Development and application of modern geophysical techniques (including radar) to the exploitation of ornamental stones

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INTRODUCTION

This report outlines BRGM's progress on the CEC MA2 CT-0354 project up to 1 July 1994. It describes the work undertaken by BRGM between 1 January 1994 and 1 July 1994, i.e. between the 5th and 11th months following the kick-off meeting.

The work carried out during this period concerned four aspects:

- a first interpretation of the November 1993 Volakas survey,
- progress on the borehole antenna,
- progress on the radar tomography programme,
- fieldwork in Greece (April 1994) and Sardinia (May-June 1994).
1. PROGRESS ON THE RADAR BOREHOLE ANTENNA AND ACQUISITION SYSTEM

The broad-band (500 MHz - 1.5 GHz) borehole antenna (9.5 cm diameter) described in the first half-yearly project report was completed at the end of March 1994. Its construction was subcontracted by BRGM to the Université des Sciences et Techniques at Lille.

The original specifications of the antenna were established at the Laboratoire de Radiopropagation et Electronique of the University of Lille. The fit of this antenna to the selected frequency range is good.

Finally the radiation tests carried out in an anechoic chamber are encouraging (Figure 1).

Following these tests it was decided to isolate the radar signal transmission cable between the network analyser and the antenna so as to avoid any coupling with this cable. To do this, the coaxial cable was covered with a very powerful electromagnetic absorbent over a length of 1 m from the antenna. Although this successfully eliminates any coupling, it has also invalidated the measured radiation diagrams.

New radiation measurements with this modification should shortly be made in the anechoic chamber at Lille.

The acquisition system for the borehole radar (Figures 2 and 3) was tested in Greece (Thassos, April 1994) and Sardinia (Budduso, June 1994) with the modification described above. The performance of the system is clearly perfectible. In particular, the main shortcoming is the slowness of borehole data acquisition where the rock is attenuating. This defect was particularly apparent in Sardinia because the granite, which contains a large quantity of amphiboles and biotites, is fairly conductive (attenuation of 6-7 dB/m at 1 GHz). Also, in spite of two amplifiers in series at the receiver, it was necessary to stack the radar signal to eliminate noise level. Stacking with the network analyser is very long and involves prohibitive measurement times. With the Thassos marble, however, which is much more resistant (1.5 dB/m at 1 GHz), delays in the measurement times were due only to shortcomings in the acquisition programme and to the manual raising of the receiving antenna.

Figure 1: Photo of the borehole antenna in an anechoic chamber.
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Figure 2: Acquisition system of the BRGM experimental radar (synthetic pulse radar).

Figure 3: Photo of the acquisition system at Budduso (Sardinia).
2. PROGRESS IN RADAR TOMOGRAPHY

2.1. THE TECHNIQUE

One of the aims of the research project is to be able to detect fracture systems in ornamental stone.

Our first hypothesis is to assume that a fracture is a plane in the mathematical sense of the term.

Also, what we call 'radar tomography' is, in fact, an automatic extraction of planes of limited or unlimited dimension from radar images made along profiles at the surface or in boreholes. The main innovation of this six-month period was precisely the use of this technique with surface radar profiles, whereas previously we had been limited to using borehole radar data.

The standard technique for plotting planes from radargrams of surface profiles is to:
- migrate each radar profile in 2D,
- pick what appears to be a plane,
- plot each picked line in 3D space,
- group the lines that appear to belong to the same plane.

This procedure, however, involves several dangers: the planes are not shown with their correct attitudes, as is illustrated by Figures 4a and 4b: Figure 4a shows a horizontal line which, in fact, corresponds to an inclined plane that is seen on a perpendicular profile (Figure 4b). Thus, if the profile perpendicular to that of Figure 4a had not been made, one may have considered plotting an inclined plane, but with a "non migrated" inclination. A migration has no effect on the horizontal plane, but does change the apparent dip of an inclined plane. Thus several straight parallel lines at increasing depths may represent an inclined plane, but not necessarily the correct inclination.

Moreover, the grouping of traces into a single plane a priori assumes ideas concerning the fracture system. This could lead to major errors of judgement.

Our radar tomography algorithm makes it possible to remedy all these problems by extracting the relevant information (the fracture planes) and providing these planes with their correct inclinations.

The technique that we have used in this project assumes no apriori knowledge. It enables an automatic extraction of the fracture planes from data collected in any geometric combination: borehole-borehole, surface-borehole, surface-surface. It is, however, possible to alter the interpretation in the light of our knowledge of the fracturing in the quarry. Schematically the procedure is as follows:
Automatic or manual (1) picking of the arrivals

For each arrival \((x_i, y_i, z_i)\), calculation of the parameters \((\alpha_1, \beta_1, \gamma_1, \delta_1)\) for the plane giving rise to this arrival

Incrementation of the accumulator \((\alpha_1, \beta_1, \gamma_1, \delta_1)\) in the parameter space

Determining the local maxima in the parameter space

For each local maximum, determining all the arrivals belonging to this plane (delimitation of the plane)

Representation, using GOCAD, of all the points of the extracted planes

Interpolation, through an ellipse, of all the points of the same plane

(1) Automatic with borehole data obtained with the BRGM experimental radar using the Prony algorithm. Manual with surface data.
Figure 4: Two perpendicular radar profiles (4a and 4b) showing the same reflector as having two different inclinations.
2.2. CALCULATING THE PARAMETERS OF A PLANE

Mathematically, an infinite plane is represented by its parametric equation:

\[ \alpha x + \beta y + \gamma z + \delta = 0 \]

where \( \alpha^2 + \beta^2 + \gamma^2 = 1 \)

From this, it can be deduced that three parameters are necessary and sufficient to describe a plane.

