A GEOPHYSICAL TRANSECT ACROSS THE CENTRAL SECTOR OF THE FERRARA ARC: PASSIVE SEISMIC INVESTIGATIONS – PART II

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Introduction. The architecture of the Po Plain foredeep filling, from Pleistocene onward, is characterized by a generally "regressive" trend, interrupted by lesser fluctuations, evidenced by the transition from offshore Pliocene deposits to marine-marginal and then to alluvial Quaternary sediments (Ricci Lucchi, 1986; Amorosi and Colalongo, 2005; Amorosi, 2008).

The great number of subsurface data collected during hydrocarbon explorations and water research (AGIP Mineraria, 1959; Aquater, 1976, 1978; Aquater-ENEL, 1981; Pieri and Groppi, 1975, 1981; RER & ENI-AGIP, 1998; Boccaletti *et al.*, 2004, 2011; Ferrara province - RER 2007) allowed to map the main quaternary unconformities: the most recent surface, at regional scale, is the base of the Upper Emiliano-Romagnolo Synthem (AES; Boccaletti *et al.*, 2004) which is made up of a series of different depositional cycles whose limits are placed in correspondence of the bottom of the "transgressive" marine deposits. The 'transgressive' portion of each cycle is characterized by the presence of fine materials (*e.g.* floodplain, marsh and coastal plain clays) with subordinated sandy intercalations. Instead, the 'regressive' sequence consists of alluvial plain deposits (*e.g.* fine sediments of overflowing river) where channel sands are subordinated in the form of isolated lenticular bodies. On the top of each cycle, the channel sands become abundant, thus forming laterally wider bodies (RER & ENI-AGIP, 1998; ISPRA, 2009).

The studies conducted by the Regione Emilia-Romagna & ENI-AGIP (1998), Boccaletti *et al.* **(2004, 2011)**, Abu **Zei**d *et al.* (2014) and Ferrara province - RER (2007) revealed that the Quaternary succession is highly deformed and confirmed that the transitions between marine-continental sediments are the result of important tectonic phases followed by periods of strong subsidence. Therefore, the strong variable thickness of the Quaternary sequence from several hundreds to few tens of meters in correspondence of the growing anticlines; *i.e.* Mirandola, Casaglia, Argenta reflects the influence of the complex evolution of the blind thrusts belonging to the Ferrara Arc.

Previous geophysical studies conducted by numerous authors (*e.g.* Priolo *et al.*, 2012; Paolucci *et al.*, 2015) focused the attention on mapping the fundamental resonance frequencies and the corresponding shear-wave velocity profiles in the area affected by the Emilia 2012 seismic sequence by independently interpret the HVSR curves (in the first case) or using a simplified power law to describe Vs variation with depth in the latter case. This way, they were able to establish a link between the two main resonance peaks to known subsurface geological contacts. However, no information on possible lateral variations could be deduced from such interpretation.

With this premise, we carried out a geophysical survey along a profile, ca. 27-km long and oriented SSW-NNE, almost perpendicular to the regional trend of the buried structures belonging

