Converted phase identification and retrieval of Vp/Vs ratios from move-out reflection analysis: application to the Campi Flegrei caldera

M. Vassallo[1], A. Zollo[1], D. Dello Iacono[1], N. Maercklin[1], J. Virieux[2]
[1] *Dipartimento di Scienze Fisiche, Università di Napoli Federico II (RISSC-Lab), Italy*
[2] *Institute Geosciences Azur, CNRS, Nice, France*

Abstract: Here, we propose a method for the determination of *Vp/Vs* ratios in a horizontally layered propagation media using maximization of a coherency function along theoretical travel-times of PS reflected phases. The theoretical travel-times are computed using the information about the propagation media that is extracted by velocity analysis or by topographic analysis performed on the first arrivals. The method is also a valid tool for the identification of the PS phases associated with a fixed seismic reflector, and it is particularly suitable for data that is stored in common mid-point and common conversion point binning; for this kind of data the hypothesis of horizontally and layered media can usually be verified.
We applied the method to both simulated and real datasets. The use of the real data that was acquired in the Campi Flegrei caldera (southern Italy) allowed us to estimate a relatively high *Vp/Vs* ratio (3.5 ± 0.6) for a very shallow layer (maximum depth, 600 m). This hypothesis has been tested by theoretical rock physical modeling of the *Vp/Vs* ratios as a function of porosity, suggesting that the shallow layer appears to be formed of unconsolidated, water-saturated, volcanic and marine sediments that filled Pozzuoli Bay during the post-caldera activity.

INTRODUCTION

Tomography is one of the most popular techniques for geophysics investigations. The tomographic models inferred from inversions of first-arrival times do not have sufficient resolution to accurately define the morphology and location of the main crustal reflectors at depth. Reconstruction of buried seismic discontinuities is usually performed by seismic reflection analysis, which in the cases of very complex media and non-conventional seismic data acquisition, cannot be processed using standard seismic exploration tools. This is especially true in the case of near-shore active seismic surveys in densely populated coastal areas, where mixed and sparse acquisition lay-outs (shots at sea and recordings on land and/or on the sea bottom) can only be used. Therefore, it is necessary to develop new techniques of data processing and analysis to be able to understand unconventional data-acquisition geometries (sparse or irregular distribution of source/ receivers) and complex waveforms in the complete incidence angle range (from near vertical, to wide angle). Once the interfaces have been found, new methods are also necessary for the characterization of rock layers in terms of lithological and rheological features. The *Vp/Vs* ratio provides a very good lithology discriminator. This elastic parameter can improve predictions of mineralogy, porosity, and reservoir fluid types (Pickett, 1963; Tatham, 1982; Rafavich et al., 1984; Miller and Stewart, 1990). Compressional seismic velocity alone is not a good lithology indicator because of the overlap in Vp for various rock types. The additional information provided by *Vs* can reduce the ambiguity involved in the interpretation. Pickett (1963) demonstrated the potential of the *Vp/Vs* ratio as a lithology indicator through laboratory research. We propose a method for the determination of the *Vp/Vs* ratio through an analysis of multi-component seismic data. The vertical components of the data are used for the determination of interface depth and the *Vp* values for normal move-out (NMO) analysis and/or tomographic studies of first arrivals. These values are used to search for the *Vp/Vs* ratio that maximizes a coherency function that is computed using the horizontal component of the data along theoretical travel-times of PS reflected phases.

METHOD

In a horizontally layered media, the travel-times of reflected/ converted PS phases depend on the P velocity *Vp*, according to the depth *h* of interfaces for the *Vp/Vs* ratio of layers and for the source-receiver offsets and depths. With active seismic data, the shot and receiver positions are well know, and the information relating to the velocity *Vp* of the propagation media are generally retrieved using the tomographic inversion of first arrivals or using velocity analysis based on NMO corrections of the PP reflected phases (Yilmaz, 1987). Using this information, the *Vp/Vs* ratio can be estimated by move-out analysis of the PS phases on the radial component, i.e. the horizontal component oriented in the source-to-receiver direction.
Fixing the interface depth and the layer P-velocity, the theoretical travel-time of a PS phase can be computed for a given value of the *Vp/Vs* ratio. Then a narrow window can be selected on the radial component of the section, beginning at the estimated arrival time of the PS phase. For each *Vp/Vs* value limited in a defined range, we can evaluate the STACKPS function, which is defined by:

