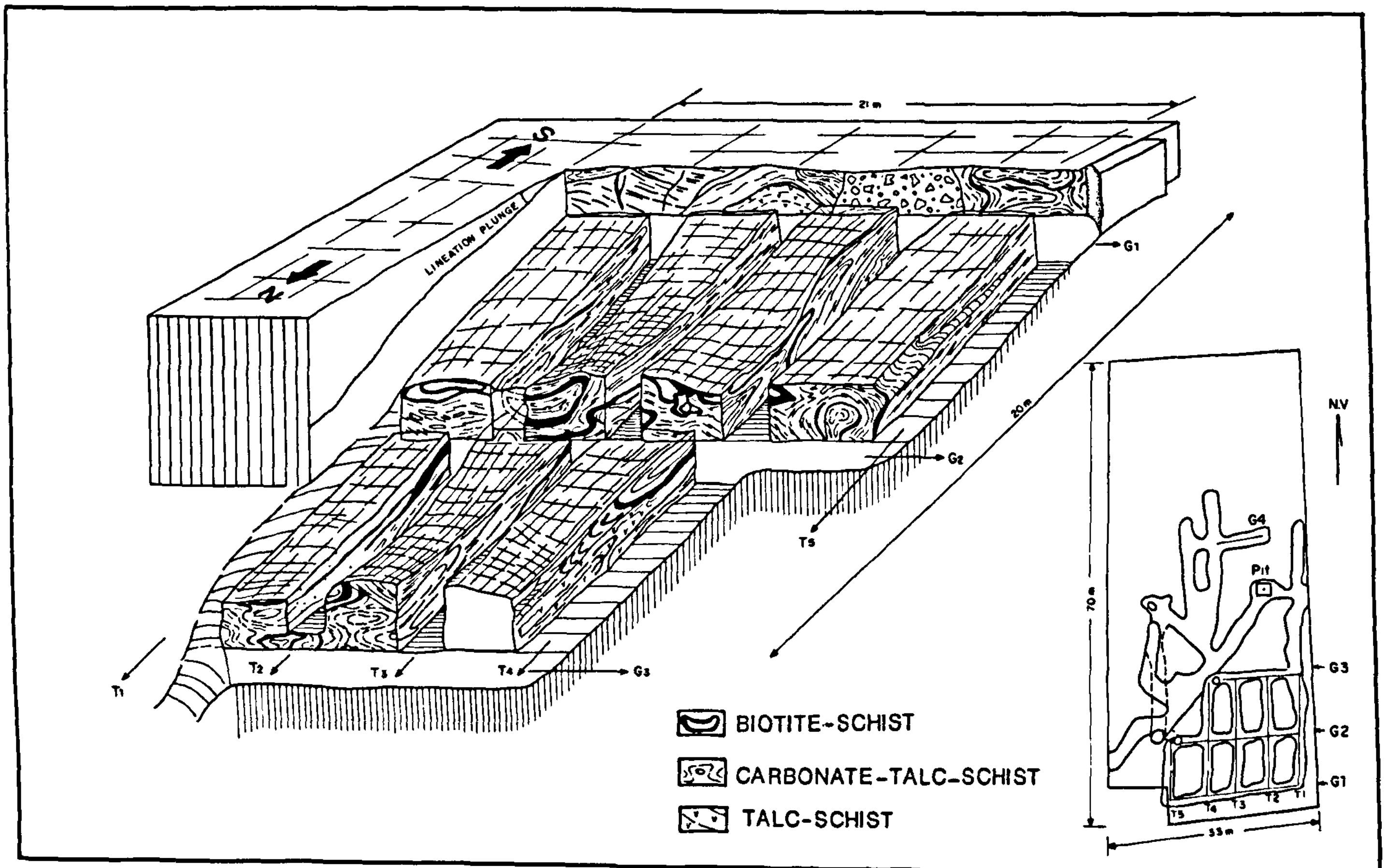

Fig 4. Structural block diagram of the Trecho Novo 167 underground mine (EMSA mining compagny). **a** Layout of the mine (level 86). The G1 to G4 galleries are horizontal, and the T1 to T5 crosscuts have axes striking 350°/15°. **b** Combination of the two sets of maps of the G and T galleries