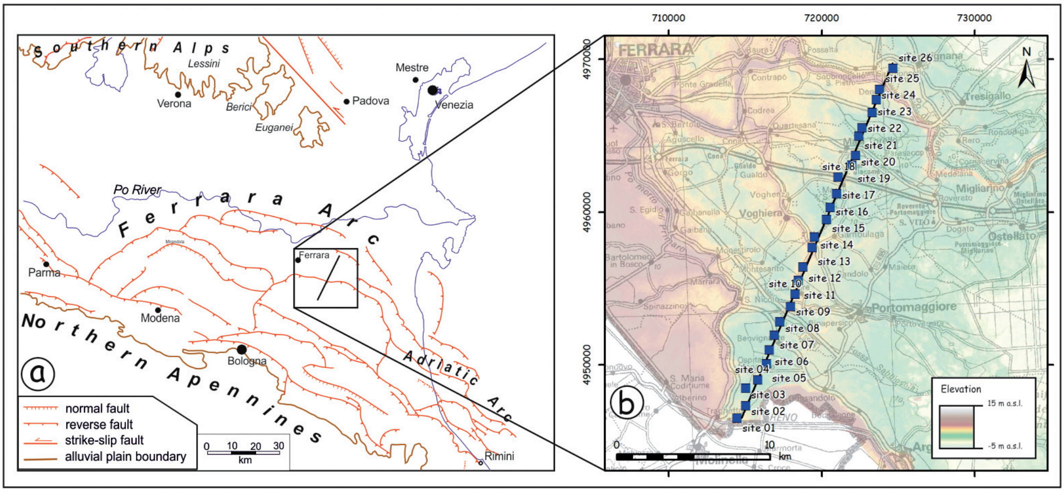

Fig. 1 – a) Simplified tectonic map of the blind northern Apennines showing the studied area [black boxes ESE of Ferrara: modified from CNR-PFG (1991)]. b) Location of the measured sites (blue dots) along investigated profile (black line).

to the central sector of the Ferrara Arc (Fig. 1a), which is one of the three arcs consisting of blind, north-verging thrusts and folds that represent the external northern Apennines front (Pieri and Groppi, 1981; Bigi *et al.*, 1982; Boccaletti *et al.*, 2004). The investigated profile runs in the middle of the elongated area investigated by the detailed gravimetric survey, described in the companion paper (see Palmieri *et al.*, 2015), between Traghetto (near Molinella) and Formignana (Fig. 1b).

Because the density variations of the Late Quaternary deposits are negligible, even performing a much denser grid of gravity measurements, the resolution of this approach, as described in the above mentioned companion paper, would not be sufficient to detect and reconstruct the surfaces and geometries of bodies in the shallow subsurface. In addition, the geometry of the sedimentary bodies, accumulated in the alluvial plain, is generally characterized by sharp lateral variations and hence the interfaces commonly lack planar geometry showing curvatures with wavelength varying between one to ten hundred meters and several meters wide. Accordingly, as far as the expected deformation structures (*i.e.* fault-propagation folds) in the youngest and hence shallowest deposits could have comparable dimensions, the gravimetric survey was integrated by geophysical measurements sensitive to more variable properties in the shallowest subsurface than density.

Therefore, our investigations based on seismic techniques, exploited the ambient seismic noise. In particular, we applied the ESAC (Aki, 1957, 1964; Asten and Henstridge, 1984; Ohori *et al.*, 2002) strategy to obtain several 1D shear wave velocity profiles, providing quantitative shear velocity models down to 120-150 m depth, and HVSR technique (Nakamura, 1989) to infer the fundamental resonance frequency and an estimate of the depth of major impedance contrast(s) at each site. Afterwards, the local 1D Vs profiles and HVSR curves were assembled in order to reconstruct two independent pseudo-2D sections. In what follow we shall show that it is possible to obtain reliable pseudo-2D sections from surface seismic noise data so emphasizing the occurrence of lateral shear wave velocity and spectral ratio amplitude variations. Further, a characterization beyond the nominal depth of 30m results in very useful information for site characterization especially for the quantitative evaluation of the local site specific seismic response (Abu Zeid *et al.*, 2012).

Data acquisition. Along the investigated profile, we carried out 26 ESAC arrays associated with single station recordings at the centre of the array, roughly one kilometre spaced. The coordinates of the investigated sites are listed in Tab. 1.

Tab. 1 - Coordinates (WGS84 – UTM, zone 32N) of the seismic noise measurements.

