Structural and mineralochemical characterization of a pegmatite deposit in the Santa Rosa Pegmatite Field, Minas Gerais Brazil

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Abstract

The Santa Rosa Pegmatite Field (SRPF), in northeastern Minas Gerais State, is one of the most important gemstone sources in Brazil. The economy of several neighboring cities greatly relies on the trade of its gemstones. However, efforts to improve gemstone mining with practical, scientific methods are scarce, making it a yet inexpensive, marginally profitable practice. In this scenario, it is opportune to encourage new approaches to optimize mining in pegmatitic deposits. This study looked into the case of a tourmaline dig in the city of Franciscópolis, near Teófilo Otoni. The pegmatite has a weakly zoned structure, and was formed during the final stages of the Neoproterozoic Araçuaí Orogeny, associated with the intrusion and crystallization of the Santa Rosa Granite. GPR profiles were executed to locate structural anomalies inside the rock and its contacts with the host rock, and mineral samples were characterized based on compositional data obtained from ICP-MS and microprobe analyses. The results provided useful information that enabled the creation of a tridimensional digital model of the dig and the pegmatite dike, and may guide future operations in the dig. In the future, the proposed methodology may be applied to more cases to generate a database of geological information that, in addition to the economic scope, could lead to a better understanding of the local granite-pegmatite systems.

Keywords: Pegmatite, prospecting, GPR, geochemistry, modeling.

1. Introduction

Gemstone mining in Brazil dates back to the 16th and 17th Centuries, when the Portuguese Crown, similarly to the Spanish Crown with the El Dorado in the Amazon, stimulated expeditions to the interior after mythical emeralds (Reis, 2010; Holanda, 2014). At present, Brazil plays a major role in the market of gemstones, with most originating from the Eastern Brazilian Pegmatite Province (Paiva, 1946; Putzer, 1976). The Santa Rosa Pegmatite Field – SRPF (Netto *et al.*, 1998), 40km SW of Teófilo Otoni, hosts several artisinal digs, some active since the 1930's.

The conditions found in the digs, however, are startlingly rudimentary, in sheer contrast with their relevance in the local economy. Workers excavate without any orientation or technical support after gem pockets, which represent a diminutive part of the pegmatite structure and are randomly scattered throughout the rock. Geological mapping, compositional characterization and geophysical survey remain a distant reality, for lack of awareness, interest or information, even of dig owners who could afford such procedures. Long periods may pass between the discovery of gems, and incomes usually cover the expenses of previous fruitless efforts, making the ventures marginally profitable.

This study proposes a strategic approach for active underground gemstone digs in the SRPF using the present network of tunnels cutting pegmatite bodies. Taking the example of a dig near Franciscópolis-MG (Figure 1), this methodology increases knowledge on a tourmaline-hosting pegmatite and, with further research, may potentially assist mining in the future. A digital model was created from GPR profiles and compositional data were used to characterize mineralogical aspects of the rock.

