Rom. J. Mineral Deposits, vol. 91 (2018), No. 1-2, p. 1-6

COMBINED MINERALOCHEMICAL, STATISTICAL AND GEOPHYSICAL (GPR) DATA AS SUPPORT FOR THE EXPLORATION OF PEGMATITE-HOSTED GEMSTONES: EXAMPLE FROM THE SANTA ROSA MINE, MG, BRAZIL

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Abstract: The Santa Rosa Pegmatite Field, near Teófilo Otoni, Brazil, is known for its gem-quality tourmalines. The investigated pegmatite formed from late-stage fluids during crystallization of the Santa Rosa Granite in the late phase of the Neoproterozoic Araçuaí Orogen, is weakly zoned, with border, wall and intermediate zones and a discontinuous quartz core. However, even though gemstones are fundamental for the local economy, exploitation remains a rudimentary practice. ICP-MS, electron microprobe and Principal Components Analyses were conducted on selected mineral samples. There are distinct chemical characteristics and statistical distributions that provide enough information to differ between mineralized and non-mineralized zones. These data combined with GPR readings to evaluate if geophysical anomalies might be considered to detect potential gem sources. This methodology is based on the application of simple techniques to easily separable minerals, making it an accessible way to guide and optimize the exploration and exploitation of gemstones.

Keywords: GPR, pegmatites, prospection, colored stones, geochemistry

1. Introduction

Gemstone mining is a traditional economic practice in Northeastern Minas Gerais State, Brazil. This region is located in the Eastern Brazilian Pegmatite Province (EBPP) (Paiva, 1946), and hosts several pegmatite districts, including the Santa Rosa Pegmatite Field (SRPF) (Netto et al., 1997), 40km SW of Teófilo Otoni (Fig. 1).

Despite the importance of gemstones for the local economy, exploitation is still rudimentary and efforts to optimize prospecting are scarce. In an attempt to partially fill that lacuna, pegmatite-hosted minerals were sampled in an underground pegmatite dig and subjected to basic chemical analyses to compare mineralized and non-mineralized points, and ground-penetrating radar profiles were performed to locate anomalies within the pegmatite, which may guide excavations.

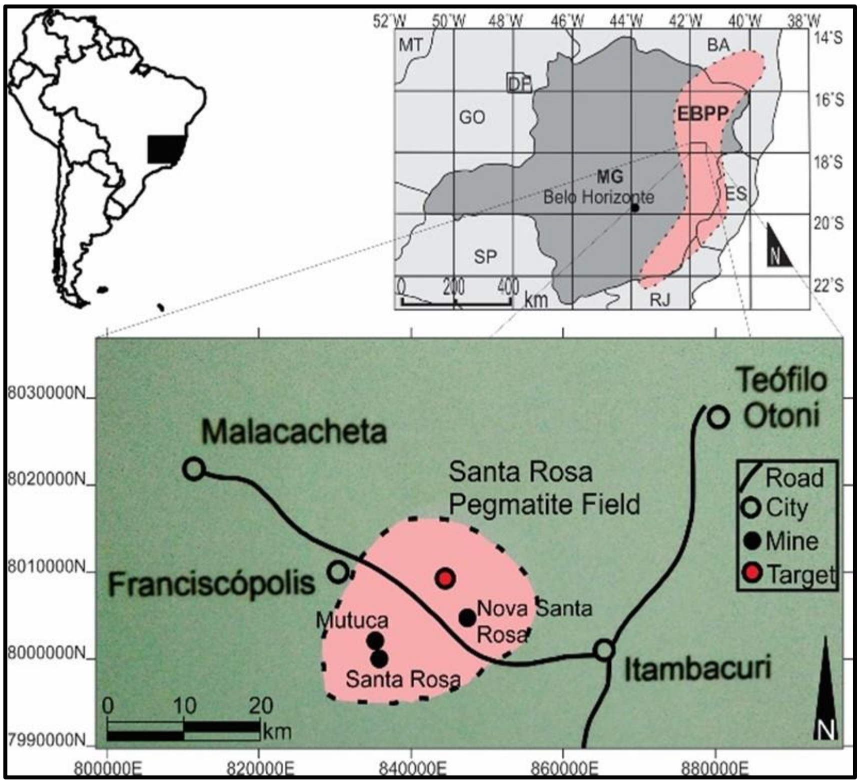

Fig. 1. Location of the Santa Rosa Pegmatite Field, its most important mines and the target dig in the Eastern Brazilian Pegmatite Province **(**modified from Cornejo et al., 2014**).**

