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Passive seismic measurements to characterize gas reservoirs in a mud volcano field in Northern Italy

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ABSTRACT

The presence of a minimum in the average Horizontal to Vertical Spectral Ratios (HVSR) of ambient vibrations has been suggested to be representative of hydrocarbon reservoirs in active oil and gas fields in the Middle East and Europe. Similar evidence has been also found in correspondence of active mud volcanoes in Italy. To explore the possibility of using ambient vibrations to identify and characterize reservoir corresponding to mud volcanoes vents, a dense network of velocimetric measurements (with average inter-distance of 30 m) has been deployed in the Nirano mud volcanoes area (Northern Italy) by considering single station and array configurations (at 59 and 8 sites respectively). Results obtained confirm that measurements with a clear HVSR minimum only characterize the area of emitting vents. In the assumption that this minimum depends on the characteristics of the reservoir responsible for fluid emissions, the Biot–Gassmann theory for seismic waves velocities of gas hydrate-bearing sediments has been considered to infer reservoir characteristics from V_s and V_p profiles obtained by the inversion of the HVSR curves. The satisfactory fit of model outcomes with observations testifies one more the effectiveness of ambient vibration measurements to characterize mud volcanoes and relevant subsoil configuration.

1. Introduction

In the last years several studies have suggested that measuring ambient vibrations could provide useful indications about location and characteristics of hydrocarbon reservoirs. In particular, experimental evidence throughout the World (e.g., Dangel et al., 2003; Frehner et al., 2006; Lambert et al., 2007; Quintal et al., 2007; Saenger et al., 2007, 2009; Sudarmaji et al., 2021) suggest that average Horizontal to Vertical Spectral Ratios (HVSR) of ambient vibrations in correspondence of oil and gas fields present a clear minimum in the frequency range of 1–6 Hz. This has been interpreted by Sudarmaji et al. (2021) as the effect of the fluid-saturated poroelastic inclusion (the reservoir) within an elastic hosting medium. An alternative interpretation has been proposed by Frehner et al. (2006) and Saenger et al. (2007) in terms of natural seismic emission of the fluid pockets within the reservoir excited by standing waves resonating between the surface and the reservoir. Both these models suggest that the HVSR minimum could represent a useful tool to delimitate and characterize the occurrence, depth, and characteristics of the hydrocarbon reservoir.

The presence of a significant HVSR minimum has been also detected in the case of mud volcanoes (MVs) fields in Italy (Antunes et al., 2022; Grassi et al., 2022; Panzera et al., 2016). These represent the surface expression of uprising deep seated overpressure fluids with gases and different types of fluidized mudstone-rich sediments, including greenhouse gases such as methane and carbon dioxide (Mazzini and Etiope, 2017). Since these emissions may significantly affect climate warming trends (IPCC, 2022), characterization of MVs and of the relevant dynamics may be of great importance (Etiope and Milkov, 2004).

Thus, the finding that HVSR minima could be used to characterize both hydrocarbon reservoir and MVs area, may suggest that ambient vibration measurements may represent an important tool for the characterization of these last structures. However, a main difference exists between the observations in these two environments about the frequency range of this minimum: 1–6 Hz in the case of hydrocarbon

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reservoirs (Dangel et al., 2003; Lambert et al., 2007) and below 1 Hz in the case of MVs (Grassi et al., 2022; Panzera et al., 2016). This could suggest a different origin of this phenomenon with respect to the case of hydrocarbon reservoirs.

In the present paper we analyse the situation of the Nirano Mud Volcanoes (NMVs) in Northern Italy (Fig. 1) where a dense network of ambient vibrations measurements has been carried out by both considering single station and array measurements (Brindisi et al., 2023; Carfagna et al., 2024). In particular, 59 single-station ambient vibration measurements have been performed by three-directional 24-bit digital tromographs (Tromino™, produced by Moho s.r.l., https://moho.world/) by covering an area of about 64 10^3 m^2 (Fig. 1). Moreover, 8 small scale L-shaped seismic arrays were deployed close to the main vents of the Nirano MVs (Fig. 1); the arrays include 16 4.5-Hz vertical geophones, and BrainSpyTM, a digital acquisition system produced by Moho S.r.l. (https://moho.world/). The geophones were deployed along two branches (i.e. eight sensors per branch), each 5 m apart. Seismic signals were collected for 1 h at 256 sps.

In the following, the main features of the NMVs are outlined at first, by accounting for outcomes of previous multidisciplinary research carried out in the area. Then, data collected are analyzed to support the hypothesis that HVSR minima are associated to buried gas reservoir. Finally, a possible interpretation of the observed features based on the Biot–Gassmann theory for velocities of gas hydrate-bearing sediments is provided (Lee, 2004).

