Travel time inversion from ground level to gallery: protocol for the characterization of P-wave seismic signature in a fractured-porous Urgonian platform at hectometric scale

Emeline Maufroy1,2*, Stéphane Gaffet1,3, Stéphane Operto1, Yves Guglielmi4 and Daniel Boyer3

1 GEOAZUR, UMR 7329, Université de Nice Sophia-Antipolis, CNRS, IRD, Observatoire de la Côte d’Azur. Sophia-Antipolis, F-06560 Valbonne, France
2 Univ. Grenoble Alpes, ISTerre, UMR 5275, CNRS, IRD, IFSTTAR. F-38041 Grenoble, France
3 LSBB, UMS 3538, Université de Nice Sophia-Antipolis, Université d’Avignon et des Pays de Vaucluse, CNRS, Aix Marseille Université, Observatoire de la Côte d’Azur. La grande combe, F-84400 Rustrel, France
4 CEREGE, UMR 7330, Aix Marseille Université, CNRS, IRD. F-13331 Marseille, France

Received June 2013, revision accepted January 2014

ABSTRACT
A tomographic P-wave velocity model is inferred from a ground level-to-gallery vertical 500 m x 800 m seismic experiment conducted at the inter-Disciplinary Underground Science and Technology Laboratory (LSBB, France). No initial knowledge of the velocity structure of the surrounding fractured-porous carbonates was previously available. Ninety-four shots at the surface were recorded by a line of 189 seismometers on the steep slope of the topographic surface and by a line of 150 geophones in an 800 m-long, 250-500 m-depth gallery. The P-wave velocities inferred from first-arrival travel time inversion display a relatively large set of values ranging from 4000 to 6000 m/s. Such Vp variations correlate well with the 5 to 20% porosity variations between the main geological units that consist of two sedimentary facies affected by a complex cemented fault zone.

Taking advantage of the known geology of the site, this study explores the influence of the acquisition geometry impacted by the topography and of the near-surface weathered zone onto the shallow Vp tomography resolution ability. Considering the mesoscopic scale of the targeted medium, reliable imaging of hectometric geological bodies with 10% contrasts in porosities can be achieved only with the simultaneous association of (i) a high density of sources and receivers in the monitoring array geometry, and (ii) the equal consideration of surface-to-gallery and surface-to-surface first-arrival travel times, as an essential constraint to correctly image the underlying structures.

INTRODUCTION
Obtaining high resolution images from ground level to 500 m depth is a major challenge of modern geophysics because of the extreme variability of the near-surface. This is mainly related to contrasting weathering grades of geological materials and to a velocity gradient that is extreme to anything found at greater crustal depths, where consolidation effects smooth out some of the differences (Barton 2007). Some of the challenges may be the dynamic response of the near-surface rocks to seismic waves, the so-called site effects (Trifunac and Hudson 1971; Tucker et al. 1984; Bouchon and Barker 1996; Lee et al. 2009a, 2009b; Chaljub et al. 2010; Maufroy 2010; Maufroy et al. 2012), the geotechnical stability problems from tunnels to dams and the karst phenomena in limestones (Sjogren 2000). A wide variety of cross-hole and between-gallery seismic experiments have been performed for many years to develop velocity models of the near surface heterogeneities and eventually relate those velocities to rock properties. A strong variability between P-wave estimations is observed depending on the method (seismic refraction, down-hole logging, cross-hole and surface exploration, Ebisu et al. 1992) which results from the strong scale dependency of seismic properties in the near surface.

Among the various geological and mechanical features that affect seismic velocities in the near-surface, complex stress effects related to topography and weathering are usually considered predominant. Indeed, it is well known that there is a compressive stress concentration at the foot of a slope and an extensive stress at the top and that, in high compressive zones where...
rock voids are in general more closed, the average seismic velocity is higher than in the extensive zones where voids are widely opened (Iannacchione and Coyle 2002). Adding to stress effects, weathering can extend at depth through high permeable heterogeneities, generating large karstic voids in limestones, for example. Such zones lead to a strong attenuation of the high frequency part of the wavefield and induce an apparent decrease of velocity in the high velocity layers (McCann et al. 1975).

In the near-surface zone, the main problem is then to estimate how accurate a tomographic image remains, given the geometry of the seismic layout, the rock geology and the vertical extent of the weathered zone.

From laboratory experiments, it is now well known that rock geology features such as mineralogy, cracks and pores, saturation conditions, fluid characteristics, temperature and formation pressure all have a role in velocity variations (Spencer and Nur 1976; Dvorkin et al. 1999 for ex.). It is even more complex in situ where metric to plurimetric joints and large voids will modify seismic wave attributes and seismic ray paths. Among many rock geologies, carbonates strongly challenge tomographic methods from the laboratory to the massif scale because they can display sharper multi-scale variations in their physical properties related to much more complex diagenetic processes than in any other rocks (Eberli and Baechle 2003). Relating those properties to seismic velocities is a big challenge because carbonates host large natural resources (water and oil) while their complex weathering can cause tremendous geotechnical problems (such as ground subsidence or differential settlement).

