Down-hole geophysical characterization of middle-upper Quaternary sequences in the Apennine Foredeep, Mirabello, Italy

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ABSTRACT

The 2012 earthquakes sequence stroke a wide area of the alluvial plain in the Emilia-Romagna Region and triggered a new research interest on the role of the subsurface stratigraphic architecture and petrophysical property distribution in the modulation of the local seismic effects. Few direct shear wave velocity V_S data were however available below the depth of 50 m. The only available V_S measurements were obtained from an anticline area, characterized by a reduced stratigraphic thickness and peculiar sedimentary facies, hardly representative of the majority of the alluvial plain subsurface. The study provides the first V_S profile available from middle-upper Quaternary successions deposited into a fast subsiding syncline area of the Apennine Foredeep Basin. The P-wave velocity V_P and the S-wave velocity V_S logs fill in the previous data gap on the geophysical parameters needed for the estimation of the local seismic response. Both V_P and V_S logs were continuously acquired to the depth of 265 m. The log records a velocity increase with depth, punctuated by sharp increases at some stratigraphic discordance surfaces. The value of 800 m/s that characterizes the "seismic bedrock", as defined by the Italian building code [NTC 2008] was never reached at any depth. The investigated succession records a depositional evolution from deltaic-marine to alluvial plain conditions, punctuated by six glacio-eustatic depositional cycles, developed in Middle-Upper Quaternary times. The stratigraphic units described in the syncline log were correlated at a regional scale, with the thinner anticline succession of Mirandola. Correlatable units deposited into syncline and anticline areas reveal similar shear wave velocity values, supporting the regional extrapolation of the measured values.

1. Introduction

In May 2012, several medium-large earthquakes impacted on a wide portion of the alluvial plain of northern Italy (Figure 1), belonging to the Lombardy, Veneto and Emilia-Romagna regions. The strongest earthquake (M_L 5.9) occurred close to Finale Emilia, while the second largest one (M_L 5.8) took place near Mirandola [Pondrelli et al. 2012]. The causative faults belong to the Ferrara Arc thrust system [Bonini et al. 2014, DISS Working Group 2015], forming the external portion of the Apennines Chain (Figure 1). The earthquake effects were modulated by the changing seismic amplification, associated with the largely variable Plio-Pleistocene successions [GeoMol Team 2015]. The thickness of the post-Miocene units varies from several kilometres in syncline areas, to 200 m, in anticline zones, near Mirandola and Casaglia (Figure 1). Large lateral variations in stratigraphic thickness are visible also within the upper Quaternary units [GeoMol Team 2015]. The seismic acceleration induced pervasive sand liquefaction phenomena within Holocene fluvial bodies [Caputo and Papathanasiou 2012, Papathanassiou et al. 2012, Emergeo Working Group 2013].

The 2012 earthquakes triggered a widespread interest on the seismic hazard assessment in the alluvial plain area of the Emilia-Romagna Region [Di Manna et al. 2012, Malagnini et al. 2012, Meletti et al. 2012, Milana et al. 2014, Papathanassiou et al. 2015, Tonni et al. 2015]. The available data on the subsurface were however scanty. The regional administration therefore collected many previously performed shallow logs, such as cone penetration tests, stratigraphic corings and water well stratigraphies, available from the shallow subsurface, and performed several new investigations, reaching an average depth of 30-50 m [Martelli and Romani 2013]. Only few data were however available from deeper levels. A measurement of the shear wave veloc-