site	type of measurement	latitude (UTM 32N)	longitude (UTM 32N)	site	type of measurement	latitude (UTM 32N)	longitude (UTM 32N)
01	array	4946530	714459	14	array	4958360	719532
01	single station	4946550	714380	14	single station	4958390	719530
02	array	4947330	715029	15	array	4959510	720312
02	single station	4947320	715028	15	single station	4959540	720302
03	array	4948470	715036	16	array	4960300	720546
03	single station	4948450	715037	16	single station	4960290	720563
04	array	4949020	715811	17	array	4961180	720964
04	single station	4949020	715802	17	single station	4961190	720981
05	array	4950090	716382	18	array	4962270	721064
05	single station	4950110	716382	18	single station	4962290	721059
06	array	4950990	716572	19	array	4963050	721965
06	single station	4950990	716573	19	single station	4963050	721951
07	array	4951940	716901	20	array	4963680	722199
07	single station	4951930	716899	20	single station	4963670	722225
08	array	4952830	717258	21	array	4964950	722408
08	single station	4952840	717285	21	single station	4964950	722387
09	array	4953800	717964	22	array	4965510	722620
09	single station	4953790	717965	22	single station	4965530	722599
10	array	4954610	718249	23	array	4966490	723283
10	single station	4954610	718264	23	single station	4966480	723278
11	array	4955510	718460	24	array	4967340	723543
11	single station	4955530	718455	24	single station	4967330	723553
12	array	4956410	718774	25	array	4968020	723757
12	single station	4956430	718772	25	single station	4968010	723763
13	array	4957680	719364	26	array	4969380	724651
13	single station	4957670	719364	26	single station	4969390	724638

The ESAC (Extended Spatial Auto-Correlation; Aki, 1957, 1964; Asten and Henstridge, 1984, Ohori *et al.*, 2002) consists of collecting the ambient seismic noise by means of an array (seismic antenna) employing vertical geophones, laid out in an L, T or X geometry, allowing for different length of the segments in order to fit the available space at the measurement site, especially when in urbanareas. Data are fourier transformed and combined keeping into account the shape of the antenna to obtain the dispersion pattern of the Rayleigh waves. Then, an inversion process allows estimating the local vertical sequence of shear wave velocity (Vs), assuming an 1-D subsurface model. In the present survey, L-shaped arrays, composed of 24 geophones, 8 m spaced, were laid out at each site. We used 3-components 4.5 Hz proper frequency geophones. Seismic noise was recorded separately both for the vertical and horizontal components, obtaining time series of 15 minutes long sampled at 500 Hz. The inversion of the dispersion curves afterwards allowed for the 1-D shear wave velocity estimation using a set of constant thickness layers. Phase velocity data inversion was accomplished using a

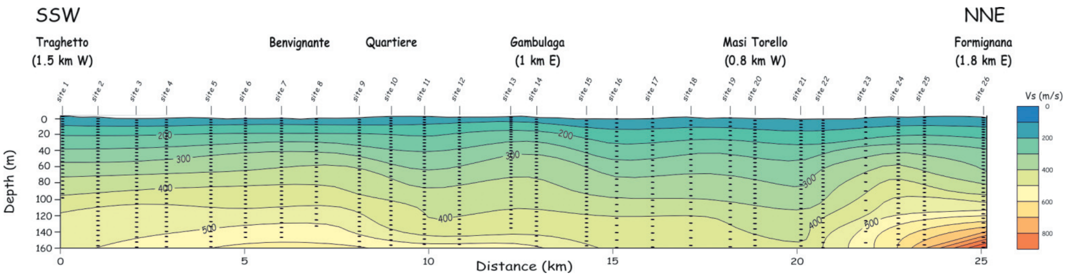

Fig. 2 – Pseudo-2D shear-wave velocity section reconstructed by the interpolation of several 1D shear-wave models obtained from the inversion of the ESAC seismic noise data.

"minimum roughness regularization" strategy, so to obtain smooth transitions with depth but still maintaining the capability of capturing the major impedance contrasts.

The HVSR (Horizontal-to-Vertical Spectral Ratio) technique, first proposed in 1970 by Nogoshi and Igarashi, based on the initial study of Kanai and Tanaka (1961), and today popular thanks to Nakamura (1989), is a "passive" method, which uses three-component recordings of ambient seismic noise to evaluate the site fundamental resonance frequency(ies), by estimating the horizontal-to-vertical ratio of the spectral amplitudes of motion. The measurements of the seismic noise were performed using a 3-component short-period seismometer (fc = 2 Hz) for time intervals variable between 30 and 50 minutes. The final HVSR curves as a function of frequency are given by the average of the H/V ratio computed for each window (window size = 60 s). The curves were computed by averaging the horizontal spectra with the quadratic average and dividing it for the vertical spectrum. Such spectra were smoothed following the filter proposed by Konno and Omachi (1986) using a constant b value of 40. Moreover, seismic noise source directionality was evaluated for all the measurements.

