GPR for mapping fractures and as a guide for the extraction of ornamental granite from a quarry: A case study from southern Brazil

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Abstract

This paper presents the results of an application of Ground Penetrating Radar (GPR) method for localizing fractures, unloading or exfoliation joints, massive blocks, and identifying the top of fresh granite. The reason for this work was to orient the mining operation in a way to optimize the extraction costs of large blocks of ornamental granite from a quarry in Capão Bonito region of São Paulo State, southern Brazil. Five GPR profiles using antennae of 25, 50, and 100 MHz were made, as well as six velocity soundings. The work was done in three distinct locations in the quarry: on the land surface above the quarry, along a road crossing the quarry, and in front or below the active quarry face.

The results led to the definition of planes of structural discontinuity extending to 25 m depth, including inclined fractures and low-angle unloading joints; as well as the localization of massive blocks surrounded by weathered material. The inclined fractures and unloading joints appear as strong reflectors (high energy), and constitute excellent basal planes for the cutting and removal of standard-sized blocks. The location of these planes is important in the exploration process, as designing the quarrying to take advantage of these structural breaks can minimize the use of explosives and greatly facilitate the extraction of commercial-sized blocks. In addition, it was possible to delineate the regions of the quarry, where high-quality homogeneous granite was located, by the absence of strong internal radar reflectors.

Knowledge of the spatial distribution of the joints and structural discontinuities, and mapping the localities of high-quality granite were fundamental for the mining engineer. This information served as the basis, and as a guide for planning the advance of the quarry front to minimize the extraction costs, resulting in significant economies for the company.

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1. Introduction and objectives

The principal objective in a quarrying operation for ornamental stone is to extract large blocks having standard dimensions and no fractures. In the planning phase and for the calculation of the volume of reserves, the mining engineer needs to know the structural characteristics of the rock mass. The mapping of the distribution and orientation of fractures and unloading joints in a quarry for ornamental stone quarry is fundamental for optimizing investments and development of activities, such that the profits can be maximized.

Ornamental stones can be classified commercially as simply granite or marble, depending principally upon their mineralogical content and genetic origin. The granites refer to silicate rocks with magmatic origin, and the marbles are carbonate rocks, which have undergone some metamorphism. From the economic point of view, occurrences of quality granites and marbles near transportation routes have a relatively high commercial value and are of considerable interest for the mining companies.

The extraction of ornamental granite is done systematically in form of blocks with commercially standard dimensions of several meters. Mining is done in quarries either by opening benches, or by cutting into enormous boulders that are partly surrounded by weathered material. These rectangular solids are usually transported to another locality, where they are cut into uniform sheets. When one face is polished they become quite valuable as decorative stone in commercial construction. The extraction of granite for use as ornamental stone is an ancient tradition. However, in Brazil, the activity has only had a significant growth in the past 20 years, beginning in Rio de Janeiro, Espírito Santo, São Paulo, Bahia, and Minas Gerais states. At present, Brazil extracts about 5% of the worldwide production of ornamental stones (Stellin and Vital, 1996).

The economic feasibility studies and the quarry planning stages first require knowledge of the volume of unweathered rock that is available for extraction (Bradley and Musetti, 1996). For this, it is fundamental that the mining engineer knows the subsurface distribution of joints, fractures, or any other discontinuities. Given widely spaced sub-vertical joints, it is the spacing between the sub-horizontal unloading joints that governs the volume of the blocks that can be removed from the potential quarry. Evaluation of the spacing of these joints can be made with help of Ground Penetrating Radar (GPR). GPR is an electromagnetic method that uses high-frequency (10 MHz–2.5 GHz) radio waves to make high resolution images of shallow geologic features, such as faults, fractures, unloading joints, and isolated boulders. The theoretical basis for this method can be found in Davis and Annan (1989), Daniels (1996), Porsani (1999), among others.

