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Session 25 - Seismological and geophysical investigation for imaging shallow geological structures and site-specific seismic hazard applications: challenges and perspectives

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Abstract: Superficial geological layers can strongly modify the surface ground motion induced by an earthquake through the so-called "site effects". One common approach to estimate these local effects at a specific site relies on the numerical simulation of the ground motion. This requires a characterization of the Earth's subsurface to build a representative model of the seismic wave propagation medium. In this study, we focus on the area of the Tricastin Nuclear Site (TNS). TNS is located over an ancient Rhône canyon whose characteristics and complex geometry make it a good candidate for generating site effects. We present here the first results of 3D medium characterization based on geological investigations and on different types of seismic data, that is, the seismic ambient noise and data from an active seismic exploration survey. The results provided by the different imaging approaches considered are complementary and the first comparison presented in this article highlights the interest of comparing these different results to obtain an overall picture of the subsurface conditions of the site.

Keywords: Seismic site effects, passive imaging, H/V spectral ratio, seismic reflection, geological investigation.

1. Introduction

It is well-known that superficial geological layers can strongly modify the surface ground motion induced by an earthquake. Soil properties in the vicinity of the Earth's surface generally become softer leading to an amplification of the seismic motion. In the case of complex geological structures, such as sedimentary deep valleys or canyons, seismic waves can be trapped, and the geometry of the soft deposits will further affect the ground motion by increasing both the duration and amplitude of the shaking. By being related to local conditions, these so-called site effects are highly variable from one site to another and still difficult to quantify for some geological configurations. That is why site-specific studies can greatly contribute to improve the hazard prediction at a specific site in comparison to ergodic estimates based on data from global databases. Two main approaches are generally adopted to estimate site effects at a specific site. The first approach relies on an empirical (or experimental) estimation through recordings of seismic motions at the site of interest. The second approach is based on the simulation of ground motion at the surface using numerical modelling of seismic wave propagation in a model of the Earth's subsurface. This latter requires a characterization of the propagation medium through geophysical investigations to build a representative model for simulations.

In this study we focus on the Tricastin area, in the Rhône valley (South-East France), where the Tricastin Nuclear Site (TNS) is located. TNS is located above an ancient Rhône canyon. This canyon was dug following the closure of the Gilbraltar strait about 6 My ago and the resulting fall of the Mediterranean Sea level during the Messinian time. The fall reached - 1500 m in some areas leading to the incision of Messinian canyons such as the Rhône canyon (Clauzon, 1982; Suc et al., 2011). After the reopening of the Gibraltar strait about 650 000 years later, the canyon was flooded and then filled with Pliocene and Quaternary sediments (sands and marls). The Rhône Messinian canyon can be locally very deeply incised in Cretaceous sandstones and limestones. This geological configuration makes the area prone to site effects. Given the presence of nuclear installations and the importance of characterizing site effects for seismic hazard assessment, IRSN as the French Technical Safety Organisation (TSO) has been conducting studies in this area for several years. Gélis et al. (2022) presents preliminary measurements to investigate the local seismic amplification related to the presence of the Rhône paleo-canyon. For this study, three seismic stations were deployed for several months in the area: two stations (BOLL and PAUL) were located on top of the paleo-canyon, the third one (ADHE) was located on a nearby reference rock site located on Cretaceous outcrops (Figure 1). At two of these three measurement sites (BOLL and ADHE), local 1D geophysical characterizations were performed to estimate shear wave velocity (Vs) profiles revealing a strong velocity contrast between the sedimentary filling and the substratum, and a canyon depth reaching locally >500 m. Station PAUL was located right near a borehole with reported geological section showing the transition between the canyon filling and the substratum at 462 m deep. From continuous recordings on the three stations deployed, Gélis et al. (2022) have reported local ground motion amplification reaching 6 for some frequencies on top of the canyon relative to nearby Cretaceous outcrops. This first study thus quantifies the seismic amplification associated with the presence of the canyon at two locations on top of the paleo-canyon.