$$STACKPS(V_p/V_s)=\sum_{t=T_{Theo}^{PS}}^{T_1^{PS}}\left(\sum_{i=1}^{N_{sis}}A_i(t)\right)^2 \qquad (1)$$

where T_{Theo}^{PS} is the theoretical PS travel-time for a given Vp/Vs value, and $T_1^{PS}=T_{Theo}^{PS}+0.3\text{s}$; $A_i(t)$ is the amplitude at time t for the i-th seismogram, and N_{sis} is the number of seismograms contained in a given seismic section.

The STACKPS function estimates the presence of a PS phase in the seismic section near to the T_{Theo}^{PS} theoretical travel-time. If there is a clear PS phase present in the section that associates with the considered reflection interface, the shape of the STACKPS function will show a clear peak that corresponds to the Vp/Vs ratio of the layer.

APPLICATION TO A SYNTHETIC DATASET

To validate the proposed methodology, we have applied it to a synthetic dataset that was calculated for a horizontally layered medium. Using the model shown in Figure 1a, we simulated a seismic experiment with an acquisition layout of one receiver located at position x = 50 m that recorded the signals produced by 80 seismic shots with a horizontal spacing of 100 m, disposed across the topographic surface. The seismograms were obtained by Norsar2d ray-theory code (Cerveny, 2001) and they are shown in the common receiver gathers (Yilmaz, 1987) sections of Figures 1a, 1c. The seismograms contain only the six primary PP and PS phases that were reflected on the three interfaces of the propagation model (Figure 1a).

Using the CVS (Constant Velocity Stack) velocity analysis (Yilmaz, 1987), we obtained information about the Vp velocity model and the depth of discontinuity h. For each PP phase individuated, we computed the STACKPS function for Vp/Vs values in the range [1.5;4] and with a window of 0.2 s. The retrieved shapes of the STACKPS function are shown in Figure 2, as the stack function *versus* the Vp/Vs ratio for each of the phases/ interfaces analyzed. The curves show a peaked shape, where the width depends on the length of the window used for the PS phase extraction and the errors in the propagation model.

For the phase reflected to the first interface, the peak is centred on Vp/Vs = 3 (Figure 2a), which corresponds to the ratio used in the first layer of the model (Figure 1a). For the phase reflected to the second interface, the peak is centred on Vp/Vs = 2.5 (Figure 2b), while for the phase reflected to the third interface, it is centred on Vp/Vs = 2.2 (Figure 2c). For these phases, the Vp/Vs values do not correspond to the values in the 2-th and 3-th layers of the model, but they are values obtained by averaging the Vp/Vs values of the layers above the interface under consideration. Using the formula proposed by

