Emeralds in the Eastern Cordillera of Colombia: Two tectonic settings for one mineralization

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ABSTRACT

Colombian emeralds are formed through a hydrothermal-sedimentary process. On the western side of the Eastern Cordillera, the deposits are linked by tear faults and associated thrusts developed during a compressive tectonic phase that occurred at the time of the Eocene-Oligocene boundary, prior to the major uplift of the Cordillera during the Andean phase (middle Miocene). On the eastern side of the Cordillera, emerald mineralization occurred earlier, at the time of the Cretaceous-Tertiary boundary, during a thin-skinned extensional tectonic event linked to evaporite dissolution. This event predates the Andean phase, during which this part of the chain was folded and thrust over the Llanos foreland.

INTRODUCTION

Like most of other emerald deposits in the world, the Colombian emerald deposits were supposed to be linked to magmatic fluids. Detailed geological and geochemical studies undertaken in 1988 have led to an entirely different and original model involving hot basinal brines (Cheilletz and Giuliani, 1996). The mesothermal-sedimentary genetic model of this unique type of emerald mineralization involves generation of brines through dissolution of evaporites by hot basinal waters, Na-Ca metasomatism (albitization and carbonatization) of black shales, and coeval leaching of beryllium. Thermochemical reduction of sulfates at temperatures to 300 °C is responsible for the precipitation of pyrite, calcite, dolomite, bitumen, and emerald.

The Colombian emerald deposits are located in the Eastern Cordillera, within two narrow bands on the west side (western zone, Muzo and Coscuez deposits) and on the east side (eastern zone, Chivor and Gachalá deposits) (Fig. 1). The Eastern Cordillera is considered to have acted since the middle Miocene (Andean phase) as a fold and thrust belt, squeezed between and thrust over its two foreland basins, the middle Magdalena basin to the west and the Llanos basin to the east (Fig. 1) (Colletta et al., 1990; Dengo and Covey, 1993; Cooper et al., 1995). The belt resulted from the tectonic inversion of the central part of a large Mesozoic basin. After a Triassic to Early Cretaceous rifting stage, the middle Magdalena and Eastern Cordillera areas became a rapidly subsiding marine backarc basin during Cretaceous time. Emerald mineralization is known to be hosted in the Neocomian series, which represents the top of the rift-stage infill, and is characterized by sandstones, limestones, black shales, and evaporites, and includes very rapid thickness and facies changes linked to synsedimentary normal faulting. The middle to Late Cretaceous backarc sequences, mainly clastic, are thicker and more uniformly distributed. By the very end of the Cretaceous, the entire basin became the eastern continental foreland basin of the Central Cordillera.

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A very peculiar aspect of the emerald mineralization in the Eastern Cordillera is its formation at two different ages measured by $^{40}Ar/^{39}Ar$ and K-Ar dating of syngenetic green muscovite crystallized on emerald-bearing vein wall rocks: one at the time of the Cretaceous-Tertiary boundary in the eastern zone and the second at the time of the Eocene-Oligocene boundary in the western zone (Cheilletz et al., 1997). A major issue is to unravel the relations between these two mineralizing events and the tectonic evolution of the Eastern Cordillera. Since 1994, precise structural studies have confirmed the compressive tectonic setting of the western deposits (Laumonier et al., 1996), but have also shown that a different scenario might have occurred in the eastern zone.

WESTERN ZONE EMERALD DEPOSITS

The western zone crops out in the core of the Villeta anticlinorium (Figs. 1 and 2A). The sedimentary series that enclose the emerald deposits (Fig. 2B) are a few hundred meters thick and are composed of, from bottom to top: (1) micritic, largely dolomitic limestones (Rosablanca Formation, Valanginian-Hauterivian); (2) calcareous black shales (Hauterivian); and (3) siliceous black shales that form the base (Hauterivian) of the thick mudstones (Barremian-Aptian) of the Paja Formation. Most of the emeralds are found in hydrothermal breccias or in carbonate-pyrite veins developed within both dolomitic limestones and calcareous black shales.