Based on these preliminary results, IRSN launched a larger project to build a 3D model of the medium in the area, its impact on the seismic ground motion and on its spatial variability. We present here the first results regarding the 3D medium characterization based on geological investigations and on different types of seismic data, that is, the seismic ambient noise (passive method) and data from an active seismic exploration survey (active method). In the following, we first present the data, followed by the applications of 3 imaging approaches based on these data. We will then discuss and propose a first interpretation of the results obtained at this stage, especially regarding the different geological or geophysical signatures revealed by the 3 approaches.

2. Data

2.1. Geological data

In the Tricastin area, the canyon is incised in lower cretaceous formation, generally down to the Barremian reef limestones called “Urgonian”. These few hundred thick limestones, gently dipping south-eastward, are overburden by detrital sand, sandstone and marls of middle to upper Cretaceous (Aptian here called “Gargasian” and Cenomanian and Turonian) into which the paleo-canyon has dug during the Messinian times (from 5.97 to 5.33 Ma) letting some remnant hills or reliefs on the eastern edge of the valley or in some preserved “islands”. The erosional surface of this canyon is called Messinian Erosional Surface (MES).

Before this study, the state of knowledge of the geometry of the canyon in this region was extremely sketchy and depended exclusively on the interpretation of rare deep drillings that crossed the entire Pliocene series (i.e. the sedimentary filling). The French geological survey (BSS-Infoterre Underground database) provide abundant data from boreholes. In the studied area, some of these boreholes have reached at least the Pliocene (mostly easily identifiable marine Piacenzian blue marls) and only few of them reached the MES. Two deep boreholes reaching infra-Pliocene basement bring information about the canyon depth and filling in the eastern part of the Tricastin valley. They both show a thick Pliocene series filling a canyon incised in Cretaceous series going from the Urgonian facies overburden by Gargasian formation. The analysis of the whole borehole dataset and field outcrops make it possible to estimate the distribution of the Pliocene filling and locally its thickness. Figure 1 shows the location of the boreholes available in the area. Gélis et al. (2022) used the above-mentioned boreholes and other data such as specific studies for the TGV fast train (Mocochain et al., 2006) or preliminary ambient noise characterizations to get a first estimate of the deepest canyon axis.

2.2. Passive recordings

In 2020, IRSN with the help of EGIS and SISPROBE companies, deployed about 400 all-in-one 3-component seismic nodes over a 10x10 km area around TNS, to record the seismic ambient noise for one month (Figure 1). A loose grid made of half the number of nodes was used to cover the entire area. Depending on field conditions, the inter-node distance may vary from 400 m to 1300 m. 179 nodes were used in a denser grid (inter-node distance of about 200-250 m) located 2-to-3 km south of TNS. This denser grid is expected to cover the narrowest and deepest part of the Messinian canyon as inferred by Gélis et al. (2022).

2.3. Active recordings and interpretation

In 2020, IRSN acquired active seismic reflection data that were collected in 2008 in the area by Gaz de France company (now named ENGIE). 11 2D seismic profiles crossed the area made of 6 E-W lines and 5 N-S lines (Figure 1). Vibrator trucks were used as seismic source except for 2 lines that were acquired in the Donzère-Mondragon canal in the eastern part of the area (for which air gun was used as seismic source).

