EMERALD DEPOSITS: A REVIEW

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Summary
A geological-mineralogical characterisation of emerald deposits is given. Basically, two main types of emerald deposits can be distinguished: (I) emerald mineralisations related to granitic intrusions, and (II) emerald mineralisations, which are mainly controlled by tectonic structures, like thrust faults and shear zones. The geological-genetic background of some specific emerald deposits is discussed.

Introduction
Beryl is not a common mineral in the continental crust, but it is significantly abundant in Al-rich granites and associated pegmatites. Emerald, the green variety of beryl, which owes its color to the elements chromium and vanadium, is scarce, because its chromophoric elements are geochemically not related to beryllium, one of its main components. Emerald deposits are known from five continents, South America being the world's most important emerald producer for many years. Emeralds have formed during practically all geological periods. The oldest emerald mineralisations developed during Archean times (about 3 Ga) in South Africa (Gravelotte mine). The Brazilian emeralds from Carnaiba and Socoto in the Bahia State were deposited during the Early Proterozoic, around 2.0 Ga, whereas those of Capoeirana, Itabira (both in Minas Gerais State), and Santa Terezinha formed during the Palaeozoic (about 500 Ma). In Colombia, the Chivor deposits in the Eastern Belt of the Cordillera Oriental are older (ca. 65 Ma) than those of the Muzo region, located in the Western Belt (about 40 Ma). In Pakistan, Swat emeralds date from ca. 23 Ma, and those from Khaltaro, which are the youngest in the world, were formed at 9 Ma. Most periods of emerald formation correspond to episodes of continental collison, which generated the formation of mountain belts and huge areas of deformation, uplift, and erosion.

Mechanism of Emerald Formation
Sources of chromium and vanadium are mafic-ultramafic igneous rocks found in suture zones and volcano-sedimentary series, as well as in sedimentary formations, like black shales. Sources of Be are pegmatitic and Al/Si-rich magmas, black shales and metamorphic rocks.

Emeralds can been found in different geological environments, related to all potential source rocks of these elements. Nevertheless, the juxtaposition of Cr/V and Be in nature requires exceptional geological and geochemical conditions. The main motor for their combination is the extended circulation of fluids. The principal mechanism responsible for emerald crystallisation are fluid/rock interactions, which allow the redistribution of elements, normally not related to each other. Isotopic composition of channel H_2O in emeralds reveals that their parental fluids typically have a metamorphic or magmatic origin, those for emeralds from Colombia are consistent with basinal brines.
Emerald growth results always 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 grain boundaries of the minerals or along closely spaced fractures. The infiltrated rocks are hydrothermally altered and the chemical components carried by the fluids (Al, Si, K, Be, F, Cl, B, Li, Rb, Nb, Ta, Mo,....) or leached from the parent rocks (Si, Mg, Na, Fe, Ca, Cr, V, Sc), will combine to form emeralds within the alteration zone, at P-T conditions controlled by the fluid circulation processes.

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

Main Types of Emerald Deposits (Geological-Mineralogical Characterisation)
Different genetic classifications have been proposed for emerald deposits in the past. Such classifications 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; (c) geochemical data, especially the types of hydrothermally altered rocks, which are found worldwide in emerald deposits.
Basically, two main types of emerald deposits can be distinguished: (I) emerald mineralisations related to granitic intrusions, and (II) emerald mineralisations, which are mainly controlled by tectonic structures, like thrust faults and shear-zones.

Type I deposits. Formation of most emerald deposits in the world relates to granitic intrusions. These deposits are characterised by mafic-ultramafic or sedimentary rocks, which are cut by granitic pegmatites, granitic dykes, or hydrothermal veins. Emerald mineralisations are located in the immediate vicinity or within the exocontact zones of pegmatite-bearing granitic intrusions. Most emerald deposits of this type are embedded in rock sequences consisting of Archean or Precambrian basement, Precambrian or Paleozoic volcano-sedimentary series, or oceanic suture zones, and granites with their magmatic to late-magmatic equivalents. Typically, in these deposits, the mafic and ultramafic rocks (serpentinite, amphibolite, talc-schists) were previously transformed by regional metamorphism.