The onshore tomographic experiment presented in this paper aims at an accurate 3-D numerical modelling of seismic wave propagation inside a realistic geological model that integrates a complex 500 m-thick carbonate series underlying a steep surface topography (Maufroy 2010; Maufroy et al. 2012). The present article focuses on the methodology for seismic imaging in the frame of a field experiment carried out in 2006 in Southern France, within the Underground Research Laboratory dedicated to inter-Disciplinary Underground Science and Technology (LSBB, http://www.lsbb.eu). The research centre reaches 500 m depth beneath the surface, within the fractured-porous carbonate platform of the Fontaine-de-Vaucluse aquifer. The experiment was designed for imaging the seismic properties along a vertical plane oriented northward. This panel was bounded by two lines of seismic sensors settled respectively within an 800 m-long gallery and at the steep ground-surface 250-to-500 m above. The seismic sources were explosive shots along the surface line of seismometers. Despite the good knowledge on the local geology (see next section), no information was available prior to the experiment concerning the wave speed of the surrounding carbonates. Thus the imaging technique used in this work doesn’t require any preliminary knowledge of the wave speed. It uses the first-arrival times of P-waves to construct the model of the P-velocity at LSBB. This smooth model of the P-velocity at LSBB, whose construction is presented in this paper, will later be the starting guess for the full waveform high-resolution inversion techniques that will be applied in the near future (Brossier 2011; Romdhane et al. 2011). It must be emphasized that this first model must be carefully built; indeed the reliability of the high-resolution images obtained afterwards strongly depends on the confidence assigned to the first model. In this study, we first discuss how the imaging protocol, from the acquisition geometry to the regularization for the travel time inversion, can affect the accuracy of the smooth seismic image in such a small-dimension tomographic layout. Secondly, the seismological observations are interpreted with the geological and petrophysical data collected on the site, highlighting the scale and accuracy of rock physics properties that can be estimated when performing a tomography from combined cross-hole and surface acquisition in such a heterogeneous fractured-porous limestone.

**LSBB GEOLOGY AND INTERIMAGES 2006 EXPERIMENT SETTING**

The galleries of LSBB are buried in the south foot of the Albion plateau which is a 1000 m-thick karstic unit located in the Southern French Alps and drained by the Fontaine-de-Vaucluse spring located 30 km westward (Maas 1968; Arnaud-Vanneau et al. 1979; Maas 1993). The laboratory is nested within the unsaturated zone of the karst, while the aquifer water table is situated about 400 m below the galleries. (Gaffet et al. 2003; Couturaud 1993). LSBB is a National Underground Facility dedicated to multi-physics and inter-disciplinary researches (e.g., thermo-hydro-mechanical couplings, hydro-magnetic perturbations induced in the unsaturated zone by seismic vibrations).

LSBB is buried within the 1000–1500 m-thick succession of Lower Cretaceous carbonates (Fig. 1). The sedimentary facies are highly contrasted from the bottom to the top of the succession characterized by a progressive evolution from basin carbonates (Hauterivian to Middle Barremian) to platform carbonates (Urgonian facies from Upper Barremian to Aptian). Basin carbonates display a relatively homogeneous 600 m-thick succession of clayey and shaly limestones. They can be characterized by porosity less than 5% (Fig. 1c). Platform carbonates display a wide variety of facies that are considered a perfect analogue to current middle-eastern oil reservoirs with porosity varying between 10 and 20% (Jurgawczynski 2007). The three Urgonian sedimentary units U1, U2 and U3 (Fig. 1b-c) can be individualized from bottom to top (Maas 1993). Unit 1 is made of a 150-to-200 m pile of bio-calcarencitic carbonates with an average porosity of 10%. Unit 2 is a 150 m-thick succession of carbonates containing ruddists and intercalated coral reefs with porosities of 15 to more than 20%. Unit 3 is a 50 m-thick succession of calcarenitic carbonates with shales and an average porosity of 10% similar to that of U1.

The regional tectonic structure of LSBB is characterized by a fractured monoclone that is oriented N80°E and dipping 10 to 20° southward from the mountain top to the valley floor (Fig. 1b). The site is cut by two main families of sub-vertical fracture
P-wave seismic signature in a fractured-porous Urgonian platform at hectometric scale

Directions, respectively N120°E and N20°E (Fig. 1d). The N120°E family is characterized by two pluri-kilometric normal faults with respectively 50 and 100 m vertical offsets, while the N20°E family corresponds to strike-slip hectometric to kilometmic faults (S.S.B.S. program 1965). Reservoir properties of the faults are much contrasted. Normal faults are characterized by a 5-to-15 m-thick damage core that is cemented by calcite elements related to the circulation of diagenetic fluids within the fault zone. That cemented zone extends from the fault zone towards the sedimentary layers giving the fault zone the final aspect of a “tree-like geometry” zone characterized by porosity less than 5%. Strike-slip faults rather display a 5-to-10 m-thick damage zone with metric to plurimetric secondary faults along which large centimetric voids or clay fillings can be observed. The result is that the N20°E faults can be considered highly porous zones in the LSBB area.

