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Determination of Depth to Carboniferous Bedrock Using H/V Spectral Ratios of Ambient Noise for Geothermal Assessment in the Lille Metropolitan Area, France

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1 INTRODUCTION

The geothermal potential of the Lille Metropolitan Area (France), specifically for open-loop applications, strongly depends on the geometry and depth of the Carboniferous limestone basement, which forms the main regional target reservoir in northern France. Understanding the structural continuity, the presence of basement faults, and the thickness of the overlying sediments is essential for designing geothermal systems, preparing drilling strategies, and assessing risks linked to deep karstic or tectonic structures. The region exhibits a pronounced geological heterogeneity, with Meso-Cenozoic sediment thickness varying laterally from a few to 200 meters over short distances due to the influence of the Variscan basement structural network, the Meso-Cenozoic transgression and depocenter location, and later the Cenozoic tectonic reactivation phase.

To address the scarcity of borehole information and to provide a systematic, spatially continuous estimation of the depth to the Carboniferous bedrock, a large-scale passive seismic survey was conducted across the Mélantois and Pévèle areas in Northern France. The applied method is the Horizontal-to-Vertical Spectral Ratio (HVSR) analysis of recorded ambient seismic noise. HVSR exploits the contrast in seismic impedance between the sedimentary cover and the underlying bedrock to extract the fundamental resonance frequency which is empirically linked to sediment thickness. Combining HVSR analysis with bedrock depth information from boreholes hence allows developing resonance-to-depth relations. These relations are subsequently used to construct “virtual boreholes” from ambient noise measurements, enabling bedrock depth estimations at locations where no direct geological information exists. This extended abstract presents the results of the depth conversion of 459 HVSR measurements, calibrated on 63 boreholes reaching the Carboniferous, providing a high-resolution view of the bedrock paleorelief and its implications for geothermal development in the Lille Metropolitan Area.

2 GEOLOGICAL AND STRUCTURAL CONTEXT

The study area is situated on the northern flank of the Paris Basin and is primarily composed of a Silurian to Carboniferous Paleozoic basement overlain by an Upper Cretaceous to Paleogene sedimentary cover. The Paleozoic basement belongs to the para-autochtonous unit (Brabant Massif) located north of the Northern Variscan orogenic front. It is structure from south to north by an eroded anticline (the deep Orchies Anticline), a faulted flower structure (the Mélantois-Tournaisis anticline) and a gentle syncline (the Roubaix syncline). Geology of the Lille Metropolitan Area Paelozoic basement is largely dominated by the Lower Carboniferous (*i.e.,* Mississipian) Tournaisian and Visean limestones, underlained by upper Devonian schists, clayey sandstones and sandstone-limestones. The surface of the Paleozoic basement exhibits a complex relief induced primarily by the reactivation of Paleozoic faults during Cretaceous and Cenozoic tectonic inversion phases. Above the basement, the sedimentary cover includes Upper Cretaceous marls and chalk, Paleogene sands and clays, and local Quaternary alluvial and loess deposits.

A major structural feature of the investigated area is the Mélantois-Tournaisis anticline, a large E–W deformational system extending from France to Belgium. This structure brings Carboniferous limestones closer to the surface along its hinge and generates significant variations in bedrock depth toward adjacent northern (*i.e.*, Flanders) and southern (*i.e.*, Orchies) synclines. Several transversal basement faults, such as the Haubourdin-Rumes fault, locally cause offsets of tens of metres in the Carboniferous top. In addition, deep dissolution depressions, likely initiated during the Early Cretaceous (Wealdian), create local hectometric to kilometric irregularities in the bedrock surface. Some depressions (like near the city of Don) are filled with several decameters of wealdian sediments, over-thickened cretaceous marls and chalks, and even quaternary alluvium. This evidences the Upper-Cretaceous and Quaternary activity of the deep dissolution mechanism responsible for the local subsidence. The combination of these structural and karstic features generates a markedly variable Paleozoic bedrock topography, which is critical to characterize for geothermal resource assessment.