2. The 'Salse di Nirano' mud volcanoes field

Salse di Nirano regional nature reserve is one of the principal MVs fields in Italy with a surface of approximately 75000 m^2 (Fig. 1). This area is located within the Apenninic fold and thrust-belt of Tortonian origin. The stratigraphic log in the area includes the outcropping 'Argille Azzurre' Formation (Plio-Pleistocene transgressive clays, including occasional sandy and conglomerate layers, with thicknesses up to 150 m) (Amorosi et al., 1998; Gasperi et al., 2005), overlying the Tortonian-Messinian 'Termina' Formation (constituted by sandy marls, fine sandstone intercalations and local masses of methanogenic limestones with microfossils, exceeding 500 m thick), overlying on its turn the Burdigalian-Serravallian 'Pantano' Formation characterized by marls and marly turbidites, having a thicknesses of about 400 m (Antunes et al., 2022; Bonini, 2007; Giambastiani et al., 2024; Nespoli et al., 2023).

The main active vents (mud pools and gryphons) are located in four major groups aligned in a NE-SW oriented anticline axis, coherent with the contractional direction in the tectonic context of the Northern Apennines (Serpelloni et al., 2005), in a topographic depression similar to a small volcanic caldera of 800 m diameter and a difference in elevation between the rim and its bottom about 50–60 m. The expelled material is semi-liquid and composed of mud and water, usually of Cl–Na type, associated with methane, carbon dioxide and subordinate liquid hydrocarbons (Martinelli and Rabbi, 1998). The whole area where the main emitting vents are located (Fig. 1) is also characterized by diffuse gas seepage (Sciarra et al., 2017, 2019) characterized by an irregular emission activity (Accaino et al., 2007; Carfagna et al., 2024). This emission is accompanied by persistent bubbling activity in the form of 'drumbeats' (e.g., Antunes et al., 2022; Brindisi et al., 2023). The sources of these 'drumbeats' are located within 10 m from the topographic surface and sparsely distributed over a wide area without any evidence of possible concentration at the main cones (Brindisi et al., 2023; Carfagna et al., 2024). In line with the outcomes of gas outflow measurements (Sciarra et al., 2017, 2019), this evidence suggests a dynamical connection between gas emission and seismic signals. Isotope geochemistry of waters expelled from MVs evidences an ancient marine origin and a thermogenic origin of methane bubbling (Mattavelli and Novelli, 1988; Martinelli and Rabbi, 1998). This indicates a relatively deep origin of the outflowing fluids, possibly at the top of the turbiditic

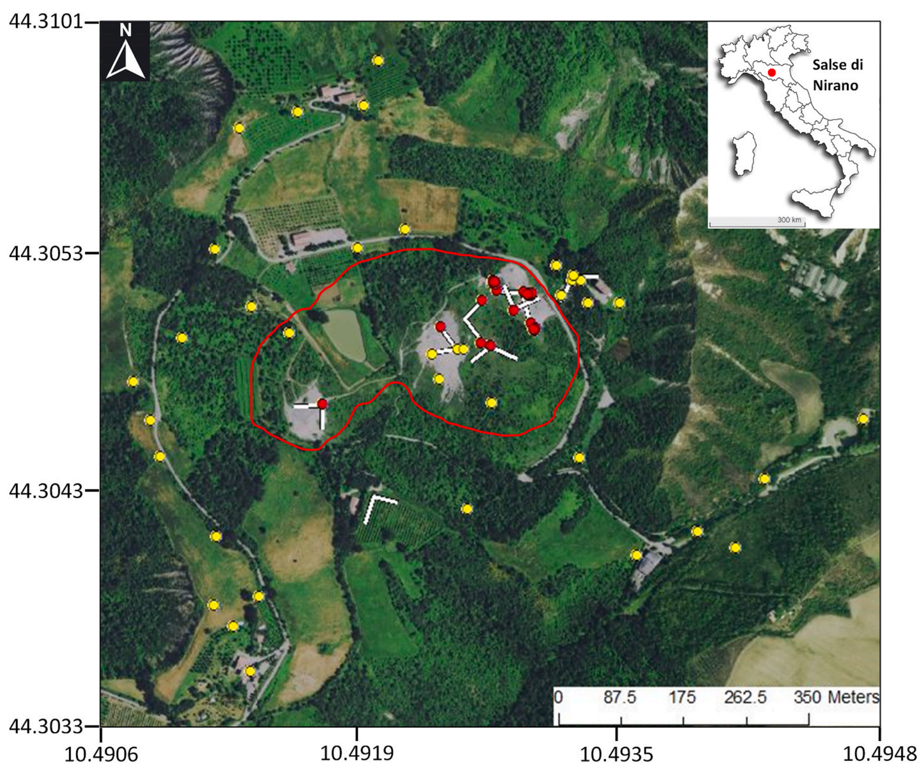

Fig. 1. Satellite image of the Nirano mud volcanoes area. Grey areas correspond to the active vents mud outflows. The red line indicates the caldera-like basin perimeter and delimits the area where Sciarra et al. (2017, 2019) identify the gas seepage. The seismic arrays are represented by the white geometries with L-shaped layout. Coloured dots (yellow and red) represent the distribution of sites where single station ambient vibration measurements have been performed: the red dots indicate sites where the HVSR curves show a clear minimum at about 0.5 Hz.