FIGURE 1
(a) Location of the Interimages 2006 experiment (vertical plane in shaded blue tones bounded by two black lines featuring the seismic sensors) inside the South slope of the Albion plateau; (b) Schematic N0°E geological cross section of LSBB site with the seismic tomographic profile superimposed in grey; (c) Lithostratigraphic succession and porosity variation of the local carbonate rocks; (d) Structural map of LSBB area with the location of the surface line of the Interimages 2006 experiment.

FIGURE 2
Shot gathers of the Interimages 2006 dataset; (a) shot #29 recorded at the underground gallery receivers; (b) zoom on five consecutive gallery receivers (black waveforms) showing delayed first arrivals and lower frequency content, indicative of a strong P-wave attenuation zone 500 m away from the northern extremity of the gallery; (c) same shot #29 recorded on the surface sensors array.
The Interimages 2006 experiment was conducted in the unsaturated zone of the reservoir. It investigated a 200 to 500 m thickness of limestones between the surface and the tunnel (Fig. 1a). The area explored by the experiment covers one major sub-vertical N120°E normal fault, a N20°E strike-slip fault and the two main sedimentary environments, respectively the platform and the basin carbonates (Fig. 1b). The 750 m-long main gallery of LSBB was equipped with 150 vertical geophones (14 Hz) distributed with a 5 m spacing along the roof of the gallery. Simultaneously, 500 m to 200 m straight above this gallery line, 189 seismometers (162 vertical and 27 triaxial CDJZ 2 Hz sensors with a 0.2-80 Hz bandpass) were aligned with a mean spacing of 4 m along the steep surface of the massif (30% slope). The seismic sources used for the experiment were 94 explosive shots (150 g equiv. TNT) buried 1.5 m below the surface and intercalated every 8 m along the surface line of seismometers. This experimental setup allows two approaches for data inversion. On the one hand a transmission configuration that only uses the recordings at depth (called “surface-to-gallery configuration” in the following), on the other hand a configuration that merges both surface and depth recordings (called “surface-to-gallery + surface-to-surface configuration” in the following). As the imaging technique used in this work is based upon the first-arrival times of P-waves, we solely consider a transmission regime of wave propagation. Some shot gathers recorded during the Interimages 2006 experiment are shown in Fig. 2.

DATA PROCESSING FOR P-WAVE FIRST-ARRIVAL TIME INVERSION

The measure of the initial time for each shot is synchronized to a GPS PPM signal. Taking into account the delay required by the electronic, the shots are triggered after 3.95 ms and the detonation finally initiates 1 ms later. The shot reference time is then 4.95 ms later than the GPS PPM signal. After the data and clock quality check, each P-wave first-arrival travel time was manually picked using Matseis application (Harris and Young 1997) on Matlab. The first-break picking uncertainties for the surface-to-gallery data are assigned according to the source-receiver distance; uncertainty is increased with distance, with values ranging from 1 to 4 ms, 1 ms representing two sampling intervals. The first-break picking uncertainties assigned to the surficial sensors are all fixed to 4 ms, the sampling interval being 8 ms. This relatively small value is chosen to take into account the high quality of P-wave arrivals, the short propagation distances, and to roughly put the same weight on the surficial sensors compared to the gallery ones.

The distribution of the surface-to-gallery apparent velocities observed from the first-arrival travel times is centred on a value of 4960 m/s, called $V_{\text{app}}$ in the following. This value is defined as the P-velocity that minimizes the misfits between observed travel times and theoretical travel times computed in a homogeneous medium. The observed standard deviation from $V_{\text{app}}$ is 206 m/s. Fig. 3 shows the propagation axes associated with the highest (Fig. 3a) and with the lowest (Fig. 3b) apparent P-velocities observed on surface-to-gallery axes. This figure gives some rough indications on the locations of the strongest heterogeneities that are being revealed after the inversion process. The highest apparent velocities concern a variety of sources along the steep surface, but they all focalize on a range of in-depth receivers located in the North (left) part of the profile (Fig. 3a). As for the lowest apparent velocities, clearly they all concentrate in the South (right) part of the profile (Fig. 3b). A strong horizontal $V_p$-gradient is therefore awaited in the final
image, but the transition between the fast area and the slow area surely has a complex structure.

The number of rays per $4 \times 4$ m$^2$ cell may exceed 200 at the centre of the profile (Fig. 4a-b). This amount is satisfactory to perform the reliable inversion of the first-arrival travel times. The ray density inevitably decreases in the vicinity of the section borders and near the receivers where some data may be missing because of temporary losses of acquisition.

The first $P$-velocity model of the LSBB carbonates is inferred from least-squares first-arrival travel time inversion based on a
classic local optimization. The tomography approach used for this study was previously described in Dessa et al. (2004). The inversion code searches for the best model that minimizes the distances between theoretical and recorded travel times. The fit between theoretical and recorded travel times is quantified and reduced when solving the inverse problem. The strategy implemented into the code to solve the inverse problem warrants a convergence after each iteration by following a linearized approach. A grid of theoretical travel times is computed for each shot at every point of the numerical model by solving the eikonal equation following a finite-difference approach (Vidale 1988; Podvin and Lecomte 1991; Hole and Zelt 1995). For a source-receiver couple \( j \), the travel time \( t_j \) is given by:

\[
t_j = \int_{\Gamma_j} u \, dl
\]  

(1)

where \( \Gamma_j \) follows the ray geometry along which time is integrated, and where \( u \) is the slowness model.