Results: pseudo-2D sections. The discrete information of all 1D models was interpolated with a minimum curvature algorithm in order to obtain the pseudo-2D velocity section. The resulting Vs profile is shown in Fig. 2. Although 1D models locally reached higher depths, the section we show reports the distribution of Vs down to an average depth of about 160 m b.g.l. (considering that the elevation of the sites ranges between 0 and 4.5 m a.s.l.). The shear wave velocity ranges between 100-150 m/s, just below ground surface, and locally reaches 600 m/s at the maximum investigation depths. The vertical gradient of Vs is stronger between sites 03-13 and between sites 21-26, while in the southernmost and central portions of the profile, between sites 01-02 and 14-20 the gradient is weaker and the Vs at 160 m b.s.l. is ca. 400-450 m/s. If we compare the Vs profile with the Structural Model of Italy (Bigi *et al.*, 1992) we observe that the strongest Vs gradients are located above the sets of thrust faults respectively pertaining to the Argenta and Ferrara anticlines; conversely, the sites where the gradient is weaker are located above a tectonically "depressed" area bounded by a reverse fault to the north.

The corresponding frequency section, obtained using the HVSRprofile routine (Herak *et al.*, 2010), which performs a side-by-side assembly of the observed HVSR-spectra, is based on the 26 single station measurements of seismic noise, elaborated following the HVSR method. Considering the characteristics of the seismometer and the influence of weather-climate conditions for frequencies below 0.5 Hz (SESAME, 2004), the analysis was limited to the frequency band between 0.5 and 5 Hz. The HVSR amplitudes, depending on the impedance contrast at the discontinuity surface, are color-coded and these are greater in the southern portion of the profile with respect to the northern one. The fundamental frequency varies along the profile from a minimum of 0.55 Hz up to a maximum of 1.6 Hz (Fig. 3a).

Assuming the Vs pattern and the fundamental resonance frequency variations to be determined by lateral lithological variations, especially in terms of differential compaction (i.e. age) of the sediments, the two pseudo-2D sections (Figs. 2, 3a) allow hypothesizing the