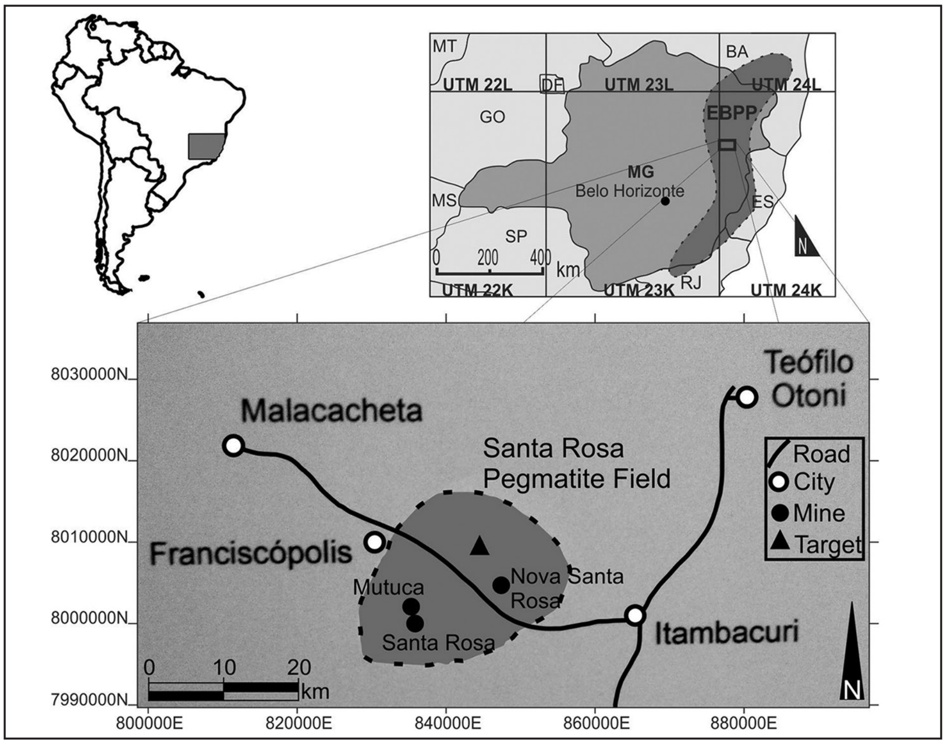

Figure 1
Location of the studied dig and the most important mines nearby in the Santa Rosa Pegmatite Field (Horn *et al.*, 2018, modified from Cornejo *et al.*, 2014).

2. Geological context

The SRPF was formed in the Neoproterozoic period, during the crystallization of the Santa Rosa Granite, a late-collisional suite of the crystalline core of the Araçuaí Orogen (Bayer *et al*., 1985, 1987; Paes, 1997; Pedrosa-Soares and Wiedemann-Leonardos, 2000; Pedrosa-Soares *et al*., 2001; Oliveira, 2016). The granite intruded the São Tomé and Tumiritinga Formations, composed of paraderived biotite schists and gneisses, deposited in a shallow marine environment in back-arc and fore-arc basins, respectively (Vieira, 2007). During the emplacement, contact metamorphism led to schist tourmalinization (Figure 2a) and the formation of tourmalinites of the Boron-rich marine units (Oliveira, 2016). Finally, late-stage fluids differentiated from the melt and crystallized as pegmatites. The exsolution of fluxing components collaborated to the formation of pockets where gemstones could develop more easily (London, 1986, 1987, 2005; Simmons *et al*., 2012).

The pegmatite studied in this research is lodged in a biotite schist of the São Tomé Formation (Figure 2b). Dipping attitudes measured in the surface and in the tunnels showed a 70ºdip towards the NW quadrant, which is concordant to the schistosity. Subordinate dikes and apophyses occur in the vicinities of the main body. The pegmatite structure is weakly zoned, often marked by tourmaline crystals or agglomerates growing from the border to the center of a zone (Figure 2c). Decimetrical quartz crystals occur in the innermost zones, forming a discontinuous core. The main mineralogy of the pegmatite is composed by quartz, alkali-feldspars, tourmaline and garnet group minerals. Apatite and zircon are also present as accessories or inclusions.

The gemological tourmalines from the dig are blue or green (Figure 2d), and are found in pockets. However, most cavities are barren, filled with water, clay and, sometimes, black tourmalines without market value. Pockets have relatively round or oval shapes, reaching at most decimetric dimensions. A distinctive feature found in the frames are star-shaped muscovite crystals (Figure 2e).

Mining is developed underground, counting solely with the aid of explosives. However, there is no kind of guidance, so workers excavate randomly until finally finding mineralized pockets, which may take months or years. As a result, income from the sale of gems usually is destined mainly to cover the previous frustrated efforts.