Then it becomes possible to compute the ray-tracing for each source-receiver couple by discrete retro-propagation following the opposite direction of the time gradient. The ray-tracing computed for every source-receiver couple allows the matrix of the Fréchet derivatives to be defined. The length of the ray-segment crossing a cell of the numerical model is computed at each cell bypassed by the ray. Considering a ray-segment, the previous equation 1 becomes:

\[
t_j = \sum_i u_i \, \delta l_i
\]  

(2)

where \( i \) is the ray-segment index and \( u_i \) the slowness value at the middle of the ray-segment \( i \). Next the derivative of the equation 2 is calculated:

\[
\frac{\partial t_j}{\partial u_i} = \delta l_i
\]  

(3)

Calculating these derivatives gives the matrix of the Fréchet derivatives \( F \), being considered as the matrix of the ray lengths. In the inverse problem, the slowness model is modified after each iteration in order to increase the fit between theoretical and recorded travel times. To solve the inverse problem, the code solves the following linear system (Toomey et al. 1994):

\[
\begin{bmatrix}
C_d^{-1/2} \Delta t^{(k)} \\
0 \\
0 \\
\end{bmatrix} = \begin{bmatrix}
C_d^{-1/2} F \\
\lambda_n S_n \\
\lambda_s S_s \\
\end{bmatrix} \begin{bmatrix}
\Delta m^{(k)} \\
\lambda_n \\
\lambda_s \\
\end{bmatrix}
\]  

(4)

where \( S_n \) and \( S_s \) are matrices of respectively horizontal and vertical Gaussian smoothing (Toomey et al. 1994), \( C_d \) is the covariance matrix of the uncertainties on recorded travel times, \( \lambda_n \) and \( \lambda_s \) are scalars controlling the balance between smoothing and fit of the data, \( \Delta m \) represents the small perturbations of the model and \( k \) is the iteration index. This system is iteratively solved with the LSQR algorithm (Paige and Saunders 1982).

A velocity of 300 m/s is introduced above the free surface to represent the air, and the free surface topography is also explicitly described in the input model to the inversion code.

Overall this inversion technique is considered as objective and robust, the uncertainty on the recorded travel times being the only uncertainty in the data (Dessa et al. 2004). Therefore no precise knowledge on the imaged medium is required for the initial model to the inversion, which is the main advantage of this technique and even a prerequisite in our case (thus our initial model is a homogeneous medium with \( V_{\text{p wave}} = 4000 \) m/s). At the same time this methodology considers only the first arrivals, which restricts the result of the imaging to a smoothed image of the medium, where the resolution is no better than the width of the first Fresnel zone (Williamson 1991).

The under-km scale dimension of the presented tomographic layout is unusual in seismic tomography approach. Yet the high frequency content of the explosive sources (20 to 250 Hz), together with the high density of receivers, allows for a comfortable use of this method. The highest resolution of the final image is estimated from the width of the first Fresnel zone, taking into account the frequency content of the seismic signals and the acquisition configuration. Because of the frequency content of the surface-to-gallery signals (mostly 20–150 Hz, up to 250 Hz for the shorter propagation paths) and the associated propagation distances (down to 200 m), the previously described tomography approach allows imaging structures that are mostly 80–100 m wide, at best down to 50 m wide (i.e. features smaller than 50 m wide are not resolved).

**SENSITIVITY OF THE FIRST-ArrIVAL TIME TOMOGRAPHY TO THE ACQUISITION CONFIGURATION AND REGULARIZATION**

We perform a simple but practical test, that we call the “homogeneous inversion test” to estimate the effects of the sensors array vs sources geometrical distribution on the seismic image bias, accuracy and resolution. We generate a synthetic travel time dataset from the propagation of \( P \)-waves in a homogeneous medium with \( V_{\text{p wave}} = 4960 \) m/s (defined previously as the \( P \)-velocity that minimizes the misfits between observed travel times and theoretical travel times computed in a homogeneous medium). A homogeneous velocity is chosen in order to emphasize the imprint of the acquisition system on the imaging. The synthetic travel time dataset is computed for the same acquisition geometry as the real Interimages 2006 geometry, i.e. using the same locations of sources and receivers. Although it is not a critical choice, the initial model to process the synthetic data inversion is also the initial model chosen for the real data inversion (homogeneous \( V_{\text{p wave}} = 4000 \) m/s). One critical point is that the value of \( V_{\text{p wave}} \) to generate the synthetic travel times has to be different from \( V_{\text{p wave}} \) to avoid \( \Delta \rightarrow 0 \) in equation 4. The travel time inversion is then applied to the synthetic dataset, using the same travel time uncertainties and smoothing regularization that are intended to be used for the processing of the real dataset. Indeed,
P-wave seismic signature in a fractured-porous Urgonian platform at hectometric scale

...and its (ii) a couple of slightly marked diagonal alignments distorting them. These diagonal effects may be observed on the right side of the profile (Fig. 4d) and are highlighted by grey dotted lines in Fig. 4c. Both features (i.e. the horizontal patches and diagonal trends) will strongly affect the final image, as illustrated in Fig. 4e showing the inversion results obtained when this over-weak smoothing is applied on the real data. Such artifacts are jointly generated by the shots-receivers geometry and by an inappropriate choice of smoothing regularization. They must be minimized otherwise they will mislead the interpretation of the final image (e.g. the horizontal patches exhibited in Fig. 4e could be considered as geological horizons).