The deposits are hectometer-sized at most and display numerous folds, thrusts, and tear faults (Laumonier et al., 1996). All the tectonic contacts are marked by centimeter- to meter-thick hydrothermal breccias that are cataclasites with clasts of black shales and albitites (i.e., massively albitized shales) within a carbonate-albite-pyrite cement. These breccias derived from a fluid-rich pulp (Branquet et al., 1999). Part of the overpressured fluids escaped and triggered intense hydraulic fracturing in surrounding rocks, especially along tear faults. In each deposit, there is evidence of complex deformation that resulted in polyphase duplex structures. For example, in the Coscuez deposit (Fig. 2, A and C) N30°E verging folds and thrusts were guided by the sinistral N20°E trending Coscuez tear fault. In the Muzo deposit

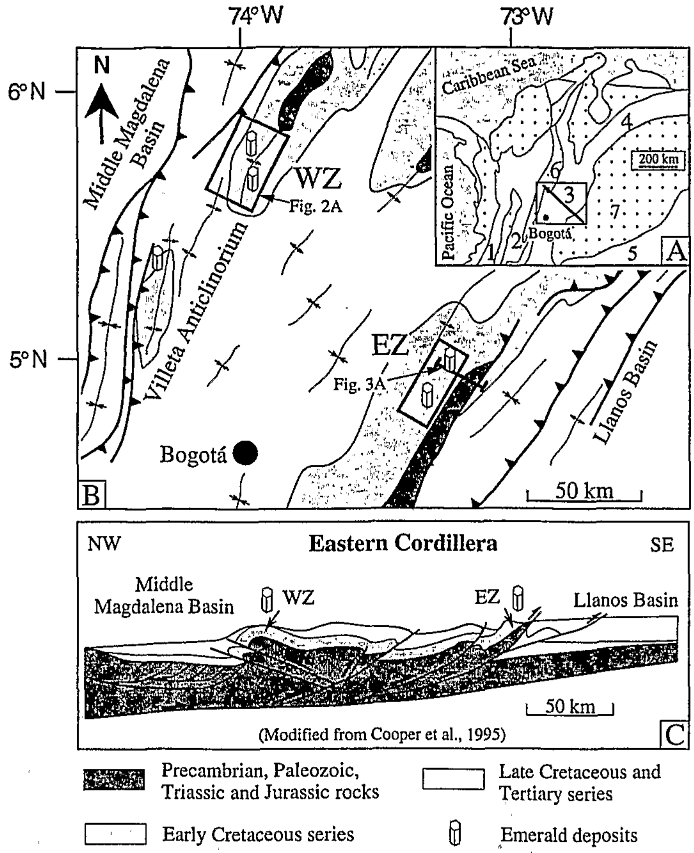

Figure 1. A: Major tectonic provinces of northwestern Colombia and western Venezuela: 1, Western Cordillera; 2, Central Cordillera; 3, Eastern Cordillera; 4, Merida Andes; 5, Guyana shield (present-day sedimentary basins are shown by dotted pattern); 6, middle Magdalena basin; 7, Llanos basin. Inset and line are B and C, respectively. B: Simplified structural map of Colombian Eastern Cordillera. Both western zone (WZ; e.g., Muzo and Coscuez) and eastern zone (EZ; e.g., Chivor and Gachalá) emerald deposits are hosted within Early Cretaceous series in large anticlinoria along Cordillera flanks. C: Cross section through Eastern Cordillera, which is bivergent fold and thrust belt overthrusting its two foreland basins, middle Magdalena basin to west and Llanos basin to east.

(Fig. 2A) early thrusts and folds were deformed by later southeast-verging folds and thrusts (Fig. 2, D and E). Later, the sinistral N140°E trending Rio Itoco tear fault divided the deposit between the Quipama and the Tequendama mines with opposite thrust vergence. A flower structure that developed at the intersection of the Rio Itoco fault with a N30°E trending strike-slip fault characterizes the small La Pava deposit (Fig. 2F). In all emerald mines, tear faults are deep-reaching fractures that acted as vertical conduits for the hot mineralizing fluids. Thus, the structures of the western zone deposits result from thrusts branched and guided by tear faults of regional extension.

