P-wave velocity, density and vertical stress magnitude along the crustal Po Plain (northern Italy) from sonic log drilling data

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Abstract

In order to better characterize P-wave velocities for the shallow crust of the Po Plain and surrounding regions, we have selected 64 deep wells mainly located in the plain and also along the Apennine belt and Adriatic coast. In particular, we have analyzed the stratigraphic profiles for all wells, and the available sonic logs (37 out of 64). From these data we have examinated the P-wave velocity trend with depth and estimated rock density following an empirical relationship between sonic velocity and density in sedimentary rocks. Then we have calculated, notably for the first time in a large area of Italy, the overburden stress magnitude for each well. For instance at a depth of 5 km we have found values varying from 105 to 130 MPa moving from the Adriatic coast to the Apennine belt. Consequently, the Apennines belt shows a maximum regional lithostatic gradient of around 26 MPa/km while the Po Plain and Adriatic region have values of around 21 MPa/km. The maximum density value that can be considered for the Apennine crustal belt corresponds to 2.65 g/cm^3; in the Po Plain the mean density is around 2.25 g/cm^3, while in the Adriatic area the average density has the lowest value in the region at 2.13 g/cm^3. Although in this area a 2D crustal P-wave velocity model does not adequately constrain the complicated and uneven tectonics, we have nevertheless established a shallow model consisting of five separate layers. The strength of this paper lies in the possible use of these direct data, together with other derived geological and geophysical information, to build a 3D model of the area.

Keywords: Europe; downhole method; body wave; crustal structure; seismicity and tectonics

1. Introduction

The Po Plain is a wide territory in northern Italy extending approximately 650 km in an E-W direction, with an area of more than 40 000 km^2. It is covered by recent alluvial deposits and up to 8 km of terrigenous Plio-Pleistocene sediments originating from both the Alpine and Apennine belts (Fig. 1). Compressional tectonic phases from Miocene to Quaternary times reduced the area of the Po Plain producing asymmetric folds overthrust towards the north involving both terrigenous sedimentary cover and the underlying Meso-Cenozoic carbonate sequence (Ghelardoni 1965; Pieri & Groppi 1981).

Present-day stress indicators derived from earthquake focal solutions, borehole breakouts and fault data, and morphological evidence from the Po Plain-Adriatic area are consistent with an active compression oriented from NNW to NNE that follows the geometry of the arc structure (Burrato *et al.* 2003; Montone & Mariucci 1999; Montone *et al.* 2012; Perotti 1991; Pierdominici *et al.* 2005; Pieri & Groppi 1981; Selvaggi *et al.* 2001). Locally, the strike–slip kinematics has been recognized and interpreted as being due to the presence of lateral ramps bordering the compressive arcs (Fig. 1).