vided the main sites for thrusting and, moreover, facilitated the migration of the tectonic movement, yielding well-developed sheath folds in a very homogeneous sequence. The axes of the sheath folds show a statistical parallelism with the tectonic lineation: their plunge ranges 10°–20° toward 345° azimuth.

The deformation in Santa Terezinha de Goiás took place mainly in the plastic field. Fault planes can be observed in the galleries, but they are part of the process of thrusting and folding. Brittle deformation is not important in the area, especially with regard to the structural control of the emerald mineralization.

The structures described above are frequently observed also in the diamond drill cores from the surrounding prospects. The sheath fold shown in Fig. 3 b, c is from the Damião prospect, which is located 2 km southwest of the Trecho Novo underground mines in the central part of the emerald district. In the Trecho Novo 167 mine, exploited by the room-and-pillar method, it was possible to follow the structures in a three dimensional projection (Fig. 4). The emeralds are hosted by carbonate-talc schists, talc schists, and biotitites, and developed along the plane of the regional metamorphic foliation. In a very few cases there are some emeralds in small fractures filled with biotitites or carbonates. It is common to find an emerald-rich zone in the core of the sheath folds, suggesting a prolate ellipsoidal shape for the orebodies, and showing a clear control along the regional stretching lineation. The sequence of drawings in Fig. 5 illustrates the structural history of the area and the controls of the mineralization process.

The Belmont emerald mine (Minas Gerais State)

This mine is located at the contact between Archean paragneiss and a highly deformed granitic unit, which belongs to the Borrachudo granite type (Schorscher et al. 1982). The metamorphic sequence is composed of meta-arenites and metagraywackes with intercalated mafic formations. The Lower Proterozoic mafic Belmont mine formations, transformed into biotite, talc-chlorite schists, are 750–1000 m wide and strike NE. They are intruded by a number of pegmatite bodies which are concentrated between the deformed granite and the schists; the pegmatites are strongly weathered and consist mainly of kaolinitic masses and quartz.

Emeralds with chrysoberyl or alexandrite are found either in the pegmatite veins or in the associated metasomatic zones of green chlorite schist and phlogopite schist. Pegmatite veins crosscutting the deformed granite are emerald free but they contain beryl and/or aquamarine (Hänni et al. in press).

A new important occurrence of emerald was discovered at the end of 1988 in the Nova Era region.