At a regional scale, within the Villeta anticlinorium, the emerald deposits are capped by the Paja Formation, which is deformed by reverse faults and kilometer-scale upright folds with crenulation cleavage that trend N30°E (Fig. 2A). Thus, an overall disharmony appears between this regional deformation pattern and the smaller and more complex structures of the deposits, implying the existence of basal and roof decollements along which the tectonic contacts visible in the deposits are branched. The basal decollement (Φ in Fig. 2B) is thought to be the evaporitic level also involved in the genesis of the mineralizing hydrothermal brines. In the Paja shales above the deposits, the regional cleavage is overprinted by the growth of chloritoid porphyroblasts during the temperature peak synchronous to emerald deposition. It thus appears that at the time of the Eocene-Oligocene boundary, this mineralizing event was coeval with local- and regional-scale structure development in the west side of the Eastern Cordillera.

EASTERN ZONE EMERALD DEPOSITS

In the eastern zone (Fig. 3A), Andean thick-skinned tectonics are responsible for the main deformation observed on regional cross sections through the Eastern Cordillera and adjacent Llanos foothills. This Andean deformation corresponds mainly to reverse faults (with an overall vergence to the southeast) and folds affecting the Paleozoic basement and its Cretaceous-Tertiary sedimentary cover. Some of these faults are inverted Early Cretaceous growth faults (Cooper et al., 1995). The Esmeralda fault (Fig. 3A) seems to represent a preserved part of an Early Cretaceous normal fault (Ulloa and Rodriguez, 1976). As the result of these Andean thick-skinned tectonics, the Chivor emerald deposit is located on a gently northwest dipping monocline situated on the western flank of a large, N30°E-trending, upright fold, devoid of cleavage (Fig. 3A). The enclosing sedimentary series (Fig. 3B) correspond to the upper part of the Guavio Formation (Berriasian), which unconformably overlies the Paleozoic basement and is overlain by the shales of the thick (2900 m) Valanginian Macanal Formation (Ulloa and Rodriguez, 1976). The series hosting the emerald-bearing veins and the hydrothermal breccias are composed of, from bottom to top: (1) shales and siltstones that are locally massively albitized (lower albitites); (2) a 1–10-m-thick, stratiform brecciated level largely made of hydrothermal breccia; (3) an albitized and carbonatized sequence (upper albitites) that is white and initially contained anhydrite beds (as evidenced by phantom nodules, chicken-wire, and tepee structures); and (4) bioherms of micritic or shelly limestones grading vertically and laterally into black shales intercalated with calcareous pebbly mudstones and olistostromes.

Within the brecciated level, disrupted blocks of the hanging wall (albitites, black shales, limestones) and caving structures are evidence for the collapse of the roof. Thus, the dissolution of an evaporitic horizon (probably initially containing also halite) appears to be a major process controlling the formation of the brecciated level. The stratiform association of evaporites, limestones, albitites, and the brecciated level is known over tens of kilometers around the Chivor deposit, owing to its folding by the Andean phase. All the emerald deposits of the Chivor mining district are located within or just above this regional level, and so define a stratigraphic emerald horizon (Fig. 3A).

The Chivor deposit reveals several obvious mineralized structures (Fig. 3C): (1) centimeter- to decameter-scale listric faults and associated rollovers; (2) meter-wide extensional fractures injected with hydrothermal breccia that form chimneys; and (3) a well-developed set of extensional fractures, striking northeast-southwest, mainly filled with carbonate and pyrite and perpendicularly crosscutting the stiff albitites. All these mineralized structures are branched from the brecciated level, which is mineralized. The small La Guala deposit, located 4 km northwest of the Chivor deposit, is hosted in the Macanal shales just above the brecciated level and shows numerous conjuguate normal faults sealed by the emerald hydrothermal paragenesis (Fig. 3C). The most developed set of these normal faults is northeast-southwest striking and southeast dipping.