Hydrothermal processes related to granitic-pegmatitic systems led to the crystallisation of emeralds in mafic-ultramafic or in (meta)sedimentary rocks. In general, the mafic-ultramafic hosts of emeralds are schistose rocks of varying composition (mostly biotite/phlogopite and actinolite/tremolite schists). Emeralds are, generally, found in black-colored phlogopite schists (e.g. schists containing Mg-rich biotite, greyish talc +- phlogopite +- chlorite), and, sometimes, within veins with white feldspar and mica. This is the case for most deposits in Africa (e.g Ndola Rural District/Zambia; Belingwe/Zimbabwe; Mananjary/Madagascar) and Brazil (Carnaiba-Socoto; Belmont mine-Capoeirana; Taua), as well as for the Ural Mountains in Russia. Further examples for granite-pegmatite related deposits in mafic-ultramafic rocks are Khaltaro/Pakistan, Poona/Australia, Hiddenite/USA, and the Kaduna-Plateau States/Nigeria. These deposits are associated with pegmatites, but their geological and mineralogical features differ from those found in the 'classic' granite-related occurrences. In Eidsvoll/Norway and Emmaville-Torrington/Australia, emeralds are hosted by (meta-) sedimentary rocks.

Type II deposits. A second group of emerald deposits is not related to granitic intrusions. In these, tectonic structures (mainly thrust faults and shear zones) are the controlling factors for the formation of emerald mineralisations. They allow the circulation of fluids, which interact with mafic rocks of volcano-sedimentary series (e.g. Santa Terezinha/Brazil; Habachtal/Austria) or in oceanic suture zones (e.g. Swat Valley/Pakistan; Panjsher Valley/Afghanistan; Eastern Desert/Egypt). The famous Colombian deposits in the Cordillera Oriental have a unique geological setting (black shale host-rocks) and a unique formation history. They result from the thermochemical reduction of evaporitic sulphate brines with the participation of organic matter from the surrounding black shales in the reactions.

Emeralds and the Geochemical Cycle of Beryllium in the Crust

The genetic model, generally proposed for the formation of emerald deposits related to granitic intrusives, involves the presence of Be-bearing granitic pegmatites within Cr/V-bearing mafic-ultramafic rocks or meta-sedimentary series. However, the intrusion of pegmatites into Cr/V-bearing rocks is not sufficient for the crystallisation of emeralds. These are not the product of a contact metamorphism around intruding pegmatites in the country rock. Rather, emeralds crystallised during a metasomatic episode due to the circulation of fluids after the intrusion of the pegmatites, and resulting in the formation of metasomatic rocks. These rocks are composed of vein-like biotite schists ('phlogopitites'), developed at the expense of serpentinites or talc-schists, and plagioclasites. Veins, composed of quartz +- albite +- muscovite +- fluorite are also, frequently, developed in metasomatic zones. Such metasomatic systems with phlogopitites and plagioclasites can be observed worldwide in the majority of these deposits.

Under these conditions, the infiltrating fluids interact with both pegmatite and mafic rocks. Chemical changes in the infiltrated rocks, precipitation of minerals (phlogopite, apatite, emerald, ...), as well as dissolution phenomena (chromite, carbonates, beryl, ...) will modify the chemical composition of the hydrothermal fluids. The quantity of emerald crystals precipitated in plagioclasite-pegmatite veins or in the surrounding schists will depend on (a) the chemical reactivity of the infiltrating fluids, (b) the permeability of the host-rocks, and, (c) the quantity of Be transported into the Cr-bearing rocks. The origin of these metasomatic fluids can be approached by combining data about the fluid inclusions and stable isotopes of emeralds and their host rocks.