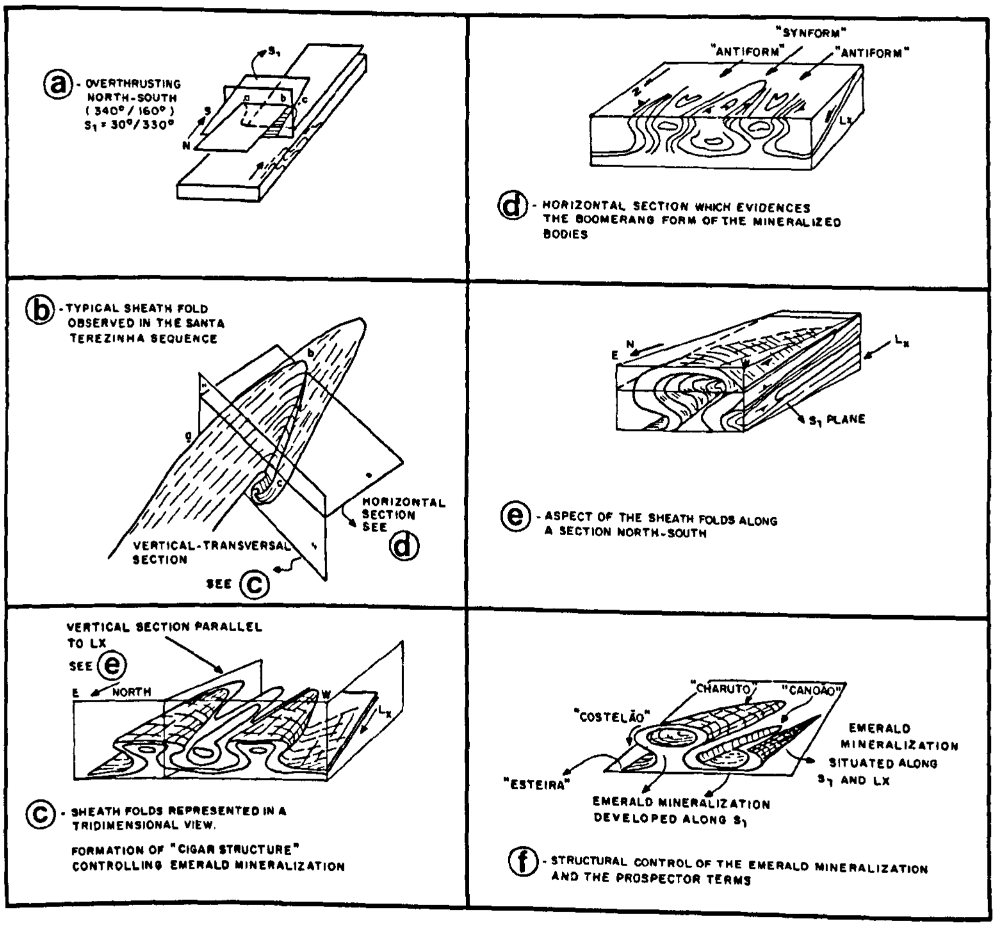

Fig. 5. Structural evolution of the Santa Terezinha volcano-sedimentary sequence and the controls of emerald mineralization

Genesis of emerald deposits of Brazil

Emerald mineralization in Brazil is located in biotite schist resulting from K-metasomatism of serpentinites, talc schists, or tremolitic schists from a volcano-sedimentary sequence usually metamorphosed in the greenschist facies. For the development of the observed metasomatic columns several factors are to be considered: the homogeneity and the composition of the formations, and the structures and channels permitting the infiltration of the ascending fluids.

The Socotó and Carnaíba deposits are an example of homogeneous series including serpentinites, intruded by pegmatoid veins related to a proximal granitic intrusive cupola (Fig. 6). In this case, the metasomatic rocks show a regular zoning; each zone has developed on both sides of the vein with a different mineral composition, separated by sharp and clear boundaries (Rudowski 1989). Santa Terezinha de Goías is a typical example of an inhomogeneous formation which had infiltrated along bedding planes and fractures contemporaneous with the main folding phase. In this case, pegmatoid veins are absent and the corresponding infiltrating zones correspond to a "main infiltrated zone" in which circulation of the fluids was intense. This circulation developed preferentially along lithological contacts, and resulted in the succession of small infiltrated zones corresponding to bed-by-bed injections. Such a mechanism leads to the development of small imbricated superposed metasomatic structures.

The importance of the infiltration process explains the size of the mineralized zone, which develops as a body of 500 m in length and a width of 60 m. The thickness of the emerald-bearing talc schist is variable and may reach maximum values of 20 m; it is related to tectonic thickening (Fig. 5), which permits the same mineralized strata to be intersected several times. It also indicates that the infiltration was previous to or synchronous with the main deformation phase, a tangential regime which seems to have acted during the Lower Proterozoic.

The formation of emerald requires the circulation of acid Be-bearing fluids also enriched in F, Cl, K, and Al in channels developed in ultrabasic rocks rich in Mg, Fe, and Cr.