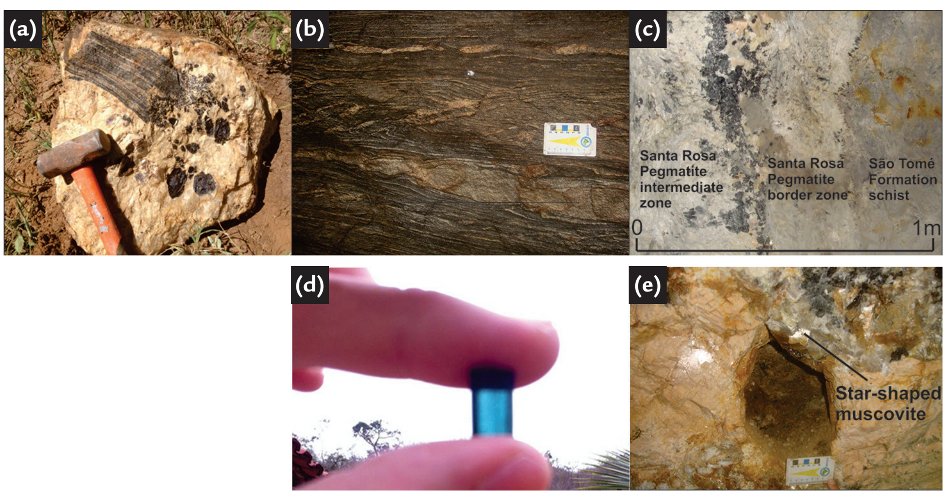

Figure 2
a) Santa Rosa Granite with a tourmalinized schist xenolith (Oliveira, 2016); b) Schist from the São Tomé Formation, host rock to the pegmatite dike; c) Contact between the São Tomé schist and the Santa Rosa Pegmatite, with its zoned structure and crystal growth from the borders of each zone to the center; d) Small sample of blue gemological tourmaline from the studied dig; e) Star-shaped muscovite framing pocket.

3. Methods

3.1 Analytical methods

3.1.1. Sampling and preparation

Samples were taken from the underground galleries, in different zones of the pegmatite (Figure 3), including points surrounding representative pockets with both gemological and non-gemological tourmalines, and a barren, clay-filled vug. Tourmaline, feldspar and garnet were then manually separated from each of the rock samples. Next, with the aid of an agate ball mill, individual sets of these minerals were powdered for ICP-MS analyses, producing a total of 41 powder sets: 16 composed of tourmaline, 16 of feldspar and 9 of garnet. Finally, 23 polished thin sections were prepared for electron microprobe analyses: 14 made of tourmaline and 9 of garnet. (Table 1).

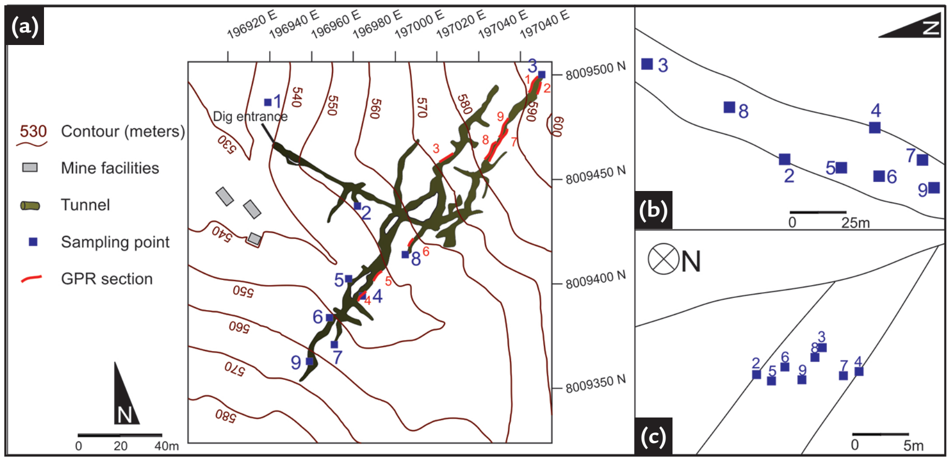

Figure 3
Location of the sampling points and GPR profiles in the underground galleries in plant view (a), with the relative position of the sampling points in the pegmatite in plant view (b) and cross-section (c). Sampling point 1 was a reject pile outside the dig.

Table 1
Sample context in the Santa Rosa Pegmatite and mineral set preparation for chemical analyses.