A methodology has been developed to determine the best smoothing regularization for reducing the risk of artifact and for performing a reliable inversion of experimental data. 400 different sets of smoothing parameters are tested (Fig. 5). The values of $S_h$ and $S_v$ (Eq. 4) are distributed over a range of 100–400 m with 100 m spacing, while the values of $\lambda_h$ and $\lambda_v$ (Eq. 4) range between 1 and 5 with a spacing of 1. Each one of the 400 patterns of geometric errors is analyzed jointly with the matching $P$-velocity profile. A set of smoothing parameters is considered as valid if the geometric error map is low and not distorted by artifacts reflecting in the $P$-velocity profile (see the valid sets represented by the filled circles in Fig. 5). Low smoothing always produces the artifacts described above. Nevertheless, too high smoothing may also be rejected since it also excessively affects the image; for instance it generates unrealistic low velocity zones at depth. As a result, only a few sets of smoothing parameters are finally selected, including the best one ($\lambda_h = 3$, $S_h = 300$ m, $\lambda_v = 4$, $S_v = 400$ m) indicated by the black arrow in Fig. 5. The latter gives the best agreement according to the minimization of the geometric errors (Fig. 4i) and to the lowest RMS values. Two final $V_p$ profiles are obtained with the best set of smoothing parameters. Figure 4g shows the $V_p$ profile deduced from the inversion of the surface-to-gallery travel times, and Fig. 4j displays the $V_p$ profile deduced from the inversion of the surface-to-gallery + surface-to-surface travel times. The RMS values achieved for both inversions respectively equal 2.4 ± 0.3 ms and 6.0 ± 0.2 ms (respectively 3% and 7% of mean travel time). The geometric error maps for both inversions (respectively Fig. 4f and Fig. 4i, to be compared with Fig. 4d for inappropriate low smoothing) show that diagonal artifacts are efficiently reduced by the optimized smoothing and horizontal patches exhibit a very low signature not exceeding the absolute value of 5%.

**SENSITIVITY OF THE FIRST-ARRIVAL TIME TOMOGRAPHY TO THE WEATHERED ZONE**

The apparent $P$-velocity on surface-to-surface propagation paths appears much slower than the apparent $P$-velocity on surface-to-gallery propagation paths, respectively 3000–4000 m/s com-

---

**FIGURE 5**

RMS values after inversion of the full Interimages 2006 dataset for 400 different sets of smoothing parameters. Each set is characterized by its smoothing quantity $f_i$ computed on the four smoothing parameters in equation 4. The empty circles represent the rejected sets of smoothing parameters for which the analysis of the corresponding geometric errors jointly with the matching $P$-velocity profile reveals strong artifacts. The filled circles point out the accepted sets. The black arrow indicates the best smoothing parameters chosen for the computation of the final $P$-velocity profile.

if the acquisition system provides sufficiently-dense ray coverage of the target, the final result of the inversion of the synthetic travel times in a homogeneous medium should be a homogeneous medium. Of course, when the ray density is not consistent on the whole profile, such a perfect result cannot be reached.

In our case, the acquisition geometry of the Interimages 2006 experiment nearly produces a homogeneous medium in the homogeneous inversion test. Some weak variations can be observed (see Fig. 4f for the surface-to-gallery configuration and Fig. 4i for the surface-to-gallery + surface-to-surface configuration). Those variations denominated "geometric errors" are visualized by subtracting the homogeneous $P$-velocity from the $P$-velocity model obtained from the inversion of the synthetic dataset. The errors are plotted as a percentage of the velocity in the homogeneous model. The homogeneous inversion test that was performed from the Interimages 2006 acquisition system leads to geometric errors between –5% and +5%. On the basis of this validation approach we estimate that the acquisition geometry of the experiment can produce an acceptable and reliable imaging of the LSBB medium.

One major usefulness of the homogeneous inversion test is that it helps to estimate the best regularization scheme for the inversion. The smoothing parameters $S_h$, $S_v$, $\lambda_h$, $\lambda_v$ (Eq. 4) are considered to be high enough when the pattern of the geometric errors does not exhibit strong or sharp patches, or linear structures mimicking ray paths that strongly reflect in the final model deduced from real travel time inversion.