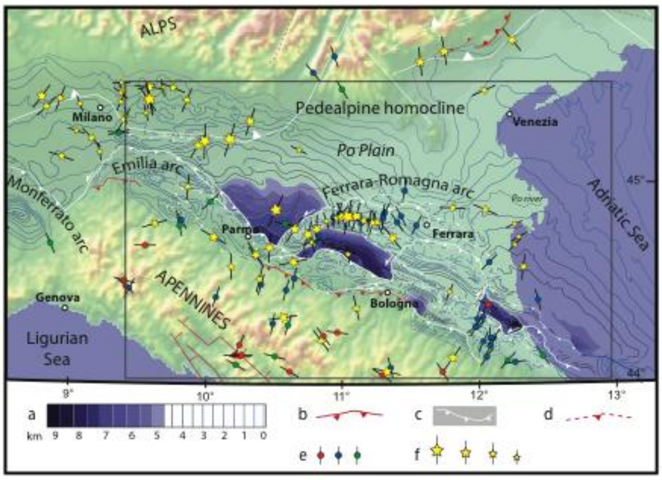

Figure 1. Schematic structural setting of the study area (Barberi and Scandone 1983). The orientation of maximum horizontal stress from present-day stress indicators is indicated on map (Montone *et al.* 2012; Scognamiglio *et al.* 2012; QRCMT database, http://autorcmt.bo.ingv.it/quicks.html). a) Isobaths of the base of Pliocene; b) emergent active faults; c) blind active faults; d) inferred active faults; e) maximum horizontal stress orientation from earthquake focal mechanisms of M≥5.0 (red = normal faulting, blue = thrust faulting, green = strike-slip faulting); f) maximum horizontal stress orientation from borehole breakouts (scaled by quality from the best to the worst); grey rectangle is the study area of Figure 2.

The broad width, abundant sedimentary cover and articulated geometry of the buried tectonic structures make the Po Plain an unusual area for seismological studies. Specifically, the definition of a reliable crustal velocity model is very useful in this area where site amplification effects can reach very high levels during large shaking. In this region the use of geological data seems to be crucial in defining a crustal velocity model, and several attempts have been undertaken in order to better constrain it. Crustal velocity models have been recently proposed (Malagnini *et al.* 2012; Vuan *et al.* 2011) using geological information gathered mainly from seismic profiles recorded by oil companies and during deep seismic sounding experiments. These models allow a better characterization of wave propagation and ground motion, and also enable better earthquake location and focal mechanism computations.

The large number of available deep wells drilled by petroleum companies although not homogeneously distributed in the Po Plain can contribute to the determination of some of the main seismological and petrophysical parameters of the crust that can then be used to build a velocity model for the upper 6-7 km of the crust. Moreover, we have noted that data directly related to P-wave velocity (Vp) do not exist with the exception of those inferred from seismic reflection profiles (on both local and regional scales) and rock density data measured in the laboratory.

In this paper we consider 64 deep wells, from 9.5° to 13°E and between 44° and 45.5°N, mainly located on the Po Plain and also along the northern Apennine belt and Adriatic coast (Table 1 and Fig. 2). Data from all wells include information relative to the stratigraphy and physical properties deduced from down-hole logs such as resistivity and gamma ray. In particular, 37 wells (Fig. 2, black stars) have also sonic log curves that display P-wave travel-times versus depth. Comparing the stratigraphy of these latter wells with the stratigraphy of the 27 remaining wells, we have retrieved P-wave velocity at depth for the complete data set (64 wells). From P-wave velocity, we have estimated the rock densities of the sequence crossed by each well and, finally, have used the densities to determine, for the first time, the vertical stress magnitudes from the surface down to a maximum depth of ~7 km.

First we illustrate the method and formulas; then we present the results in terms of homogeneous areas and compare our velocity and density values with published data. Then, we illustrate the trend of lithostatic gradient and discuss the results primarily concerning differences found among the deep wells from the Apennine belt and Po Plain. Finally, we propose a possible crustal velocity model that takes into account the tectonic setting of the area.