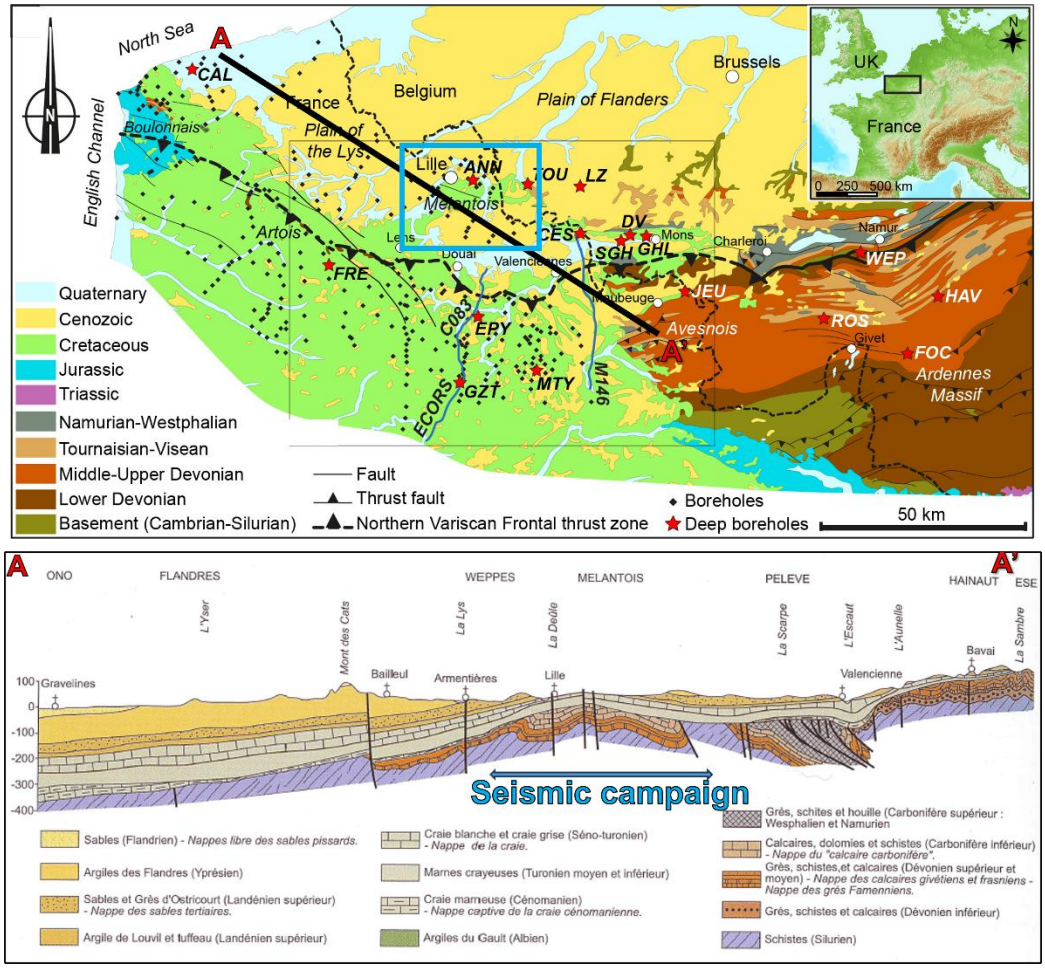


Figure 1: Top) Geological setting of the Mélantois region (after Chantraine et al., 2003). The blue frame shows the region of investigations. Bottom) NW-SE cross-section through the Mélantois region (after Beckelynck, 1981).