In the case of the Socotó and Carnaíba deposits, the source of beryllium is related clearly to pegmatitic fluids whereas, more than one source of origin may be proposed in the case of Santa Terezinha de Goiás deposit: (1) a syngenetic one, based on a possible remobilization during the regional metamorphism of beryllium contained in acid volcanics (quartz-sericite schist, Q.S.S.) intercalated within carbonate-talc schists (CTS; Costa 1986; Schwarz 1986, 1987); (2) an epigenetic one (Giuliani and Couto 1988a, b; Silva and Giuliani 1988).

We think that hypothesis (1) may not suitable account for the origin of beryllium because the fluid flow process is clearly related to an infiltrational mechanism and displays clear tectonic and lithological control. Hence, some questions remain to be answered with regard to the leaching of beryllium by hydrothermal fluids. What is the Be

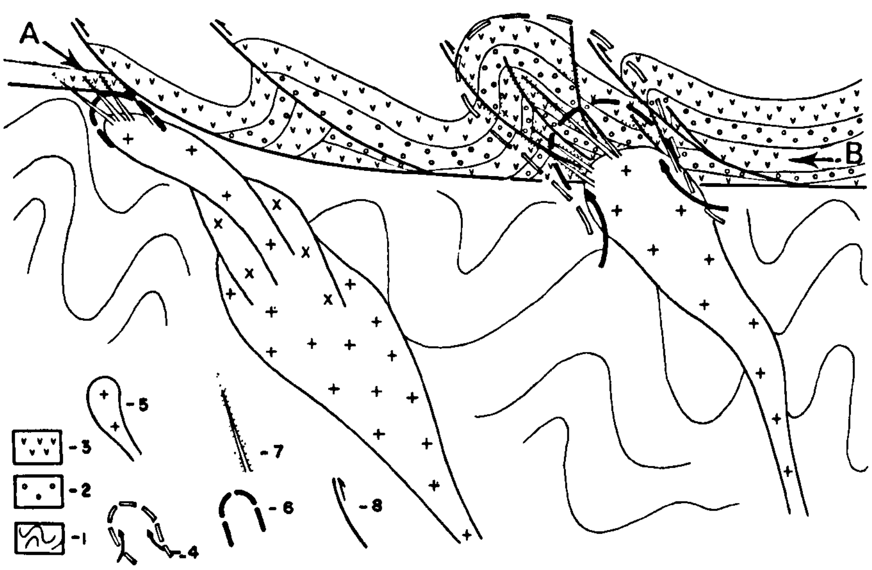

Fig. 6. Model for the type-I emerald deposit clearly associated with pegmatitic veins derived from younger granitic intrusions and crosscutting a volcano-sedimentary sequence. A, *Socotó* prospecting pits (Bahia State) where the mineralization is linked to pegmatoids; the granitic intrusion is absent at the level of observation. B, *Carnaíba* mining district (Bahia State), the typical "granitic emerald-type deposit" showing the relationships between leucogranite, pegmatitic veins, and its consequent hydrothermal metasomatism. 1, Archean basement; 2, quartzite; 3, serpentinite; 4, convective hydrothermal system; 5, granitic intrusions; 6, "molybdenite cup" developed around the granite; 7, pegmatitic (pegmatoid) vein; 8, thrust fault

content of the Q.S.S.? At the moment no data are available; if they are Be-rich, the K-, Al-, Si-, and F-rich infiltrating fluids reacting with the Cr-free Q.S.S. would result in the formation of beryl; no beryl mineralization has yet been encountered in the Q.S.S.

Following the epigenetic model, the Santa Terezinha de Goiás emerald mineralization will appear to be the result of a two-stage process: (1) a metamorphic reaction stage producing the observed characteristic banding, i.e., metamorphism developed by cation exchange, (2) later infiltration of hydrothermal fluids causing the replacement of the preexisting layers and the formation of the stratiform emerald mineralization.