Point	Sample	Context	Mineral set			Polished sections for EMPA	Pulverization for ICP-MS
			Tour	Garn	Feld		
1	1A	Reject pile	X	X	X	Tourmaline, garnet	Tourmaline, garnet, feldspar
	1B		X	X	X	Tourmaline, garnet	Tourmaline, garnet, feldspar
2	2A	Upper contact	X			Tourmaline	Tourmaline
	2B				X	-	Feldspar
3	3	Pegmatite, near quartz core	X			-	Tourmaline
4	4	Base contact	X	X	X	Tourmaline, garnet	Tourmaline, garnet, feldspar
5	5A	Tourmaline-bearing pocket (non-gemological)	X	X	X	Tourmaline, garnet	Tourmaline, garnet, feldspar
	5B			X	X	Garnet	Garnet, feldspar
6	6A	Tourmaline-bearing pocket (gemological)	X		X	Tourmaline	Tourmaline, feldspar
	6B				X	-	Feldspar
	6C		X		X	Tourmaline	Tourmaline, feldspar
	6D				X	-	Feldspar
	6E		X	X	X	Tourmaline, garnet	Tourmaline, garnet, feldspar
7	7A	Vug near base contact	X		X	Tourmaline	Tourmaline, feldspar
	7B		X		X	Tourmaline	Tourmaline, feldspar
	7C		X	X	X	Tourmaline, garnet	Tourmaline, garnet, feldspar
	7D	São Tomé Fm. schist	X			Tourmaline	-
	7E	Non-tourmaline-bearing pocket near base contact	X	X	X	Tourmaline, garnet	Tourmaline, garnet, feldspar
	7F		X	X	X	Tourmaline, garnet	Tourmaline, garnet, feldspar
8	8	Pegmatite, near quartz core	X			-	Tourmaline
9	9		X			-	Tourmaline

3.1.2 Chemical analyses

The powdered samples were sent to the laboratories of SGS Geosol Ltda., Vespasiano, MG, for ICP-MS analyses. Lithium metaborate was used to aid the sample dissolution in the flux and element standards were supplied by Merck (Darmstadt, Germany).

Electron microprobe analyses (EMPA) were conducted in the Center of Microscopy at the Federal University of 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 counting time of 15s (Si, Na, Ti, P, F, K, Mg, Ca and Fe) and 30s (Al, Cr, Mn). Mineral standards from NIST (Gaithersburg, MD, USA) were used as reference.

Mineral structural formulae were calculated with spreadsheets developed by Tindle (2002) and Tindle *et al.* (2002) and Brady and Perkins (2016). For tourmalines, approximations proposed by Burns *et al.* (1994) and Clark (2007) were used and Henry and Guidotti (1985) and Henry *et al.* (2011) were referred to for classification.

3.2 Principal Components Analysis (PCA)

The PCA method was applied to major element compositional data obtained by ICP-MS analyses to identify whether certain groups of minerals (particularly those sampled near mineralized pockets) would form a separate group from the general distribution.

In compositional data, variables – elements – are not independent, a desirable condition for the application of PCA, as the values must sum to a constant (100%). This problem was solved by using the *centered logratio* transform (Aitchison, 1982), which converts the values into a new, unconstrained set of data.

3.3 Modeling

3.3.1 Topographic survey

The topography of the tunnels and the starting and finishing points of the GPR sections were registered by performing laser readings with a total station. Starting from the entrance, where the geographic coordinates were known with a GPS device, the station was moved underground, and oriented by reference checkpoints. The points were extracted on the software Data Geosys.

3.3.2.1 Background on pegmatite-hosted gemstone prospecting

The pioneering studies employing GPR in the study of pegmatites were Patterson (1996), Cook (1997) and Patterson and Cook (1999). Independently, Patterson (1996) used GPR to map aplitic pegmatite dikes in the Little Three Mine, California, while Cook (1997) listed this method as a promising tool for gemstone prospecting in pegmatites. Together, these authors proved GPR to be successful at locating pockets in the Himalaya Mine, California, verifying even that high frequency (1GHz) antennae are capable of distinguishing between mineralized and non-mineralized pockets (Patterson and Cook, 1999).

3.3.2.2 Application

In this study, nine GPR profiles (locations in Figure 3a) were executed on the underground walls of the dig, using 100 and 200MHz antennae in a common offset setting. Despite not being able to differ mineralized pockets from barren ones like 1GHz, these frequencies are still capable of detecting anomalies – planar or punctual – within the pegmatite structure while also having a much greater power of penetration (10-20m versus less than 1m), enough to reach the edges of the rock, necessary for constructing a geologic model of the area.