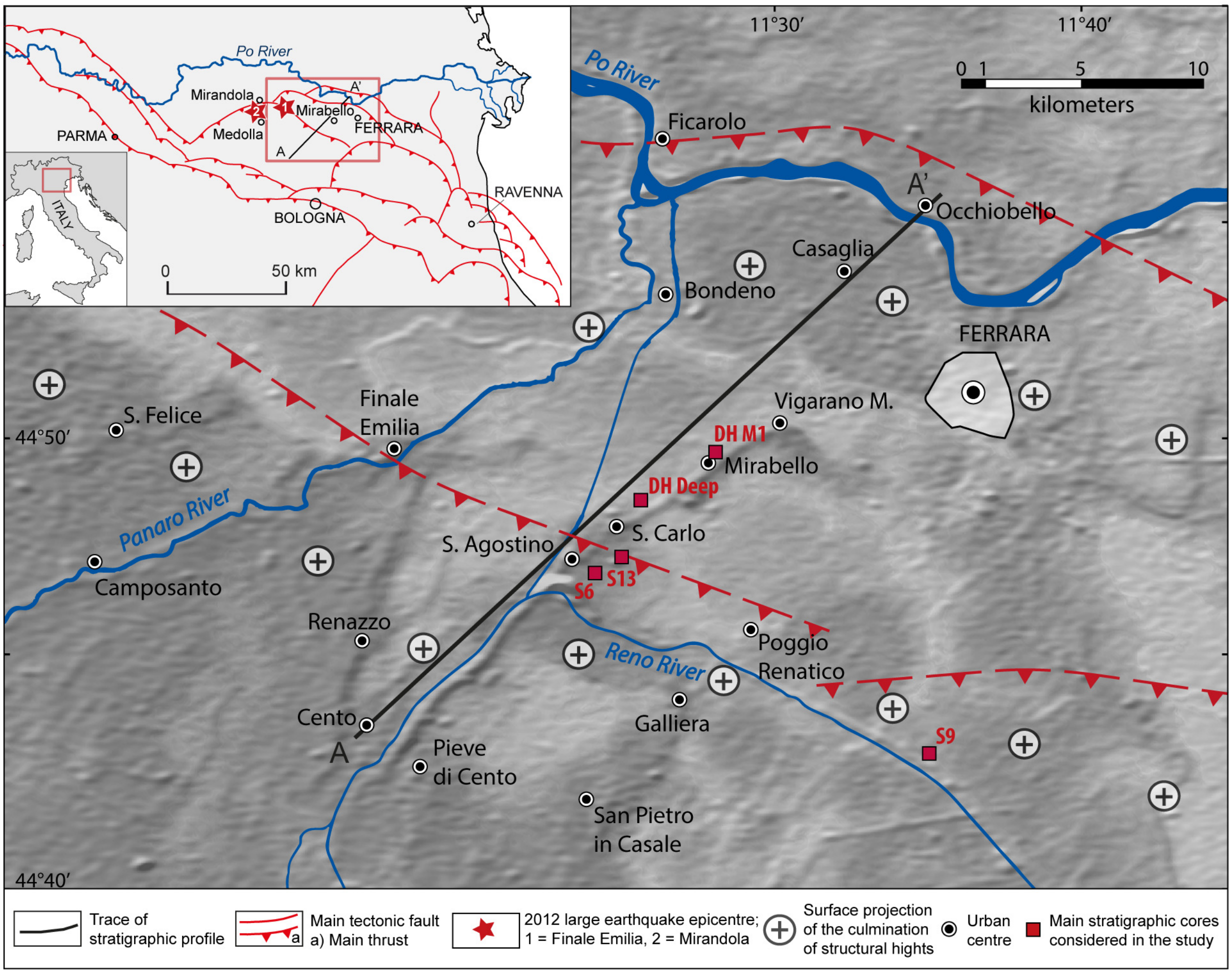

Figure 1. Altimetry map of the study alluvial plain area with the position of the discussed logs. Some of the major subsurface overthrusts are schematically illustrated. The line A-A' depicts the location of the geological profile of Figure 2.

ity V_S was not normally available at depths exceeding 30-50 m. A crucial parameter for the estimation of the local amplification was thus widely lacking. Direct V_S measurements exceeding the depth of 50 m were acquired only at two sites, near Medolla and Mirandola (Figure 1), down to the depths of 101 m and 127 m respectively [Martelli and Romani 2013, Paolucci et al. 2015, Garofalo et al. 2016]. These two sites are less than 4 km apart and belong to an anticline area [Tarabusi and Caputo 2016]. The logs therefore show comparatively thin stratigraphic successions, with sedimentary facies quite different from those accumulated into the vast majority of the Emilia-Romagna Region (Figure 2).

The extrapolation of the aforementioned geophysical data to the thick successions accumulated into the syncline areas was therefore uncertain. Direct V_S measurements from syncline regions were clearly needed to improve the accuracy of the local seismic response studies. The present research, for the first time, provides a V_S distribution acquired from a deep down-hole test carried out in a syncline area. The investigation was performed in the middle-upper Quaternary succession accumulated into the fast subsiding syncline zone south-west of Ferrara, between the villages of Mirabello and San Carlo (Figure 1).