An alternative genetic model for emerald deposits in schist-type host rocks has been proposed by Grundmann and Morteani (1989). Based on their studies of the emerald occurrences in the Habachtal/Austria, Gravelotte/South Africa, and Poona/Australia, these authors conclude, that emerald growth took place during syn- to post-tectonic reactions under low-grade regional metamorphism. They point out, that the formation of schist-hosted emeralds cannot be due to contact-metamorphic reactions related to the intrusion of pegmatites or invading pegmatitic fluids. Emerald growth results from the circulation of fluids along the boundary pegmatite/host rock, and does not originate from pegmatitic fluids.

In emerald deposits, where mineralisations are controlled, mainly, by tectonic elements, the absence of granites and pegmatites opens the debate on the origin of the hydrothermal fluids and the source of the element beryllium, necessary for emerald formation. It is apparent, that the fluids responsible for emerald formation within shear zones or in locations controlled by thrust faults, may have quite different origins (basinal brines, metamorphic or magmatic). Beryllium may originate from a magmatic, a metamorphic, or even a sedimentary environment.

Emeralds in the Colombian deposits in the Cordillera Oriental are related to basinal brines, which were responsible for the dissolution of evaporite levels, intercalated into the black shale series. A magmatic origin for the parent fluids of emeralds can be disregarded, beryllium has a sedimentary origin.

For the deposits in the Swat-Mingora region in Pakistan, the mineralising fluids and the source of Be are considered to be of magmatic origin, despite the fact that there are no granitic intrusives within the mineralised structures.

In the Santa Terezinha de Goiás mining region, granites and related pegmatites are absent. Isotopic data of the fluids involved in emerald formation are consistent, both with magmatic (Al-rich crustal granites) and metamorphic origin. Rather, based on the ductile behaviour of the shear-zone and the chemical composition of the mineralising fluids, a metamorphic origin is proposed for the parental fluids of emeralds.

In the Austrian Habachtal and in the deposits of the Egyptian Eastern Desert, the formation of emerald-bearing biotite schists is due to metasomatic reactions between ultramafic rocks and mica-rich quartz-feldspathic rocks, which took place during regional metamorphism under greenschist to amphibolite facies conditions (Grundmann and Morteani, op.cit.). The fluids involved in emerald formation are metamorphic, beryllium has a local source. Be-bearing Al-silicates (feldspar and muscovite) were replaced by Be-poor minerals (biotite, chlorite, talc). The beryllium „released“ during these processes is available for the crystallisation of emerald.

Discussion of some specific Emerald Deposits and their Geological-genetic Background

(1) Schist-type deposits (Brazil, Africa, India, Australia, Europe)

Includes all deposits, where emerald mineralisations are associated with granitic dykes and hydrothermal veins cutting mafic-ultramafic or sedimentary rocks. Most of the so-called schist-type deposits are located in rock sequences consisting of Archean or Precambrian basement, Precambrian or Paleozoic volcano-sedimentary series or oceanic suture zones, and granites with their magmatic to late-magmatic equivalents. Generally, the pegmatites crosscut the contact zone of the pluton and intrude the surrounding rocks or roof of the granite. For this reason, Beus (1966) called them ‚granitic pegmatites of the crossing line'. These rocks and hydrothermal veins result from the circulation of fluids within the pre-existing rocks (i.e., pegmatite or granite and mafic-ultramafic rocks). It has been shown, that the mica-plagioclase and phlogopite rims and veinlets resulted from metasomatism of previous pegmatite dikelets and their adjacent mafic-ultramafic rocks. Desilicated pegmatites (i.e., pegmatites, which lost their silica, owing to fluid percolation, mainly dissolving quartz and K-feldspar) are not due to pegmatitic processes, but rather to hydrothermal ones (greisen processes, e.g. formation of rocks composed of quartz-muscovite assemblages), as described for granitic systems (Scherba, 1970). Geological, mineralogical, and geochemical pecularities of these desilicated pegmatites differ from the classical ones. Emerald mineralisations belong to vein-like bodies which formed, in part, from hydrothermal fluids, originating from the alteration of pre-existing granitic rocks.