3.3.2.3 Processing

Data processing was performed on the Interpex Gradix software, applying the following steps:

a. Declipping;
b. Dewow;
c. Time zero setting;
d. Window traces;
e. Background removal;
f. Gaussian filtering – 100 and 200MHz;
g. Topographic correction;
h. Depth conversion – wave travel velocity: 110m/ns.

3.3.3 Digital modeling

Information on the morphology and the contacts between the Santa Rosa Pegmatite and the São Tomé schist on the surface are available on a private map elaborated during previous basic surveys, available in the mine support facilities. On the Micromine 2016 software, topographic, geologic and geophysical data were combined to create a 3-D model of the pegmatite and the dig.

4. Results

4.1 Mineral characterization

4.1.1 Feldspars

Feldspars are mostly white or tan, and occasionally pink. Closer to the surface, due to weathering, yellowish shades and kaolinization are observed. Graphic texture is often present in intermediate zones of the pegmatite, where crystals reach up to decimetric dimensions. Samples belong to the series defined by the microcline-albite (K-Na) edge of the K-Na-Ca classification.

4.1.2 Tourmalines

Tourmalines are dark-colored, with shades of gray, brown, green, blue and black. Discrete magnetism is also observed. Intergrowth with feldspar and/or quartz is often present. Millimetric sulfide and mica crystals are scarcely observed as inclusions. Specimens were classified as Li-poor-rock schorls (Henry and Guidotti, 1985) and belong to the alkali and X-vacant groups (Henry *et al.,* 2011). Element distribution in tourmalines vary throughout the mine, but no pattern is observed.

4.1.3 Garnets

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, which is expected in pegmatites (Manning, 1983). Chemical compositions form an intermediate range between almandine and spessartine ($Alm_{58\text{-}76\%}$, $Spss_{21\text{-}40\%}$).

4.2 Element distribution

Throughout the dig, peculiarities are 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 rock. However, near the gem-bearing pocket, these elements reach their lowest values (Figure 4a).

Nearly all elements are evenly distributed in feldspars. Yet, samples from the barren vug 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 average (Figure 4b). Furthermore, high K specimens occur solely near mineralized pockets.

As for internal compositions, fluctuations in element percentages inside mineral grains are common, but discrete. That is true even for samples from the vicinities of pockets – which are affected by late-stage substitution processes. Nevertheless, some distinguishing features are observed between minerals from various sampling points. Figure 5 represents the most important internal variations in mineral compositions. In tourmaline grains from the contact zones of the pegmatite, the Fe content has a constant distribution in the former, while showing 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.

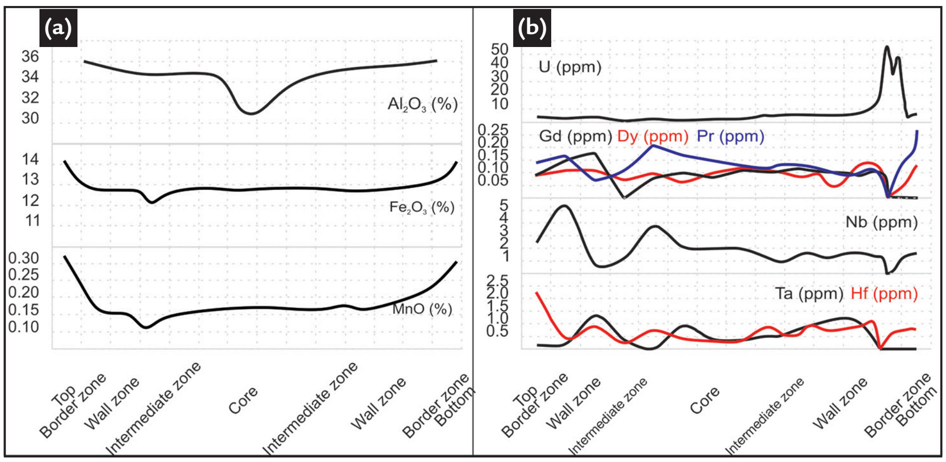

Figure 4
Significant element content variations in minerals from different zones of the Santa Rosa Pegmatite. a) Al_2O_3, Fe_2O_3 and MnO distribution in tourmaline samples; b) U, Gd, Dy, Pr, Nb, Ta and Hf distribution in feldspars.