2. Regional setting

The SRPF is located between the cities of Franciscópolis and Itambacuri, in the crystalline core of the Neoproterozoic Araçuaí Orogen. Its formation relates to the emplacement of the Santa Rosa Granite, a late-collisional suite (Bayer et al., 1985; Pedrosa-Soares et al., 2001). The granite intruded paraderived biotite schists and gneisses of the São Tomé and Tumiritinga Formations, marine units deposited in arc-related basins. This was the second plutonic event in the area, following the also late-tectonic intrusion of the São Vitor Tonalite (Oliveira, 2016; Vieira, 2007). B assimilation occurred during emplacement, causing schist tourmalinization (Oliveira, 2016; Fig. 2c).

3. Geology of the studied area

The studied pegmatite is an 8m thick dike, intruding biotite schists of the São Tomé Formation concordantly to its foliation. Its structure is zoned (Fig. 2a), marked by crystal growth towards the center and a small, discontinuous quartz core. Tourmaline crystals or agglomerates growing from the margin of a zone to its center are a frequent feature. Subordinate pegmatite intrusions and apophyses are found in the main dike's vicinities.

Gem-tourmalines in the dig are blue or green and may occur in pockets, cavities formed by late-stage substitution processes controlled by the exsolution of fluxing components from the melt (London, 1986, 1987). These geodes may also contain black, non-gemological tourmaline or no tourmaline whatsoever, on which case filling is composed of clay, mud and water. Pocket frames in the studied dig are usually marked by the presence of star-shaped muscovite crystals (Fig. 2b).

Fig. 2. Typical aspects from the Santa Rosa Pegmatite area. a. Zoned structure; b. Star-shaped muscovite framing pocket; c. Tourmalinization of schist xenolith (Oliveira, 2016).

4. Material and methods

4.1. Sampling and preparation

Pegmatite sampling took place in the underground galleries (Fig. 3), in different zonal contexts of the dig, including points surrounding representative pockets with both gemological and non-gemological tourmalines, and a clay-filled pocket. Tourmaline, feldspar and garnet were then manually separated from the rock samples and prepared for chemical analyses. Finally, polished thin sections were prepared: 14 made of tourmaline, 9 made of garnet.

4.2. Analytical methods

Electron microprobe analyses (EMPA) were conducted in the Center of Microscopy at the Universidade Federal de Minas Gerais, Belo Horizonte, MG, by cross-sections in several mineral grains to provide data about internal zoning and chemical variations. The equipment used was a JXA-8900RL probe. Readings were conducted under 15kV voltage and 20nA current, with a counting time of 15s (Si, Na, Ti, P, F, K, Mg, Ca and Fe) and 30s (Al, Cr, Mn).

ICP-MS chemical analyses of total minerals were done in the laboratories of SGS Geosol Ltda., Vespasiano, MG, using pulverized samples (16 of tourmaline; 9 of garnet; 16 of feldspar) in Lithium metaborate flux.