2. Structural and stratigraphic framework

The study area belongs to the external part of the Apennines Chain, buried beneath the recent alluvial plain. This portion of the chain consists of blind thrust and fold structures [Pieri and Groppi 1981, Boccaletti et al. 2004], generated through Neogene and Quaternary times [Ghielmi et al. 2013, Vannoli et al. 2015]. The fast regional subsidence of the southern portion of the foredeep basin is superposed to the ongoing fault-fold deformation [Carminati et al. 2010]. The syncline areas thus record much larger subsidence values than the anticline ones. The lateral variation of the subsidence rate strongly influenced the stratigraphic thickness (Figure 2), the sedimentary facies architecture and the petrophysical parameters distribution [Bigi et al. 1992] and thus the seismic wave propagation properties of the Plio-Pleistocene units. The Quaternary of the region records the impact of active tectonic deformation and of massive climatic and eustatic fluctuations. The whole of these factors induced key stratigraphic

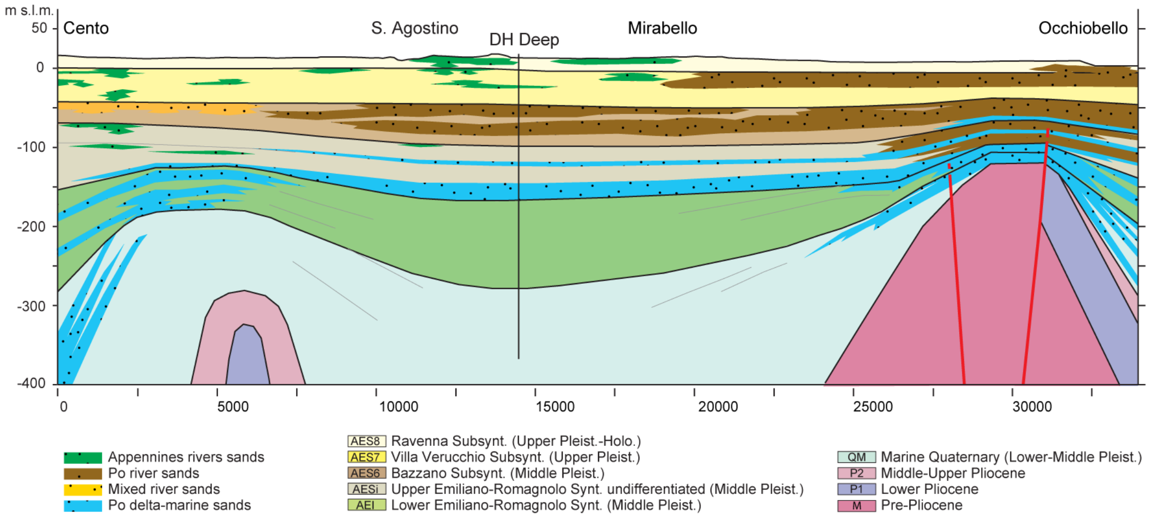

Figure 2. Geological cross section interpreting the first 400 m of subsurface between Cento and Occhiobello. The impact of the active tectonic deformation and the associated differential sediment compaction on the stratigraphic geometry is clearly visible. Vertical exaggeration × 25 (modified after Martelli and Romani [2013], Paolucci et al. [2015]).

surfaces that support the subdivision of the sedimentary successions into allostratigraphy units, organized in different hierarchical levels [Regione Emilia-Romagna et al. 1998]. Two main synthems are separated by a discordance surface, associated with a structural reorganization of the foredeep basin area. The synthems are further subdivided into a number of subsynthems (Figure 2), recording the large glacio-eustatic and climatic fluctuations. The transgressive surfaces induced by the eustatic rises associated to deglaciation were chosen as the subsynthem basis. The base of each subsynthem unit corresponds to the deactivation of the synglacial coarse-grained sedimentation, accumulated into middle alluvial plain environments. Syn-transgressive units are capped by organic-rich marsh mud, deposited into lower alluvial plain settings, or, in the deeper portions of the successions, by marine-deltaic sediments. The regressive trend of the alluvial plain successions culminates into a new interval of synglacial lowstand sands. The ongoing transgressive-regressive cycle has been ascribed to the Ravenna Subsynthem (AES8), the base of which correlates with the Stage 1 of the global Marine Oxygen Isotope curve [Martinson et al. 1987], corresponding to the base of the Holocene (about 14 ka). The lower boundary of the underlying Villa Verucchio Subsynthem (AES7) is assigned to the Marine Oxygen Isotope Stage M.O.I.S. 5e, (about 120 ka) whereas the base of the previous Bazzano Subsynthem (AES6) correlates with M.O.I.S. 7 (about 240 ka). Moving downwards, two further depositional cycles are ascribed to the undivided lower portion (AESi) of the Upper Emiliano-Romagnolo Synthem and lack a formal stratigraphic terminology. The Lower Emiliano-Romagnolo Synthem shows several transgressive-regressive pulses, recording a globally shallowing evolution.