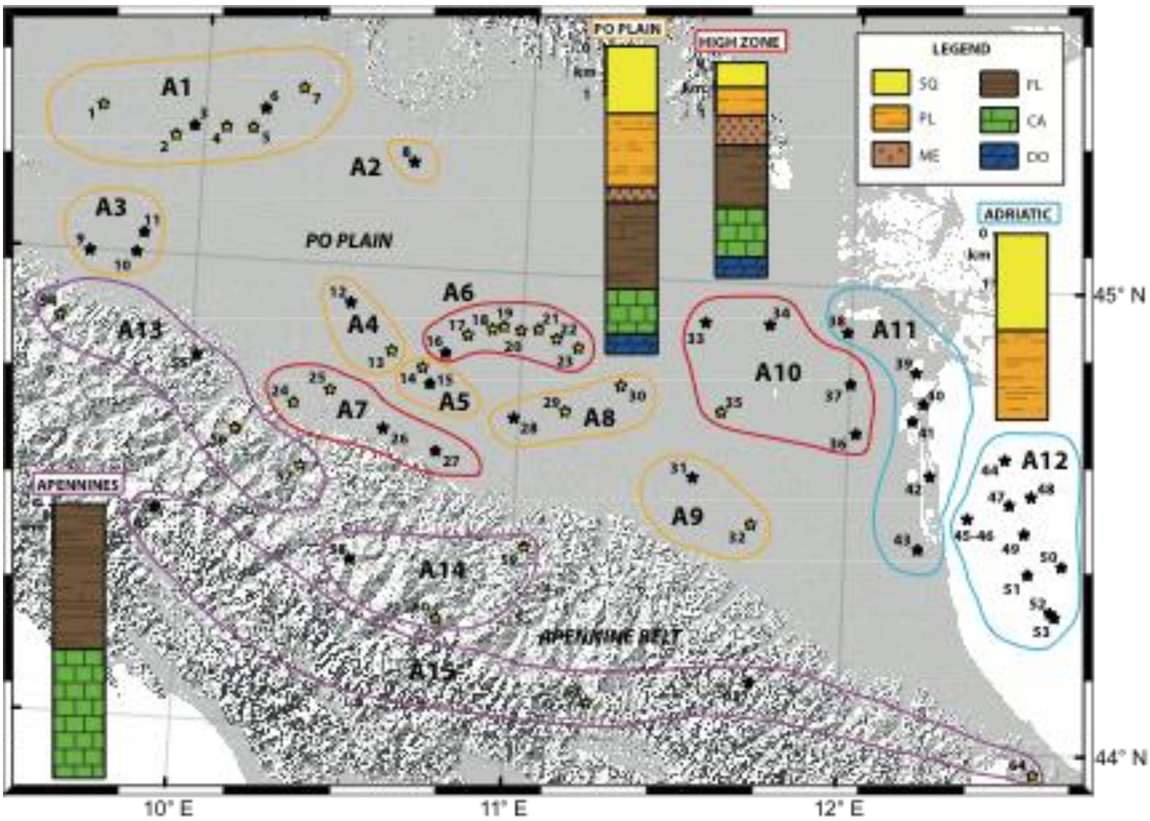

Figure 2. Well location (from 1 to 64) and groups (from A1 to A15). Black stars indicate wells with sonic logs. The four schematic stratigraphy columns show the average thickness of lithology-groups (see definition in paragraph 3 of Methods): Po Plain (A1 to A5, A8 and A9 groups); high zone (A6, A7 and A10 groups); Adriatic (A11 and A12 groups); Apennines (A13 to A15 groups). Legend: SQ Quaternary sedimentary sequence; PL Pliocene sequence; ME Messinian sequence; FL Flysch unit; CA Meso-Cenozoic calcareous and marly sequences; DO Triassic dolomite sequence.