sequences of the Tertiary ‘Marnoso-Arenacea’ Formation, located at depth of few km from the surface (Bonini, 2007; Giambastiani et al., 2024). Possibly fluid outflow form depth can be due to the leak of a top membrane or fault seal in the above reservoir, which promotes the rise of fluids through thrust faults crossing the nearly impermeable Jurassic-Oligocenic Ligurian Units up to a possible secondary reservoir within the relatively permeable Epi-Ligurian units (the Termina Formation) at a depth of about 400–500 m. The presence of this intermediate reservoir is confirmed by gravimetric measurements (Nespoli et al., 2023) putting in evidence a negative gravity anomaly (about −1500 μGal) which is compatible with the presence of a gas-saturated volume with a porosity in the order of 30–40%. This zone extends for about 200 m width, 1300 m length and about 500 m thick, from beneath the topographic surface (about 200m a.s.l.) down to about −300m a.s.l. This low density volume may be related to gas and/or mud saturated in a rock with a large amount of matrix or fracture porosity (e.g, Mauri et al., 2018 a; and b). From here to the surface, vertical conduits are expected to exist making possible the movements of fluids to the surface crossing the ‘Argille Azzurre’ Formation (Accaino et al., 2007; Carfagna et al., 2024). The presence of these shallow ducts down to depths of some tens of meters has been also suggested by measurements and modelling of resistivity (Accaino et al., 2007; Lupi et al., 2016; Oppo et al., 2017) and passive seismic (Carfagna et al., 2024) measurements.

Seismic investigations carried out in the area where the main emitting vents are located and outside of it (Accaino et al., 2007; Antunes et al., 2022; Brindisi et al., 2023; Carfagna et al., 2024) indicate the following configuration of the shallower subsoil: inside of the caldera-like basin perimeter, the first few meters from the surface are characterized by an average S-wave velocity (V_s) of about 130 m/s and a P-wave velocity (V_p) in the range 200–240 m/s. Outside of the caldera-like basin, in the first few meters of depth, the average V_s value is equal to 200 m/s. Below this shallow layer, both zones present a small increase of V_s values: a small increase in the range 160–200 m/s inside the caldera-like basin perimeter and 400 m/s outside. However, a significant difference exists in the V_p values inside and outside the caldera-like basin perimeter (550 m/s and 1300 m/s respectively).

3. HVSR survey

Seismic surveys carried out in the area so far allowed the seismic characterization of the shallowest part of the subsoil involved in the emission process. To extend downward this characterization and understand if the presence of the HVSR minimum detected by Antunes et al. (2022) is actually confined to the area inside of the caldera-like basin perimeter, an extensive survey of ambient vibrations was performed. At each site, ambient vibrations were acquired for 20 min with a sampling frequency of 128 Hz in absence of significant wind and meteorological disturbances. In general, all cautions suggested by the best practice (e.g., SESAME, 2004) have been considered. Collected data were processed by following Picozzi et al. (2005). Specifically, the single components spectra were computed by averaging 20 s long time non-overlapping windows; a baseline correction and a 5% cosine taper were applied to each window, and the spectra were smoothed using a triangular moving window with a frequency-dependent half width (20 per cent of central frequency). Based on these estimates, the ratios of average spectral amplitudes of ambient vibrations measured along the vertical and horizontal directions of ground motion have been computed at each frequency to obtain the HVSR curve (e.g., Molnar et al., 2022). Since the main interest is devoted to the deeper subsoil structure, the analysis focused on the low frequency part of the HVSR curves (<1Hz).

In this range, at some sites the HVSR curves show the clear presence of a minimum around 0.5 Hz (Fig. 2a) confirming the evidence of Antunes et al. (2022). This minimum is associated to a relative maximum in the average spectral amplitudes in the Fourier spectrum relative to the three components of ambient vibrations (Fig. 2b).