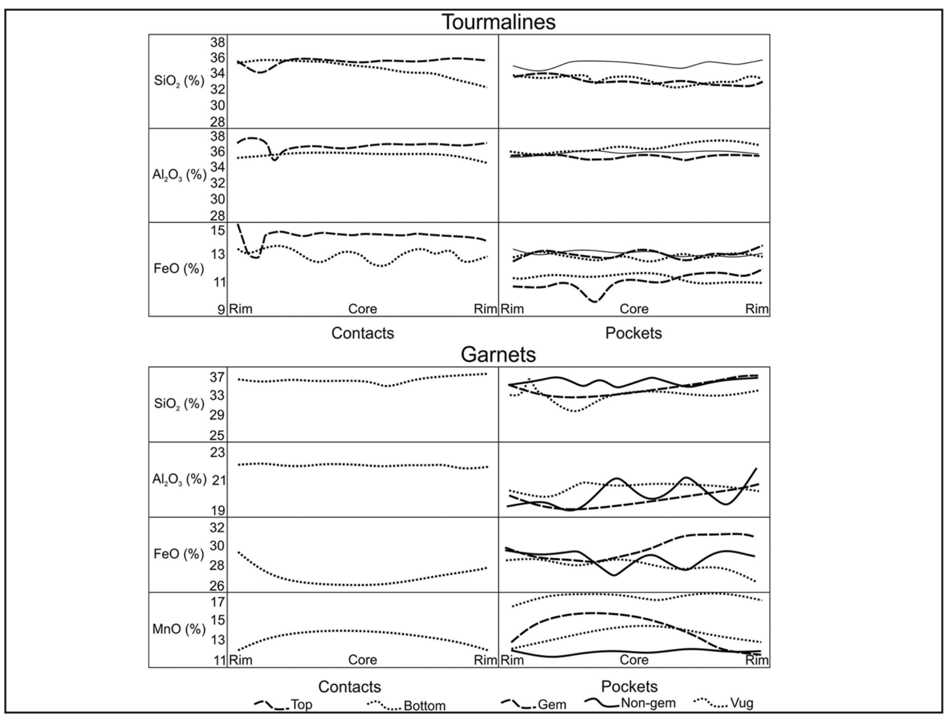

Figure 5
Representative schemes synthetizing the internal distribution patterns of selected elements in tourmaline (41) and garnet (28) grains from the Santa Rosa Pegmatite, obtained from EMPA profiles.

4.3 Principal components analysis

The PCA method showed no particular distribution that distinguished tourmaline (Figure 6a) 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 (Figure 6b). 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).

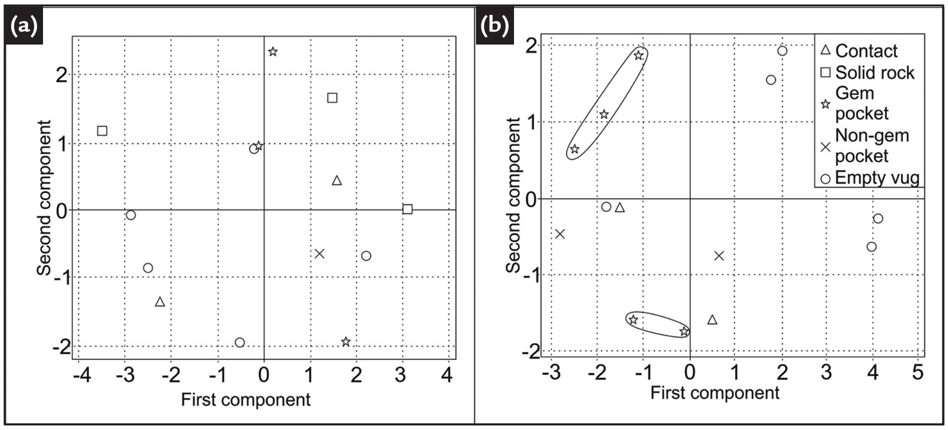

Figure 6
Score plot diagrams generated by PCA analyses of major element compositional data of tourmaline (a) and feldspar (b) samples.