It appears that the initiation and the development of all these structures are coeval with hydrothermal fluid circulation and the emerald deposition. Most of these synmineralization structures are clearly extensional and point to a relative movement of the hanging wall of the brecciated level toward the southeast, but the slip could have been small (some hectometers at most). This southeast-directed movement is interpreted as a normal downdip slip on the brecciated level, which acted as a local detachment. The brecciated level is an evaporite dissolution residue, suggesting that the lubricating agent of this detachment was the evaporite-dissolving and mineralizing fluid rather than a viscous flow of salt. The slip might have been gravity driven on a favorably inclined slope (Fig. 3C). Thus, in the eastern zone, the synmineralization deformation corresponds to a thin-skinned extensional tectonic event of limited extent at the time of the Cretaceous-Tertiary boundary, controlled by evaporite dissolution and gravity driven.

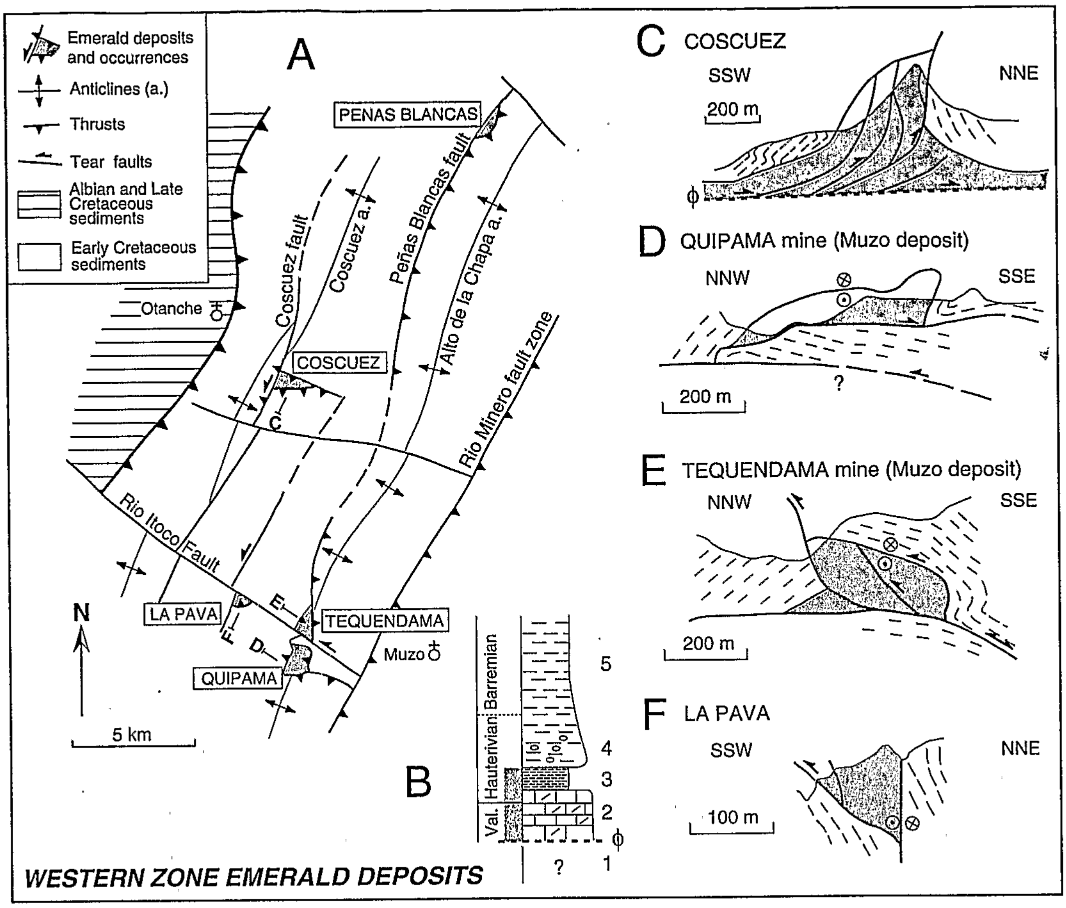

Figure 2. A: Structural sketch map (location in Fig. 1B) reinterpreted from Rodríguez and Ulloa (1994) for regional structures and from our original data for deposits (slightly enlarged). B: Schematic lithostratigraphic log: 1, lowermost Cretaceous rocks do not crop out; 2, Valanginian-Hauterivian dolomitic limestones; 3, Hauterivian calcareous black shales; 4, Hauterivian siliceous black shales; 5, Barremian-Aptian mudstones. Φ represents basal decollement. C, D, E, F: Cross sections (see A for locations) of emerald deposits; 2–3 sequence is in green and hydrothermal breccias marking thrust and fault planes are in red.