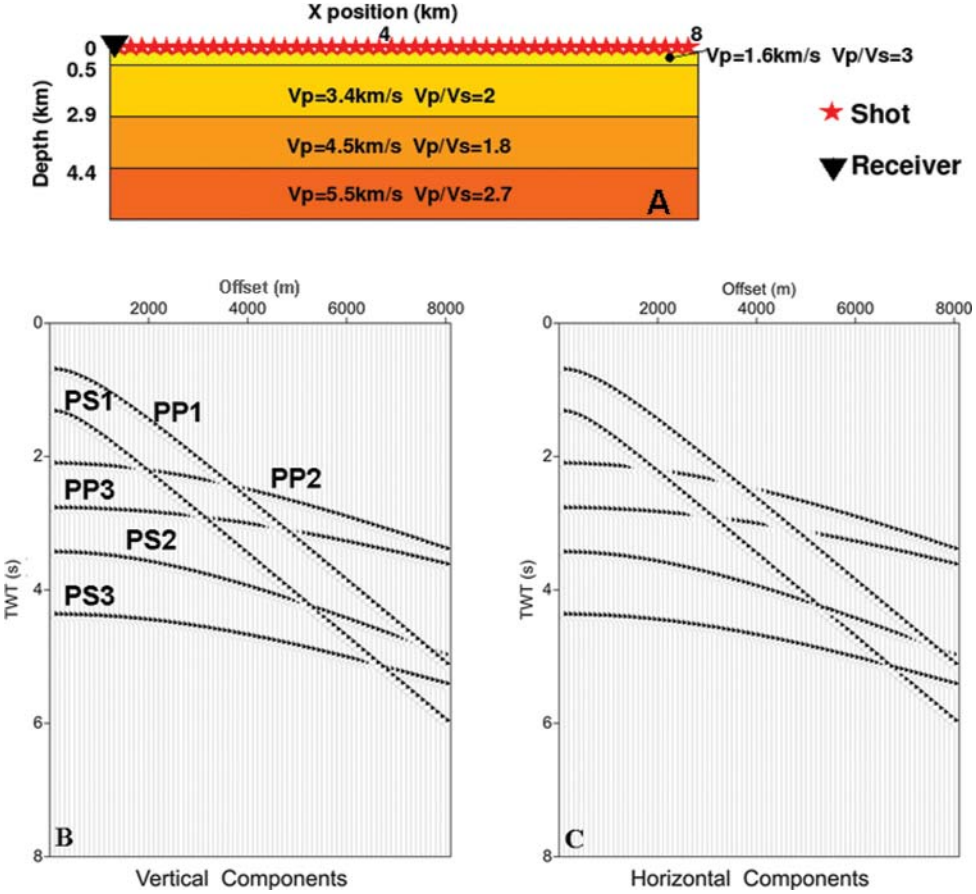


Fig. 1. Model adopted for the generation of synthetic seismograms (a) and synthetic zero offset section (b), (c). The traces in the section were normalized for the maximum trace value and were filtered with an AGC filter.

Stewart et al. (1997), it is possible to estimate the *Vp/Vs* ratio of a medium composed of several horizontal and flat layers with different *Vp/Vs* ratios. Appling the Stewart formula to our model, we obtain for the second interface a *Vp/Vs* of 2.3, and for the third interface, 2.2; these are close to the values obtained performing our analysis. The reliability of the retrieved values can be verified *a posteriori* by the construction of an NMO-corrected section, where the seismograms are corrected by the NMO for the PS phase using the *Vp/Vs* ratios found for each interface. We expect a PS-aligned phase at the theoretical travel-time. The sections corrected by the NMO are shown in Figures 2a-c. For the different layers, a clear aligned phase is seen in correspondence with the theoretical travel-time (red arrow).