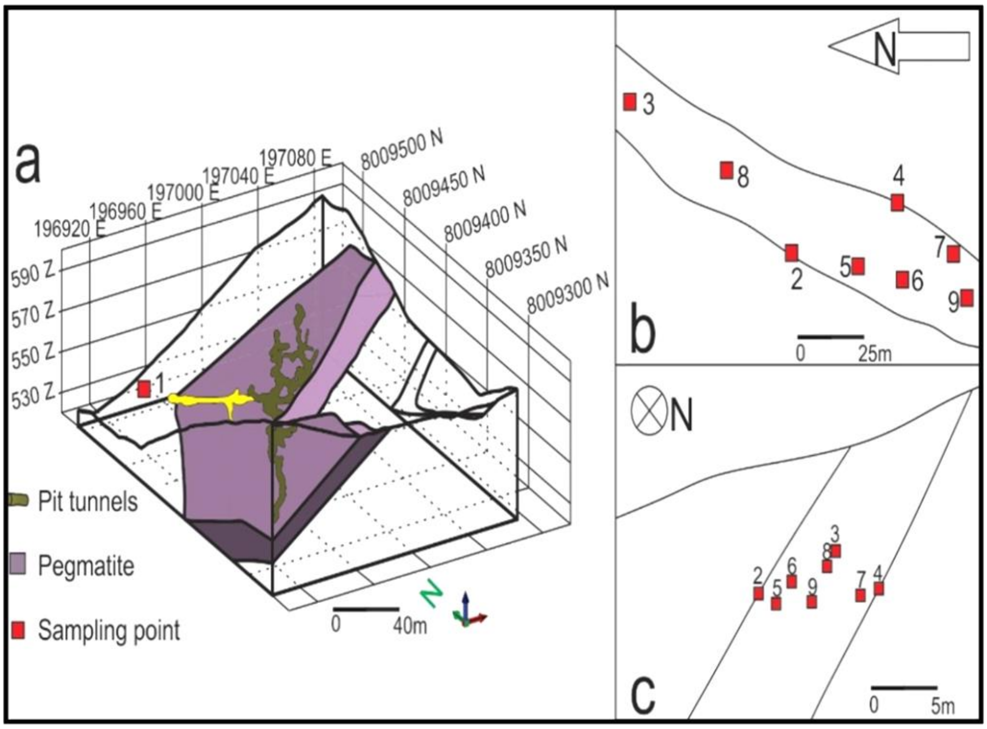

Fig. 3. Santa Rosa Pegmatite (a), with sampling points relative positions in plant view (b) and cross-section (c).

4.3. Ground-penetrating radar (GPR)

Ground-penetrating radar was proved a successful tool for gemstone prospecting in pegmatites by Patterson and Cook (1999). Being so, nine GPR profiles were executed on different sections of the dig, aiming to detect the contacts between the pegmatite and the hosting schist, as well as the planar and punctual anomalies within the rock structure. The data were acquired using antennas of 100 and 200MHz central frequencies.

4.4. Principal Component Analysis (PCA)

The PCA method was applied to major element compositional data obtained by ICP-MS analyses. The raw data were converted using the *centered logratio* transform (Aitchison, 1982) and scores were calculated with the assistance of correlation matrices. It was not the scope of this work to determine possible correspondences between the components and physical factors acting during the mineral crystallization, although studies regarding that matter might be performed in the future. PCA was rather used as a basic tool, to identify whether certain groups of minerals (particularly those sampled near mineralized pockets) would stand out from the general distribution.

5. Results

5.1. Mineral characterization

Feldspars are mostly white or tan, and occasionally pink. Closer to the surface, due to alteration, yellowish shades and kaolinization processes are observed. Graphic texture is often present in the intermediate zones of the pegmatite, where crystals reach up to decametric size. Samples belong to the series defined by the microcline and albite vertices of the K-Na-Ca classification diagram.

Tourmalines are dark-colored, with shades of gray, brown, blue and black. A discrete magnetism is also observed. Intergrowth with feldspar and/or quartz is often present. Millimetric sulfide and mica crystals are scarcely observed as inclusions. The analyzed specimens belong to the alkali and X-vacant groups and were classified as Li-poor-rock schorl. Elements distribution in tourmalines may vary throughout the mine, but no pattern was observed.

Garnets are red or brown in color and, like tourmalines, are slightly magnetic. Small quartz or zircon crystals are frequent as inclusions. Samples are Mn-rich. Chemical compositions form an intermediate range between almandine and spessartine (Alm$_{58\text{-}76\%}$, Spss$_{21\text{-}40\%}$).