4.4 Modeling

4.4.1 GPR sections

The GPR profiles were successful at finding the edges and anomalies in the pegmatitic body. Reflection patterns in the dike are marked by series of strong, parallel lines (S), broken only by hyperbolic features (A) or signal discontinuities (D). A change of pattern into a weaker, diffuse signal occurs on the pegmatite-schist contact, due to the contrast of wave impedance on the interface. The position of the contact surfaces on the profile depends on the position of the tunnel section in relation to the strike of the pegmatite dike. Figure 7 shows examples of radargrams acquired on the walls of the tunnels, and their respective interpretations.

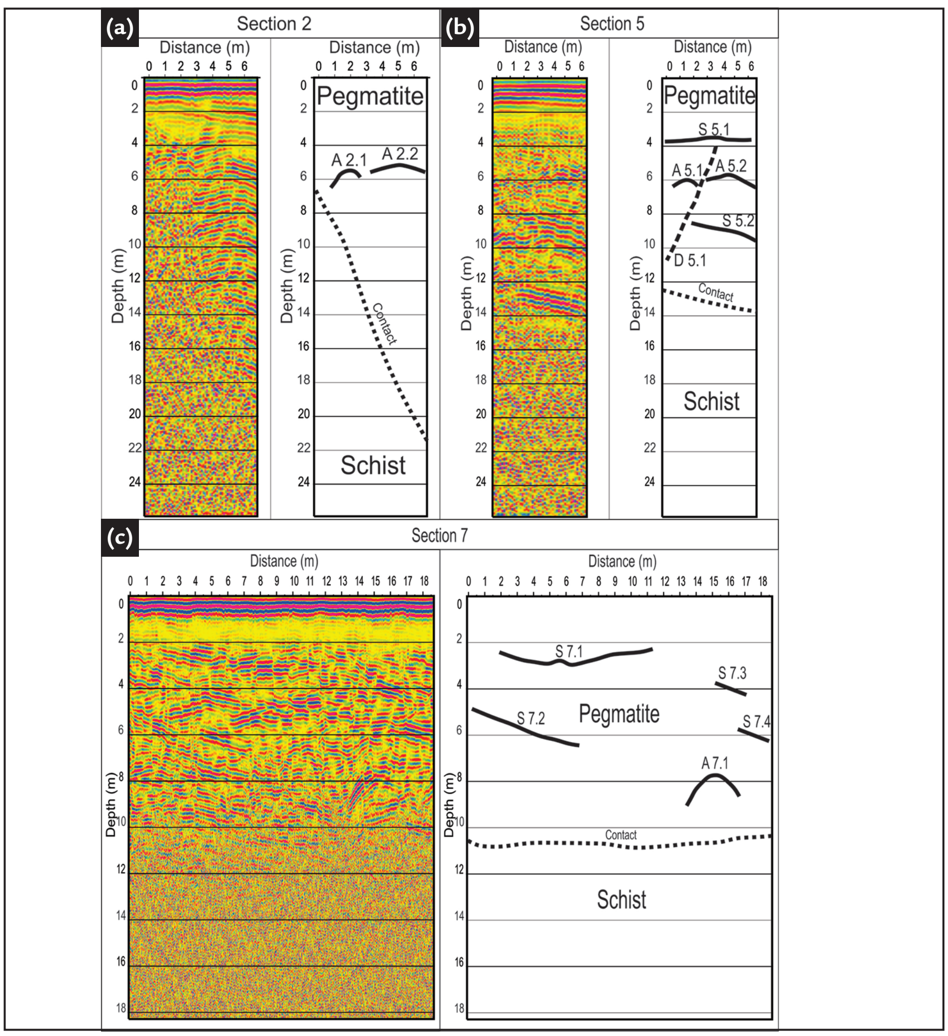

Figure 7
Examples of radargrams acquired after the execution of the GPR sections on the walls of the tunnels of the Santa Rosa Pegmatite and their respective interpretations. a) Section 2; b) Section 5; c) Section 7.

4.4.2 Digital model

Figure 3a shows the plant view of the tunnels and the locations of the GPR sections, registered during the topographic survey. The geophysical data allowed the creation of a block diagram for the local geology (Figure 8a). The resulting model for the main pegmatite was an 8m-thick, sheetlike dike, dipping approximately 70º towards NW, which fits the distribution of galleries observed and registered during the study (Figure 8b).