3 METHODOLOGY

Ambient noise recordings were acquired using three-component 5 Hz SmartSolo seismic nodes deployed at 459 locations across the Lille metropolis and Pévèle region. The sensors recorded vertical and horizontal ground motion over several hours to several days, enabling a robust characterisation of local seismic noise. Fourier spectral analysis was applied on horizontal and vertical recordings using Geopsy (Wathelet et al. 2000). Division of the mean horizontal ratio over vertical ratio generates the H/V spectral ratio. The impedance contrast is then shown as a peak in the H/V spectra at the fundamental resonance frequency (f_0). For each station, f_0 was determined when a clear and stable peak was identifiable. A secondary peak f_1 was frequently observed and was interpreted as the resonance associated with hardground layers within the Upper Cretaceous chalk ("Tuns"), acting as additional impedance contrasts. To convert the resonance frequency into sediment thickness or depth to the Paleozoic bedrock, empirical power-law relationships between f_0 and depth were constructed using ambient noise recordings above 63 boreholes from the French geological database (BSS of the french geological survey BRGM) where the depth to Palaeozoic rocks is known (26 to 160 meters). These calibration points include both shallow and deep basement occurrences, ensuring a robust regression across the full range of geological settings and depths.

The best-fitting model relating sediment thickness h to resonance frequency is:

$$h = 241.542 * f_0^{-1.621} \quad (1)$$

however, this relationship was constructed using all datapoints. The center of the Mélantois anticline is only covered by Cretaceous marls and chalk, whereas its flanks are covered by Paleogene sands and Cretaceous marls and chalk. This difference in geology causes a knickpoint in derived powerlaw relation. Hence, better results are obtained when splitting the power law relation in a Mesozoic part (green line in fig. xx) and a Meso-/Cenozoic part (orange line in fig xxx), according to following equations:

$$\text{Mesozoic cover only: } h = 683.71 * f_0^{-2.528} \quad (2)$$

$$\text{Meso-Cenozoic cover: } h = 205.692 * f_0^{-1.2} \quad (3)$$

The Mesozoic power law has a less steep slope than the Meso-Cenozoic power law, representing faster shear-wave velocities (Vs) for marly and chalky cover, than compared to a combined Meso-Cenozoic cover.

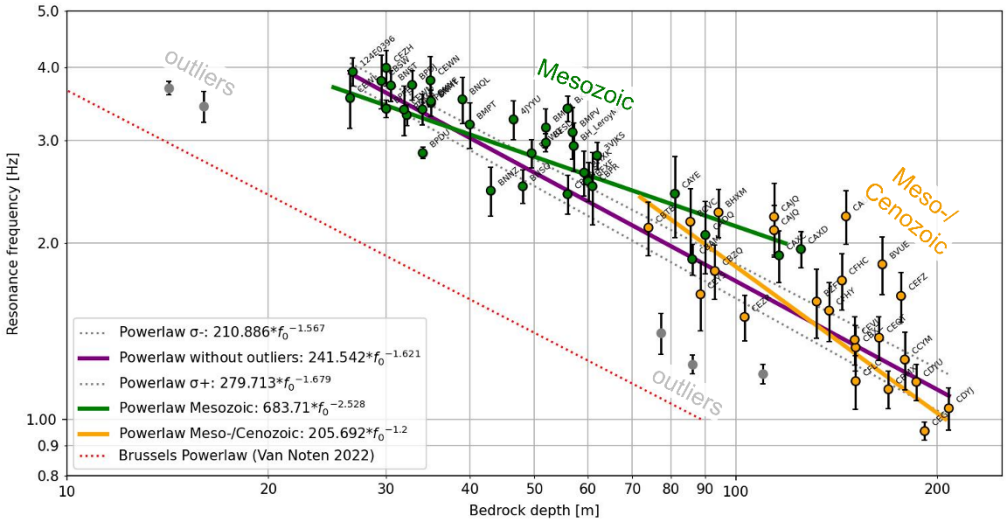


Figure 2: Powerlaw relation between depth to Carboniferous bedrock (m) and resonance frequency (Hz), obtained from HVSR analysis. Purple line shows power law derivation through all boreholes. Green and orange lines show geology-dependent power law derivations.