5.2. Element distribution

Throughout the dig, peculiarities can be observed in the compositions of tourmaline and feldspar samples. In tourmalines, Al contents decrease from the border zones of the pegmatite to the core, maintaining an approximately constant level in the intermediate zones. Fe and Mn percentages are also highest in the borders and roughly constant in the rest of the dike. However, near the gem-bearing pocket, these elements reach their lowest values (Fig. 4a).

Nearly all elements are evenly distributed in feldspars. Yet, samples from the barren pocket stand out from this trend, as Dy, Gd, Pr, Hf, Nb and Ta contents fall below detection limits, while U percentages are much higher than the average (Fig. 4b). Furthermore, high-K specimens occur solely near the mineralized pocket.

As for the internal compositions, fluctuations in element percentages inside mineral grains are common but discrete. This is valid even for samples from the vicinities of the pockets – which are affected by late-stage substitution processes. Nevertheless, some distinguishing features are observed between minerals from various sampling points.

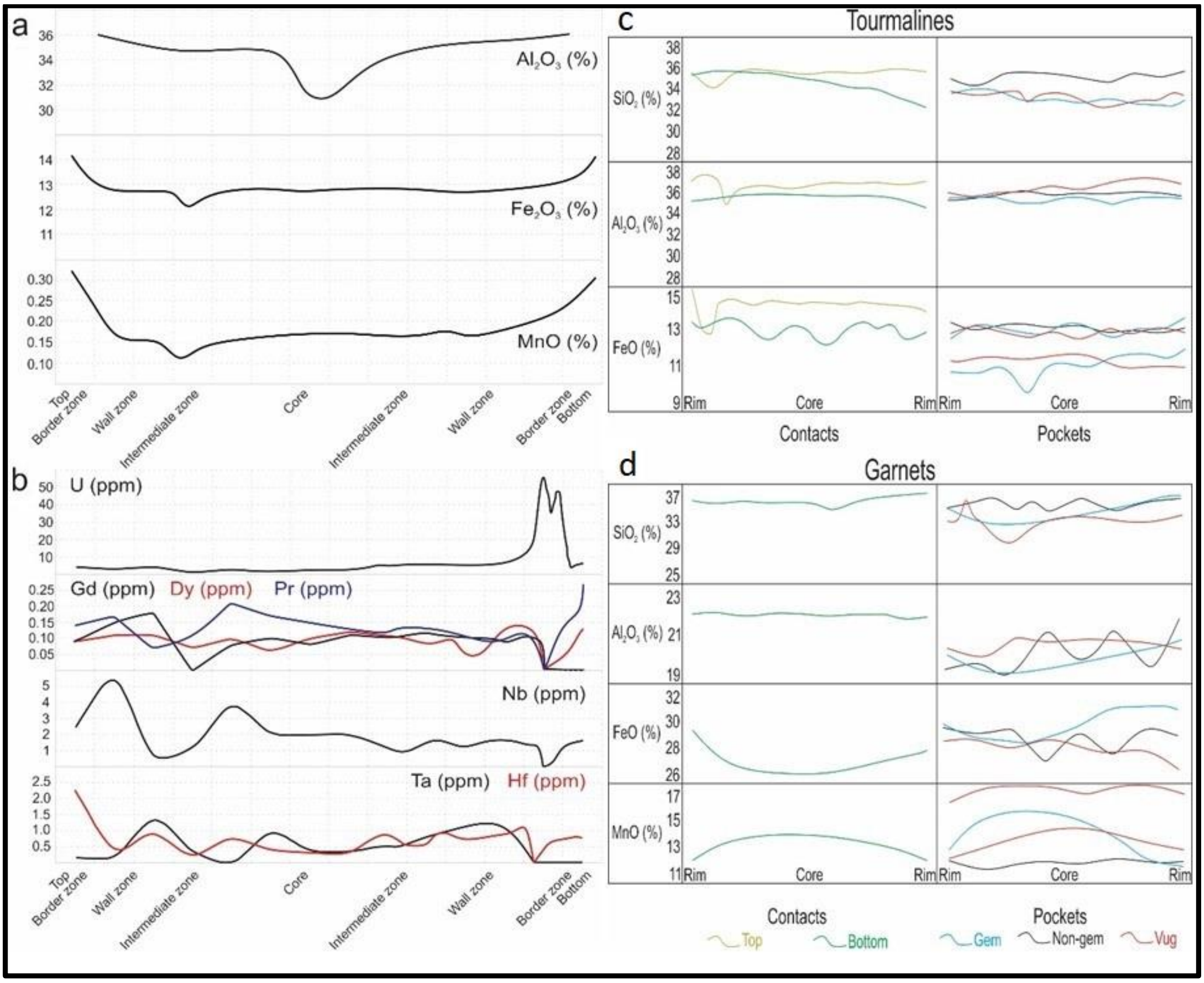

Fig. 4. Representative scheme synthetizing element distribution patterns from the Santa Rosa Pegmatite. a. Selected main elements distribution in tourmalines in an idealized cross-section of the pegmatite by whole mineral composition; b. Selected trace elements distribution in feldspars in an idealized cross-section of the pegmatite by whole mineral composition; c. Tourmaline grain profiles by microprobe; d. Garnet grains profiles by microprobe.

Figures 4c and 4d present the most important internal variations in mineral compositions. In tourmaline grains from the upper and base contacts, Fe content has a constant distribution in the former, but a more erratic behavior in the latter. Some garnets – including all samples from the gem-bearing pockets – are zoned, with an increase in Si and Al from the core to the rims, accompanied by Mn decrease.

Minerals from the pocket zones also have traits that may be used for comparison. Tourmaline grains from the gem pocket and the barren, clay-filled cavity are characterized by Al > Si. Also, some of these samples have lower Fe content than those from the other pockets. Tourmalines from the non-gemological pocket show similar Al and Si quantities and high Fe percentages.

5.3. Principal Components Analysis

The PCA method showed no particular distribution that distinguished tourmaline (Fig. 5d) and garnet samples from mineralized and non-mineralized zones. For feldspars, however, an important feature is observed. When the analysis is applied to major element composition, samples from gem-producing pockets fall into two isolated groups from the rest (Fig. 5c). Both groups have negative score values for the first component and high module values for the second (positive for K-feldspars and negative for Na-feldspars).