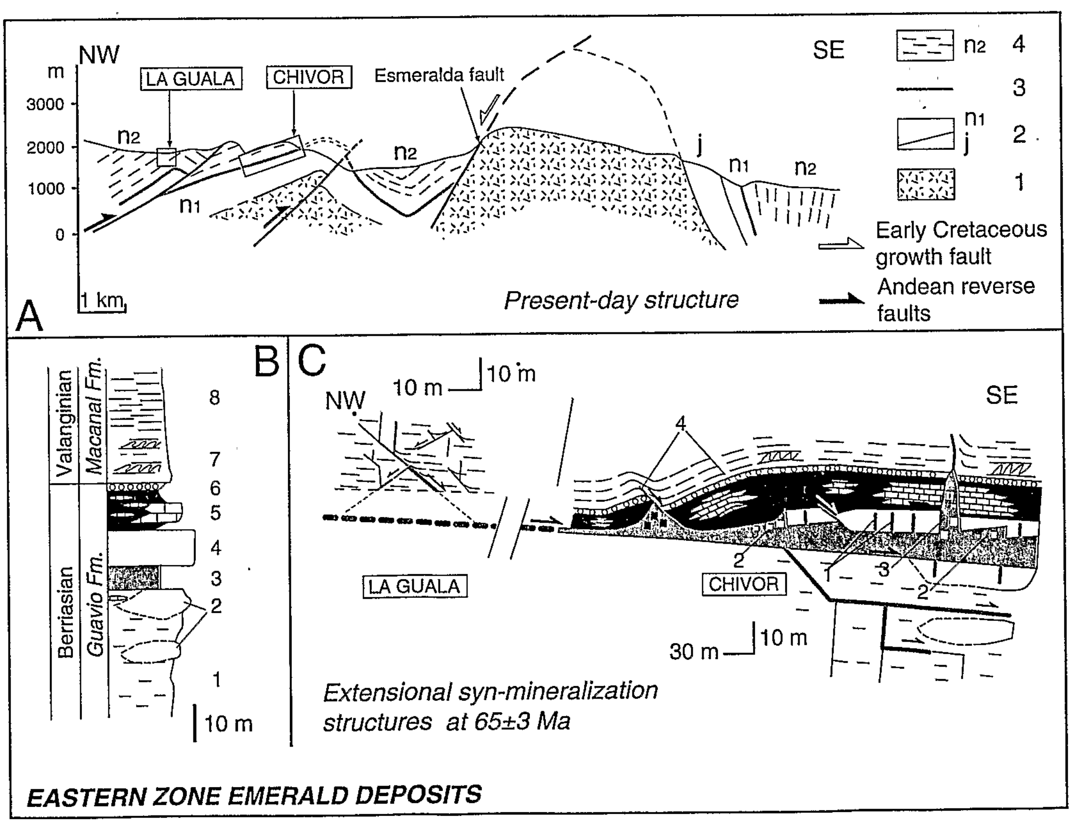

Figure 3. A: Simplified regional cross section (location in Fig. 1B): 1, Paleozoic basement; 2, Jurassic and Berriasian sedimentary rocks; 3, brecciated level; 4, Valanginian Macanal Formation. Insets are locations of C. B: Schematic lithostratigraphic log of Chivor deposit: 1, shales and siltstones with lower albitites, 2 and 3, brecciated level; 4, upper albitites; 5, black shales, limestone lenses, calcareous pebbly mudstones; 6, olistostrome; 7, slumped shales; 8, shales. C: Extensional synmineralization structures in pre-Andean attitude, i.e., with southeast-directed dip (schematic). Red shows main brecciated level and associated mineralized faults and fractures. La Guala deposit contains conjugate normal faults with slight movement toward southeast. In Chivor deposit are: 1, set of extensional fractures to 10 m high and 1 m wide perpendicularly crosscutting albitites (in yellow); 2, lateral erosion (caving structures) of upper albitites and incorporation of blocks in thick brecciated level; 3, collapse of blocks of limestone and albitite in subvertical chimneys; and 4, rollovers associated with listric normal faults.