In Santa Terezinha, the fact that the main mineralized zone is bounded by relatively impermeable formations explains why the fluid flow must have been usually along bedding planes and not across them. The formation of the stratiform emerald deposit and its associated biotitite is not a single phenomenon; it may be related to an important geothermal anomaly implying the emplacement of granitoid plutons not necessarily present at the same level as the mineralized formations. In such a ductile shear zone environment, intrusion of felsic granitoids into greenstone belt along thrusts generated during its emplacement is common (De Wit et al. 1987). Such structures have been observed in the adjacent Crixas greenstone belt (H. Jost, personal communication).

Hypothesis (2) does not require a direct magmatic origin for the mineralizing fluids but more likely some sort of a long-term equilibration. The convective hydrothermal systems would cause mixing of dilute meteroric or metamorphic waters with solutions evolved from the crystallization of the pluton.

The origin of the pegmatites of Belmont mine district is more ambiguous. The pegmatites may be part of those described by Schorscher et al. (1982) as being related to the Brazilian tectono-thermal event (500 Ma). They intrude the basement complex, the Rio das Velhas, and Minas rock, which do not show signs of regional metamorphism and tectonic deformation. Their composition is that of common quartz-feldspar pegmatites of the Itabira mining district, leading us to compare them with the important and famous aquamarine-beryl pegmatite province of Minas Gerais.

The emerald occurrences of Tauá (Schwarz et al. 1988) and Coqui (Mariano et al. 1988) are also characterized by the absence of undeformed intrusive granitoids. The mineralization is related to the intrusion of a dikes swarm consisting of beryl, garnet, tourmaline, colombo-tantalite, and aquamarine, pegmatites within Archean talc schists intercalated in augen gneisses. These pegmatites belong to the Solonopole-Quixeramobim Province, famous for its aquamarine production.

Emerald deposits of Brazil are attributed to infitrational metasomatic processes involving acid-base interaction, perfectly illustrated by the Carnaíba deposit. As the magmatic solutions penetrate the serpentinites, the basicity of the solution increases as a result of the dissolution of bases, especially Mg, from the wall rocks. Thus, the concentration of all the other bases in the solution increases, specially the activity of the alkali oxides such as K_2O and Na_2O, as well as the alkalinity of the solution. In this chemical system, a zone of alkalinity is formed around the basic rocks owing to high diffusion of potassium inducing the K-metasomatism (potassium being more electropositive than sodium, e.g., more basic). The "acid wave" produces a great base lixiviation in the lower part of the flux with the concentration and precipitation of the less mobile components such as W and Mo (e.g., the Marota and Braúlia pits), which form the molybdenum-silica cap around the granite. In the upper part of the hydrothermal fluid circulation system, the precipitation of the bases will predominate resulting in the vertical zoning observed in Carnaíba.

The granitic pegmatites are desilicated and have an albitic composition. Beus (1966) referred to this albitic type as "granitic pegmatites of the crossing line" while Korzhinskii (1970) refers to them as "desilicated pegmatites". They appear to be related to complex mineral-fluid equilibrium due to the reactive nature of the basic rocks, as in the cases described for gem minerals associated to charnockites (Rupasinghe and Dissanayake 1985; Silva and Siriwardena 1988).

Table 1. Geology, mineralogy, and chronology of the three main types of emerald deposits of Brazil. Ba, Bahia State; GO, Goiás State; CE, Ceará State