A deeper insight may be also obtained by comparing spectra of

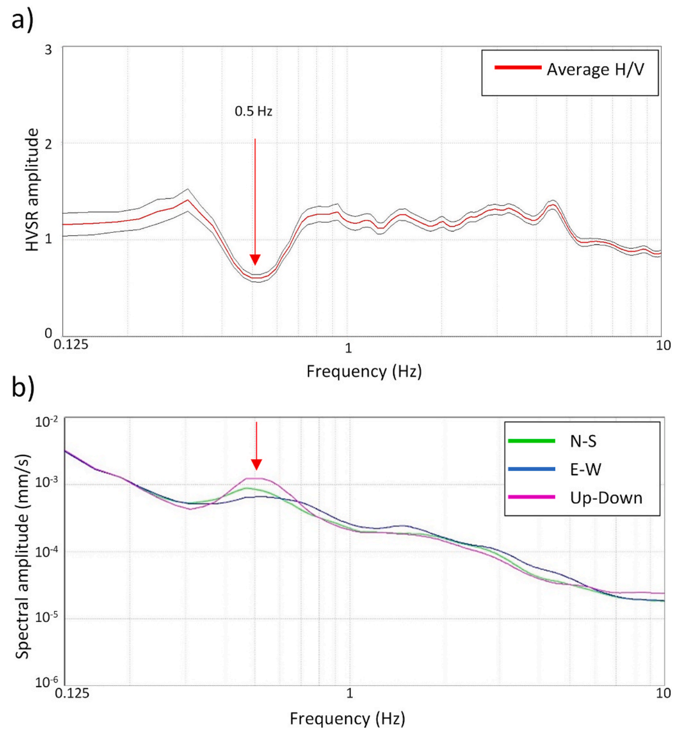

Fig. 2. (a) Experimental HVSR curve in the area where the emitting vents are located as function of the frequency **(a)** and corresponding FFT amplitude spectra of the three ground motion components in velocity **(b)**.

ambient vibrations measured in the same time interval at sites where the HVSR minimum is present and at those where it is absent (Fig. 3). One can see that around 0.5 Hz, vertical components are enhanced where the HVSR minimum is present (Fig. 3a), while only a minor amplification effect concerns the horizontal components (Fig. 3b). These findings suggest that around 0.5 Hz any resonance phenomenon may occur due to energy trapping of seismic waves relative to the vertical ground motion component.

Aiming at characterizing the overall features of the ambient vibration wavefield, a Hierarchical Cluster analysis has been performed (Everitt et al., 2001). To this purpose, the Euclidean distance between the HVSR shapes in the range 0.1–1 Hz has been used to evaluate similarity among the curves and the Ward’s agglomeration method has been considered to classify measurements. Two main clusters (Fig. 4a and b) were identified based on the presence (cluster 1) or absence (cluster 2) of the HVSR minimum around 0.5 Hz. All the measurements relative to the cluster 1 concentrate in the area where the emitting vents are located (Fig. 1), and where the negative gravity anomaly detected by Nespoli et al. (2023) is more evident. This suggests a structural connection between the HVSR minimum, the emission process and the location of the possible gas/fluid reservoir.

4. Body wave velocity profiles from HVSR curves

A very rough estimate of the depth (H) where the seismic impedance contrast responsible for the amplification of vertical ground motion component observed at sites in the cluster 1 can be provided by the simple quarter wavelength approximation (Joyner et al., 1981) via equation $H = V/4\nu$, where V is the harmonic average body wave velocity above the contrast and ν is the frequency of the HVSR minimum (0.5 Hz). By considering P phases with an estimated velocity of the order of 600 m/s (see section 2), H results of the order of some hundreds of meters.

To explore in more detail the possible deeper structure of the area, the HVSR curves have been inverted to define V_s and V_p profiles

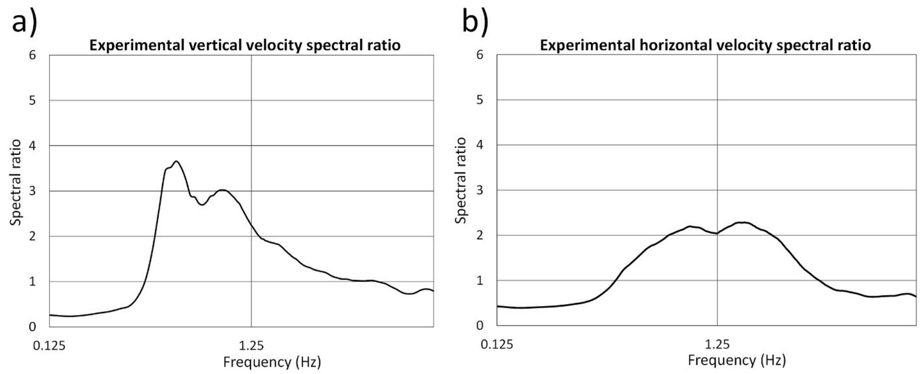

Fig. 3. Spectral ratios of average amplitude spectra (in velocity) of ambient vibration measurements outside and inside the area where the emitting vents are located **(a)** vertical component. **(b)** N-S horizontal component.

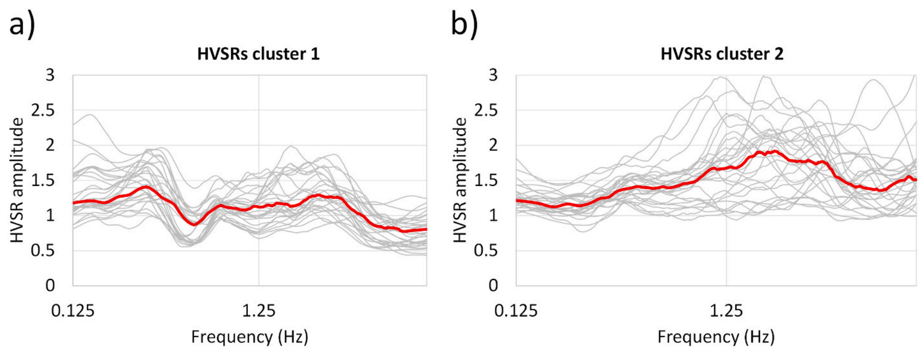

Fig. 4. HVSR values as a function of the frequency relative to measurements in cluster 1 **(a)**, which includes 35 measurements, and cluster 2 **(b)**, which includes 24 measurements. See text for details. The red lines represent the mean HVSR curve of cluster 1 **(a)** and cluster 2 **(b)**.