The use of GPR to locate fractures in granitic rocks has been reported in the literature since the beginning of the 1990s. Some of them are: Tillard (1994), Serzu et al. (1996, 1998), Grasmueck (1996), Liner and Liner (1997), Dérobert and Abraham (2000), Pipan et al. (2000), Seol et al. (2001, 2002), Lualdi and Zanzi (2003, 2004), and Orlando (2003). In Brazil, the following have reported the use of GPR on granites: Botelho and Araújo (1996), Botelho et al. (1996, 1999), Botelho and Mufti (1998), Souza and Porsani (2002), and Souza (2002).

In this study, GPR was used to characterize the planes of discontinuity in an ornamental granite quarry in Capão Bonito City, in SE Brazil (Fig. 1). Five profiles were carried in three distinct parts of the quarry (Fig. 2). The objectives of the profiling were to locate fractures, unloading joints, isolated boulders, and the top of the fresh granite, so that the quarry development could be done in the most cost-effective way.

The ornamental granite of Capão Bonito is well known on the international market as a reddish rock that is isotropic and invariant in the entire exposed area of the pluton. It is characterized by coarse-grained texture, primarily pink feldspar, quartz, biotite, and magnetite. Because of its highly homogeneous texture and its reddish color, it is known and sought after by decorators and worldwide architects. This led to intense quarrying activity throughout the outcrop area of the pluton. Presently, Capão Bonito granite, or Ruby Red Granite as known commercially, is being exported as ornamental stone to Italy and Japan (Stellin and Vital, 1996).

Mapping of fractures and unloading joints helped the development of the quarry in a rational and cost-effective manner. This information was fundamental for guiding the development of new benches by
Fig. 1. Location map of Capão Bonito City, São Paulo State, SE Brazil.

Fig. 2. Topographic map of granite quarry and location of GPR profiles.
avoiding areas with close-spaced fractures, optimizing thus the extraction process and increasing benefits.

2. Local geology

The quarry is located about 20 km from Capão Bonito, and about 350 km from São Paulo City, in SE Brazil (Fig. 1). The area is on the border of Paraná Basin, and is characterized mainly by granitic rocks and granitoid bodies, while locally there are occurrences of diabase dikes intruded into fracture zones (Chiodi Filho et al., 1983).

According to Filipov (2002), the most significant geologic structures that occur in the area are three fracture sets, a conjugate pair with strikes varying between N60E and N80W having dips always greater than 60°. The third fracture set strikes in the range from N10W to N10E. In addition to these families of fractures, there are pronounced sets of unloading joints with dips normally lesser than 17°. These low-angle joints are also called the running planes of the blocks, or the preferential plane of anisotropy of the rock. These planes are very important in the quarrying of the benches, as they are used for extraction of the massive blocks. They lead to considerable cost savings in the extraction process, minimizing the use of explosives.

During the geological examination of the area it was noted that the granitic bodies contain structures, such as fracture zones (both inclined and sub-horizontal), blocks of various sizes isolated by deep weathering, and a diabase dike filling a sub-vertical fracture (Fig. 2) in massive granite in the upper part of the quarry (area-I). Within the quarry, a spring, which was the source of Alves creek, was noted. It is likely this creek is maintaining saturation of fractures to this level. If it is true, then it was presumed that the fractures would be readily visible using GPR because of the large contrast in relative permittivity between massive granite, and the water-filled fractures (Olhoeft, 1998).

3. Acquisition and data processing

The field work was done using Ramac GPR system (Mala Geoscience). Five reflection profiles totaling 760 m were recorded using constant offset between transmit and receive antennae. In this work, frequencies of 25, 50, and 100 MHz were used. The 25 MHz antennae were used to map the deepest discontinuities, while the 100 MHz were used for higher resolution studies of the shallower part of the massive. GPR profiles were located in three distinct parts of the quarry: the highest topographic part (area-I), along a road that crossed the quarry (area-II), and at the quarrying front (area-III). Fig. 2 shows the topographic map of the quarry and the location of GPR profiles. Fig. 3 shows the photographic view of survey area.