Table 1. List of wells

Id	Area	Lat N	Lon E	m asl	Depth
1	P	45.31	9.69	74	2600
2	P	45.26	9.91	62	2489
3	P	45.28	9.97	63	2030
4	P	45.28	10.07	53	2936
5	P	45.28	10.15	55	3600
6	P	45.33	10.18	58	2400
7	P	45.38	10.30	73	6704
8	P	45.23	10.65	32	5312
9	P	45.00	9.67	83	2250
10	P	45.00	9.81	58	3880
11	P	45.04	9.83	43	2649
12	P	44.92	10.47	25	5446
13	P	44.82	10.61	25	6513
14	P	44.79	10.70	31	5046
15	P	44.75	10.73	35	1493
16	P	44.83	10.78	25	4686
17	P	44.86	10.84	20	4546
18	P	44.88	10.91	19	5510
19	P	44.88	10.94	18	4156
20	P	44.88	11.00	19	3230
21	P	44.88	11.05	18	5000
22	P	44.86	11.10	20	3336
23	P	44.84	11.17	18	2948
24	P	44.70	10.32	146	3109
25	P	44.73	10.43	76	3334
26	P	44.65	10.59	107	2727
27	P	44.61	10.75	97	1527
28	P	44.69	10.99	26	3985
29	P	44.71	11.14	20	3700
30	P	44.77	11.31	16	4280
31	P	44.58	11.53	16	3820
32	P	44.48	11.71	13	3600
33	P	44.91	11.56	8	3419
34	P	44.91	11.75	2	3486
35	P	44.72	11.61	9	3500
36	P	44.69	12.03	-3	1503
37	P	44.79	12.00	-2	2456
38	P	44.90	11.99	-2	6118
39	P	44.82	12.20	0	3660
40	P	44.75	12.23	-1	4600
41	P	44.71	12.20	-1	4185
42	P	44.60	12.25	1	4416
43	P	44.44	12.22	0	3080
44	sea	44.64	12.48		3725
45	sea	44.51	12.37		4946
46	sea	44.51	12.37		3093
47	sea	44.54	12.50		4385
48	sea	44.56	12.56		3900
49	sea	44.48	12.55		4360
50	sea	44.41	12.66		4300
51	sea	44.39	12.56		3259
52	sea	44.31	12.63		3895
53	sea	44.30	12.64		4359
54	AP	44.86	9.60	450	2721
55	AP	44.79	10.02	279	2510
56	AP	44.64	10.15	525	3603
57	AP	44.56	10.35	500	2040
58	AP	44.37	10.51	771	3319
59	AP	44.41	11.04	252	4202
60	AP	44.25	10.78	725	2832
61	AP	44.45	9.92	942	5811
62	AP	44.08	11.25	665	7810
63	AP	44.14	11.73	530	5062
64	AP	43.95	12.59	65	5130

P= Po Plain; AP= Apennines;
m asl= meters above sea level
depth= total well depth

2. Seismotectonic background

At a large scale, the northern Apennine fold and thrust belt is the result of convergence between the African and European plates that has occurred since the Late Cretaceous (e.g., Robertson & Grasso 1995) and developed prevalently in the Neogene. Its tectonic evolution is due to the migration of deformation from west to east toward the Adriatic foreland domain, as a consequence of the retreating subduction of the NW-W dipping Adria microplate (Doglioni 1991; Faccenna *et al.* 2003; Jolivet *et al.* 1998; Malinverno & Ryan 1986; Patacca *et al.* 1990). In this context, extension in the western part of the belt (i.e., the Toscana region) and compression in the east have been active contemporaneously and migrated toward the foreland, from Late Miocene to Recent (among many others: Carmignani & Kligfield 1990; Elter *et al.* 1975; Frepoli & Amato 1997; Lavecchia *et al.* 1994; Mariucci *et al.* 1999). This extensional-compressional pairing is nowadays well defined and recognizable through earthquake focal mechanisms and the distribution of other present-day stress data (Fig. 1).

In particular, the study area is defined by the southern alpine folds in the north, the Pedealpine Homocline in the central part, and in the south by three main buried folded arcs: the Monferrato, Emilia and Ferrara-Romagna arcs (Fig. 1). They represent, at a broad scale, the northernmost portion of the external northern Apennines arc, whereas at a regional scale their internal structure is complicated by the presence of minor arcs. Along the structure of Ferrara-Romagna, three relatively minor groups can be identified: the Ferrara, Romagna and, more to the east, Adriatic folds (along the Adriatic coast and off-shore). As previously mentioned, the main geological peculiarity of the Po Plain is the considerable thickness of Plio-Quaternary hemipelagites and turbidites and recent alluvial deposits.