3. Data acquisition methodology

The Mirabello drill (Latitude: 44.8100°; Longitude: 11.4264° WGS84) crossed a middle-upper Quaternary succession, reaching a depth of 372 m. The deep borehole was used to perform a down-hole test, hereafter named DH Deep. Both compressional (V_P) and shear (V_S) wave velocities were measured, down to the depth of 265 m. Figure 3 shows a schematic plan layout of the seismic sources, surface geophones and the core location.

A grout mixture was pumped into the core and a PVC pipe, with an internal diameter of 162.8 mm, was installed, down to 265 m. An additional steel casing, with an internal diameter of 263 mm, was emplaced in the upper 18 m. Three different seismic sources were used (Figure 4): an impulsive source of 250 kg, hitting vertically a steel square from a height of 3 m, to generate compressional (P) waves; two symmetric pendulum hammers, hitting horizontally a steel rectangular base pressed vertically against the soil, to produce horizontally polarized shear waves (SH).

The seismic sources triggered a data recording system measuring the travel time of the wave train from sources to receivers. The deep DH receivers consisted of three uniaxial, one vertical and two horizontal, 10 Hz geophones. Seven 14 Hz geophones, three vertical and four horizontal, were placed at the surface, to support

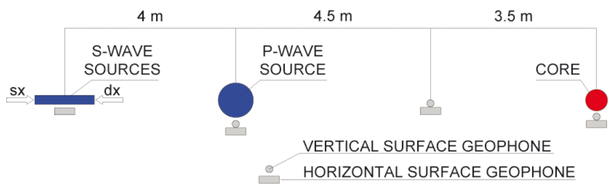

Figure 3. Schematic plan layout of the down hole seismic investigation.

Figure 4. The three sources of seismic waves energized at the surface (see text).

the rephasing correction to the recorded DH seismograms. The system recorded 2000 samples, at a sampling time interval of 0.5 m/s. The P and S waves arrival time was interpreted according to ASTM D7400-14 [2014]. The DH Deep data were acquired from the depth of 18 m down to 265 m, because of the steel casing of the uppermost part of core. An estimation of the V_S in the uppermost 18 m was derived from the closest down-hole sounding, the DH M1 (Figure 1). The latter sounding was performed in 2012 by the Regione Emilia-Romagna, about 2800 m to the north-east of the DH deep site. The two adjacent logs are in good agreement in the shared 18-30 m stratigraphic interval and therefore a reasonable level of confidence can be estimated for the interpolation of the upper 18 m of the study log. Figure 5 provides the seismograms acquired at the 265 m depth, produced by the vertical hammer blow (black line "P-wave shot") and by the horizontal hammer blows striking the anvil on the two opposite sides (red line "S-right wave shot" and blue line "S-left wave shot"). The acquired stratigraphic and geophysical data are illustrated by Figure 6.

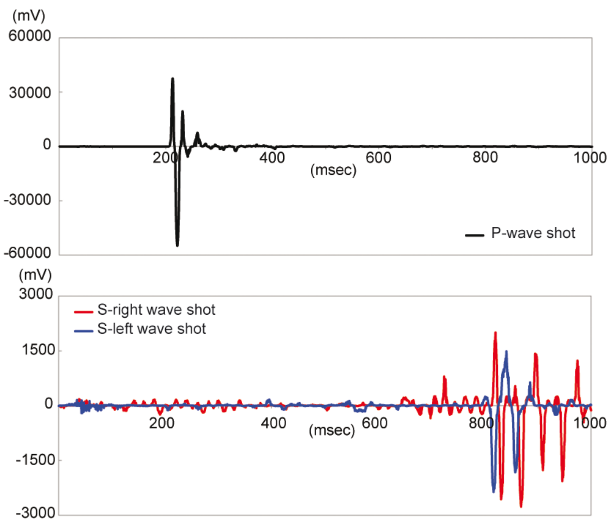

Figure 5. Seismograms acquired at 265 m from the DH deep test (Figure 6a).