compatible with observations. To this purpose, several physical models are available for the direct modelling of the HVSR curves (see, e.g., Albarello et al., 2023). Since the interpretation of the HVSR minimum is of main concern and that around the HVSR extrema body waves are expected to play a major role (Albarello and Lunedei, 2011), the preferred model has been the one proposed by Herak (2008) and then implemented by Bignardi et al. (2016). In this model, the HVSR curve is assumed to correspond to the ratio of response functions relative to *P* and *S* phases for the vertical and horizontal components respectively. The body wave inversion has been performed using the code OpenHVSR (Bignardi et al., 2016). OpenHVSR is a Matlab program for the simultaneous modelling and/or inversion of massive HVSR datasets, obtaining the 2D and 3D subsurface distribution of the viscoelastic parameters; this program is based on code ModelHVSR (Herak, 2008), capable of obtaining the 1D distribution of the elastic properties of a subsurface by the inversion of a HVSR curve. The input data consists of experimental HVSR curves; the inversion strategy is based on the guided Monte Carlo method (MC), where at every iteration a randomly perturbed version of the best fitting model is produced and used to compute a set of simulated curves to be compared with the experimental HVSR curves (Bignardi et al., 2016). The generation of numerous test models allows to explore the parameters field in search of a new and best fitting model. In the OpenHVSR interface is possible to choose which material parameters (i.e. degree of freedom) are randomly perturbed during the inversion process and set the maximum amount of the perturbation. The parameters involved are compressive and shear wave velocities (V_p, V_s), and corresponding attenuation factors (Q_p, Q_s), density (ρ), thickness (H); density variations will have a negligible effect (Herak, 2008). In the inversion procedure, the configuration relative to the shallower part has been constrained by the outcomes of the previous seismic investigations (see section 2).

The mean HVSR curves of cluster 1 and 2 have been calculated to determine the subsoil configuration within the area where the emitting vents are located and outside. Best fitting solutions and the relative profiles are reported in Fig. 5.

This analysis has been performed for all HVSR curves considered in this study and in each case the best fitting profile has been selected. In the assumption that body wave profiles obtained from the HVSR curves in each cluster are representative of the same subsoil configuration, to estimate the uncertainties of these measurements, the maximum and minimum value of V_s and V_p values at each depth relatively to the HVSR curves in the two clusters have been computed (Fig. 6).

The main seismic impedance contrasts in the body wave velocity profiles both inside and outside the area where the emitting vents are located can be associated to the main lithological interfaces in the study area (Fig. 6e). V_p increase at the depths around 450 m can be associated to the bottom of the 'Termina' Formation at the contact with the 'Pantano' Formation. At about 200 m of depth, the contact is located between the 'Termina' and the 'Argille Azzurre' Formation. At about 50 m of depths the Plio-Pleistocene clays are in contact with clayey mud deposits inside of the caldera-like basin perimeter and with altered clays outside.

5. Modelling body waves velocity profiles by the Biot-Gassmann theory

A comparison between the representative profiles of the two clusters shows that V_p values relative to the sites outside the area of emitting vents are generally larger than those relative to the area inside, down to a depth of about 450 m from the surface. Since no evidence exists about the possible presence of any lateral variation in the lithostratigraphical configuration between the area of emitting vents and surroundings (Fig. 6e), we hypothesize that these differences are related to the presence of uprising fluids below the area of emitting vents. In particular, the