Thus a radar arrival \((x_i, t_i)\) located on the profile of equation \(y = y_a\) defines the point \((x_i, y_a, t_i)\).

Assuming that the reflection of the radar wave on a fracture plane respects the law of geometrical optics on the reflection, then the angle of reflection = the angle of incidence. One therefore assumes that no diffraction has taken place.

![Figure 5: Illustration of the reflection principle.](image)

Note that the receivers and transmitters may be either in the borehole or at the surface.

Thus, for a radar arrival whose travel between transmitter \((x_e, y_e, z_e)\) and receiver \((x_r, y_r, z_r)\) is given by the time \(t\), one can calculate the coordinates of the vector \(\vec{n}\) normal to the plane, as well as the distance to the origin of the point \((P)\) giving rise to the reflection. From these calculations, one can determine the coefficients \((a, b, g, d)\), parameters of the reflector plane.

2.3. PARAMETER SPACE

We have seen from the equation that three parameters suffice to characterize a plane. Therefore, for each detected arrival, one can calculate a triplet \((ao, bo, do)\) corresponding to the plane at the origin of this arrival. In the space \((a, b, d)\), one increments the voxel (3D pixel) corresponding to this \((ao, bo, do)\). These steps are repeated for each detected arrival.

In this way, one obtains a three-dimensional space for which each voxel \((a, b, d)\) has a quantity that represents the number of times that the plane with the \((a, b, d)\) has been encountered.

Thus, to extract the planes of this parameter space, it suffices to look for the local maxima. Different methods for extracting maxima from a 3D space have been tested, and we have now implemented the algorithm by "K-means".
No method is entirely satisfactory in our case because the large maxima are accompanied by large secondary lobes which effectively mask other maxima that are smaller than the secondary lobes. It is therefore necessary to eliminate these secondary lobes.

The size of the elemental voxel is very important; on one hand it determines the precision that one wishes to obtain on the fracture plane, and on the other hand it controls the number of planes that one can extract. If the voxels are too small, the accumulator will not be very large and thus few planes will be extracted, although each plane will be defined by very precise parameters. As against this, very large voxels will contain several accumulation zones, each defining planes for which the parameters are very variable around a central value.

### 2.4. RECONSTRUCTING THE FRACTURE PLANES

This step is very important and certainly the most difficult. Up to now the problems of physics have been disregarded, all work having been done in mathematical space. This last step in reconstructing the fracture plane from radar data takes account of the geophysical conditions of the data measurements.

The results obtained during the preceding step are thus a list of accumulators in the parameter space representing fracture planes having the parameters of these accumulators.

But the parameters \(a, b, g, d\) represent the planes of the equation \(a\xi + b\eta + g\zeta + d = 0\), which are thus of infinite extension. When the fracture planes are of finite extension one must find their boundaries, but it is not certain that one can calculate their true extension since the radar antennae have a limited "field of vision" and the radar signal a limited scan. Therefore one can only calculate an apparent extension of the fracture planes.

To do this, one excludes the radar arrivals that do not correspond to an accumulator and one represents/plots the arrivals \((x_1, y_1, z_1)\) corresponding to an accumulator in three-dimensional space.

For each series of points corresponding to a plane, the GOCAD modeller is used for calculating the average plane passing closest to these points.

In this way, from radar data, it has been possible to:

1) extract the radar arrivals,
2) calculate the parameters of the fracture planes,
3) select the arrivals effectively corresponding to fracture planes,
4) interpolate and plot these fracture planes in 3D.

### 2.5. RESULTS OBTAINED TO DATE WITH THIS TECHNIQUE

The computer processing part of the programme has now been completed, although the stability of the algorithm has not enabled convincing results to be obtained on actual radar data (recorded in Greece and Sardinia). However, we have been able to test this programme on synthetic data for which the conditions are known precisely.
We constructed a 1D direct radar signal propagation and reflection model to provide synthetic type data. In this way it has been possible to calculate the radar traces resulting from cross-hole reflection on several fracture planes of variable extension and parameters (variable positions and orientations). We also added "grey" noise of about -70 dB to these data (see Figure 6) so that the synthetic radar traces have the same appearance as real traces. We then looked for the different radar arrivals and calculated the parameters of the fracture planes. Finally we determined the radar arrivals corresponding to the maximum accumulators. The results are relatively satisfactory since 100% of the reflection planes were located, although only 80% of these planes were correctly situated and oriented. The defaulting plane is symmetrical, in relation to the plane defined by the boreholes, to the plane causing the reflections. Finally, it appears that the area of these planes is generally underestimated (see Figures 7 and 8). This last error is logical because the amplitude of the reflections from the furthest parts of a fracture plane is very attenuated by the ground, thus it is very difficult to pick the radar arrivals corresponding to these reflections. This drawback is not penalizing because it means that it is impossible to reach what is inaccessible.

![Graph](image.png)

**Figure 6:** Direct model without noise (top) and with noise (bottom) in the time domain (reflectors at 10.0, 12.3, 12.9, 14.1, 16.5 and 17.8 m).
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Figure 7: 3D view of fracture planes. Synthetic data used in the inverse modelling.

Figure 8: 3D view of the inverse modelling results (tomography) from the synthetic data with noise.

The BRGM always considered the geophysical survey at Volakas as a field trial in order to determine the actual problems related to quarry work and so to better understand the needs of the ornamental-stone operators. Above all it enabled us to test the performances of the different survey tools (radar and seismics). The details of this survey have already been given in the previous six-monthly report.

3.1. SEISMIC TOMOGRAPHY ON A BLOCK

The first seismic arrival was picked on all the data obtained with the PUNDIT. The seismic wave travel times were inverted using 3D seismic tomography software obtained from the Laboratoire Central des Ponts et Chaussées (LCPC) of Nantes. The result is a volume of seismic velocities from which we were able to extract planes with a constant height.