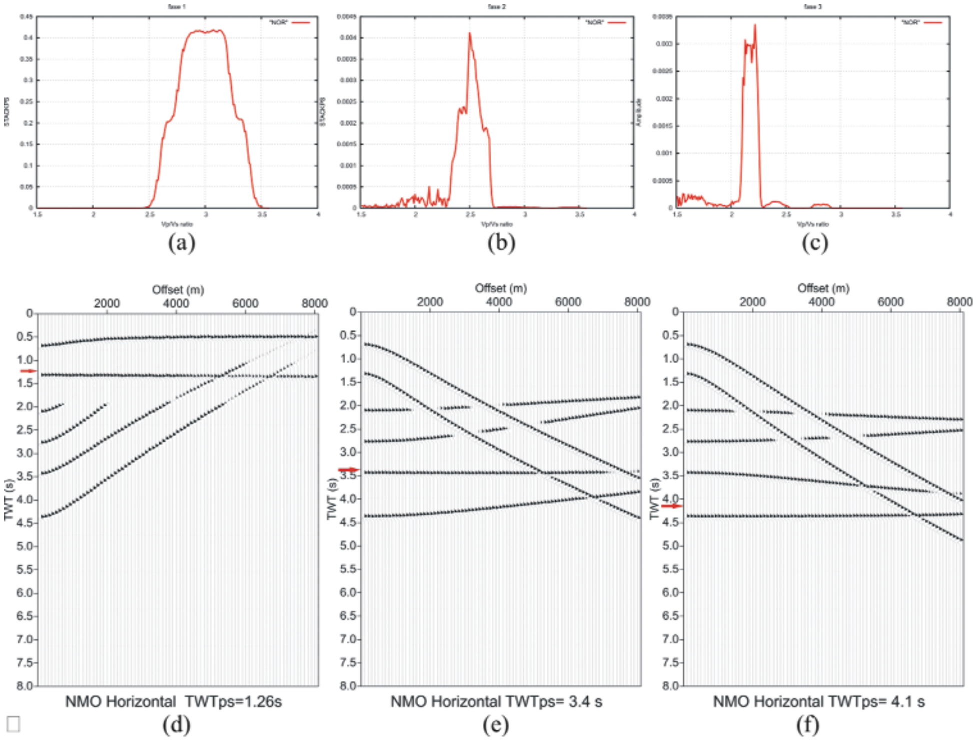


Fig. 2. Results of the method for the first interface **(a)**, **(d)**; the 2nd interface **(b)**, **(e)**, and the 3rd interface **(c)**, **(f)**. Panels **(a)**, **(b)** and **(c)** show the shapes of the STACKPS function, while the sections **(d)**, **(e)** and **(f)** are PS move-out corrected sections. The NMO was applied using the value of *Vp/Vs* which maximized the relative STACKPS function. The red arrow on the left side of the panels indicates the theoretical PS travel-time.

Application to the SERAPIS data

We applied this method to a dataset acquired during SERAPIS (Zollo et al, 2003), which was carried out in the gulfs of Naples and Pozzuoli (Southern Italy) in September 2001 (Figure 3). The aim of SERAPIS was to reconstruct the structure of the Campi Flegrei caldera, to individuate the presence and the forms of potential superficial magma reservoirs, and to define the geometric relationships between the volcanic structures and the carbonatic bedrock. Several important features about the caldera and the regional geology were revealed by these tomographic studies (Zollo et al., 2003; Judenherc & Zollo 2004), although the tomographic models provided give us a smooth velocity model that does not have sufficient resolution to accurately define the morphology and depth of seismic reflectors present in the area under investigation. For these reasons, we have here performed a seismic reflection analysis