(2) Kaduna-Plateau States/Nigeria

The beryl/emerald mineralisations in the central Nigerian Kaduna and Plateau States are associated with granitic pegmatites of two periods of magmatism (Schwarz et al., 1996): (a) the Panafrican orogeny (600-450 Ma), equivalent to the Brasiliano thermal event in Brazil; (b) the Mesozoic orogeny (190-144 Ma) with the intrusion of alkaline granites of ring complexes, which contain important Sn-Nb-Ta-Zn mineralisation (Kinnaird, 1984). In the older pegmatites, emerald is associated with aquamarine, beryl, and tourmaline. In the younger granites, emerald is found with quartz, blue topaz, beryl/aquamarine in pegmatitic pods of biotite-alkaline feldspar granites. These traps are found in the roof zone of the intrusions and in the margins of the granitic cupolas. The pegmatite pods are not affected by metasomatism and beryl and emerald formed during late magmatic and early hydrothermal stages. Both, Be and F are enriched in the alkaline granites and a magmatic origin of the mineralizing fluids is constrained by the oxygen composition of emerald (Giuliani et al., 1998). The source of Cr and V is problematic because the mineralisations are restricted to intragranitic pegmatite pods. However, the pods, occur close to the roof zone and near the contact zone with the country rocks. Thus, Cr and V may have been incorporated in the fluids from pervasive metasomatism during the granite emplacement and consequent cooling. Structural setting and styles of mineralisation of the ring complexes of Nigeria are characterised by extensive fluid interaction with the volcanics The special genetic conditions of Nigerian emeralds result in a unique set of geological and mineralogical-gemmological features. Apparently, they represent a true pegmatite-related granitic cupola mineralisation type.

(3) Santa Terezinha de Goiás (Campos Verdes)/Brazil

In the Santa Terezinha de Goiás deposit, the infiltration of hydrothermal fluids was controlled by tectonic structures such as thrust faults and shear zones. Pegmatite veins are absent and the mineralisation is stratiform. Emerald is disseminated within phlogopitites and phlogopitised carbonate-talc schists (Gusmão Costa, 1986; Biondi, 1990; Giuliani et al., 1990). Talc-schists are the favoured rock types for thrusting, and the formation of sheath folds. Emerald-rich zones are commonly found in the core of sheath folds and along the foliation. Two types can be distinguished (Biondi, 1990): (a) a carbonate-rich ore, composed of dolomite, talc, phlogopite, quartz, chlorite, tremolite, spinel, pyrite, and emerald; (b) a phlogopite-rich ore composed of phlogopite, quartz, carbonates, chlorite, talc, pyrite, and emerald. Hydrothermal processes are controlled by thrust development of Brasiliano age (510 Ma; Ribeiro-Althoff et al., 1997), which was a major tectonic-mineralising event, affecting the entire central Goiás region. The brittle-ductile deformation, contemporaneous with the mineralisation, was strongly accompanied by fluids migrating along shear planes under lithostatic fluid pressure at 500°C. The conditions of ore deposition indicate that fluids were released within the greenschist-amphibolite facies transition. Considering the absence of granites and pegmatites in the mined area, together with the lack of tourmaline in the metasomatic rocks, the control of the mineralisation by shear zone structures and the composition of the fluids, a metamorphic origin is proposed for the parental fluids of emeralds.

The absence of pegmatites and the low Be-concentration in the Santa Terezinha volcano-sedimentary series (Be < 2 ppm) exclude any local magmatic or proximal origin for this element. The remaining hypothesis involves Be-bearing metamorphic fluids released at the greenschist-amphibolite transition (T=400-500°C), or fluids generated at higher grades of metamorphism and channeled along transcrustal structures at the brittle-ductile transition zone.