First of all, a first simple straight-path seismic wave model was tested. This model presumes that the seismic waves propagate in a straight line between the transmitter and the receiver. It has the great advantage of being rapid in its execution and of converging when the velocity variations are not too great locally. On the other hand it never provides absolute velocity values because a seismic wave always propagates along the shortest time path. The results are illustrated in Figure 9.

Tests were then made with a more precise, but more unstable model. The curved-path propagation model presumes that the seismic waves propagate along a curve giving the shortest travel time (Fermat principle). The inversion results are shown in Figure 10.

Figure 11 compares the residuals of the straight-path and curved-path inversions. It is seen the straight-path model converges rapidly whereas the curved-path model diverges totally. Also the results of the straight-path model are more reliable than those of the curved-path model.

3.2. SURFACE RADAR SURVEY OVER THE WORKING FACE

The interpretation of this radar survey has not advanced very far since the last project progress report. Only the different radar arrivals for the profiles made on the top of the block have been digitized, because this very old-fashioned method of manual picking requires a great deal of time. The arrival times, however, provided the basic data for the first test of the reflection radar tomography programme in March; unfortunately, the result was not convincing (Figure 12). This work was used mainly for testing the qualities of GOCAD and the radar tomography software.

These data have not since been re-entered in new versions of the tomography programme because we have acquired other data of clearly better quality.
Figure 9: Velocity tomogram for a block of marble at Volaex. Surface-penetration model.
Figure 10. Velocity tomogram for a block of marble at Volakas. Curved-path model.

GRECE - PREMIER BLOC de MARBRE
Apres 8 iterations - Rais circulaires

VITESSE m/s

- ABOVE 5000
- 4800 - 5000
- 4600 - 4800
- 4400 - 4600
- 4200 - 4400
- 4000 - 4200
- 3800 - 4000
- 3600 - 3800
- 3400 - 3600
- 3200 - 3400
- 3000 - 3200
- BELOW 3000

AGIS • s
§
tu
s*
o

GRECE - PREMIER BLOC de MARBRE
VITESSE m/s
1 | ABOVE 5000
1 | 4800 - 5000
1 | 4600 - 4800
1 | ... - 3400
1 | 3000 - 3200

BELOW 3000
z-1.2m
z-0.9m
z-0.6m
z-0.3m

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Figure 11: Comparison of residuals between the straight-path (top) and curved-path (bottom) models for the Volakas seismic data.
Figure 12: GOCAD 3D view of a reflection tomography from surface radar data at Volakas. The results are not very convincing.
4. THASSOS SURVEY (GREECE, APRIL 1994)

The Thassos survey took place from 18 April to 3 May 1994, under the supervision of J.C. Gourry, in the Itkinos Hellas marble quarry next to the road between Thassos and Panaghia. The surface radar measurements were carried out by J.C. Gourry and P. Villard (BRGM research student). The borehole measurements were made by A.M. Delabricre and Y. N'Gyucn from the Laboratoire de Radiopropagation et Electronique of the University of Lille (France). Finally, the sonic measurements on the block of marble were entrusted to J. Alexandre of the LCPC (Nantes, France).

A very powerful television transmitter located a few kilometres from the quarry caused a major disturbance in the borehole radar measurements because the television transmissions are in the same frequency range as that used for the borehole radar. Moreover, it is likely that the very high noise visible on the surface radar images were caused by the same transmitter.

The marble of the quarry is very homogeneous but contains numerous fractures in the survey area (Figures 13 and 14).

The following geophysical measurements were made:
- 60 surface radar profiles, 15 m long and spaced 20 cm apart with a 10 cm spacing, using a PulseEKKO 1000 surface radar with a 900 MHz antenna.
- 30 surface radar profiles, 15 m long and spaced 20 cm apart with a 40 cm spacing, using a PulseEKKO 1000 surface radar with a 450 MHz antenna.
- 2 borehole tomographies using the BRGM experimental radar (measurements between -3 and -6 m) with a 10 cm spacing, giving 900 measurements per borehole doublet.
- 1 seismic tomography on a block of marble (2 x 1.3 x 0.7 m): measurements on the diagonals of the five visible faces with a 15 cm measurement step.
- 1 radar tomography on the same block of marble using the same spacing, but on only four faces.
- 11 radar profiles, 2 m long and spaced 10 cm apart with a 2.5 cm measurement step, on the same block of marble using the PulseEKKO 1000 radar (900 MHz antenna).
- a topographic survey of the radar survey area.

4.1. SEISMIC TOMOGRAPHY ON A BLOCK

4.1.1. Method and facilities

From the Volakas survey, we learnt various lessons, the most of important of which is to use a much faster acquisition system. The PUNDIT provides high-quality measurements but is not suited to acquiring the numerous data needed for seismic tomography.

One method of increasing the acquisition rate is to use numerous sensors for each blast. This is why we rented the acquisition station belonging to the Laboratoire des Ponts et Chaussées (LCPC) of Nantes, which comprises:
- a Krenz acquisition system linked to a PC,
- 10 small-diameter (1 cm) accelerometers with amplifiers and preamplifiers.
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Figure 13: Photo of the working face at Thassos. The radar readings were taken on the bench.

Figure 14: Another photo of the working face at Thassos
The seismic source is selected by the operator (hammer, vibrator, etc.)

One of the accelerometers is used as a TB (Time Break). It is located close to the source and acts as a time reference because it triggers the acquisition of the seismic signals for a given time lapse.

The dimensions of the marble block to be sounded were 1.98 x 1.3 x 0.74 m. As a result of the studies by V. Gautier (1991), the measurement points were arranged on the diagonals at 15 cm intervals.