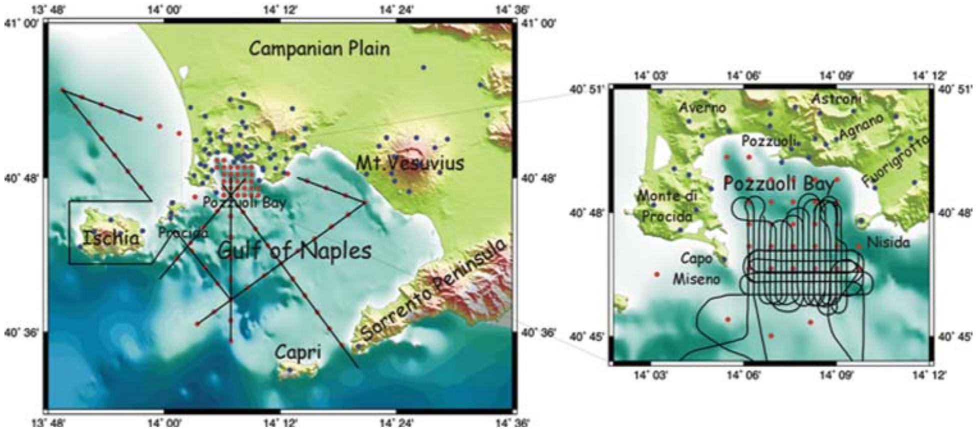


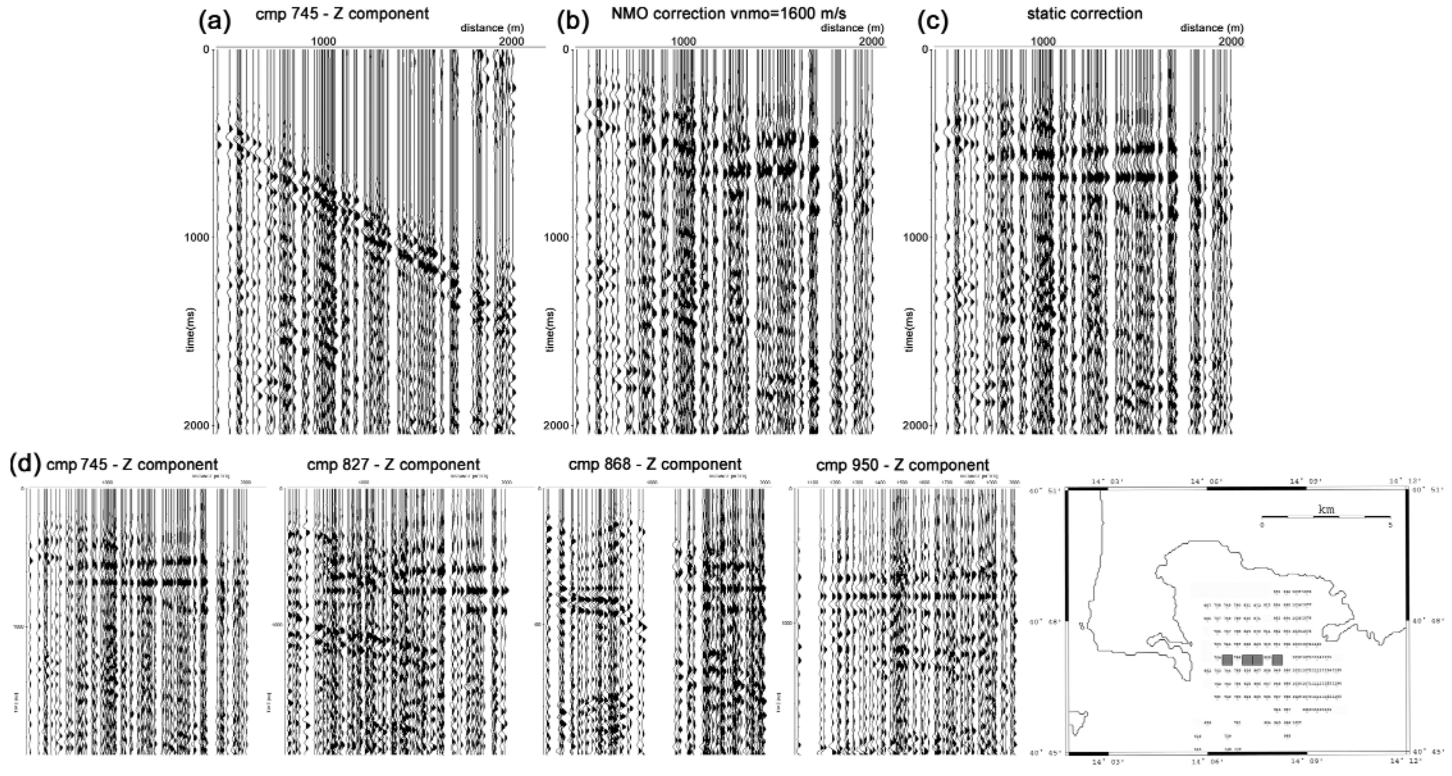
Fig. 3. Map of the area investigated during the SERAPIS experiment (left side), and zoom in on Pozzuoli Gulf (right side). The black lines trace the path of the vessel during the survey. The red circles show the positions of OBS, and the green ones the positions of land-stations deployed during the experiment.

on the acquired data, with the aim of reconstructing the reflector discontinuities and studying the seismic properties of the volcano-clastic layers.

We used the data acquired in the Pozzuoli Gulf for our analysis. The recorded seismic traces were arranged in common mid-point gathers: the Pozzuoli Bay area was subdivided into square cells, and the mid-point positions between the corresponding sources and receivers were calculated for each trace considered, taking a distance of 2,000 m as the maximum offset. All of the records where the mid-point fell into a given cell have been grouped in the same CMP (Common Mid Point), independent of the source-receiver azimuth. This kind of data storage reduces the influence of interface morphology irregularities on the reflected phases. Given the distribution of the sources and receivers during the SERAPIS experiment, the cells with most records are those in the central part of the Bay, between Capo Miseno and the island of Nisida. After several trials, a cell size of 500 m^2 was chosen, based on the criteria of having a sufficiently high number of traces in each CMP gather (>30) and having a dense coverage of the area under investigation.

The two-way times of a PP reflected arrival have been picked on the vertical component sections that were corrected for a move-out velocity of 1,600 m/s. We have chosen 10 CMPs that show relatively high signal-to-noise ratios for the PP phase and good lateral coherency. Examples of processed CMPs are shown in Figure 4. A total of 1,108 readings of the PP arrival times have been performed, providing a eman value of 0.64 s for the two-way travel-time (TWT), with a standard deviation of 0.06 s (Figure 5). Assuming the mean two-way time of the PP phase as the zero-offset time for the identified reflector, and using the mean P-velocity profile inferred from the seismic tomo-

Fig. 4. Example of the CMP gather section (745) after filtering, AGC and normalization **(a)**. Note the reflection hyperbola with its apex at about 0.7 s TWT. **(b)** NMO correction of the previous section, with Vnmo = 1,600 m/s. Note the aligned reflection phase at about 0.7 s TWT. **(c)** Static phase correction at 0.7 s TWT. **(d)** Example of the presence and coherency of superficially reflected phases on adjacent CMPg sections (vertical component). In the righthand map, the positions of CMPs are shown.