These relations yield predicted bedrock depths with an uncertainty of approximately 10–15%. The negative exponent confirms the expected inverse sensitivity between frequency and sediment thickness, with lower frequencies reflecting thicker sediment packages. Once calibrated, these equations were applied to all HVSR stations to derive sediment thickness estimates and, by subtraction from ground elevation, the depth of the Carboniferous surface. This representation allows creating a Virtual Borehole for each measurement, following the strategy of Van Noten et al. (2022).

Finally, several regional transects were constructed by projecting all the virtual boreholes along key geological directions across specific structural domains. These profiles allow the correlation of anomalies in the HVSR-derived bedrock surface with known or inferred geological structures.

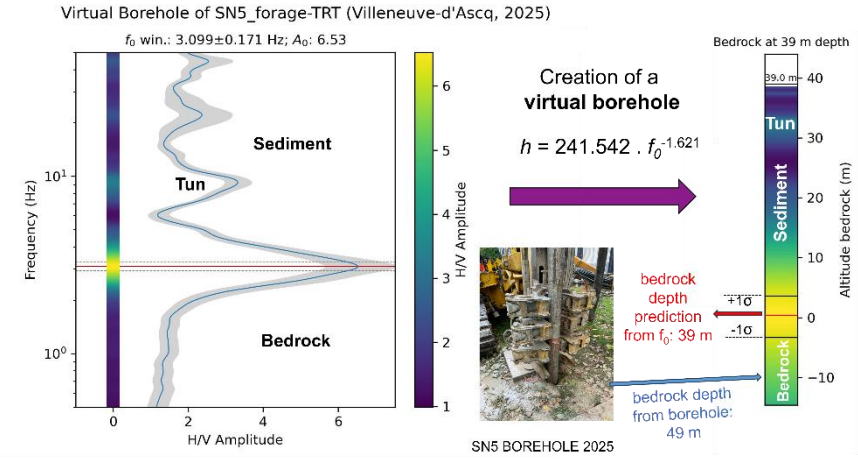


Figure 3: Creation of a virtual borehole (after Van Noten et al. 2022). The left diagram shows an H/V spectra computed from a one-day ambient noise recording next to the geology building of the University of Lille. Using the Mélantois powerlaw relation between resonance frequency and depth, the HVSR curve is converted to depth to create a virtual borehole.

4 RESULTS

4.1 Resonance Frequencies and Sediment Thickness

Fundamental resonance frequencies across the region vary from ~0.7 Hz in areas with thick sedimentary cover to > 5 Hz where the basement lies only a few m to the surface. The application of the calibrated power-law shows that sediment thickness ranges from approximately 35-40 m on structural highs to more than 200 m in synclinal or fault-controlled depressions. Stations located on or near the hinge of the Mélantois anticline display high resonance frequencies associated with shallow depths, whereas stations in the Flanders and Orchies basins show much lower frequencies consistent with a deeper basement.

A secondary peak is commonly observed between ~3 and 8 Hz. This peak is interpreted as representing the position of the Turonian–Coniacian hardgrounds, which are regionally extensive within the chalk succession. Local variations in this peak help identify spatial changes in Tun depth, so chalk thickness, internal layering and presumably syn-Cretaceous history of the sedimentary basin subsidence.