With five accessible faces, it was possible to trace $14 + 9 + 15 + 9 + 13 = 60$ measurement points. The travel time was measured between each pair of points, i.e. 1300 measurement points.

After manually picking the first arrival on each seismic trace, we inverted the travel times in 3D to obtain a velocity tomography using the RAI-3D software developed by and still under test at the LCPC at Nantes.

4.1.2. Results

The results of this 3D velocity tomography were plotted as planes extracted from the volume of velocities; four planes were extracted with constant heights of 0.1 m, 0.25 m, 0.45 m and 0.6 m. As at Volakas (see Chapter 3.1.) both a simple straight-path seismic wave propagation model and a curved-path propagation model were tested. The respective results are shown in Figures 15 and 16.

Figure 17, which compares the residuals of the straight path and curved path inversions, shows that the straight-path model converges rapidly whereas the curved-path model has a more chaotic behaviour but appears to converge after eight iterations.

In both cases the velocity planes show similar variations. One can distinguish a vertical cylinder of low speeds centred in the block; this zone, which is probably weathered, stretches to the corner with coordinates (0,0,0).

The curved-path model, however, shows gentler velocity variations and less detail.

One now has only to compare the velocity planes with the marble slabs cut from the block by Iktinos Hellas.

4.2. BOREHOLE RADAR

The radar used in the boreholes was the BRGM experimental radar (synthetic pulse radar or step frequency radar) with the broad band antennae (0.5 to 1.5 GHz) developed at the University of Lille (see Chapter 1). The assembly used for the measurements is shown in Figure 2 and described in Chapter 1.
Figure 15: Straight-path seismic velocity tomogram obtained at Thassos.
GRECE - DEUXIEME BLOC de MARBRE

Apres 8 iterations - Rais circulaires

VITESSE m/s

ABOVE  7000
6800 -  7000
6600 -  6800
6400 -  6600
6200 -  6400
6000 -  6200
5800 -  6000
5600 -  5800
5400 -  5600
5200 -  5400
5000 -  5200
BELOW  5000

Figure 16: Curved-path seismic velocity tomogram obtained at Thassos.
Figure 17: Comparison of residuals between the straight-path (top) and curved-path (bottom) models for the Thassos seismic data.
Due to the slowness of acquisition with this type of radar, we could only sound two borehole doublets:
- doublet D1 (boreholes 1 and 2) between -3 m and -6 m at 10 cm steps,
- doublet D2 (boreholes 2 and 3) between -3 m and -6 m with 10 cm steps.

For each receiver position, we recorded the coefficients $S_{11}$ and $S_{21}$ (see Chapter 3 of the Technical Annex to the Annual Report 01.12.1992 - 30.12.1993) for the 31 positions of the transmitter (10 cm steps between -3 m and -6 m). The parameter that interests us is $S_{21}$ (see Figure 18) because it reflects the transmission between transmitter and receiver; it is recorded in the frequency domain and then reconstructed in the temporal domain by simple inverse Fourier transform. Figure 19 shows the wiggle mode of this coefficient for a single receiver position and the 31 transmitter positions.

An analysis of the measurements revealed a high background noise caused by the television transmitter a few kilometres from the quarry. Hence, after applying the Prony algorithm to extract the arrival times, it was extremely difficult to locate the reflection planes in this data "soup". Nevertheless we do not despair of being able to present some results in the next six-monthly report.

Although we are not in a position to present results for this borehole radar survey, we can draw the following conclusions:

- approximately 20 hours are required to record 900 measurement points in a rock such as the Thassos marble, i.e. relatively resistant: the more conductive the rock, the more the measurements need to be stacked in order to eliminate noise, hence the longer the acquisition time;
- measurements of $S_{11}$ (reflections towards the transmitting antenna) are not necessary for calculating the transmission between transmitter and receiver;
- one must be far from any television transmitters, civil and military radars, etc. (Annan, 1992).

These first results were fundamental for preparing the mission in Sardinia.

In addition, with the research team from the University of Lille, we wanted to test the broad-band, high-frequency antenna on a pulse surface radar, i.e. a radar such as the GSSI Sir 10 and Sensors & Software PulseEKKO 1000. As it is very difficult to connect these borehole antennae directly to a commercial radar, we constructed a pulse surface radar using a signal generator with a frequency generator for the transmitter and a digital oscilloscope for the receiver. It was also necessary to add several electronic components in order to trigger the radar pulse.

Unfortunately this experimental pulse surface radar was equally as sensitive to noise as the synthetic pulse radar. In spite of this problem, we were able to verify the good quality of the antennae throughout an entire day, until an electronic relay broke.

The same experiment was repeated in Sardinia. Conclusions concerning the possibility of adapting the borehole antennae to a standard radar will not be available before December.
Figure 18: Example of the S21 coefficient (module above, phase below) obtained in a borehole at Thassos.
Figure 19: Borehole wiggle radargram obtained at Thassos for a single receiver position and 31 transmitter positions. Note the high noise level of the readings.
Figure 20: Topography of the Thassos site.
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Figure 21: Surface radar profile. Thassos. Profile Y0000.

Figure 22: Surface radar profile. Thassos. Profile Y0200
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Figure 23: Surface radar profile. Thassos. Profile Y0600.

Figure 24: Surface radar profile. Thassos. Profile Y0800.
Figure 25: Surface radar profile. Thassos. Profile Y1000.
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To the front

Legend

THASSOS - GREECE
IKTINOS HELLAS SA
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Figure 26: Situation of the planes extracted for the estimation of the fracturation amount
Figure 27: Interpretation of the quality of the Thassos marble through applying a value to each pixel based on criteria of: (1) very fractured, (2) slightly fractured and (3) unfractured.
4.3. SURFACE RADAR

4.3.1. Topography

The surface behind the working face surveyed by radar was almost perfect. But a slight hollow (35 cm deep) in the centre of the zone made it necessary to estimate the topography in order to correct the radar profiles. Figure 20 shows the radar profiles that were made, although only main profiles are shown so as not to overload the figure. From this map one can very easily extract elevation sections along the radar profiles.