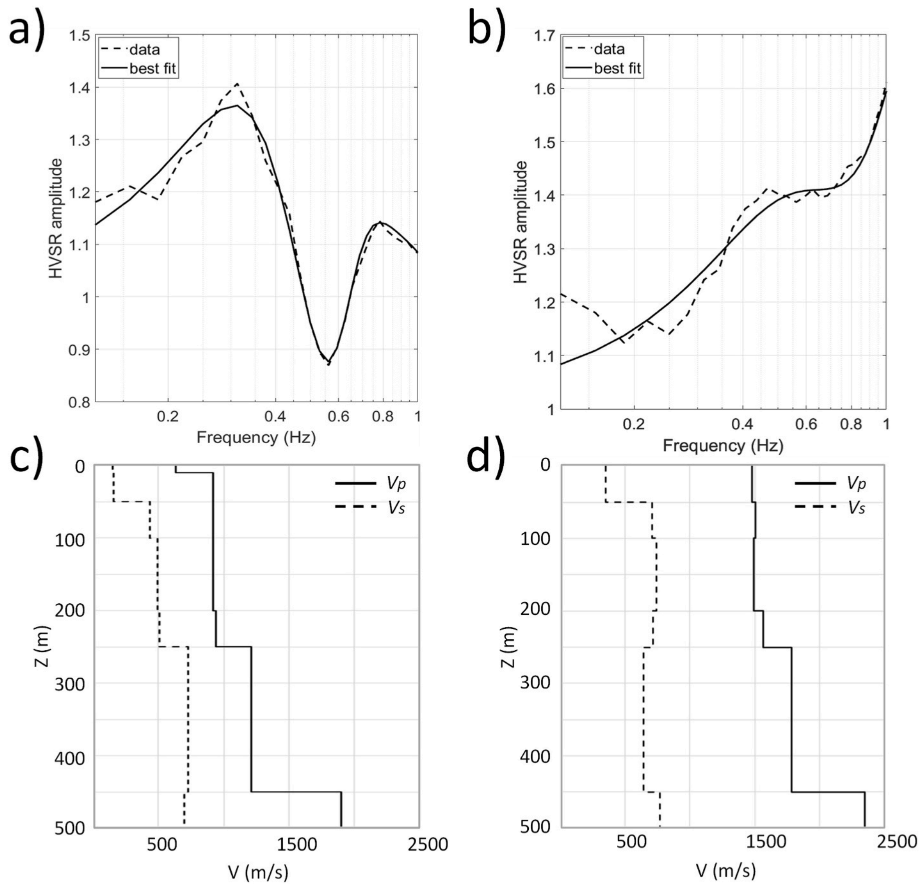

Fig. 5. Outcomes of the inversion procedure. Comparison between the best fitting HVSR curve obtained by the inversion procedure (solid line) and the data, represented by the mean HVSR curve (dashed line) of cluster 1 **(a)** and cluster 2 **(b)**. The corresponding V_s and V_p profiles considered to obtain the best fitting curves in (a) and (b) are reported in **(c)** and **(d)** respectively.

relatively large decrease of V_p values inside the caldera-like basin is interpreted as the effect of the presence of gas (mainly methane) and mud stored below the area where the emitting vents are located at least down to some hundreds of meters depth.

To evaluate the feasibility of this hypothesis to explain the observed differences, we refer to the Biot-Gassman theory in the form proposed by Lee (2004), and hereafter indicated as BGTL.

In line with the considerations proposed by Tinivella (2002), the characteristic parameters relative to each layer inferred from the modelling of the HVSR curves have been considered to identify where patchy or uniform distribution of free gas in the pore space is expected (Lee, 2004). Based on this position, we analyzed the body wave velocity profiles shown in Fig. 6a and b by considering the different lithotypes in the subsoil and the detected impedance contrasts (Fig. 6e). In the assumption that no lithological differences exist between the area of emitting vents and surroundings, the values of the bulk and shear elastic moduli relative to the hosting material have been inferred from estimated values of V_p, V_s and density (Mari, 2019).

In the BGTL model, the V_s and V_p profiles relative to fluid-bearing sediments depend on the porosity (ϕ), water saturation (S_w), clay volume content (C_v) and on two calibration constants: 'e', and 'm'. Realistic ranges of variation relative to these parameters as a function of the lithologies present in the area are reported by Lee (2004) and Yu et al. (1993). Further constrains are as follows: the average density of the fluid bearing sediments (containing water and mainly methane) it has been assumed ≈ 1500–1600 kg/m^3 (Nespoli et al., 2023), and for the water-bearing sediments, that are located outside of the caldera-like basin perimeter, has been assumed ≈ 1850 kg/m^3 for the surface clays and 2000–2200 kg/m^3 for the Miocene rocks from 100 to 1000 m of depth (Nespoli et al., 2023).

By considering these constraints, the values relative to the free parameters (ϕ, S_w, C_v, e and m) have been obtained by an inversion procedure aiming at best fitting the experimental V_s and V_p profiles in Fig. 6. The outcome of this procedure for the area inside the caldera-like basin is reported in Fig. 7a.

Since the volume of the reservoir is equal to ≈2 10^8 m^3 (Nespoli et al., 2023), considering the weighted average of ϕ and S_w as a function of depth it was possible to get an estimate of the total amount of gas in the reservoir (≈3.9 10^7 m^3).

6. Discussions and conclusions

The forward modelling of body waves confirms that the spectral anomaly identified by the minimum situated around 0.5 Hz may be due to a strong V_p impedance contrast at 450 m, which may be linked to the contact between 'Pantano' and 'Termina' Formations (Giambastiani et al., 2024). This discontinuity could represent the base of a polyphasic reservoir (containing mainly mud, water and methane), similarly to the case of Salinelle MVs analyzed by Panzera et al. (2016).

The above interpretation does not contrast with the interpretation of Frehner et al. (2006) and Saenger et al. (2009). By these Authors the link between the HVSR minimum and the presence of a reservoir can be revealed when a large difference exists between Young's modulus (E) of the materials within and outside the reservoir. In the case of Nirano, the Young modulus inferred from the values obtained within the reservoir is about one half of the one outside (1.13 GPa and 2.17 GPa respectively).

