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# Ground-penetrating radar method used for the characterisation of ornamental stone quarries

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## HIGHLIGHTS

- In quarry studies, GPR allow the differentiation of the marble from schists.
- GPR technique could be used for the design the quarry advance faces.
- GPR response is better for sub-horizontal than for sub-vertical discontinuities.
- The GPR is a appropriated technique for evaluating the block quality.
- The proposed processing method is adequate for the detection of anisotropies.

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## ABSTRACT

In the work non-destructive ground-penetrating radar (GPR) was used to probe the texture and presence of anisotropies in different types of carbonated rocks intended for ornamental use.

First, GPR on the different facies of a marble quarry in Macael (Almería, Spain) was applied where alternating layers of marble and mica schists can be found. GPR allows for the differentiation of the marble units from the mica schist units, which makes GPR a good tool for indirectly evaluating the reserves in a deposit. In addition, it allows for the detection of the different anisotropies in the marble units (holes, fractures), and this information could be utilised to formulate a work-plan design. Antennae of different frequencies were employed (100, 250 and 800 MHz) for these purposes, and the 250 MHz antenna had the most effective probing capacity for obtaining an accurate depth resolution.

Second, a GPR study was conducted in three types of rock known commercially as *Macael Marble*, *Crema Marfil* and *Red Travertine* before the block-cutting process. For this configuration, the 800 MHz antenna was used to differentiate the textures of each type of rock as well as the location of a variety of anisotropies, and the results showed that GPR is an effective tool for evaluating the block quality, determining whether resins must be injected to consolidate the block and estimating the orientation of the cutting process.

In the work, the use of a supervised two-dimensional (i.e., radargram) probabilistic latent component analysis (PLCA) approach is proposed to highlight only the information from target objects (i.e., marble anisotropy) provided by the radargram, which facilitates the data interpretation by the user. This approach can search activations of the georadar pulse across both dimensions. Once the analysis has been performed, a variable-gain compensation process is proposed to outperform the energy losses that result from the reflections of the signal when a different material is found.

The results have shown that the GPR method can be utilised as a tool for the diagnosis of stone materials prior to their use in artistic work or monuments; therefore, GPR may be considered a technique for material selection. The presence of discontinuities (sometimes visible to the naked eye) explain many of the phenomena and typologies of the stone after its eventual alteration, and such discontinuities could be avoided by means of this pre-emptive work.



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## 1. Introduction

Determining the texture of stone and spatial distribution of structural discontinuities, such as cavities, fractures, foliations, etc., is of utmost importance for the design of work plans and subsequent exploitation of quarries. The texture characterisation of the deposit, identification of weakness zones, and possible cartographic description of such zones by means of indirect techniques could assist in the calculation of reserves and design of the advance faces of a quarry, which would reduce extraction costs.

In addition, the evaluation and characterisation of extracted blocks by non-destructive techniques is a necessity because it allows for the location and sizing of possible defects or imperfections within the block (cracks, fractures, holes, etc.), which could maximise the exploitation of the blocks with a subsequent increase in profitability and reduction of the environmental impact of the material processing industry.

Previous works have analysed non-destructive characterisation techniques for stone materials. Sarpün and Kilickaya [19] utilised ultrasonic relative attenuation (URA) to estimate the grain size in marble and obtained similar results to that of conventional optical methods. However, ultrasonic transmission techniques have also been utilised for the study of mineralogical composition as well as for the characterisation of structural discontinuities in ornamental rocks [18,16]. Recently, Cerrillo et al. [3] obtained good results with statistical linear correlations between the parameters of ultrasound techniques and physical and mechanical properties of granite. Therefore, these authors consider this technique to be of great use for the study of granite material.

Ground-penetrating radar (GPR) is a non-destructive technique that has been widely used, and Sigurdsson [21] performed the first studies in limestone quarries to conduct lithographic characterisations. Sigurdsson and Overgaard [22] studied limestone with GPR (using a 100 MHz antennae), which allowed them to differentiate zones with textural variations (bryozoan limestone, coral limestone and wackestone). Grandjean and Gourry [5] and Kadioglu [8] applied this technique for the detection of fractures in marble quarries in Greece and Turkey, respectively, Lualdi and Zanzi [11] and Arosio et al. [1] in Italy and Porsani et al. [17] used these techniques on granite quarries in Brazil.