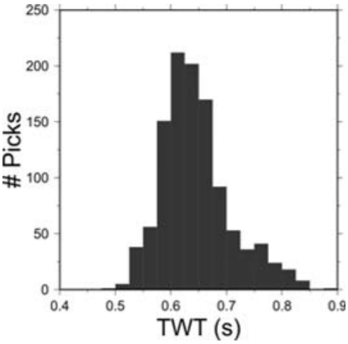


Fig. 5. Distribution of the 1,108 PP pickings.

graphy in the Pozzuoli bay area, an interface depth of 600 m ±120 m is obtained. The depth uncertainty is determined by propagating the errors on time picks (0.06 s) and on P-velocity (0.2 km/s) through the formula $h=(T_0V_p)/2$. The *Vp/Vs* ratio has been estimated for each CMP using the move-out analysis of the PS phases described above, applied at radial components, i.e. the horizontal component oriented in the source-to-receiver direction (Jurkevics 1988). We used the radial components for PS identification because in the absence of azimuthal anisotropy, the energy of S waves will be recorded primarily on the radial (inline horizontal) component of the receiver.

Given the mean interface depth and P-velocity layer, the theoretical travel-time of a PS phase can be computed for a given value of the *Vp/Vs* ratio. Then a narrow window (0.3 s) was selected on the radial component CMP section, beginning at the estimated arrival time of the PS phase. For each *Vp/Vs* value limited to the range [1.5;5.5], we evaluated the STACKPS function (1). The STACKPS function versus *Vp/Vs* was computed for 27 CMPs using a step of 0.01 in the *Vp/Vs* quantity. We selected the CMP sections for which a relatively high number of traces was available (>60) and where there was a good offset coverage (at least 750 m to 1,950 m). Several examples of STACKPS functions are shown in Figure 6, where the functions have been normalized to their maximum values. For the selected CMPs, the shapes of the STACKPS functions generally show a single, broad peak centred at *Vp/Vs* values ranging between 3.0 and 4.0.

An estimate of the *Vp/Vs* ratio at each CMP is obtained by the value corresponding to the maximum of the STACKPS function. Figure 7 shows two examples of the PS move-out corrected radial section at CMP 908 and CMP 951, using the value of *Vp/Vs* that maximized the relative STACKPS function. This example shows good agreement between the aligned PS phase and the theoretical travel-time estimated.

To obtain a weighted mean value of *Vp/Vs* in the considered shallow layer, along with its relative uncertainty, we defined the uncertainty of each *Vp/Vs*