Deposits Occurrences		Type I		Type II	Type III	
		Carnaíba (1) Socotó (2) BA	Pirenópolis GO	Santa Terezinha de Goiás GO	Itabira MG	Tauá (1) Coqui (2) CE
Volcano-sedimentary series (V.S.S.)	Nature	Serpentinites	Talc-chlorite schist	+ carbonate-talc schist + chlorite schist + quartz-sericite schist	– biotite schist – talc-chlorite schist	– amphibolite – biotite schist – tremolite schist – augen gneiss
	Metamorphism	greenschist facies	greenschist facies	greenschist facies	greenschist facies	amphibolite facies
	Age	Lower Proterozoic	Middle Proterozoic	Lower Proterozoic (?)	Lower Proterozoic	Upper Proterozoic
	Name	V.S.S. of Serra da Jacobina	Araxá Series	V.S.S. of Santa Terezinha	metasediments of Minas Supergroup	(1) Independencia complex (2) Caico and Nordestino complexes
Intrusive rocks	Nature	pegmatite veins	pegmatitic veins	–	pegmatitic veins	pegmatitic veins
	Typical mineral association	beryl (molybdenite)	garnet	–	beryl aquamarine	columbite tantalite beryl aquamarine (2) cassiterite (2)
	Related γ	(1) Carnaíba (2) Campo formoso	Quebra Rabicho			
	Age	Transamazonic 1.9 Ga	pre-Uruçuano (?)	–	probably Brazilian 0.5–0.7 Ga	Brazilian? (1) Brazilian (2) 0.5–0.7 Ga
Emerald and metasomatic rocks	Nature	phlogopitite	phlogopitite	+ phlogopitite + phlogopitite-talc carbonate schist + phlogopitite-carbonate schist	phlogopitite	phlogopitite
	Typical mineral association	molybdenite alexandrite (1) scheelite apatite tourmaline phenakite (2)	tourmaline apatite (cassiterite)	pyrite chromite (Mg, Al) carbonate (Mg)	alexandrite chrysoberyl	apatite bismutite (1)
	Emerald composition	(2) (2)				(1) (2)
	Cr_2O_3	0.28 0.29	0.08	0.57	0.31	0.19 0.04
	FeO	0.62 0.75	0.61	1.15	0.73	1.05 0.04
	MgO	1.51 2.05	2.73	2.84	1.48	2.48 0.66
	Na_2O	1.29 1.09	1.77	1.77	0.92	1.84 0.59

Summary and conclusions

Brazilian emerald deposits are found in a typical geological setting with Archean basement and supracrustal, ultramafic, and granitoid rocks. The tectonic relationships with their surroundings are not yet entirely understood, but three main types of emerald deposits may be characterized:

Type I: Typical deposits associated with mafic-ultramafic rocks, granitic proximal intrusives, and related pegmatites; for example, the Carnaíba and Socotó prospecting pits (Bahia State).

Type II: Important emerald-biotite schist deposits characterized by the absence of pegmatitic veins and developed in ductile shear zones; for example, the Santa Terezinha de Goiás prospecting pits (Goiás State).

Type III: Deposits related to the presence of aquamarine, beryl and/or Nb-Ta-cassiterite-bearing pegmatites of uncertain origin, such as the Belmont mine (Minas Gerais State).

The different features of these three types of deposits are presented in Table 1. Some conclusions may be drawn as follows. In all the deposits, emerald mineralization is found in biotite schists, and each type is characterized by a typical ore paragenesis. In the granitic type, Mo and to a lesser degree, W are important metals associated with emerald; for instance, the Carnaíba mining district is at the moment responsible for the total Brazilian molybdenite production. In type II, pegmatites are absent and emerald mineralization is contemporaneous with the structural evolution of sheath folds in a ductile shear zone. In this case, the "biotitization" is associated with intense pyritization yielding frequent pyrite-emerald intergrowths. It appears that the Santa Terezinha geological and structural setting is favorable for the investigation of metals such as gold which is already exploited in the surrounding Archean basement. In the third type of deposit, aquamarine (Belmont mine) or Sn, Nb-Ta aquamarine (Coqui, Tauá) are the main characteristic minerals of the pegmatites.

The differences in ore paragenesis and emerald chemistry are probably related to differences in fluid composition; the first investigations in fluid inclusions in emerald (Cheilletz 1988; Giuliani and Weisbrod 1988; Hänni et al. in press) confirm a notable variation in bulk composition and salinity of the fluids related to each type of emerald deposits.

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