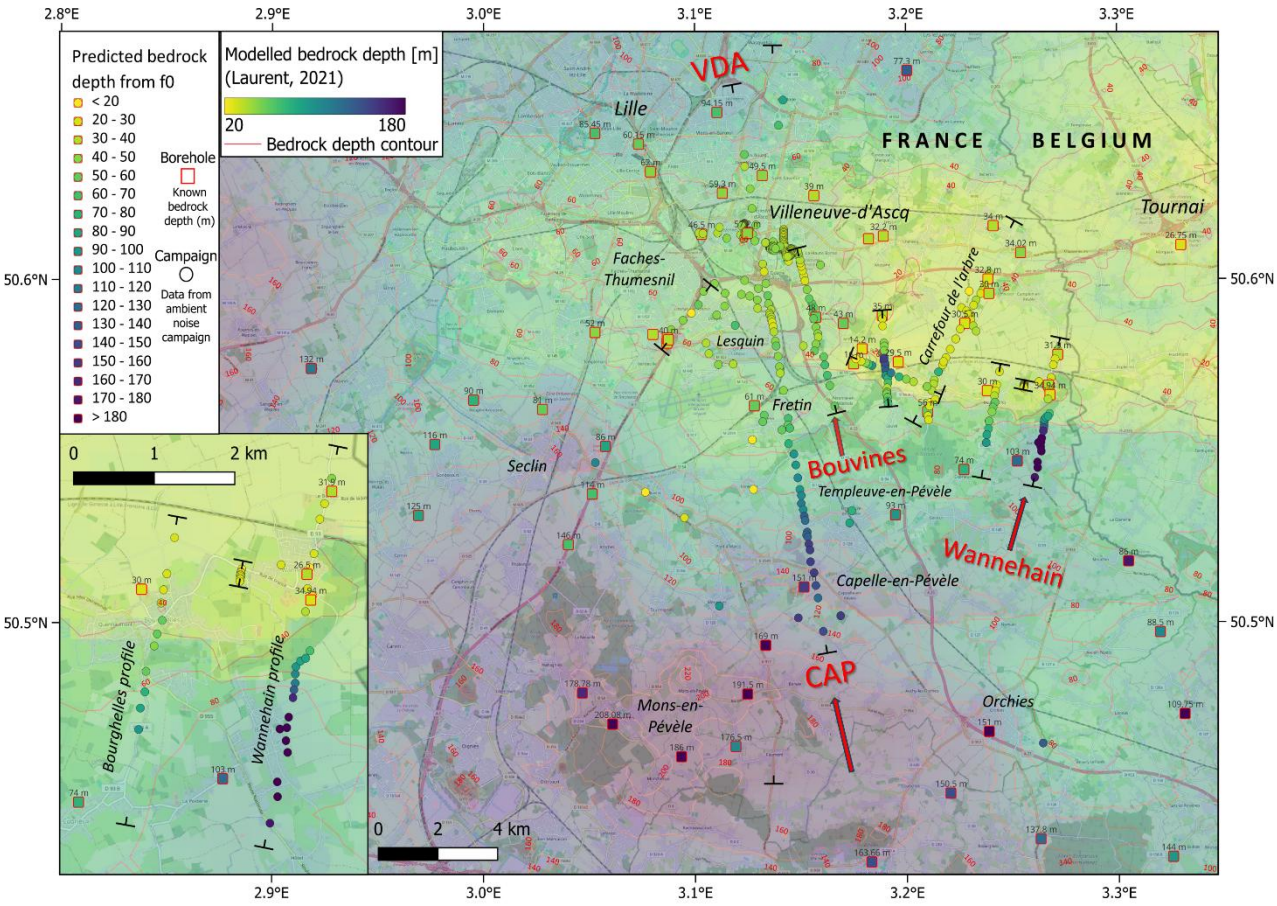


Figure 4: Detailed map of the survey layout in the Mélantois region. Squares show locations where ambient noise recordings were performed above boreholes with known bedrock depth. Circles show measurements organized in linear surveys and correspond to locations where depth to bedrock was computed from the derived power law relations. Three cross-sections are shown in Fig. 5.

4.2 Bedrock Paleorelief and Structural Features

The reconstructed paleotopography of the Carboniferous bedrock reveals several characteristic features:

4.2.1 Structural Highs:

The Mélantois Dome forms a broad shallow region where the Carboniferous can be reached within a few tens of meters (Figure 5). These highs are consistent with the known regional uplift associated with the Variscan front and subsequent inversion.

4.2.2 Fault Offsets:

Multiple locations exhibit abrupt steps in the bedrock surface, matching the orientation and position of known basement faults. Vertical offsets of 10–15 m are quantified in several transects, confirming the continuity of fault structures beneath the sedimentary cover.