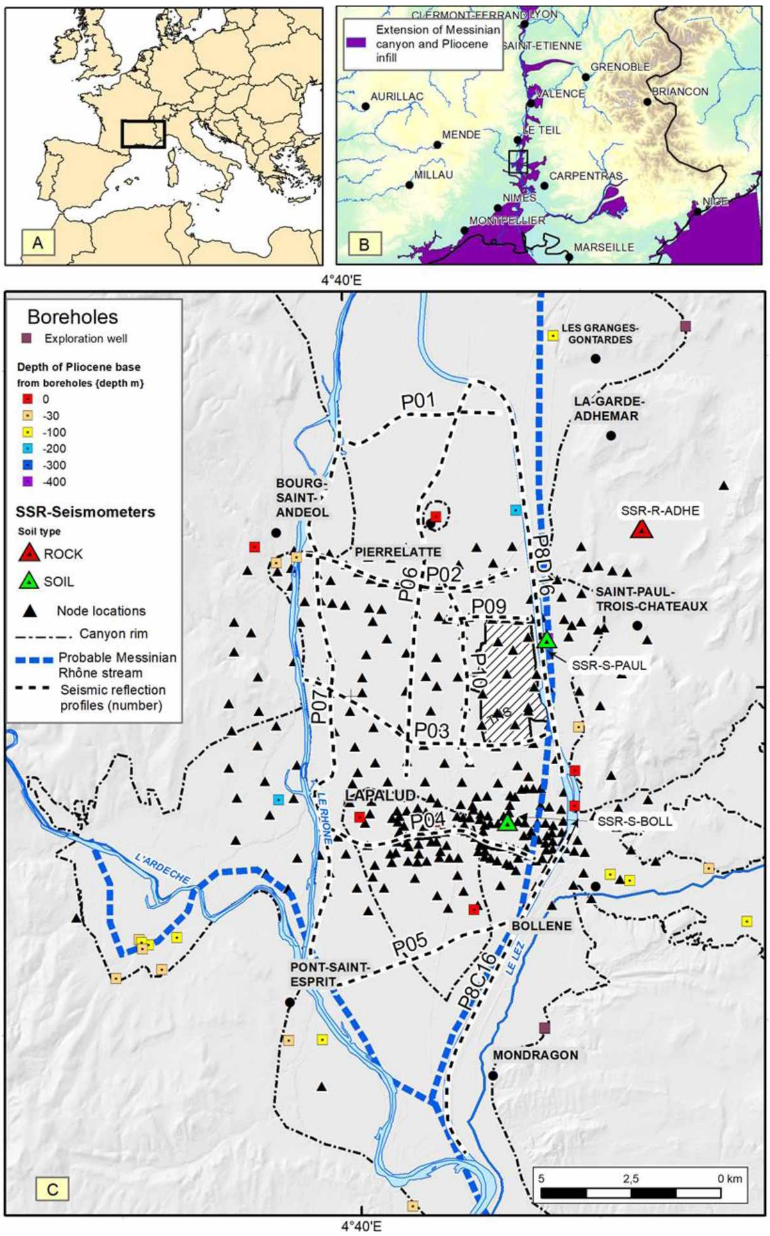


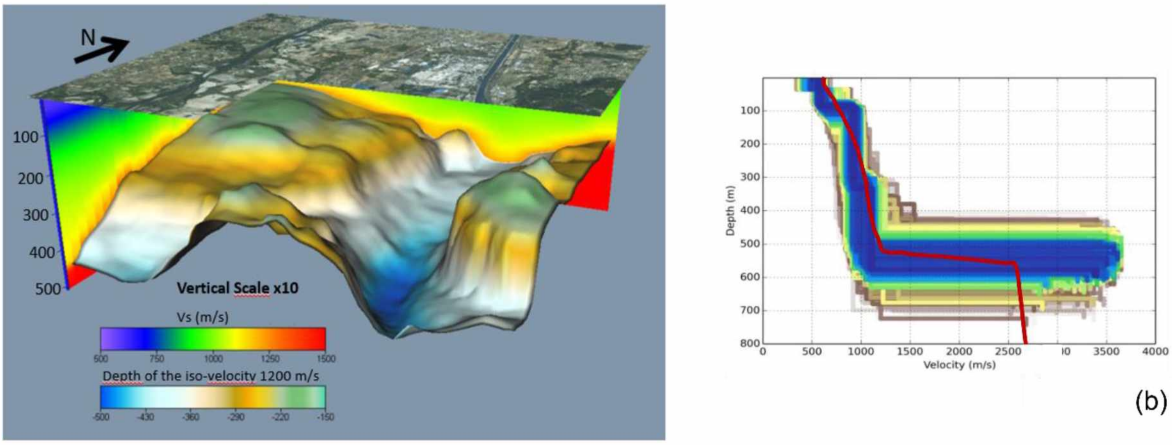
Fig. 1 – Location of datasets that have been considered in the present study: the borehole information from BSS (BRGM borehole database, coloured squares), the 11 seismic lines acquired from ENGIE company (black dashed lines) and the 400 nodes (black triangles). Note that the outline of some seismic lines may cover the triangles used to represent the 400 nodes (both experiments following the road network). For sake of clarity, we still chose to display the whole datasets on the same figure. The 3 stations (BOLL, PAUL and ADHE) deployed in previous studies are displayed as coloured triangles.