4. Stratigraphy and seismic velocities

The stratigraphic succession logged in Mirabello was correlated with the V_P and V_S profiles plotted over depth at the same site (Figure 6a). The velocity logs acquired in Mirandola [Martelli and Romani 2013, Garofalo et al. 2016] were associated with our stratigraphic interpretation (Figure 6b) of the published lithology log [Regione Emilia-Romagna et al. 1998, Martelli and Romani 2013], based on our direct examination of the sediment cores and the knowledge of the regional stratigraphy framewok.

The correlation of successions drilled at Mirabello and Mirandola were based on published information, mainly deriving from the national geological mapping project (CARG) [Cibin and Segadelli 2009] and from regional geological profiles [Martelli and Romani 2013]. The logs provided also some dating evidence, particularly through ^{14}C analysis from the younger intervals. Several continuously cored logs were studied in proximity of the Mirabello drilling site, within the framework of the geological mapping project [Cibin and Segadelli 2009]. Particularly useful was the comparative analysis of the log 203/S9, providing an allostratigraphic framework of the sedimentary succession to the depth of 220 m and reaching the Lower Emiliano-Romagnolo Synthem. The succession crossed by the core 203-S9 shows thicker correlative stratigraphic units than that revealed by the Mirabello drilling (203/S9 unit bases: AES8 21 m, AES7 68 m, AES6 98 m, AESi 187 m). From the core 203/S9, significant palaeo-environmental and micropalaeontological data were derived [Fiorini and Colalongo 2009]. The stratigraphic interpretation and dating of the upper portion of the study drilling was improved by the correlation with other two adjacent logs, the 203-S6 and the 203-S13 (Figure 1) reaching the depth of 34 and 68 m respectively. The correlation with the section cored at Mirandola has been based on our direct sedimentological and stratigraphical examination of the continuous cores, on the published lithological logs [Martelli and Romani 2013], and on the correlation with published stratigraphic profiles [Pao-lucci et al. 2015].

The regional correlation demonstrates that the Mirabello drilling crossed the entire Upper Emiliano-Romagnolo Synthem and Lower Emiliano Romagnolo Synthem and a large portion of the Marine Quaternary. Within the succession, each subsynthem has an average thickness of about 35 m and shows a similar internal organization. The drilled succession records a globally shal-