Figure 4c and Fig. 4d illustrate the influence of the smoothing on the results obtained in the homogeneous inversion test when the quantity of smoothing is set to half of the optimal value. Using such a configuration, some absolute values of the geometric errors are higher than 5% and the geometric error map exhibits (i) broad 200 m-thick sub-horizontal patches that are intersected by (ii) a couple of slightly marked diagonal alignments distorting them. These diagonal effects may be observed on the right side of the profile (Fig. 4d) and are highlighted by grey dotted lines in Fig. 4c. Both features (i.e. the horizontal patches and diagonal trends) will strongly affect the final image, as illustrated in Fig. 4e showing the inversion results obtained when this over-weak smoothing is applied on the real data. Such artifacts are jointly generated by the shots-receivers geometry and by an inappropriate choice of smoothing regularization. They must be minimized otherwise they will mislead the interpretation of the final image (e.g. the horizontal patches exhibited in Fig. 4e could be considered as geological horizons).
pared to 5000–5500 m/s. This slower surface $P$-velocity is explained by the superficial weathered zone that remains along the mountain slope, and characterized by 2 to 10 m-thick scree deposits and decimetric to pluri-metric wide-opened karstified fractures.

Adding the travel times associated with the low-velocity weathered zone sampled by the surface-to-surface acquisition (Fig. 4h) to the inversion dataset significantly increases the level of confidence in the in-depth location of the higher-velocity area. The lateral extension of the high-velocity zone is mainly constrained by the surface-to-gallery data while its vertical delimitation results from the introduction of the surface-to-surface travel times (compare the extension of the blue area between Fig. 4g and Fig. 4h). On this image from surface-to-gallery travel time inversion (Fig. 4g), it is not clear whether the high-velocity patch extends from the gallery up to the surface or stays confined at depth. The addition of the surface-to-surface travel times to the surface-to-gallery ones helps to better constrain the vertical extension of the higher-velocity area relative to the lower-velocity area. It is now clear that the high-velocity patch nowhere joins the topographic surface (Fig. 4j). The tomographic image of this high-velocity patch shows a lateral diagonal elongation that remains immovable regardless of any perturbation tests we performed, and despite any higher smoothing settings or higher time uncertainties on the over-dense diagonal propagation paths.

It is noteworthy that the surface-to-gallery travel times do not allow imaging of the near-surface weathered zone. Indeed the image in Fig. 4g does not exhibit any velocity decrease or low $V_p$ zone near the topographic surface. As for the surface-to-surface data, they mainly contain information on surficial paths. They cannot be used alone for the tomography but are helpful to better constrain the image of the medium at the near-surface scale. Hence the combination of surface-to-gallery + surface-to-surface travel times is essential to produce a realistic and accurate image of the medium between the topographic surface and the underground gallery of the LSBB.

**FINAL $V_p$ IMAGE FROM FIRST-ARRIVAL TIME INVERSION AND NEAR-SURFACE CARBONATES PROPERTIES**

The final image (Fig. 4j) integrates all surface-to-gallery + surface-to-surface paths with time uncertainties on picks varying with the distance and smoothing parameters chosen to keep the lowest geometric errors. The global RMS value of this inversion equals $6.0 \pm 0.2$ ms (7% of mean travel time). The resolution is estimated by a classic checkerboard resolution test (Fig. 6a) which allows the delimiting of different levels of confidence in the final image. The resolution is highest at the centre of the profile (inner zone of maximum confidence delimited by solid black lines); it decreases progressively towards the sides (second zone delimited by dotted black lines, where the imprint of the acquisition system is strong). It is noteworthy that although the vertical resolution is poor in this second zone, the horizontal resolution is high enough to distinguish horizontal variations of velocity. The resolution is minimal on both northern and southern sides of the profile where the $P$-velocity features appear poorly defined. The poor resolution at both sides is due to the weak ray coverage on these sides and cannot be improved. In a general way, the resolution pattern (Fig. 6a) strongly correlates with the ray density that itself mirrors the geometry of the seismic array (Fig. 4b).

The $V_p$ image displays a large range of $P$-velocities ranging between 4000 and 6000 m/s (Fig. 7a). These high $V_p$ values are in good agreement with the $V_p$ values determined by Bereš et al. (2013) from another seismic experiment conducted between the horizontal in-depth galleries of LSBB. The image shows at depth two main areas, i.e. respectively in the northern (denoted B) and in the southern (denoted A) parts of the profile, characterized by average $V_p$ respectively of 5500 m/s (North) and 4500 m/s.
P-wave seismic signature in a fractured-porous Urgonian platform at hectometric scale

P-wave velocities (Fig. 3a). It appears for the surface-to-gallery inversion (Fig. 4g) and for the surface-to-gallery + surface-to-surface inversion (Fig. 4j). The narrow zone \( V_p \) is considered a real higher-velocity feature whose contours and exact location are also observable (e.g., induration of the fault zone, absence of soil and surficial alteration, or inversion artifact). That higher-velocity feature is not accurately described in text; the points denoted \( \alpha \) and \( \beta \) are also shown as watermarks. Some areas of different velocity are denoted by red letters and further described in text; the points denoted \( \alpha \) and \( \beta \) are also shown in Fig. 6b without the superimposed marks. (b) Geological and petrophysical interpretative cross-section.