3. Imaging approaches

3.1. Ambient Noise Surface-Wave Tomography (ANSWT)

In low-to-moderate seismicity area such as the metropolitan France, the amount of seismic data (earthquake recordings) may be a limitation for specific seismic hazard studies. Given its permanent nature, the exploitation of seismic ambient noise is of particular interest in this context. Since surface waves are strongly present in the ambient noise recorded at the surface, the dispersion of Rayleigh and Love waves can be used to obtain an S-wave velocity model. This “passive” tomography (ANSWT) has proved to be useful in imaging the subsurface from local (e.g. Mordret et al., 2014) to crustal scales (e.g., Shapiro et al., 2005; Nishida et al., 2008). We present here results of a depth inversion of surface waves reconstructed from noise cross-correlation functions computed between each station pair of the 400-node network. The Vs model is obtained with a joint inversion of Love and Rayleigh wave group velocity dispersion curves. To improve the depth inversion, we used average phase velocity curves in 3 areas defined by a clustering approach gathering velocity measurements laterally homogeneous. It is worth noting that the resulting 3 areas are very consistent with the major geological units in our target zone. The set of estimated local 1D models constitutes the 3D Vs model. It is worth noting that such 3D model in Vs is of particular interest for estimating S-wave amplification and its spatial variability at the scale of the sedimentary canyon.

The model obtained confirms the strong velocity contrast between the sedimentary filling and the substratum and brings to light the 3D geometry of the sedimentary canyon. Figure 2(a) shows the isovelocity surface area Vs=1200 m/s extracted from the resulting 3D Vs model, identified as a good indicator of the sharp transition between the sedimentary filling and the substratum and therefore used to infer the location of the bottom of the canyon (or MES) in this model. From this isovelocity surface, we clearly see the N-S imprint of the Rhône paleo-canyon in the eastern part of the area. The southern part of the canyon is revealed deeper and narrower. We can also clearly observe the signature of the deep canyon of the Ardèche river in the southwestern part and the confluence zone of the 2 (paleo)-rivers. It is worth noting that in overall, the main geological features revealed by this velocity model show a good agreement with the expected geometry of the geological structures in the area. Moreover, the 1D Vs profile at BOLL extracted from this 3D model is in very good agreement with the estimation by Gélis et al. (2022) using Ambient Vibrations Arrays (AVA) (Figure 2(b)), especially regarding the depth of the main interface (i.e. the bottom of the canyon - MES) and the velocity in the sedimentary filling. The two approaches do not perfectly agree regarding the amplitude of the velocity contrast (larger for AVA), since velocity at depth is associated with larger uncertainties and difficult to determine from AVA given the resolution capabilities of considered arrays.



(a)

Fig. 2 - (a) Isovelocity Vs=1200 m/s surface area extracted from the Ambient Noise Surface Wave Tomography (ANSWT). (b) 1D Vs models obtained from the inversion process from Ambient Vibration Arrays (AVA) at BOLL site. Colour stands for the misfit value in the inversion procedure (from Gélis et al. 2022). The 1D velocity profile at BOLL extracted from this-study 3D Vs model is superimposed in dark red.