4.3.2. Radar survey over the working face

The radar survey over and behind the working face was carried out within a rectangular zone (15 m x 11.8 m) containing the four boreholes (Figure 20). The rectangle was based on the positions of the boreholes: point (0, 0) on borehole F3 and point (11.4, 0) on borehole F4.

Two radar frequencies were used: 900 and 450 MHz. The radar was a Sensors & Software PulseEKKO 1000.

The following table gives the specifications of the radar profiles that were run.

<table>
<thead>
<tr>
<th>Antenna frequency</th>
<th>Spacing</th>
<th>Profile spacing</th>
<th>Profile length</th>
<th>Trace stacking</th>
</tr>
</thead>
<tbody>
<tr>
<td>900 MHz</td>
<td>10 cm</td>
<td>20 cm</td>
<td>15 m</td>
<td>8</td>
</tr>
<tr>
<td>450 MHz</td>
<td>20 cm</td>
<td>40 cm</td>
<td>15 m</td>
<td>8</td>
</tr>
</tbody>
</table>

The profile spacing was made deliberately very small so as to be able to select the optimum spacing for retaining the maximum amount of information and to enable the reflection radar tomography programme to be adapted to the surface data.

A few examples of the radar profiles are shown in Figures 21 to 25. It is seen that the depth of investigation reached 5 m at 900 MHz and 8 m at 450 MHz. Numerous fractures are visible on these images, as well as some characteristic voids. But one should also note the high noise level around the main fracture, which is very disturbing. This large fault, which crosses the whole of the surveyed zone, is seen in Figure 13; all the fractures visible at the surface behind the working face were detected by the ground penetrating radar (GPR). One can also see numerous small short fractures (Figure 21); it would be interesting to know the aperture of these fractures to verify whether, as at Volakas, it is possible to detect fractures of 1 mm aperture.

One of the challenges, therefore, is to eliminate the noise around these fractures and also to eliminate the numerous multiple reflections that disturb the interpretation.

Then, once the noise has been eliminated, all depends on the results expected by the operator of the marble quarry. The quarry operator could have two different requirements:

- he could be interested in the average fracture ratio per m³, whereupon one could supply a fracture zone map of the quarry; or
- he may want to know the exact position of each flaw in the marble that he is working, whereupon it would be necessary to have recourse to a tomography software programme which reconstructs the exact position of each fracture in 3D.

It is obvious that the second approach is much more complicated than the first. But it is necessary to ask the quarry operator what it is that he requires if one does not want to carry out unnecessary work.

An approach to determining the quality of the marble is given in Figures 26 and 27. Through simple visual analysis of the radar profiles we were able to distinguish three fracture criteria: (1) very fractured, (2) slightly fractured and (3) unfractured. For each vertical plane (1 m spacing between planes) we applied a fracture ratio per square of 0.25 m x 0.25 m.

We were not able to provide a 3D plot of the fracturing behind the working face from these surface radar data because it is still very difficult for us to automatically pick the different radar arrivals. The deadlines for providing this reconstruction of the fracturing are given in Chapter 6.3.

4.4. RADAR SURVEY OF A BLOCK

Two types of radar survey were carried out on the block of marble:
- radar profiles spaced at 10 cm intervals on one face of the block,
- radar tomography measurements.

4.4.1. Reflection radar

Eleven profiles, 2 m long and spaced 10 cm apart, were run on the marble block (Figure 28).

![Figure 28: Radar profiles (dotted lines) on the marble block: profiles 10 cm apart.](image)
Figure 29: Radar profiles on a block. Note the poor resolution.
The profiles were made using a 900 MHz antenna which, in spite of its small size, proved to be too large with respect to the size of the block; the length of the 900 MHz antenna is 23 cm, which is an eighth of the block length. Therefore, in order to avoid edge effects, we had to begin the profiles 25 cm in from the edge and to end them 1.75 m in from the edge. Thus only 3/4 of the block could be sounded.

In addition, the spatial Nyquist frequency is

\[ n_x = \frac{c}{4f\sqrt{k}} \]

where \( c \) = speed of light in a vacuum, \( f \) = radar frequency, and \( k \) = the electrical permittivity of the medium. Moreover, in the Thassos marble, \( k = 6.8 \), from whence \( n_x = 3.2 \) cm. In order to remain below the spatial Nyquist frequency, we chose a measurement step of 2.5 cm. Even at this measurement interval, the definition is not very good (Figure 29). It is therefore necessary to use the radar in continuous acquisition mode, with all the defects of this technique: poor spatial location, impossibility of correct stacking.

The results of this step mode sounding, using a stacking of 64 traces, are all the same interesting because one sees numerous reflections that can be related to those recorded by seismic tomography. Nevertheless, it is difficult to make a more detailed analysis of these radar images because of the poor spatial resolution at 900 MHz frequency owing to the wave length of about 13 cm.

4.4.2. Radar tomography

This technique enables us to acquire radar signals transmitted between a transmitter position that is separate from the receiver position (Figure 30).

So far the data have been recorded and the first arrivals picked on all the radar signals. The time reference (initial time) was determined by joining the transmitting and receiving antennae.

This new sounding technique is discussed in Chapter 6.4.

4.5. ESTIMATION OF THE ELECTROMAGNETIC WAVE VELOCITY AND ATTENUATION IN THE MARBLE

One of the simplest methods for estimating this velocity is to carry out a surface radar survey in CMP or WARR (Common Mid-Point or Wide Angle Reflection and Refraction) mode (Figure 31). But the presence of a subhorizontal reflector plane is an essential condition in both cases, and such a radar reflector does not exist in the Thassos quarry. The demonstration of this is provided by Figure 32, which represents a CMP profile; only the direct wave signal is seen.