(4) Habachtal/Austria

The Habachtal deposit in the Austrian Alps, has beeen studied in detail by Grundmann, Morteani and co-workers (e.g. Grundmann and Morteani, 1989; Nwe and Grundmann, 1990). This alpine deposit is located in a contact zone, which overthrusts the volcano-sedimentary 'Habach formation' on the ortho-augengneisses (central gneisses). The mineralised zone, called "blackwall zone", corresponds to a tectonic zone (shear zone), formed by ultramafic rocks (serpentinites) intercalated between orthogneisses and amphibolites. Emerald is disseminated in phlogopite schists (phlogopitites), talc-actinolite and chlorite schists. The metasomatic process, which produced the stratiform "blackwall zone", liberated sufficient beryllium from the host rocks, mainly from muscovite schists, and chromium from the serpentinite, permitting the crystallisation of emerald.

(5) Swat Valley/Pakistan

The emerald deposits of the Swat Valley and the Afghani Panjsher Valley are both thrust controlled (Kazmi and Snee, 1989; Bowersox et al., 1991; Hussain et al, 1993; Dilles et al., 1994; Arif et al., 1996): the Main Mantle Thrust in Pakistan and

the Karakorum Thrust in Afghanistan. The suture zone, which marks the collision of the Indo-Pakistani plate with the Kohistan arc sequence is composed of a number of fault-bounded rock melanges (blueschists, greenschists, and ophiolitic melanges).
The ophiolitic melange, which contains the Pakistan emerald mineralisations, is composed mainly of altered ultramafic rocks with locally cumulated pillow lavas and metasediments. Emeralds occur within hydrothermally altered serpentinites, generally showing metasomatic zonings (Dilles et al., 1994).

(6) Panjsher Valley/Afghanistan
The Panjsher emerald deposits are located in the Herat-Panjsher suture zone in the Panjsher Valley. The deposits are found along shear zones crosscutting Paleozoic metasedimentary rocks (limestones and slates), which were intruded by diorite-gabbro and quartz-porphyry dikes and sills (Kazmi and Snee, 1989). Emerald is contained within quartz-ankerite-pyrite veins. Hydrothermal alteration is evident by strong silicification, albitization, carbonatization and phlogopitization of the host-rocks. Oxygen and hydrogen isotopic composition of quartz and emerald are consistent with both a magmatic or metamorphic origin (Giuliani et al., 1997).

(7) Cordillera Oriental/Colombia
The Colombian emerald deposits define two narrow zones, located along the two major polyphased thrusted limits of the Eastern Cordillera, corresponding to the original borders of the sedimentary basin in Createceous time. The eastern emerald zone (EEZ) consists of the mining districts of Gachalá, Chivor, and Macanal. The mining districts of Muzo, Coscuez, and La Palma-Yacopí are located in the western emerald zone (WEZ).
The genesis of the Colombian emerald deposits has provoked much debate during this century. The deposits are hosted by Early Cretaceous black shale series, devoid of any granitic intrusives. Emerald is an accessory mineral found within carbonate-pyrite veins. Geochemical studies by Canadian and French scientists indicated the lack of any igneous activity related to the genesis of these deposits (e.g. Ottaway et al., 1994; Cheilletz and Giuliani, 1996). The favoured genetic model involves the interaction of basinal fluids with evaporites and organic matter contained within black shales, at temperatures of about 300°C. Fluid inclusions in emeralds are derived from the dissolution of primary halite (Banks et al., 1995), the source of Be is local (Kozlowski et al., 1988; Giuliani et al., 1990; Ottaway et al., 1994).
In the two emerald zones, emerald-bearing veins are spatially associated with stratiform breccias and albitites, the latter resulting from the Na-metasomatism caused by hydrothermal fluids of the black shales.
All geological and geochemical data favour an hydrothermal model, which involves the circulation of hot basinal fluids (at temperatures about 300°C), circulating along thrusts and faults.

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