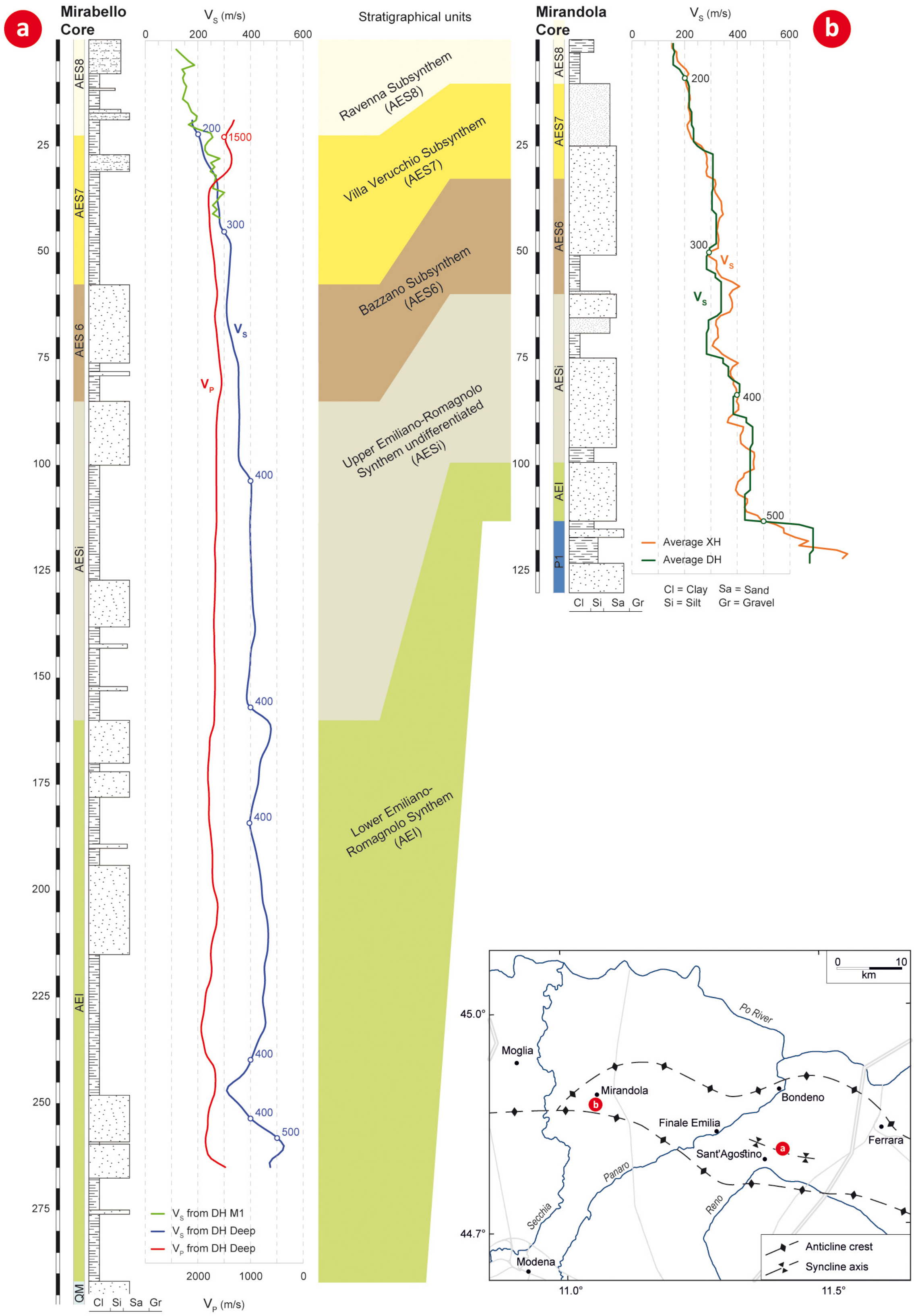

Figure 6. Stratigraphic column and seismic velocity logs from the Mirabello (a) and Mirandola (b) sites. The map shows the location of the two log sites and a schematic representation of the main syncline and anticline axis in the region.

lowing evolution, from marine environments to alluvial plain systems, spanning over a time period of roughly 600,000 years.

The stratigraphic organization correlates with the measured velocity values. The V_P log (Figure 6a) confirms the presence of fully water saturated deposits between 18 m and 265 m, providing an average value of 1500-2000 m/s through the investigated depth. The V_S increases gradually with depth, from 116-200 m/s, in the Ravenna Subsynthem, to 310-525 m/s, in the Lower

Emiliano-Romagnolo Synthem (Table 1).

In the Mirabello succession, the Ravenna Subsynthem AES8 frames the first 22 m of subsoil and consists of outcropping Reno river sands, soft organic-rich marsh muds, with very low S-wave velocities, and older pedogenized continental silts, showing comparatively higher V_S values. Fine-grained sediments dominate the Villa Verrucchio Subsynthem AES7 (23-58 m), associated with some fluvial sand intercalations, deposited by Apennine rivers. The AES7 unit top is associated with a sharp increase of the S-wave velocities, while at the lower portion of the unit a further V_S increase is recorded, probably associated to pedogenized levels enriched in carbonate concretions. Thick bodies of fluvial sands deposited by the Po River [Cibin and Segadelli 2009] dominate the Bazzano Subsynthem AES6 (59-85 m), but finer-grained sediments are nevertheless well developed in the lower portion of the unit. The underlying AESi unit (86-162 m) consists of two transgressive-regressive cycles, separated, at about 127 m, by a transgressive surface. Foraminifera, palecypod bioclasts and gastropods (*Turritella*) were sampled from the marine portions of the unit. The lower part of the upper cycle (105-127 m) is associated to a further increase of the S-wave velocity. At about 161 m, the study well crossed the top of the AEI Synthem. The synthem consists of thick sandy or argillaceous bodies, deposited into marine, deltaic and alluvial plain environments. The fine-grained unit below 210 m correlates with a marine interval preserving infralittoral zone foraminifera [Fiorini and Colalongo 2009]. The unconformity marking the unit top correlates with a sharp increase of the V_S values, almost reaching 500 m/s. Few further peaks of V_S are associated to underlying thick layers of sand (160-165 m and 255-260 m). The AEI unit contains biogenic methane that could have affected the lowering of both V_P and V_S values, at depths between 235 and 260 m.