Thanks to these elements, we can assume that the reservoir we are looking for extends to a depth of about 500 m, which is in line with

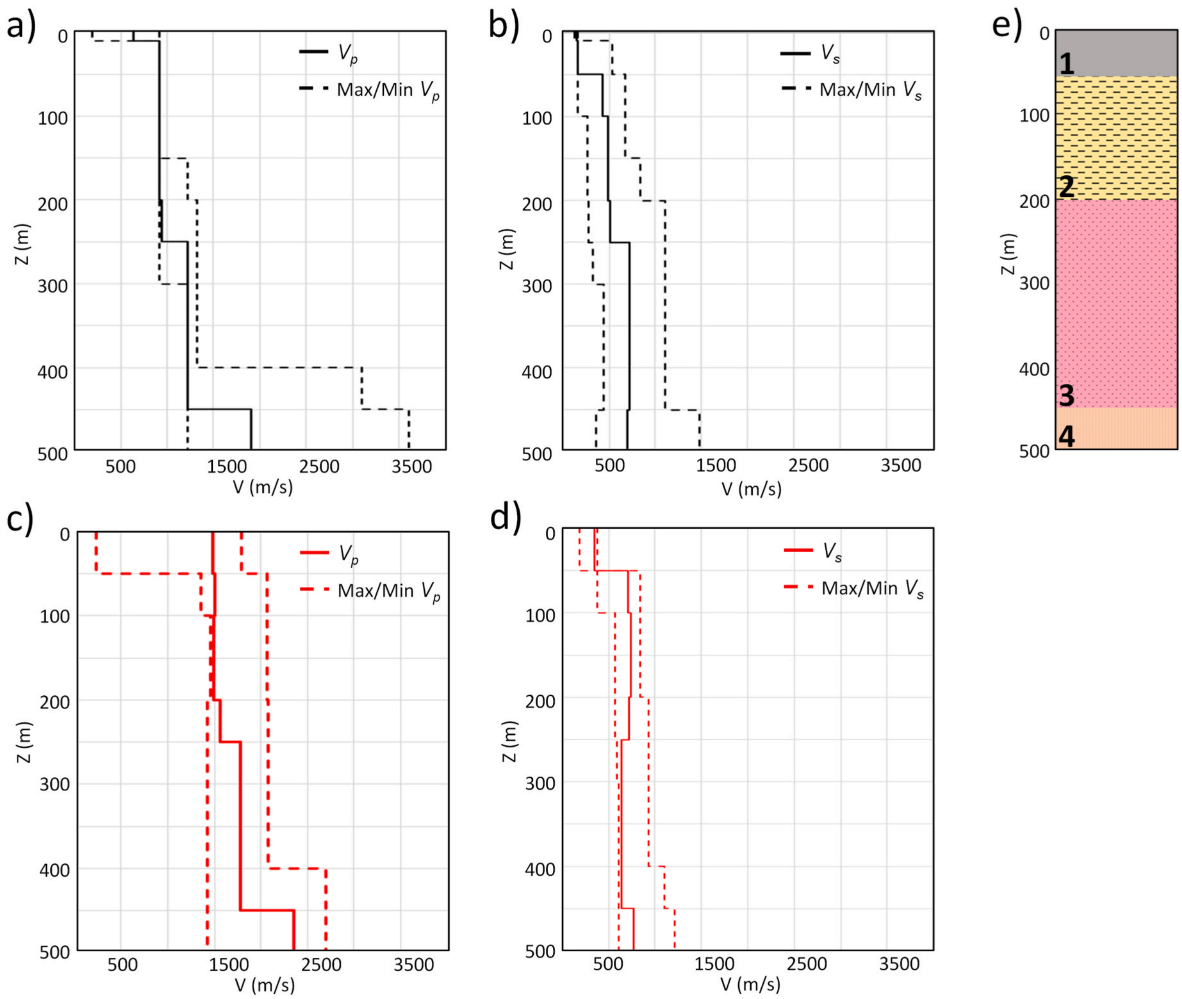

Fig. 6. Representative body wave velocity profiles relative to the area where the emitting vents are located **(a, b)** and surrounding **(c, d)** areas. **(a)** The solid line represents the V_p profile showed in Fig. 5c, the dashed lines represent the profile of the maximum and minimum V_p value at each depth. **(b)** The solid line represents the V_s profile showed in Fig. 5c, the dashed lines represent the profile of the maximum and minimum V_s value at each depth. **(c)** The solid line represents the V_p profile showed in Fig. 5d, the dashed lines represent the profile of the maximum and minimum V_p value at each depth. **(d)** The solid line represents the V_s profile showed in Fig. 5d, the dashed lines represent the profile of the maximum and minimum V_s value at each depth. The litostratigraphical interpretation of the profiles is reported in the inset **(c)**: *1* clayey mud deposits/altered clays, *2* 'Argille Azzurre' Formation (Plio-Presistocene), *3* 'Termina' Formation (Tortonian-Messinian), *4* 'Pantano' Formation (Burdigalian-Serravallian).

outcomes by Nespoli et al. (2023). In addition to this, its mean porosity results to be in the order of 30%, as attested by Nespoli et al. (2023), representing the intrusion of fluids (water and methane) in the damage zone of a subvertical conduit which feeds shallow fluid reservoirs just below the MVs.