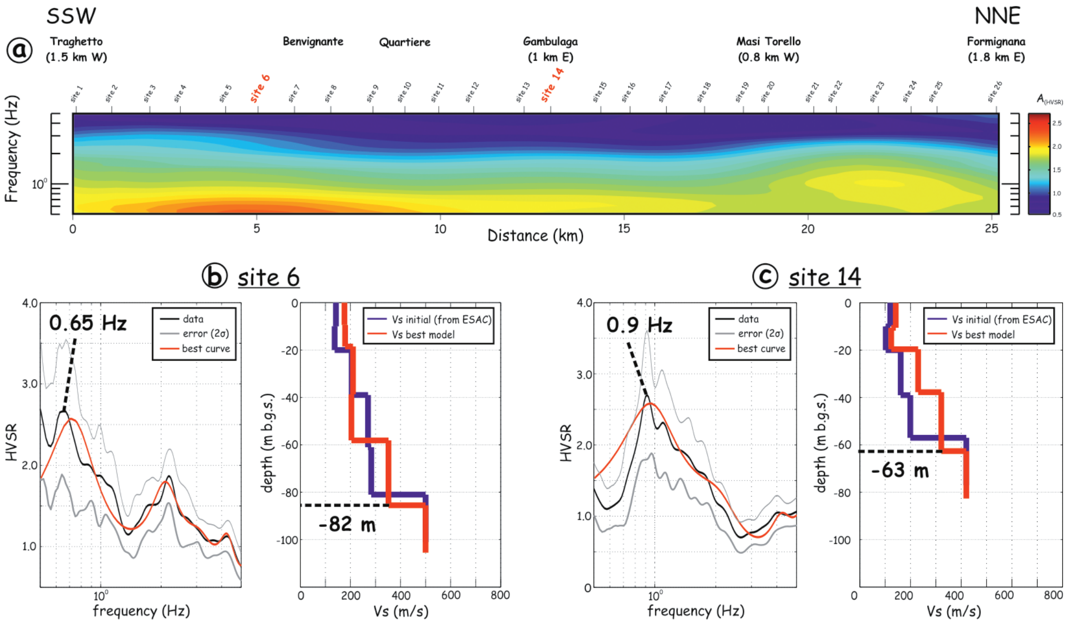

Fig. 3 – a) Smoothed HVSR profile obtained by gridding each average HVSR curve, between 0.5 and 5 Hz. Relative amplitudes are color-coded (see colorbar). The HVSR spectra of each measurement, which were grouped together according to a comparable fundamental resonance frequency, are also shown. b) Result of the HVSR curve inversion of site n. 6 with the "OpenHVSR" routine. On the left graph are shown the observed HVSR spectra (black line) and the best curve obtained after the inversion procedure (red line). On the left diagram are shown the Vs starting model from ESAC survey (blue line) and the final Vs profile relative to the best HVSR curve (red line). c) Result of the HVSR curve inversion of site n. 14.

occurrence of buried anticline structures in correspondence to the "condensed" stratigraphy and their recent tectonic evolution. This is further confirmed by a preliminary inversion of some ad-hoc selected HVSR curves, performed using the open source "OpenHVSR" routine, developed by our research group to specifically invert large HVSR datasets; which shall be freely available soon. In Figs. 3b and 3c the obtained results of two HVSR curves are shown. The smooth Vs subsurface model obtained from the ESAC was used as starting model for the HVSR inversion. This allowed to start from a model already in the basin attraction of the HVSR inversion global minima. We were so able to optimize the local Vs profiles to both minimize the ESAC and the HVSR objective functions even if the two inversion routines are based on different assumptions.

Despite these limitations,, the resultant depth of the major impedance contrast is consistent with those of the other geophysical tests and available information about the subsurface stratigraphy. The comparison with the available stratigraphic data (RER & ENI-AGIP, 1998; Ferrara province – RER, 2007; Martelli *et al.*, 2014) indicates a good correspondence with the known main stratigraphic unconformities. In particular, the seismic pseudo-bedrock here detected could correspond to the contact between two Middle Pleistocene sedimentary cycles, both belonging to higher rank sedimentary cycle represented by the Upper Emiliano-Romagnolo Synthem (AES).

Conclusions and future works. The reconstructed pseudo-2D sections document the possibility to highlight the recent tectonic activity of buried structures underlying the eastern sector of the Po Plain by means of low-cost geophysical surveys (not expensive equipment nor large teams). The seismic passive methods allowed collecting a massive dataset in a short period of time, which in turn, allowed retrieving a large number of local 1D shear wave velocity profiles that were capable of exploring the subsurface down to ca. 150-200 m depth. Further, the fundamental resonance frequencies and the depth to the major impedance contrast of the investigated sites were obtained. Accordingly, it is possible to carry out a sufficient number of such measurements in order to derive reliable pseudo-2D sections, several kilometers-long, so emphasizing the possible occurrence of lateral shear wave velocity (and amplitude) variations, which will likely reflect the stratigraphic changes.

Although we did not observe in the reconstructed Vs pseudo-2D section the velocity values that should be expected for a strict definition of the position of the seismic bedrock (i.e. Vs≥ 800 m/s), it is however possible to recognize a pseudo-bedrock located roughly at 100-150 m depth and characterized by Vs values between 400 and 500 m/s. As a benefit result, the subsurface characterization beyond the traditional 30 m represents a very useful information toward a better urban planning and to a more realistic evaluation of the local site response, especially in view of anticipating new laws that may in the future prescribe to extend this kind of investigations to higher depths.

The comparison between the results described and discussed above with those of the companion paper (see Palmieri *et al.,* 2015), suggests that the shallow stratigraphic features documented in this work can be directly associated with the deep ongoing tectonic activity of the blind thrusts throughout the Quaternary.

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