The correlative anticline succession of Mirandola is much thinner than the Mirabello one. From the previously described correlation, we can confidently assume that AES unit is about 100 m thick, is enriched in fluvial sands, and lacks any marine influence. The succession nevertheless records S-wave velocity trends and values [Garofalo et al. 2016] similar to the Mirabello ones (Table 1, Figure 6a). The correlation between the AEI unit in Mirabello and the pebbly sands drilled at Mirandola (Figure 6b) below 100 m, showing clasts of Palaeozoic acidic volcanites with porphyric structures, is uncertain. The lowermost portion of the Mirandola succession, underlying a sharp unconformity surface, was ascribed to the Lower Pliocene [Paolucci et al. 2015, Tarabusi and Caputo 2016]. This unit consists of lithified turbiditic sands, clays and marls, deposited into deep

Unit	Mirabello	Mirandola
AES8	116 – 200 (161)	158 – 213 (174)
AES7	207 – 326 (281)	218 – 308 (251)
AES6	310 – 356 (334)	284 – 339 (312)
AESi	355 – 464 (394)	284 – 460 (375)
AEI	310 – 525 (434)	430 – 449 (439)

Table 1. V_S values (m/s) measured within correlative stratigraphic units in the syncline site of Mirabello (Figure 6a) and in the anticline succession of Mirandola (Figure 6b). For each stratigraphic interval, the lowest, highest, and average values are indicated.

marine environments, and shows the highest V_S values, above 600 m/s [Garofalo et al. 2016]. These are the highest values recorded from the study successions, but they are still lower than the values officially assumed for the "seismic bedrock" [EN 1998-5 2004, NTC 2008].

5. Discussions and conclusions

The deep down-hole test performed in Mirabello, reaching a depth of more than 250 m below surface, has provided a unique deep seismic log from a tectonic active syncline area of the Apennine Foredeep Basin. No direct V_S measurements deeper than 50 m were previously available in the syncline areas affected by the 2012 Emilia earthquakes. The new log, integrated by the correlation with the previous logs available in the region, supports a well constrained seismo-stratigraphic model of the interval spanning from the Lower Emiliano-Romagnolo Synthem to the Recent outcropping sediments (Figure 6). A good correlation is visible between the shear wave velocity distribution and the stratigraphic organization of the depositional succession. Stratigraphic discordance surfaces are related to sharp increases in the V_S values, particularly at the boundary between the Lower and Upper Emiliano-Romagnolo Synthems. The logs from the syncline area of Mirabello was correlated with the thinner succession of Mirandola, deposited into an anticline area. Mirandola was the only site in the Emilia-Romagna Region where direct V_S measurements were previously available from a deep level, and where down-hole and cross hole tests were performed and validated by different international research groups [Garofalo et al. 2016].

Correlatable units in the Mirabello and Mirandola boreholes show very similar S-wave velocity trends and values (Table 1, Figure 6a,b). The good agreement confirms the reliability of the deep down-hole interpretation at the Mirabello site. The small variations detectable between the two logs can be explained considering both the variation in sedimentary facies and lithologies and the different effective stresses of the Mirabello and Mirandola subsoils. The stronger compaction affecting the deeper argillaceous intervals at Mirabello influences the development of V_S values similar to those recorded in correlative coarser grained intervals preserved at shallower level in the Mirandola succession.

The average seismic values recorded in Mirabello can be extrapolated with some confidence to the widespread syncline successions, through large portions of the alluvial plain. The new dataset here provided can support the definition of the input parameters for the seismic response analyses in similar Emilia-Romagna stratigraphic context, characterized by the absence of deep V_S profile and the presence of a deep seismic bedrock.

Neither the Mirabello log nor the Mirandola one reached a V_S value of 800 m/s, which officially defines the "seismic bedrock" into the European Building Code [EN 1998-5 2004] and the Italian building code [NTC 2008]. Some extra investigation, based on indirect surface approaches, as large 2D passive seismic arrays [e.g. Di Giulio et al. 2016], can be useful to obtain deeper velocity profiles, which, even if less accurate [Garofalo et al. 2016], will integrate the provided direct seismic velocity measures, supporting a better constrained and more reliable ground response analysis.

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