On the other hand, it was possible to estimate this velocity by the least squares method using the travel time of the direct wave between the transmitter and the borehole receiver. This gives a velocity of 10.8 cm/ns in the 500 MHz to 1.5 GHz frequency range, and thus a relative electrical permittivity of 7.7.

We also estimated the attenuation of the electromagnetic waves by using the experimental radar (the HP Network Analyzer) and subtracting the energy recorded in air from that recorded in the rock between boreholes for a same distance between antennae and for a path in unfractured marble. These strengths being expressed in dBm, the Thassos marble gives an attenuation of 1.5 dB/m at 1 GHz.
Figure 30: Radar signal transmitted on a marble block between a transmitter and a distinct receiver.
Modem geophysical techniques to exploitation of ornamental stones

Figure 31: Explanation of the CMP or WARR survey techniques.

Figure 32: CMP profile at Thassos. Only the direct wave is seen owing to the absence of a horizontal reflector.
5. BUDDUSO SURVEY (SARDINIA, MAY-JUNE 1994)

The Budduso survey took place in the Manu Graniti granite quarry at Budduso from 16 to 20 May 1994 under the supervision of J.C. Gourry (Mission 1) then from 27 June to 1 July 1994 under the supervision of J.M. Miehe of the BRGM (Mission 2). This Sardinian quarry had already been studied by PROGEMISA research teams. The surface radar measurements were made by J.C. Gourry and G. Richalet (BRGM) during Mission 1, and the borehole radar measurements were made by J.M Miehe assisted by A.M. Delabrière, Y. N'Gyuen (Laboratoire de Radiopropagation et Electronique of the University of Lille) and F. Le Jeune (BRGM) during Mission 2. No sonic measurement was made on the granite blocks.

The fact that the survey took place in two missions was due to a breakdown of the network analyser and the HP-IB link card. This made it necessary to return to the site one month later after the repairs had been carried out (Mission 2).

Because the survey zone was far from the working face, it was difficult to make a visual assessment of the fracture ratio. But correctly stored cores from the boreholes showed the granite to contain numerous zones of wide-aperture fractures.

The ruggedness of the survey area (Figure 33) resulted in profiles of varied lengths, and it was necessary to carry out a topographic survey of the entire area to the nearest centimetre in order to correct the radar images.

The geophysical measurements carried out were:

- 32 surface radar profiles, 15 m long on average and spaced 40 cm apart with a 10 cm measurement step, using a PulseEKKO 1000 surface radar and a 900 MHz antenna.
- 32 surface radar profiles, 15 m long on average and spaced 40 cm apart with a 40 cm measurement step, using a PulseEKKO 1000 surface radar and a 450 MHz antenna.
- 2 borehole tomographies using the BRGM experimental radar (receiver measurements between -2 and -8 m for the two doublets with a 40 cm measurement step; transmitter measurements between -2 and -6 m with a 20 cm measurement step for doublet 1 and between -1 and -6.2 m with a 40 cm measurement step for doublet 2) giving approximately 500 measurements.
- a topographic survey of the radar survey area.

5.1. ESTIMATION OF THE ELECTROMAGNETIC WAVE VELOCITY IN THE BUDDUSO GRANITE

The presence of subhorizontal reflector planes (Figure 34) enabled the velocity of the EM waves to be estimated by CMP with the 225 MHz antennae. This velocity was then calculated using the processing software provided by Sensors & Software (Figure 35), which gives the average velocity as 13 cm/ns, thus an electrical permittivity of 5.3.
Modern geophysical techniques to exploitation of ornamental stones

Figure 33: Photo of the Budduso site (Sardinia).

Figure 34: CMP radar profile obtained at Budduso at 225 MHz.
Figure 35: Calculation of the EM wave propagation velocities. Note the accumulation around 13 cm/ns, corresponding to the velocity of the radar waves.

It was not possible to measure the velocity by CMP at 900 MHz because the reflector plane was at 4.4 m, and the CMP requires a minimum antenna separation of 5 m. The path would have been 6.6 m to reach this plane whereas the maximum scan distance at 900 MHz is 5.5 m. We therefore used the velocity at 225 MHz for the profiles obtained at 900 MHz by assuming a weak velocity dispersion.

5.2. SURFACE RADAR

5.2.1. Topography

The survey area in the Manu Graniti quarry at Budduso being very rugged, it was necessary to carry out a topographic survey (Figure 36).

The survey was done carries out a Wild LNA 2 automatic laser level having a measurement precision of 1 cm. The points were surveyed every metre in a N-S direction and every 0.8 m in a E-W direction.

5.2.2. Radar survey over the working face

Due to the numerous obstacles in the survey area, it was not possible to run complete profiles over the whole area (Figure 36). Nevertheless, the complexity of the site enabled us to validate our techniques on all types of terrain.

One can estimate the depth of the scan to be 5.5 m with the 900 MHz antenna and 9 m with the 225 MHz antenna.

Unlike at Thassos, there was no electromagnetic noise. In addition, the radar images were very clean and the fractures clear. However, the images also show numerous multiple reflections that need to be eliminated.
The radar data reveals two fracture sets in the granite within the surveyed area (Figures 37 and 38). The profiles also show an increase in the fracture ratio from west to east (boreholes S1 to S4). Using the criteria defined for the Thassos marble (see Chapter 4.3.2.), it was possible to plot the fracture ratio of the granite to a depth of 6 m (Figures 39 and 40).

5.3. BOREHOLE RADAR

The borehole radar survey, using the BRGM experimental radar, was done during a second mission because of technical problems that occurred during the first survey in Sardinia.