3.2. Noise-based Horizontal-to-Vertical Spectral Ratios (HVSR)

The same ambient noise dataset has been used to compute Horizontal-to-Vertical Spectral Ratios (HVSR) at each node position. HVSR measurements are commonly carried out to assess the local fundamental resonance frequency of the medium (e.g. Nakamura, 1989; SESAME team, 2004). We computed HVSR curves using 1 day of data chosen arbitrarily (day 63: Tuesday, March 3, 2020). The HVSR curves were computed on 100-s-long windows using the Geopsy software (Wathelet, 2008; Wathelet et al., 2020). We applied STA/LTA filtering to remove transient signals in the continuous recordings. The spectral ratios were computed by using the average of the horizontal components. Criteria of reliability based on recommendations from the SESAME project (SESAME team, 2004) are considered to classify measurements regarding HVSR peak typologies and to determine the resonance frequency. Given the density of measurements, we chose to interpret only HVSR peak with amplitude larger than 3. Figure 3 displays a few examples of HVSR curves obtained.

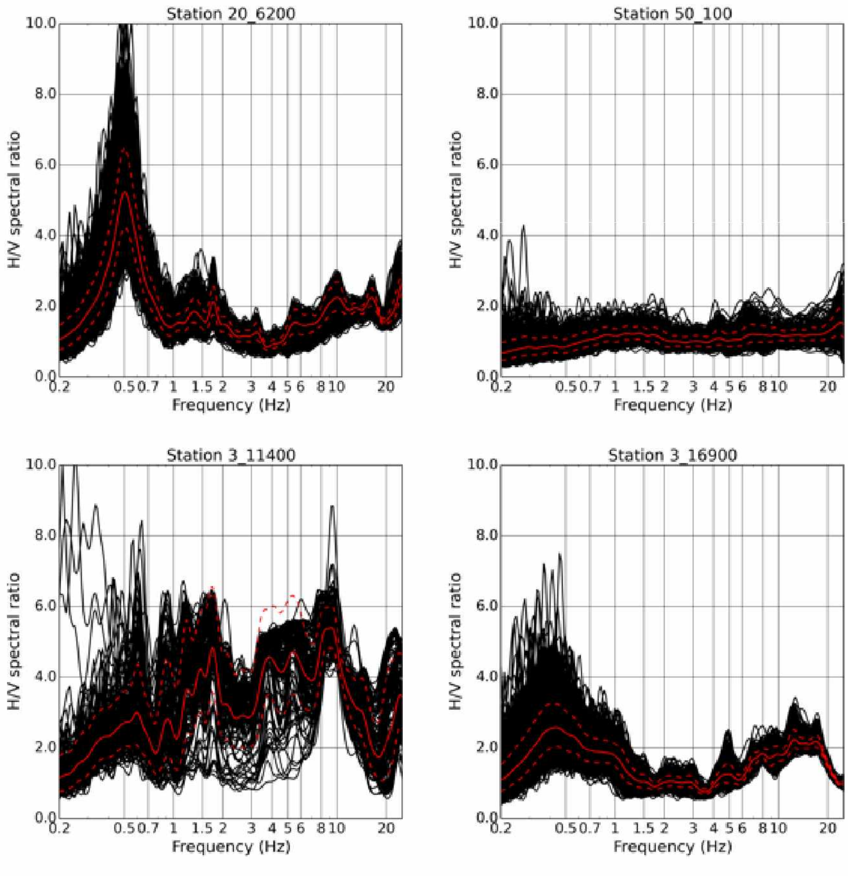


Fig. 3 – Examples of HVSR curves measured. Black lines stand for single HVSR computed on 100-s-long signals. The solid (resp. dashed) red line stands for the mean (resp mean +/- one standard deviation) HVSR curve. The top line shows examples of interpreted HVSR curves on top of the sedimentary canyon (with a clear low frequency peak, from which f0 is deduced, left) and on nearby rock outcrops (flat HVSR curve, right). The bottom line shows HVSR curves that were not interpreted, because of the absence of a clear peak (left) or amplitude lower than 3 (right).