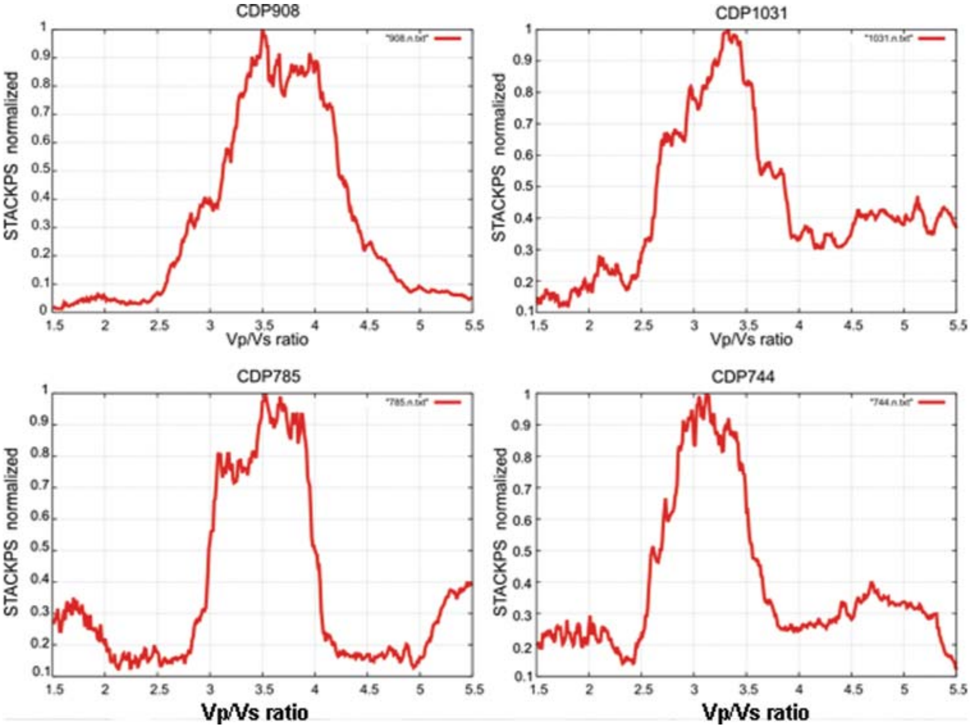


Fig. 6. Examples of the STACKPS functions normalized to the maximum values. The function generally shows a single, broad peak centred at *Vp/Vs* ratios ranging from 3.0 and 4.0.

estimate as the half-width of the STACKPS function at a level equal to half of the maximum amplitude. The weighted means and standard errors were therefore computed using the inverse of the uncertainties of the Vp/Vs estimates as weighting factors. This procedure provided a value for the whole layer of $Vp/Vs = 3.5 \pm 0.6$.

CONCLUSION

We have here proposed a method for the individuation of PS phases in seismic sections and for the determination of the Vp/Vs ratio of layers present into the propagation model. The method is based on optimizing the STACKPS function (1), computed using the data along the analytic travel-times of PS reflected converted phases. The method is applicable for the hypothesis of the propagation media being horizontally layered, and for this reason, it is more simply applicable to data stored in a common mid-point gather or a common conversion point gather. The theoretical PS travel-times

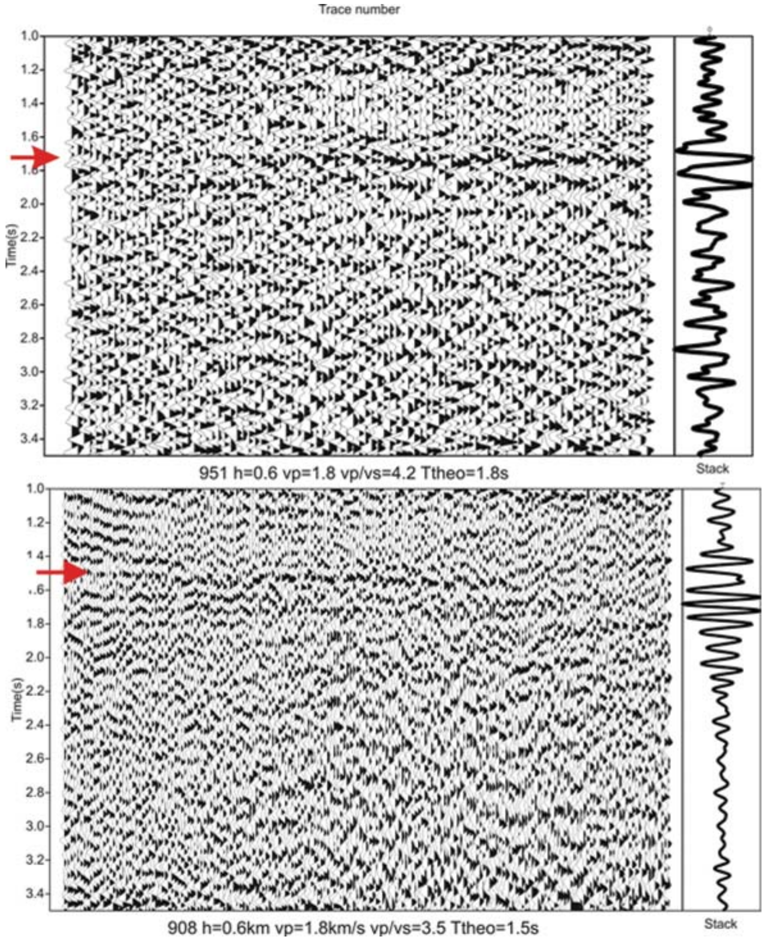


Fig. 7. Examples of the PS move-out corrected radial section for CMP 908 (top) and CMP 951 (bottom). The NMO was applied using the value of *Vp/Vs* that maximizes the relative STACKPS function. The red arrow at left side of panels indicate the theoretical PS traveltime. The thick traces on the right sides of the panels show the stack trace computed using the traces stored in the section.

are computing using the information on the propagation media (depth of interface and *Vp* of layer above the interface) that are obtained performing the CVS (Yilmaz, 1987) analysis on the PP reflected phases or using the tomographic models obtained by inversion of first arrivals.