The original intention was to make two tomographies over a depth of 8 m with a 20 cm measurement step, using a common borehole so as to obtain the maximum amount of data. However, from the first calibrations, it appeared that the Budduso granite was much more absorbent than predicted; the granite is very rich in biotites and amphiboles, and has a fairly high conductivity. It was therefore necessary to add a second amplifier in series to the standard assembly (Figure 2). As this additional electronic component introduced noise, it was then necessary to increase the acquisition time for each measurement. Moreover, it was not possible to completely dewater the boreholes, and the borehole antennae are not watertight. Finally, it was also necessary to make a downward revision of our measurement predictions.

Two doublets were run according to the following characteristics:

<table>
<thead>
<tr>
<th>Doublet No.</th>
<th>Transmitter borehole No.</th>
<th>Receiving borehole No.</th>
<th>Relative positions of the transmitter</th>
<th>Transmitter measurement step</th>
<th>Relative positions of the receiver</th>
<th>Receiver measurement step</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>S1</td>
<td>S4</td>
<td>-2 to -6 m</td>
<td>20 cm</td>
<td>-2 to -8 m</td>
<td>40 cm</td>
</tr>
<tr>
<td>D2</td>
<td>S2</td>
<td>S4</td>
<td>-1 to -6.2 m</td>
<td>40 cm</td>
<td>-2 to -8 m</td>
<td>40 cm</td>
</tr>
</tbody>
</table>

As a result of our experience at Thassos, we gained time by recording only the S21 parameters.

An inverse Fourier transform on the S21 parameters obtained for a same transmitter position provided an image in which the first arrivals and a few aligned second arrivals from the same reflectors are clearly distinguishable (Figure 41). It was these second arrivals that we attempted to group with our reflection tomography software.

We succeeded in applying our processing system (see Chapter 2) to the Budduso data, and extracted 9 fracture planes that were plotted using GOCAD (Figure 42). This first display of the fracturing from borehole data is very encouraging for the future of this technique.
Figure 36: Topographic survey around the drilled area at Budduso.
Figure 37: Radar profiles obtained at Budduso in the west of the area with the 900 MHz antenna. Profile Y0160 (top) and Y0480 (bottom).
Figure 38: Radar profiles obtained at Budduso in the east of the area. Profile Y0960 at 225 MHz (top) and Y1200 at 900 MHz (bottom). Fracturing decreases towards the west of the area (Figure 37).
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Figure 39: Position of the extracted planes for the estimation of the fracturation ratio.

BUDDUSO-SARDINIA
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TOPOGRAPHY

Legend

S3 Borehole

Extracted plane for the estimation of the fracturation amount

Figure 39: Position of the extracted planes for the estimation of the fracturation ratio.
Figure 40: Estimation of fracture ratio per plane.
(1) very fractured, (2) slightly fractured, (3) unfractured.
Figure 41: Cross-hole wiggle radargram for a single transmitter position and 41 receiver positions.
Figure 42: Inversion of borehole radar arrivals and G-map 3D view of the fracture planes.
6. FORECAST FOR THE NEXT SIX MONTHS

6.1. BOREHOLE RADAR ANTENNA

The standing wave ratio (SWR) of the present biconical antenna is very satisfactory, and performance with respect to the strength transmitted by the antenna could not be significantly improved. Three parameters of the antenna, however, are perfectible: its directivity, its coupling with the coaxial borehole cable and its diameter.

It appears possible to deal with these three parameters simultaneously by using another form of antenna, which is much more difficult to develop. One can considerably reduce the diameter of this antenna and it would then be possible to consider a half-space screen to improve the antenna's directivity.

Antenna directivity is fundamental to improving the quality of borehole measurements since it would provide a better precision when determining the fracture planes with the inversion software.

Finally, the last advantage of this new antenna is the perfect decoupling of the antenna and the borehole coaxial cable.

Development tests on this new antenna will begin around September or October at the electronics laboratory of the University of Lille.

6.2. FUTURE OF THE HIGH RESOLUTION SEISMICS

The results from seismic tomography on the block obtained at Volakas were fairly disappointing because there was no good correlation between the seismic velocity anomalies and the imperfections in the marble. The reason for this is possible due to too wide a spacing between the measurement points, i.e. a spacing that did not provide the desired precision.

So far the block that was analysed at Thassos has not been dressed and so it has not been possible to compare photographs of the slabs with the seismic velocity inversions. But apparently the seismic results at Thassos show a better inter-correlation than those at Volakas. Therefore, in spite of all our reservations concerning this technique (very long acquisition, inversion and interpretation times), hope still exists that it can be developed for industrial use.

There is also a problem concerning high-frequency seismic tomography equipment which is reflected in its slow acquisition and data undersampling. A search for a new equipment (high-frequency acquisition system, sensors and transmitters adapted to high frequency - about 20 kHz) is being carried out and will continue during the coming months. Already several alternatives have been earmarked, and testing of this experimental system could take place in 1995.

The radar, on the other hand, is providing satisfactory results with respect to our requirements at the present state of the project: rapid measurement and image analysis, quality results.
6.3. AUTOMATIC PICKING OF SURFACE DATA

As with standard reflection seismics, one of the main problems with surface radar is to be able to process the radar echoes automatically. This requires deconvolution of the radar signal (at present not achieved very satisfactorily) so as to eliminate all the multiple arrivals (standard basic processing with seismic reflection). Only then can one proceed with automatic picking of the echoes.

One of the objectives at BRGM is to use a seismic reflection software for processing radar data and for computing the different radar arrivals to be integrated into the inversion software.

In the near future we expect to use the "SU" software developed by the Colorado School of Mines.