The fundamental resonance frequency f0 is associated with the peak measured at low frequency on the HVSR curves. From this HVSR-deduced f0 and an estimate of the time-average Vs in the sedimentary filling (Vs_sed), one can deduce an estimate of interface depth

(H) using the classical formula f0=Vsup/4H (Ibs-von Seht and Wohlenberg, 1999) for each HVSR measurement (i.e. every node location). Here, we used 1D Vs profiles extracted from ANSWT 3D model (discussed in section 3.1) at each node location to compute Vs_sed locally. The resulting f0-based surface will be discussed in section 4 in comparison to imaging features revealed by the other approaches considered in this study.

3.3. Processed active seismic reflection data

To set the structural framework for the interpretation of the seismic profiles, several geological sections were made in the area based on the geological maps and borehole information extracted from the BRGM InfoTerre database (BSS) (Figure 4, bottom). A detailed analysis of all digitized drilling documents such as geological logs, water boreholes, etc. was then carried out. The dataset was integrated into a geophysical model on a workstation with Kingdom software. The few boreholes available in the area provide calibration points, in particular regarding the depth of the interfaces identified in the boreholes of St-Paul-Trois-Châteaux and Pierrelatte. One of the seismic profiles is being reprocessed to estimate the velocity of the compressional waves (Vp). In the meantime, some data at larger scale suggest that the overall Vp velocity in the Pliocene filling is on the order of 2000 m/s (J.-L. Rubino, pers. Comm., Roure et al., 2009), which allows the two-way time expressed in milliseconds to be converted to first order into meters. From this assumption, all the available MES horizons were then converted to depth to produce a 3D topography of the MES, using borehole information and rims identified on map or on field as constraints. This topography will be discussed in section 6 in comparison to features revealed by the other imaging approaches.