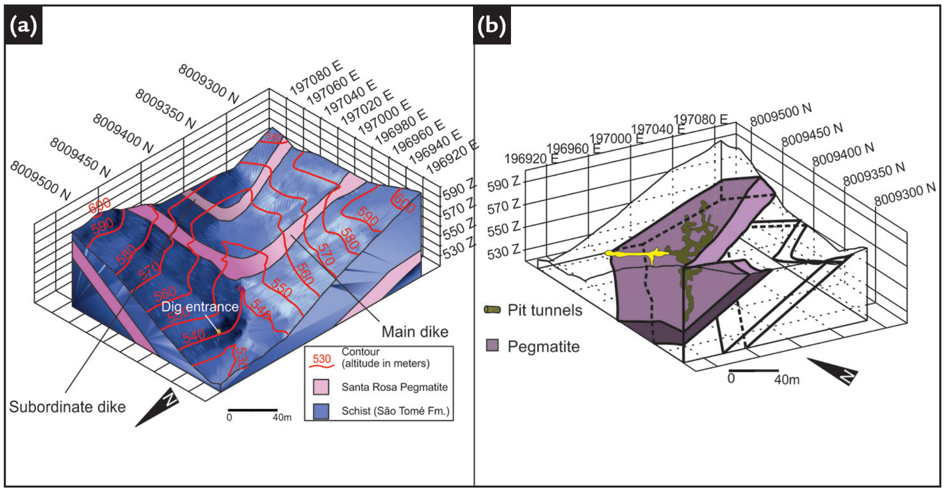

Figure 8
a) Geological block diagram of the study area; b) Block diagram of the main pegmatite dike, containing the galleries inside.

5. Discussion

Distinguishing features are present near pocket zones. Feldspars from these vicinities stand out from the others in 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, since not only does it direct excavations towards punctual anomalies, but also allows the evaluation of the potential for success of the effort beforehand.

Regarding the statistical analyses, it was not the scope of this study to determine correspondences between the components and physical factors that could drive mineralochemical variations in the pegmatite during crystallization, although studies regarding that matter might be performed in the future by Factor Analysis, a more thorough statistical method.

The GPR sections provided geological contacts that resulted in a model for the pegmatite dike, coherent with the attitudes measured in the surface and in the galleries, as well as the distribution of tunnels dug in the rock. Plus, the anomalies found may fit two categories: surfaces (S, D), which may be caused by planar structures, such as fractures, and points (A), which may correspond to xenoliths, vugs or pockets. Even though it is not possible to establish the nature of punctual anomalies, they constitute a primary object of interest for excavations.

This methodology may be expanded to deeper, more robust and extensive studies regarding not only gemstone prospecting, but also the geologic evolution of the Santa Rosa Pegmatite Field and its relationship to the surrounding granitic intrusions. Even though this study employed a basic approach, principal components analysis, if performed to a larger extent, is a powerful statistical method that may assist in the identification of various factors that controlled crystallization, which may provide important insights regarding how the SRPF was formed.

6. Conclusion

The analyses conducted in this study were capable of identifying structural and chemical characteristics of the Santa Rosa Pegmatite and its minerals that are interesting for the expansion and optimization of the activities in the dig. ICP-MS and PCA analyses of tourmalines and feldspars produced results that establish whether or not a mineral was formed near a mineralized pocket. The contacts found in the GPR sections are coherent with the pegmatite dipping attitude in the surface, and the resulting tridimensional model is coherent with the distribution of the galleries.

With better understanding of the pegmatite, prospective methods may be deployed to identify potential zones of interest. The approach used in this study does not ascertain whether the targets will be fruitful. However, more precise methods such as that of Patterson and Cook (1999) have a more limited range of action (high GPR frequencies reach less than 1m inside the pegmatite), which is not compatible with the metric dimensions of the pegmatite dikes of the Santa Rosa Pegmatite Field. Moreover, the application cost of the studies is accessible for the local enterprises, making them appropriate for the current activities and brownfield research in the numerous underground digs in the region.

The methodological approach presented herein thus provides a scientific support that gemstone digs in the Santa Rosa Pegmatite Field lack. Mining in the region is currently a random practice, and knowing the physical and chemical peculiarities of the pegmatites is the first step to create parameters for prospective methods that, in the future, may make the process more efficient and profitable.

Acknowledgments

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