6.4. RADAR TOMOGRAPHY OF VELOCITY AND ATTENUATION IN TRANSMISSIONS ON BLOCKS

A trial of radar tomography on a block was made at Thassos (Greece), using the same block as was used for the seismic tomography, and following the same procedure as with the seismics. The radar transmitter was positioned and the travel time of the electromagnetic waves was measured at several receiver points located on the diagonals of the block. The radar data obtained are given in Figure 43.

By picking the first arrivals and by calculating the amplitude of the first arrival, one can respectively obtain a velocity tomography and an attenuation tomography in 2D or 3D using the RAI-3D software. In both cases one finds oneself up against the inversion of a linear problem (Leggett et al., 1993). Numerous publications cite very interesting results derived from the radar tomography technique.

In the present case, in order to sound the block from many different angles, measurements were made with the transmitter and receiver on adjacent faces. Certain waves, however, pass through air after leaving the block below critical incidence (Figure 44). This is why one has the impression of noting a sudden increase in velocity with only a slight change in the position of the receiver (Figure 43).

When one inverts the travel time of the radar waves that passed through air, using the RAI-3D software which does not take this phenomenon into account, one obtains a very steep velocity gradient at the edge of the block; this has no significance, but greatly disturbs the inversions which tend to diverge. Similarly with attenuation tomography, the results would not be good using the RAI-3D software.

If one only used the measurements obtained for the transmitters-receivers located opposite each other, there would no longer be a problem of propagation in air below critical angle. However, measurements below certain angles would be missing, resulting in a poor estimation of the velocities.
Figure 43: Radargram obtained from transmission on a block. Owing to certain waves passing through the air, the estimation of velocity in the rock is often erroneous.
6.5. CRITERIA FOR DISTINGUISHING FRACTURES

A fracture is much more complex than a simple reflector plane detected by radar. It is characterized by numerous other parameters such as orientation, position, surface, aperture, place in a fault network, etc.

At present only its orientation, position and surface are determined. Although fundamental, this information is not sufficient for the quarry operator who has to diagnose the condition of his working face or of a block to bedressed.

Among the other parameters, one which would be of considerable help to the quarry operator is the fracture aperture. A fracture aperture of 1 mm has a different significance from one of 1 cm. Even though one can qualitatively assess the aperture from a radar image, one cannot estimate it quantitatively.

A simple modelling of the reflection of an electromagnetic wave from a layer of air of finite thickness separating two half-spaces having identical properties (Figure 45a) makes it possible to calculate of the reflection coefficient ($R_t$), which is directly related to the thickness ($t$) of the layer of air (Annan, 1992; Yilmaz, 1987):

$$ R_t = \frac{R}{1 - R^2} \frac{2t\omega}{V_2^2} \quad \text{if} \quad \frac{t}{V_2} \ll 1 $$  \hspace{1cm} (1)

where $v_1$ = the EM propagation velocity in medium 1,
$v_2$ = the EM propagation velocity in medium 2,
$\omega = 2\pi f$ where $f$ = the frequency of the radar antenna,
$R$ = the reflection coefficient without the strip of air.

$$ R = \frac{\sqrt{K_1} - \sqrt{K_2}}{\sqrt{K_1} + \sqrt{K_2}} $$
where $K_1$ and $K_2$ are the electrical permittivities of mediums 1 and 2 (Figure 45b). This relationship is only valid at high frequency in very resistant mediums.

Also

$$v' = \frac{c}{\sqrt{\epsilon}}$$

where $c$ = the speed of light in a vacuum.

Figure 45a: Normal incidence reflection for a thin layer.

One can see that the effect of the layer of air is not insignificant. These equations also show that it is possible to display a reflection from a very thin fracture (around 1 mm) at high frequency because the reflection coefficient ($R_t$) is proportional to the frequency and the thickness ($t$) of the thin layer.

It is, however, fundamental to be able to estimate the reflection coefficient ($R_t$) in order to calculate the thickness of the layer of air. This is only possible if one is able to determine the attenuation of medium 1 from the following equations:

$$A = A_0 e^{-\alpha r}$$

and

$$R_t = \frac{A}{A_0}$$

where $\alpha$ = the attenuation of medium 1,
$r$ = the path followed by the radar wave,
$A_0$ = the amplitude of the transmitted signal,
$A$ = the amplitude of the received signal,
$n = 0$ for a 1D guided wave,
$n = 1/2$ for a 2D guided wave,
$n = 1$ for a spherical wave (close field)
$n = 2$ for a lateral wave (far field).
It is then follows, according to (1), (2) and (3), that:

\[ t = \frac{e^{-\alpha r}}{r^{\alpha}} \frac{1 - R^2}{L} \frac{L_1}{4\pi} \]

As \( R \) is dependent on \( K_1 \) and \( K_2 \), it is necessary to know the electrical permittivities or the velocities of mediums 1 and 2.
CONCLUSION

The BRGM work on the project is very slightly ahead of schedule. After 10 effective months of work, the first series of field surveys was completed at the end of June. The radar tomography program functions with synthetic data and requires only routine improvements (stability, conditioning, etc.) to be valid for field data.

Nevertheless, one cannot consider interpreting the radar measurements until the software is working perfectly. At present, it is only possible to provide the fracturing ratio of a block or working face, without being able to accurately determine the position of the fractures.

The specifications of a future seismic acquisition system for sounding blocks have been defined: sensors, amplifiers and pre-amplifiers, acquisition card, processing software. Also, in spite of the major shortcomings of the technique, the acquisition system is ready to be set up and tested during a future survey.

Surface radar has been shown to be very effective for locating fractures in granite and marble. Nevertheless, it is absolutely essential to develop an algorithm for the automatic picking of echoes from pulse radar data so as to fully automate the processing of these radar data.
REFERENCES