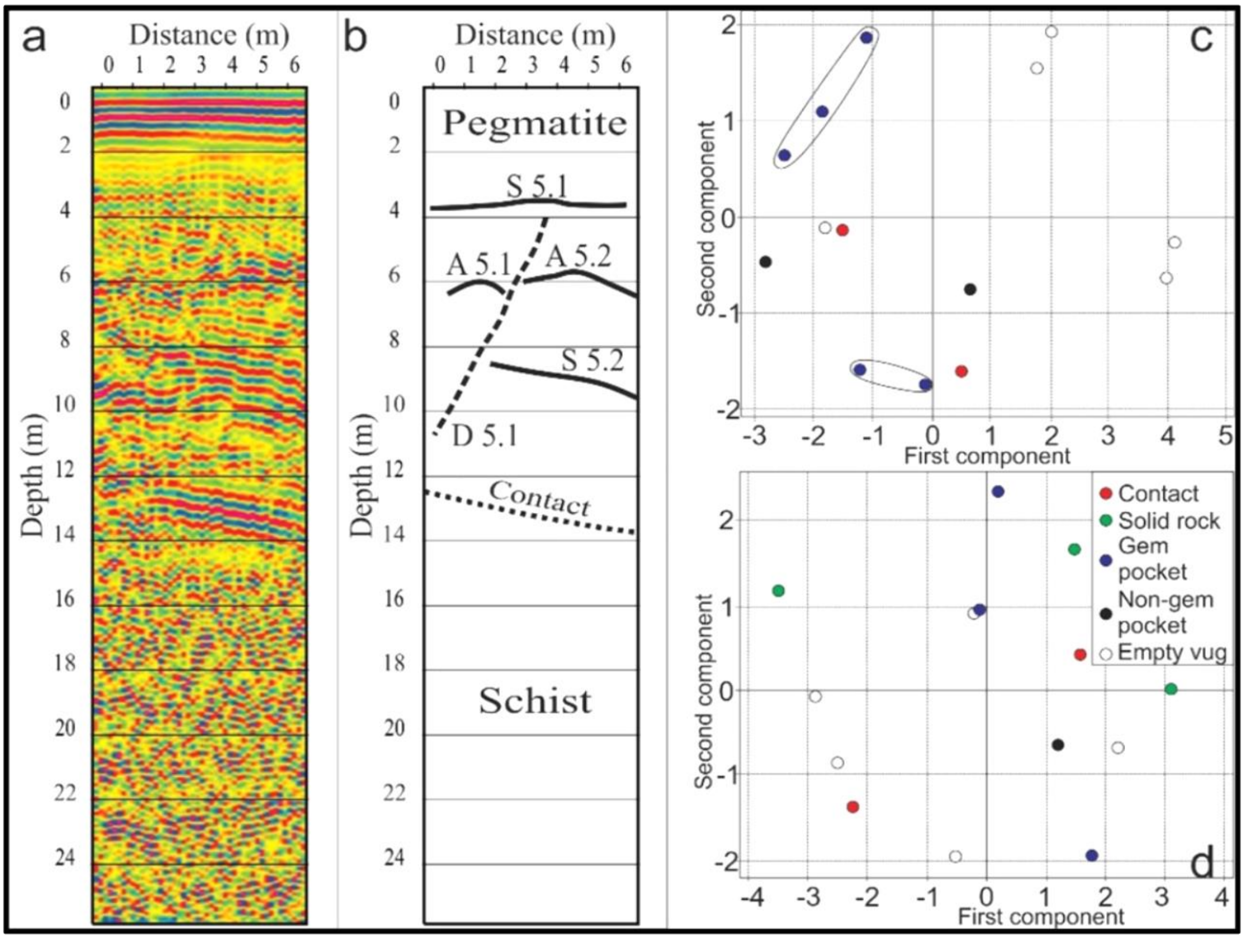

Fig. 5. Radargram (a) and interpretation (b) from the 5th GPR reading. Anomalies indicated by "A" are punctual, while planar anomalies are designated by "S" and linear discontinuities are represented by "D". Score plot generated with the use of the PCA method for major element compositional data of feldspar (c) and tourmaline (d) samples.

5.4. Ground-penetrating radar

The GPR profiles were successful at finding various structures in the pegmatitic body, as exemplified by Figures 5a and 5b. Radargram interpretation made it possible to create a digital model of the pegmatite body (Fig. 3a) and a total of eight hyperboles were detected, which means that GPR was able to locate punctual anomalies inside the rock.

6. Discussion

Distinguishing features are present near the pocket zones. Feldspars from these vicinities stand out from the others in the statistical distribution, and high-K minerals are restricted to mineralized zones. Moreover, Al > Si and low Fe and Mn contents in tourmalines and Fe and Mn zonation in garnets also indicate gem-bearing pockets. Combining this information with GPR readings may importantly assist the search for gems in the dig. It not only directs excavations towards punctual anomalies, but also allows the evaluation of the effort's potential for success beforehand.

This methodology may be expanded to studies regarding not only gemstone prospecting, but also the geologic evolution of the Santa Rosa Pegmatite Field and its relation with the surrounding granitic intrusions. GPR proved itself a useful tool for underground geologic mapping, Patterson and Cook (1999) showing that higher central frequencies on GPR are capable of making the difference between mineralized and non-mineralized pockets. Even though this work employed a basic approach, the Principal Components Analysis, if performed to a larger extent, it is a powerful statistical method that may assist the identification of various factors that controlled crystallization, which may provide important insights regarding how the SRPF was formed.

7. Conclusions

The analyses performed in this work provided data that may objectively guide and optimize the search for gems in the tourmaline dig. ICP-MS and PCA analyses of tourmalines and feldspars produced criteria to establish whether a mineral was formed near a mineralized pocket. This information, combined with GPR readings, has the potential to significantly increase the mine productivity, which currently still has to resort to trial and error.

8. Acknowledgements

We thank CNPQ, FAPEMIG for the financial, UFMG, and Mine Invest LTDA for the logistical support.

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