Initially, to validate the code, we applied it to a synthetic CRG dataset that was calculated for a horizontally layered velocity model. The subsequent application to real radial component CMP gathers acquired in the Pozzuoli Gulf allowed the constraining of the mean *Vp*/*Vs* ratio in the shallow sediment to 3.5 ±0.6. Together with the estimated P-wave velocities, this mean value provided shear-

Tab. 1. *Vp/Vs* ratios and errors estimate for several of the CMP using the proposed method.

CMP	Vp/Vs	Σ
703	3.2	0.6
704	3	0.5
707	3.3	0.75
744	3.1	0.45
745	2.2	0.6
747	4	0.5
748	3.7	0.55
784	3	0.95
785	3.5	0.5
825	4.2	1
866	3.3	0.6
868	3.2	0.8
907	4	0.75
908	3.5	0.55
910	4.3	0.5
948	3.2	0.8
951	4.2	0.55
989	3.9	0.7
1032	3.9	0.55
1035	2.6	0.5
1072	2.7	0.5
1073	3.8	0.7
1075	3.9	0.55
1112	2.9	0.83
1113	4.6	0.6
1114	3.9	0.5
1152	3	0.45

wave velocities of 450-515 m/s. The robustness of this result is confirmed by the clear alignment of the PS arrivals at the theoretical arrival times on moved-out radial sections obtained by using Vp = 1600-1800 m/s and Vp/Vs ratios that maximize the STACKPS function (1) defined above. It is worth noting that the high Vp/Vs ratio represents a mean estimate of the whole shallow layer, and thus such a value can be strongly influenced by the saturation conditions of the rocks in the first hundreds of meters (Zimmer, 2004).

REFERENCES

V. Cerveny. Seismic Ray Theory. Cambridge, 2001.

S. Judenherc and A. Zollo. The Bay of Naples (Southern Italy): constraints on the volcanic structures inferred from a dense seismic survey. J. Geophys. Res., 109:doi:10.1029/2004GL019432, 2004.

Jurkevics, A. (1988). Polarization analysis of three-component array data. Bulletin of the Seismological Society of America, 78(5), 1725--1743.

Miller, S.L.M. and Stewart, R.R., 1990, The effect of lithology, porosity and shaliness on P and S wave velocities from sonic logs: Can J. Expl. Geophys., 26, 94-103.

Picket,, G.R., ,963, Acoustic character logs and their applications in formation evaluation: 1. Can. Petr. Tech. 15, 659-667.

Rafavich, F., Kendall, C.H.St.C., and Todd, T.P., 1984, The relationship between acoustic properties and the petrographic character of carbonate rocks: Geophysics, 49, 1622-1636.

Tatham, R.H. and Stoffa, P.L., 1976. Vp/Vs a potential hydrocarbon indicator. Geophysics 41, pp. 837-849.

Stewart, R. R., Qi Zhang Bland, H. C. and Guthoff, F. Average versus interval vp/vs. CREWES Research Report, Volume 9, 1997.

Yilmaz, O. Seismic data Processing. Investigation in Geophysics. Society of Exploration Geophysicists, 1987.

Zimmer, M. Controls on the seismic velocities of unconsolidated sands: Measurements of pressure, porosity and compaction effects. PhD thesis, Stanford University, Stanford, CA, 2004.

Zollo A., S. Judenherc, E. Auger, L. D'Auria, J. Virieux, P. Capuano, C. Chiarabba, R. de Franco, J. Makris, A. Michelini, and G. Musacchio 2003. Evidence for the buried rim of Campi Flegrei caldera from 3-D active seismic imaging. Geophysical Research Letters, VOL. 30, NO. 19, 2003.