4.2.3 Dissolution Depressions:

Gradual deepening of the bedrock surface, sometimes exceeding 200 m in depth (Figure 4), suggests the presence of large dissolution pockets developed in the Carboniferous limestone prior to Cretaceous transgression. These features generate slowly varying HVSR responses and explain local discrepancies between predicted and observed depth residuals.

4.2.4 Synclinal Lows:

Area's south of Villeneuve-d'Ascq, around Bouvines and toward Bachy (Figure 4), exhibit consistently lower resonance frequencies and deeper Carboniferous surfaces, in agreement with the regional geological framework.

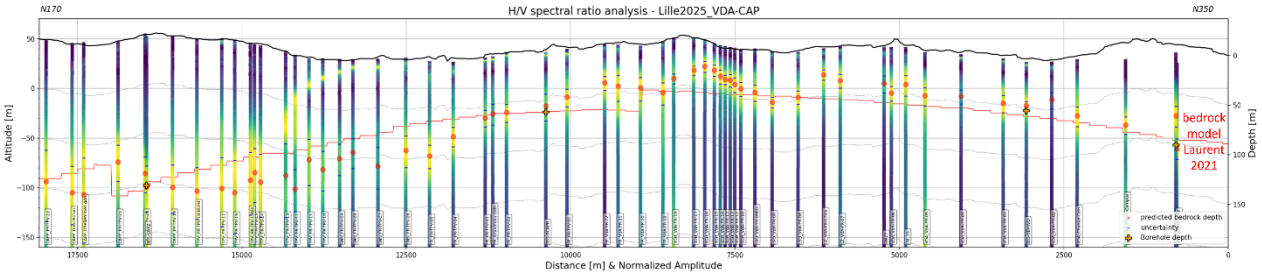


Figure 5: N-S cross-section through the Mélantois dome using virtual boreholes created by HVSR analysis of recorded ambient noise. Red dots correspond to resonance frequency peaks in the H/V spectrum converted to depth. See Fig. 2 for location. Red line gives the bedrock model from Laurent (2021) constructed using only boreholes.

4.3 Virtual Boreholes

Applying borehole-calibrated relations to all stations enables the construction of synthetic borehole logs at arbitrary locations. For example, at a representative site close to the geology building of the University of Lille, the predicted depth to bedrock is 39 m (Figure 3), which slightly underestimates the measured 49 m depth at a nearby control borehole. However, such agreement still demonstrates the method's reliability for pre-drill reconnaissance. These virtual boreholes provide a continuous subsurface reference model for geothermal targeting, site ranking, and risk mitigation.

5 IMPLICATIONS FOR GEOTHERMAL EXPLORATION

The results demonstrate that HVSR is a powerful method for mapping the depth to the Carboniferous geothermal reservoir across densely urbanised and geologically complex regions. The ability to resolve structural highs where the reservoir lies within 40–80 m of the surface is of particular interest for medium-depth closed-loop or coaxial systems, as well as for future experimental installations. Structural lows and dissolution depressions require specific attention because they may influence drilling risk, reservoir connectivity, and the thermal performance of heat-exchange systems.

Moreover, the identification of basement faults provides essential information for reservoir modelling, as these structures can either enhance permeability or compartmentalise the reservoir, depending on their orientation, fill, and reactivation history. The HVSR-based regional model also offers a valuable baseline for neotectonic studies and can guide future geophysical surveys, including seismic arrays or electrical resistivity tomography.

6 CONCLUSIONS

A large-scale passive seismic analysis has enabled reliable mapping of the Carboniferous bedrock beneath the Mélantois–Pévèle region, in northern France. 459 HVSR measurements calibrated on 63 boreholes provide a robust relationship between resonance frequency and sediment thickness, with predictive accuracy of 10–15%. The method successfully delineates structural highs, fault offsets, synclinal depressions, and dissolution pockets, all of which contribute to the complex configuration of the Carboniferous limestone reservoir. These findings represent a critical step toward optimising geothermal development in the Lille metropolitan area and

provide an operational framework for geological and geothermal investigations in other regions with similar geological complexity.

Acknowledgements

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