The satisfactory fitting between the body waves profiles below the emitting vents and those inferred by the BGTL model suggests that the remarkable V_p reduction compared to the outside is due to the presence of gas and to the mode of its saturation in the pore space. In contrast, *S*-waves are weakly affected by the presence of gas (Lee, 2004) and this explains why V_s profiles are approximately the same both internally and externally from the eruptive area (Fig. 6a and c). Furthermore, the *P*-wave sensibility to gas allows to outline a V_p profile (Fig. 6a) which better define both the impedance contrast between Termina and 'Argille Azzurre' Formation, and that at 10 m depth, delimiting the superficial layer where the bubbling phenomenon takes place (Carfagna et al., 2024).

Trying to reconstruct a possible interpretation of the Nirano subsurface model, a simplified geological sketch has been proposed (Fig. 6e). The subsoil of the area inside of the caldera-like basin perimeter can be described as follows from the bottom to the top. At 500 m of depth we find the 'Pantano' Formation, representing the bottom of a polyphasic reservoir (the 'Termina' Formation) which extends for about 300 m towards the surface. This formation underlies 'Argille Azzurre' Formation where are situated the ducts of rising mud, water and methane (Accaino et al., 2007; Carfagna et al., 2024) until 50 m depth, where the clayey mud deposits outcrops.

In conclusion, our results support the feasibility of passive seismic methods (and in particular the HVSR curves) to investigate the presence of a hydrocarbon reservoir in the subsoil and to estimate the gas concentration in a reservoir system. Since single station three-directional measurements are necessary on purpose, the proposed combination of HVSR measurements and BGTL modelling could be also applied offshore when Ocean Bottom Seismometer (OBS) seismic data are available.

CRediT authorship contribution statement

Albachiara Brindisi: Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Enrico Paolucci:** Investigation, Data curation. **Nicolò Carfagna:** Investigation, Data curation. **Dario Albarello:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Conceptualization.

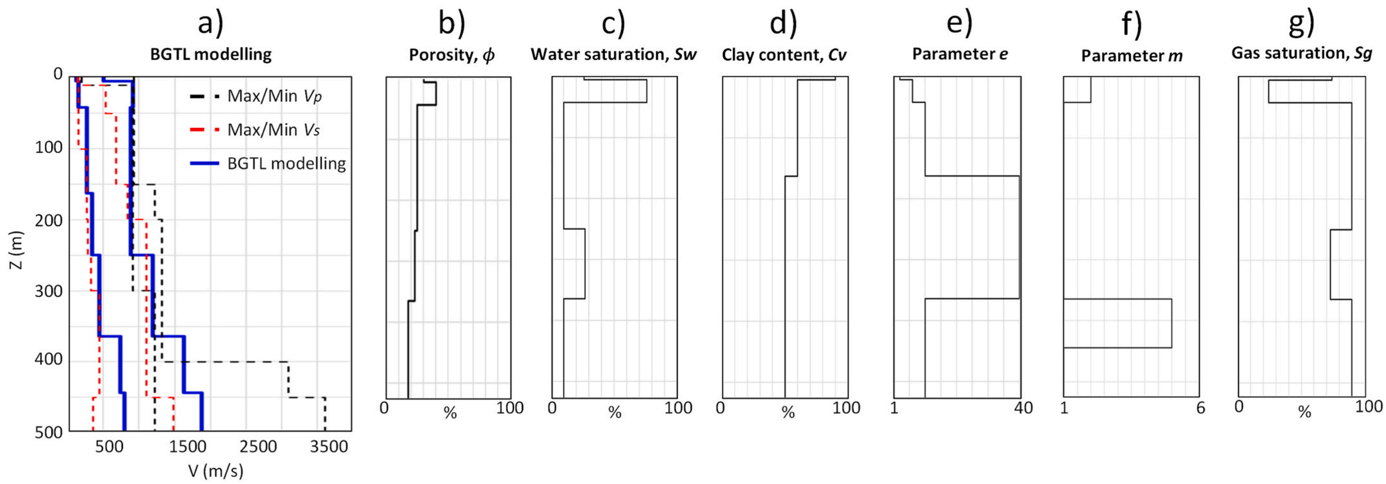

Fig. 7. **(a)** Red and black dashed lines represent the profile of the maximum and minimum V_p and V_s value at each depth shown in Figs. 6a and 6b respectively. The blue lines identify the best fitting profiles obtained by the BGTL modelling considering: the porosity (*f*) profile **(b)** expressed in percentage; the water saturation (S_w) profile **(c)** expressed in percentage; the clay volume content (C_v) profile **(d)** expressed in percentage; the calibration constant (*e*) profile **(e)**; the calibration constant (*m*) profile **(f)**, and the gas saturation (S_g) profile **(g)** expressed in percentage.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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