The work proposes to apply the GPR technique as a non-destructive analysis technique for the evaluation and characterisation of stone materials. GPR was applied to the material from the beginning of the exploitation process, i.e., from its extraction from the quarry. It is our intention to determine the usefulness of GPR at this initial phase to evaluate the stone deposit and locate the fracturing, stratification and schist contents of the massifs to be exploited. This application would allow for an assessment of profitability, as well as for the optimisation of the traditional exploitation criteria.

Once the blocks have been extracted, it would be helpful to determine their internal structure (fissures, cavities, layers, etc.) before initiating the process of block rolling. Based on the information provided by these non-destructive techniques, it would be possible to evaluate whether the block must be consolidated by means of resins or other components, establish injection points (if consolidations is necessary) and optimise the process of cutting or lamination of the block. Thus, a more efficient exploitation of the material and reduction of residues would be achieved. We aim to determine the usefulness of GPR techniques at this phase.

However, detecting a true discontinuities remains a challenging problem in the field of the GPR. Although there are numerous processing algorithms used in commercial GPR systems (e.g., background removal, [9,26]), most provide data that must be interpreted in terms of the "experience" of the user. To minimise the errors produced by an incorrect interpretation by the user, probabilistic latent component analysis (PLCA) has been demonstrated to be a useful tool for denoising or separating targets from non-target sources [14,10].

Moreover, the presence of discontinuities and structural defects in stone materials explains many of their phenomena and typologies witnessed after alteration. Such phenomena and defects are

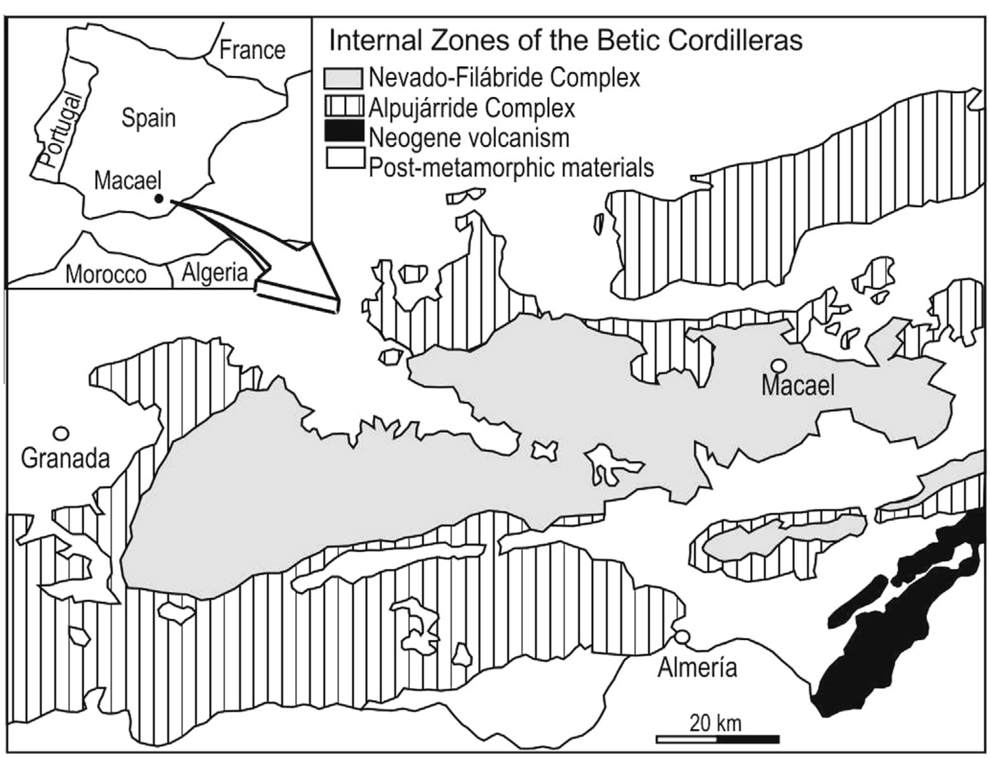


**Fig. 1.** Simplified geological map of the inner zones of the Baetic System showing the location of the studied region (from [28]).