FIGURE 7
(a) Final \( V_p \)-velocity profile computed from the Interimages 2006 dataset, with the limits of the main geological units superimposed in black. The resolution limits previously shown in Fig. 6 are also superimposed on (a) as watermarks. Some areas of different velocity are denoted by red letters and further described in text; the points denoted \( \alpha \) and \( \beta \) are also shown as watermarks. Some areas of different velocity are denoted by red letters and further described in text; the points denoted \( \alpha \) and \( \beta \) are also shown in Fig. 6b without the superimposed marks. (b) Geological and petrophysical interpretative cross-section.

(South). That separation into two areas was already observable from the spatial distribution of the highest and lowest apparent \( V_p \)-velocities (see Fig. 3). The geological cross section superimposed on the seismic image (Fig. 7b) interprets the separation between the two areas as a major normal fault (denoted C in Fig. 7a). This fault is sub-vertical, mapped N120°E by geologists and intersects the LSBB galleries. The \( V_p \)-contrast between the two blocks is related to the vertical shift of the fault compartments. The downward offset of the southern compartment \( A_2 \) allows only the lower-\( V_p \) Urgonian carbonates facies to be described.

From surface to depth, a sharp vertical gradient characterizes the northern block where a transition appears with depth from \( V_p = 4000 \) m/s (\( A_1 \)) to \( V_p = 5500 \) m/s (\( B \)). This vertical \( V_p \)-gradient observed within the northern block corresponds to the transition of Urgonian carbonates facies between the Bedoulian and Barremian limestones. Concerning the northern \( A_1 \) area, the lower \( V_p \) value of 4500 m/s determined above 300 m-depth characterizes the high porosity of Urgonian carbonates (10–20% average porosity; Jurgawczynski 2007). The high \( V_p \) value of 5500 m/s determined below 300 m-depth (area \( B \)) is characteristic of the low porosity carbonates within the Barremian limestones (less than 5%, see Fig. 7b). These conclusions are strengthened by the results of Fournier et al. (2011) showing the link between \( P \)-velocity and porosity from petrophysical measurements on carbonates samples collected in nearby locations. Indeed Fournier et al. (2011) found out that the value of \( V_p \) decreases with increasing porosity from the Barremian limestones to the Urgonian carbonates. The values given in their study are in complete accordance with the ones deduced from the Interimages 2006 experiment: the low-porosity (below 5%) carbonates show a high \( P \)-velocity reaching 5500–6000 m/s, while the higher-porosity (20%) carbonates show a \( P \)-velocity decreasing to 4000 m/s.

In the southern block \( A_2 \), a decrease of \( P \)-velocity down to 4300 m/s is observed in a small zone around the point denoted \( \alpha \) (distance 500 m, depth 500 m). This value concerns the same 5 consecutive sensors in the LSBB gallery for all shots (see inserted zoom box shown in Fig. 2a–b). These five sensors systematically display lower \( V_p \) signed by delayed arrival times (the apparent velocity on these sensors even goes down to 3900 m/s), with lower amplitudes and lower frequencies of the first arrival wave. All of those variations are characteristics of an attenuation zone. This attenuation zone is consequently about 25 m thick (estimated from the spacing between the five sensors) and can be identified in the gallery as the N20°E fault zone with plurimetric fractures, displaying clay infillings and large voids (Fig. 7).

The shallow 50 m-thick altered layer under the topographic surface is characterized by \( V_p = 4000 \) m/s. A narrow zone with higher \( V_p = 4500 \) m/s is seen near the surface around the point denoted \( \beta \) (distance 425 m, depth 200 m). It is interesting to observe that this noticeable feature is also collocated to a relatively stronger geometric error (see Fig. 4i) and to the experimental configuration of the surface which exhibits uncovered and not karstified sharp limestone slab precisely in this area. That collocation of perturbations leads us to question the reliability or even the significance of that spatially limited zone with higher \( V_p \) value (e.g., induration of the fault zone, absence of soil and surficial alteration, or inversion artifact). That higher-velocity feature is persistent for all generated models and is also directly observable in the apparent \( P \)-velocities (Fig. 3a). It appears for the surface-to-gallery inversion (Fig. 4g) and for the surface-to-gallery + surface-to-surface inversion (Fig. 4j). The narrow zone \( \beta \) is considered a real higher-velocity feature whose contours and exact \( V_p \) value may have been affected by the acquisition geometry. Indeed this acquisition geometry is not dedicated to imaging such narrow features, whose characteristics cannot be accurately determined by only the first-arrival travel time inversion.

Geological arguments do exist to validate the presence of the higher \( V_p \) zone detected at that exact location. The zone \( \beta \) stands right above the \( V_p \) transition zone denoted \( \alpha \) in the gallery.
(Fig. 7a). The transition between the two blocks described above (A/B northward and A2 southward) is characterized by a mainly vertical patch denoted C, displaying high velocities and heterogeneous contours. That heterogeneity (grey bold dotted line in Fig. 7a) links the surface higher \( V_p \) zone (\( \beta \)) with the gallery \( V_p \) transition zone (\( \alpha \)). Indeed Bereš et al. (2013) also found out from their in-depth experiment that the direction of highest \( P \)-velocity in the LSBB area was parallel to the local direction of fracturing (mostly vertically oriented). Our smooth \( V_p \) image (Fig. 7a) allows for reflection of the complex structure of the normal N120°E fault that is characterized by a low-porosity cementation, with metric to pluri-decimetric extensions affecting the adjacent limestones (patch C, a strong feature that first-order impacts the apparent \( P \)-velocities as it is shown in Fig. 3a).