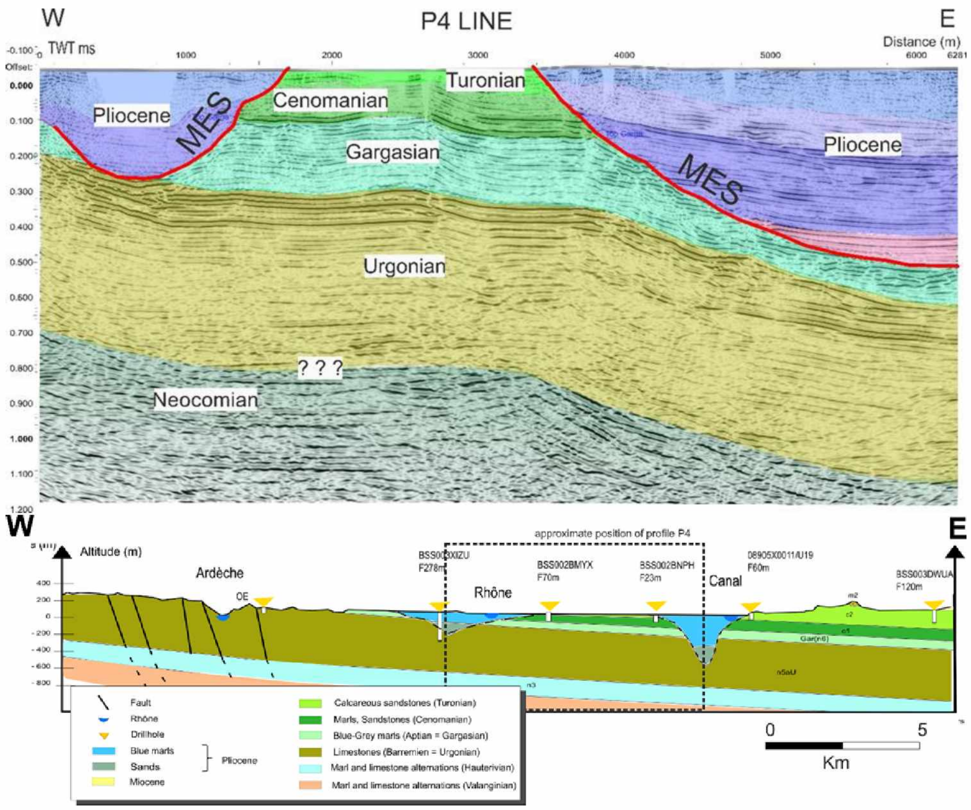


Fig. 4 – Up: example of interpreted seismic line (profile P4) clearly showing the Messinian Erosional Surface (MES) concealed by the thick Pliocene series. This E-W 6-km-long profile (see location on Figure 1) cuts the "Lapalud" island which is a paleo relief of lower to upper cretaceous detrital sediments. The Urgonian limestones shows a gentle slope dipping eastward. Some perturbations in the series could be attributed to reef formation. The vertical scale is in two-way traveltime and this scale can be at first order converted in depth (1 ms = 1 m) considering Vp estimates in the canyon filling of about 2000 m/s. Down: geological cross section performed previously to the seismic line interpretation. The central part of this section broadly corresponds to the seismic line P4.

4. Comparison and first interpretation.

Figure 5 shows the comparison of the surfaces deduced from the 3 geophysical approaches considered in this study. Discrete depth values estimated in the area have been interpolated to produce these surfaces. At first order, we find good agreement between the different imaging approaches considered in terms of overall geological structure. For example, the N-S imprint of the Rhône Messinian Canyon in the eastern part, deepening southward is revealed by the 3 figures. We also observe the paleo-canyon of the Ardèche river in the very southeastern area. In the detail, the 3 images show some differences. We propose here some explanations for these discrepancies, based on the assumptions behind each method.

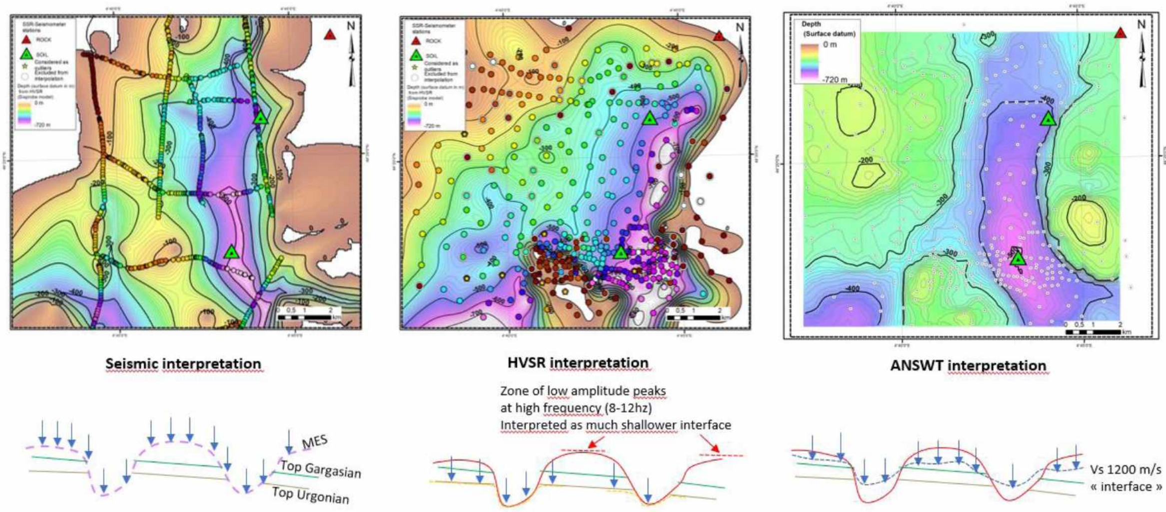


Fig. 5 – Comparison of interpolated surfaces (using topo2raster tool in ArcMap software) deduced from the 3 imaging approaches considered in this study: the MES deduced from the interpretation of seismic reflection profiles (left), interface of the main contrast inferred from HVSR-based f0 (middle), isovelocity Vs=1200 m/s deduced from ANSWT (right). It is worth noting that some f0 values have not been considered to build the background surface via the interpolation. These values are shown by stars and white outlines in the middle figure. Bottom sketches give a first interpretation of features revealed by the different approaches.