The data were acquired with antenna separations of 4 m (25 MHz), 2 m (50 MHz), and 1 m for the 100 MHz pair. The interval between traces was 0.5 m, and 512 stacks were used to make one trace. All the data were obtained in this step by step mode, with the antennae positioned with their E-axes perpendicular to the traverse direction to optimize coupling (Annan and Cosway, 1992; Versteeg, 1996).

GPR profiles are presented with both time and depth scales, and time to depth conversion is explained in the following. Along the transect lines, six velocity soundings of the Wide Angle Reflection and Refraction type (WARR) were conducted. They were done with both 50 and 100 MHz antenna systems, using a trace spacing of 0.1 m. Four WARR soundings were acquired along the reflection profile located in area-II: two soundings using 50 MHz and two using 100 MHz antennae. The other two WARR soundings were acquired along the reflection profile located in area-I, using 50 and 100 MHz antennae. In this article, the best WARR results in terms of penetration, resolution, and clarity in hyperbolic reflectors, were obtained with 100 MHz antenna performed along the reflection profile located in area-I. Therefore, only one WARR sounding is presented here.

The average velocity of radio wave propagation in the subsurface was determined by the semblance, and NMO-Normal Move Out methods (Yilmaz, 1987). The results were similar, therefore, only the results obtained by semblance method will be presented in this paper. Fig. 4 shows WARR sounding obtained at 75 m position along GPR profile on upper quarry area (area-I), and its correspondent semblance analysis. The arrival of the air and ground wave, as well at 170 and 280 ns two clear hyperbolic reflections whose
analyses resulted in velocities of 0.105 and 0.11 m/ns, can be observed in this figure.

Usually, an error is associated with estimated velocity due to width of the contour curve, and one brief qualitative analysis is presented to follow. The implications of the estimated velocity, at depth of the fracture zones, are presented in the discussion of results.

In the velocity analysis by the semblance method, the obtained values correspond to the center of the contour curve, and they are associates to the semblance peak. As observed for the time of 170 ns, the center curve presents a minimum velocity of 0.095 m/ns and maximum of 0.115 m/ns. In relation to the central value of velocity (i.e., 0.105 m/ns), there is an associated error of ±0.01 m/ns. It corresponds to an error in the estimated depth of ±9.5%. For the time of 280 ns, the analyses of the error associated with the velocity are similar. However, for the conversion from time to depth, the root mean square velocity of 0.117 ± 0.01 m/ns was calculated (Dix, 1955). This velocity corresponds to an error in estimated depth of ±8.5%. This error seems to be reasonable for the 100 MHz antennas, however, the error increases when it is lesser than 100 MHz.

For later migration processing and for conversion times to depths a velocity model (for profiles from area-I) and constant velocity of 0.10 m/ns (for profiles from areas-II and -III) were used. The velocity model, such as \( v_1 = 0.10 \text{ m/ns for } T_1 \text{ of } 0-170 \text{ ns, and } v_2 = 0.117 \text{ m/ns for } T_2 > 170 \text{ ns, was used for area-I.} \)

GPR data were processed using GRADIX software package (Interpex). Band-pass filters were applied to improve the signal-to-noise ratio. Time-varying gains were applied (linear, spherical, and exponential) to compensate for the absorption, spherical divergence, and scattering of the signals. Frequency–wave number...
(fk) filtering was applied to remove lateral reflections from the quarry walls. Fk migration was also used to spatially re-position dipping reflectors in the subsurface. Topographic correction and the conversion of the time profiles to depth were done using a constant velocity of 0.10 m/ns. A moving average spatial filter 3 traces wide was applied to provide some horizontal smoothing. Finally, Hilbert transform (energy) was used to emphasize the energy of reflector due to the planes of discontinuity in the granite (Grandjean and Gourry, 1996; Dérobot and Abraham, 2000; Orlando, 2003).