Laboratory analyses of fault rock samples in porous carbonates (Tondi et al. 2006; Tondi 2007) show scaling with respect to host rock and thus are affected by a porosity reduction from 20–30% down to 0–5%. The cementation of the normal N120°E fault zone and of the adjacent porous protolith is interpreted as a significant local decrease of the porosity within the Urgonian facies and therefore to be responsible for the observed increase in \( P \)-velocity (Fig. 7b).

CONCLUSION: CONTRIBUTIONS TO NEAR-SURFACE SEISMIC IMAGING OF FRACTURED-POUROUS CARBONATES

This study shows the ability of the first-arrival travel time inversion to image the seismic \( P \)-wave velocity distribution of an onshore topographic medium at the under-kilometric scale. This medium was investigated by using surficial explosive sources recorded simultaneously by sensors at surface and at depth. The key question was to define a protocol to distinguish real seismic patches from artifacts produced by the geometry of the sources-receivers distribution. The medium being considered as entirely made of limestone with \( V_p \) value greater than 3500 m/s, the challenge was to distinguish variations smaller than 10% of the values themselves. This study reveals that the imprint of the acquisition system is strong in such a nearly homogeneous case, and consequently the artifacts could take an important part of the final image. The developed methodology to compute the geometric errors allows those artifacts to be discriminated in a simple way. It also helps to determine the best smoothing regularization that reduces the artifacts as much as possible while keeping low RMS values. The strategy followed in this work consists of minimization of the geometric errors with respect to the lowest RMS values, followed by resolution estimates from checkerboard tests. Those estimates help to delimit different domains of resolution: a central zone of highest vertical and horizontal resolution, an intermediate zone where the resolution is mainly horizontal, and finally the external zone of no resolution. At last the application of this strategy allows for the construction of a reliable geological interpretation of the completed tomography.

This study also illustrates the importance of completing the cross-hole configuration (composed of mainly vertical propagation paths) with a surface-to-surface acquisition (composed of mainly horizontal propagation paths) in order to improve the imaging resolution on both horizontal and vertical axes. Adding the surface-to-surface acquisition into the surface-to-gallery inversion dataset allows the surficial weathered zone to be imaged, and significantly increases the level of confidence in the in-depth location of higher-velocity areas. However, some bias remains in the final image due to the lack of horizontal propagation paths at depth. The application of elastic full-waveform inversion techniques (Brossier et al. 2009; Brossier et al. 2010; Brossier 2011; Romdhane et al. 2011) to this case will allow reflected and PS converted waves to be taken into account to improve the angular coverage of the medium. Added to this better coverage of the medium, the elastic full-waveform inversion will include the S-waves of smaller wavelengths into the inversion dataset, which will furthermore improve the overall resolution of the imaging.

The final \( P \)-velocity profile at LSBB clearly shows a sharp vertical gradient of velocity from surface to depth. This vertical gradient is entirely related to the superficial weathered zone and to the facies transition between the high-porosity Urgonian carbonates and the low-porosity carbonates within the Barremian limestones.

The rock porosity is a predominant rock property that influences the \( P \)-wave propagation in the near surface carbonates. Laboratory measurements done on samples show that porosity contrast of 10–20% induces \( P \)-velocity contrast of 1000–2000 m/s (Fournier et al. 2011). The Interimages experiment shows such variations of \( P \)-velocity. Of course a detailed interpretation of the porosity variations between the sedimentary facies in the lithological succession at metric to plurimetric scale cannot be processed. Nonetheless considering larger pluri-decimetric to hectometric scales, faults were individualized as well as porosity-related changes within the Urgonian facies. The obtained seismic image enables the identification of a fault with a complex sub-vertical geometry deduced from a patch of high \( P \)-velocity. The ability to reach the pluri-decimetric scale is of importance for the exploration of carbonate reservoirs, since it allows the identification of cemented zones that may strongly influence the seismic waves’ propagation and that may also act like impervious barriers to fluid circulation.

ACKNOWLEDGEMENTS

The Interimages 2006 experiment was made possible thanks to: (i) the IHR network (Imagerie Haute Résolution, INSU/CNRS) for the surface seismic array, (ii) the academic seismic networks from the Universities of Pau, Paris-Sud, Grenoble and Toulouse (France) for the gallery geophone array, (iii) the CEREMA (Nice, France) for the summit array, and (iv) the LSBB 3-D seismic array. This work was funded by LSBB (http://www.lsbb.eu), the University of Nice (France), the GEOAZUR Laboratory and the Seiscope project.
We thank Gérard Massonat from TOTAL for providing comments.


REFERENCES