The methods considered are based on geological observations and on different physical properties of the seismic waves, thereby revealing different geological or geophysical features. The interpretation of the seismic reflection profiles allows for imaging the geometry of the geological layers and interfaces, in particular the morphology of the canyon through the MES (figure 5 left). By contrast, ANSWT provides a seismic velocity model, in which interfaces between geological layers would be expressed through Vs contrast. In other words, 2 different geological layers with similar Vs will not be distinguished in the ANSWT image (see illustration on the right sketch on Figure 5). As for the depth interface estimated from HVSR measurements, it is worth noting that the estimation of the depth interface relies on local 1D assumption that presents some limitations in incised valleys with 2D/3D geometry. Figure 5 (middle) therefore needs to be considered as first-order exploration particularly at the edges of the canyon.

However, the surface deduced from HVSR also reveals features we do not attribute to this local 1D approximation. By contrast to the other 2 methods, the interface depth deduced from HVSR shows a surface that dips slightly to the southeast, as expected for the Urgonian limestones in the geological model of the area. This surface is thus interpreted as the signature of the impedance contrast located at the top of the Urgonian formation. However, in the southern central area, HVSR does not map the top of the Urgonian formation but a much shallower interface (see sketch in the middle of Figure 5). This could be related to our interpretation of HVSR peaks. Indeed, here we only interpreted clear peaks for which HVSR amplitude is higher than 3. Some broad low-frequency peaks with amplitude lower than 3 were not taken into account to avoid an overinterpretation of HVSR curves. This shows that assumptions made to guide the f0 measurement (on amplitude, width of the peaks) necessarily impacts the interpretation. Indeed, in complex geological setting such as the one in this area, different discontinuities can cause seismic resonance leading to multiple peaks in HVSR curves (see discussion on the influence of two superposed geological layers in Cushing et al., 2020). Depending on the criteria used, the picked frequency may correspond to different interfaces probably reflecting the interface that causes the main 1D resonance and therefore not necessarily a unique continuous geological interface. However, this “main” resonance can be seen as a characteristic feature of the underground structure in terms of seismic response. To conclude, this comparison between 3 different methods raises the question of the nature of the dominant interface in terms of seismic site response (top of the Urgonian Limestones vs MES) and its continuity throughout the target zone. This will be addressed in ongoing studies in the area, including through numerical simulations.

5. Conclusion and perspectives

This paper presents preliminary results using combined geophysical and geological approaches to get a first 3D characterization of the Earth’s subsurface in the Tricastin area. Each geophysical method presents its own advantages, limitations, and relies on different assumptions. The results provided by the different imaging approaches considered are complementary (Vs, geometry of geological layers, interfaces causing the dominant resonance) and the first comparison presented in this article highlights the interest of comparing these different results to obtain an overall picture of the subsurface conditions of the site.

This paper must be considered as a progress review of our ongoing project in the area. Further studies are underway to refine these first results. For example, the ANSWT Vs model presented here is considered as a first-step 3D Vs model. It needs some improvements especially in the area of strong lateral contrasts, in this context of complex geological medium. This work is being made within the framework of two collaborative projects: first, the French-German DARE project funded by the French and German national research agencies (*“Using dense seismic arrays for the estimation of site effects in low-to-moderate seismicity regions – Application to the Rhône Messinian canyon”*, 2020-2023). In this framework, we are pursuing the imaging study to refine the characterization of the medium and in a second phase, to evaluate the impact of this complex geological structure on the seismic ground motion through different approaches (numerical and empirical approaches). As for the geological model, this will be further studied in the context of a collaboration that is being set up around the geological study of the Messinian canyon in the Rhône Valley, at larger scale.

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