4. Interpretation and discussion of results

The profiles of GPR reflections show detailed images of inclined and sub-horizontal reflectors to approximately 25 ± 2.2 m depth, as well as hyperbolic shallow diffractors. The prominent fractures are always associated with high energy reflections of EM signal (Orlando, 2003). In general, reflectors were interpreted based on available geologic information and correlated with the known planes of discontinuity in the subsurface. The profiles are corrected for topography, and the vertical axes show depth (left) and two-way travel time (right).

Fig. 5 shows a 100 m-long 50 MHz profile obtained along the same line near the highest topographic part of the quarry (area-I). Fig. 5a shows the unmigrated profile, and Fig. 5b, the migrated profile. Fig. 6 shows the conversion of this migrated section to energy. On this section, red indicates high energy, and blue corresponds to low energy. This profile was along a road, where the weathered layer was thicker. In the first 5 ± 0.47 m of depth, the reflectors are irregular and correspond to the cover of altered granite. Between distances coordinates of 6 and 12 m one can see a region with nearly absent reflections, or low GPR reflection energy (Fig. 6). According to field observations, this region contains the altered near-surface portion of a diabase dike, which filled a sub-vertical fracture. Note that the sub-vertical fracture does not have a GPR signature, except an absence of reflections due to attenuation of the electromagnetic waves in the clayey material resulting from the alteration of diabase.

There are two strong reflectors paralleling the topography: one at about 10 ± 0.95 m (A), and the other at 16.4 ± 1.4 m depth (B). Both are associated
with high energy on Fig. 6. According to the local geological mapping (Chiodi Filho et al., 1983), these reflectors could be related to the contact between the weathered granite and the more unaltered granite below. This contact is associated with sub-horizontal fractures (unloading joints) which are probably filled with water due to the proximity to headwaters of Alves Creek. The large amplitude of the reflectors is likely due to the large contrast in dielectric constant between water and granitic rock (Olhoeft, 1998).

Note also a hyperbolic reflector (C) on the unmigrated profile (Fig. 5a) at the 55 m coordinate, with depth to its top at about 10 ± 0.95 m. On the migrated profile (Fig. 5b) this feature becomes narrower and smoother, but is still a zone of high energy (Fig. 6), probably related to a block isolated by weathering.

The strong sub-horizontal reflector (D), between the 65 and 95 m coordinates (Fig. 5b) at about 25 ± 2.2 m depth and associated with high energy (Fig. 6), indicates the presence of a second water-filled unloading joint. This very likely delimits the top of the fresh granite, first level, as mapped in this area by Chiodi Filho et al. (1983). Below this depth there is an absence of reflections and consequently low return energy, suggesting the existence of homogeneous granitic rock without fractures, and hence rock of good quality for extraction (Orlando, 2003).

One inclined reflector is identified (E) between 75 and 95 m coordinates that reaches to about 6 ± 0.57 m in depth. This reflector is related to an inclined fracture. There is also another reflector (F), that accompanies the topography between 140 and 170 m coordinates, at about 9 ± 0.8 m depth, and that is probably related to a sub-horizontal fracture. Along the entire profile one can observe a zone with a notable absence of reflectors below about 10 ± 0.95 m depth. This is interpreted as the top of homogeneous, unfractured fresh granite, rock of primary interest for commercial extraction (Orlando, 2003).

Fig. 8a shows a 100 MHz GPR profile, 62 m long, obtained in front of the active mining bench (area-III). This profile was entirely over fresh granite. Field observations indicated the fresh rock was considerably fractured, and the fractures were wet, which should have made them easily detectable GPR targets (Olhoeft, 1998). Fig. 8b shows the profile after the transformed energy of Fig. 8a.