DISCUSSION AND CONCLUSION

Apart from the geochemical processes (and hence the emeralds), which were basically the same in the western and eastern zones, the two groups of deposits differ in many points. In the western zone, the mineralizing fluids were generated in an evaporitic level someplace under the deposits, then migrated upward and turned to overpressured fluids through the enclosing series, where hydrothermal breccias and intense hydraulic fracturing developed along thrusts and faults. In the eastern zone, all the geochemical processes occurred in the mineralized series, which contained an evaporitic level, in relation to an extensional deformation. The deposits of the eastern zone are almost autochthonous, while in the western zone, they appear allochthonous relative to the source of the mineralizing fluids. In the western zone, traps for the mineralization were small but complex compressive structures guided by tear faults, whereas the eastern deposits are scattered along a regional brecciated level. In both groups of deposits, thick, impermeable shales (Paja Formation in the western zone and Macanal Formation in the eastern zone) acted as a seal for the fluids.

The genesis of the western deposits is the consequence of an overall west-northwest–east-southeast shortening characterized by folding and thrusting along tear faults at the time of the Eocene-Oligocene boundary (38–32 Ma). Middle Eocene folds and thrusts truncated by regional unconformity in the middle Magdalena basin (Schamel, 1991) and a generalized sedimentary hiatus spanning the early and middle Eocene in the entire Eastern Cordillera (George et al., 1997) have been reported. Folding and thrusting in the west side of the Eastern Cordillera began at this time while the main uplift occurred later during the subsequent Andean tectonics (middle Miocene). In the eastern zone, the regional structures are Andean and obviously postdate the emerald mineralization. The mineralization-related structures are small and define thin-skinned extensional tectonics, possibly gravity driven and enhanced by the escape of the evaporite-dissolving and mineralizing fluids. Therefore, around the time of the Cretaceous-Tertiary boundary, something must have triggered these extensional structures and then initiated the mineralizing process. A slight tilting of the Cretaceous series attitude might have been sufficient to induce local detachments on evaporites associated with a release of residual fluids. Whether this tilting is produced by extensive, compressive, or transpressive regional tectonics is not yet known. At the time of the Cretaceous-Tertiary boundary, the northwest South America passive margin became a convergent active margin. The Llanos basin (in the Cusiana field) also records a major unconformity within a hiatus spanning the Cretaceous-Tertiary boundary (Cazier et al., 1995), which could correspond to the Laramide phase 1 of Casero et al. (1997). Somehow, the mineralization and the associated thin-skinned extensional structures in the eastern zone must be linked to this tectonic event.

The Colombian emerald deposits are almost exhausted, and the finding of new deposits will necessitate prospecting that is structurally oriented, focusing on the localization of: (1) structural traps along regional tear faults in the western zone and (2) the stratiform brecciated level in the eastern zone. In summary, in the Eastern Cordillera of Colombia, the east side story was quite different from the west side story.

ACKNOWLEDGMENTS

We thank MINERALCO S. A. and the Colombian emerald mining companies for logistical support; N. Tchegliakova and S. Reboulet for faunal determinations; P. Baby, P. Cobbold, and G. Mascle for helpful comments; M. Ford for editorial assistance; and B. Colletta and L. Groat for their constructive reviews. The study was supported by the French Ministry of Education, Institut de Recherche pour le Développement, and European Commission DG XII grant CT 94-0098.

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Manuscript received November 30, 1998
Revised manuscript received March 22, 1999
Manuscript accepted March 29, 1999