This profile is characterized by various inclined reflectors, from the surface to about 20 ± 1.7 m depth. The S/SW part of the profile is marked by a high degree of scattering of GPR signal by fractures (Fig. 8a), and corresponding high energies (Fig. 8b). Hence this is a zone of granites less favorable for extraction due to frequent fractures (Orlando, 2003). There is a strong sub-horizontal reflector (G) at a depth of about 15 ± 1.3 m that accompanies the topography. This sub-horizontal reflector is interpreted as an unloading joint, and corresponds to the running plane of the block. It also delimits the top of the fresh
granite, 2nd level. The reflection is probably due to the irregular surfaces of the fracture planes, which has a local thickness in the order of 10 cm. Evidence of wet fractures, both inclined and sub-horizontal, are found along the front of the active mining bench, and are compatible with the fractures mapped by GPR. Additionally, two regions characterized by the absence of reflectors are identified in the granite massive, both associated with low GPR reflected energy. Region (H) is located between two inclined fractures, and the other is region (I), below the unloading joint. These regions suggest the existence of homogeneous, unfractured granite which should be of great interest for the extraction of large blocks of good quality.

The integrated interpretation of GPR profiles, of the available geological information, and field observations leads one to an integrated model for the
structures in the quarry area. Fig. 9 shows the synthesis of these results, via a topographic/structural schematic section that crosses the studied area (Fig. 2). In the structural model for the granitic rock, the unloading joints are not continuous, as they may show variations in the opening of joints. These results were useful in the mine planning, and assisted in orienting the advance of quarrying operation to avoid areas of low-quality fractured and weathered granite, thus reducing the operating costs of this quarry.

5. Conclusions

GPR profiles of 25, 50, and 100 MHz recorded in the granite quarry near Capão Bonito, SE Brazil, were very useful in characterizing the planar structural discontinuities (both inclined and sub-horizontal), as well as in locating blocks isolated by deep weathering in the subsurface. The results also revealed zones with near-absence of reflectors (and corresponding low energy) associated with transmission of GPR signal through homogeneous, fresh granite without fractures.

At the highest topographic part of the quarry (area-I), where the weathered layer is thickest, 50 MHz antennae produced the best results, penetrating to 25 m depth. However, in front of the active quarry bench (area-III), where fresh granite outcropped, the best results were obtained with 100 MHz antenna pair, which showed a detailed image to 15 m depth. Both a velocity model (for profiles from area-I) and constant velocity of 0.1 m/ns (for profiles from area-II and -III) were used for the conversion from time to depth. They were derived from WARR sounding acquired in study area.

The most promising zones for extraction of large commercial blocks of ornamental granite were: (i)
area-I, between the first and second unloading joints, and below 25 m depths; (ii) area-II, below 10 m of depth; and (iii) area-III, region (H) between two inclined fractures from 0 to 30 m coordinates, and region (I) located below the unloading joint at 15 m depth.

The sub-horizontal fractures located high in the quarry (area-I) and along the front of the active quarry bench (area-III) are excellent basal planes for the extraction and removal of large blocks of standard dimensions. These planes correspond to unloading joints and are locally known as running planes for the blocks, in the ornamental stone industry. Successful mapping of these joints is very important for the extraction process, because they bring cost savings by minimizing the use of explosives, and greatly ease the extraction of the commercial blocks during bench mining.

The results show GPR method does not locate sub-vertical fractures. However, those wider fracture zones filled with clayey material do show a GPR signal characterized by lack of reflections; thus allowing them to be identified. On the other hand, the absence of reflection usually indicates the fresh rock. The discrimination between vertical fracture zones and fresh rock can be obtained through joint interpretation with geologic information.

Mapping the spatial distribution of the subsurface inclined fractures, unloading joints, massive boulders, and of the zones lacking reflectors was important to identify the most favorable regions for extraction of granite blocks of the best quality. These results were fundamental for the mining engineer, and provided the basis, and as a guide for planning the layout of the quarry, and to orient the mining front in such a manner as to minimize the operating costs for the company.

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**References**


Lualdi, M., Zanzi, L., 2003. 2D and 3D GPR imaging to map the fractures and to evaluate the integrity of limestone ornamental rocks. Proceedings of the Symposium on the Application of Geophysics to Environmental and Engineering Problems (SAGEEP’03), San Antonio, Texas, USA, pp. 613–622.