The subsurface position of the front of the northern Apennines accretionary prism has been defined only in the last three decades when the intense petroleum exploration undertaken by AGIP (now Eni S.p.A.) used seismic data and deep wells to constrain its complicated geometry (Pieri & Groppi 1981). Late-Oligocene to Plio-Pleistocene compressional tectonic phases have produced asymmetric folds overthrust towards the N and NE, involving both the terrigenous sedimentary cover and the Mesozoic carbonate sequence (i.e., Ghelardoni 1965). Detailed studies of the present-day stress field along the external margin of the northern Apennines have added new information concerning the buried front beneath the sedimentary cover of the Po Plain, although the activity of the system from the Middle Pleistocene to the Present is still debated (Benedetti *et al.* 2003; Bertotti *et al.* 1997; Boccaletti & Martelli 2004; Fantoni & Franciosi 2010). Available geophysical and geological data actually indicate that the Late Quaternary activity of the buried thrust-related folds is centered beneath the Po Plain, as documented by GPS data and by historical and instrumental seismicity, indicating that flexural retreat of the subducting lithosphere in these areas is still active (Malinverno & Ryan 1986; Patacca & Scandone 1989; Doglioni *et al.* 1999).

As briefly mentioned previously, ongoing kinematics is mainly constrained by earthquakes: seismicity is concentrated along the pede-Apennine trust front, but it is also scattered along the outer thrust fronts of the Po Plain (Cocco *et al.* 1993; Frepoli & Amato 1997; Gasparini *et al.* 1985; Selvaggi *et al.* 2001). In particular, the 2012 seismic sequence (for a complete discussion see volume edited by Anzidei *et al.* 2012) that hit the Emilia-Romagna area occurred along the Ferrara arc at depths between 0 and 10 km. Earthquake focal mechanisms show compressional kinematics with E–W oriented nodal planes, suggesting that two south-dipping blind thrusts were activated during the ML 5.9 and ML 5.8 mainshocks (Emergeo Working Group 2012 and 2013; Pondrelli *et al.* 2012; Scognamiglio *et al.* 2012) and confirming the activity of the external buried fronts (e.g., Boccaletti & Martelli 2004; Burrato *et al.* 2003; Montone & Mariucci 1999).

In fact, active compression in the area is well defined by thrust focal mechanisms with ~N-S oriented P axes (see the blue symbols of earthquakes in Fig. 1). The same pattern is also documented by several breakout data that although less regular are either parallel to this trend or locally follow the geometry of the structures, suggesting a tectonic structural control on the orientation of stress (see the maximum horizontal stress orientations from the borehole breakout analysis in Fig. 1). Close to this area, contemporaneously active extension predominates along the Apennine belt, with normal-faulting focal mechanisms (see the red symbols for earthquakes in Fig. 1) characterized by N-S to NE-SW extension for earthquakes, borehole breakouts and active fault data (in Fig. 1 ~E-W and NW-SE maximum horizontal stress orientations).

3. Methods

In order to infer the *in situ* Vp at depth in the various stratigraphic units of the Po Plain and surrounding regions using sonic log data, we have selected 64 deep wells from different zones within the plain, along the Apennine belt and Adriatic coast. Table 1 summarizes the well information (locations, elevations, and depths) ordered by latitude from north to south.

The borehole sonic instrument contains one or more transmitters that emit high-frequency (generally 20-24 kHz) acoustic waves travelling through the formation to two or more receivers that record full waveforms. The difference in the arrival times of the sonic wave trains recorded by the detectors is then used to determine the sonic velocity. Travel time, or slowness, usually is reported on the logs in microseconds per foot and typical scale for sedimentary rocks ranges from 40 to 140 μs/ft (Fig. 3). Slowness can be used to obtain the velocity of elastic waves through the formation. Sonic logs provide information to calibrate seismic data and to derive porosity, but also can be used to identify fractures, compaction and over-pressure zones. For example, the gas presence is shown on the sonic log by an increase in slowness corresponding to a drop in sonic velocity (Fig. 3). The sonic tool has a small depth of penetration (2.5 to 25 cm) and works at a higher frequency than seismic waves, therefore direct comparisons with seismic data must be done carefully. Nevertheless, a borehole sonic tool is one of the most important tools for in situ measurements of rock physical properties at depth.

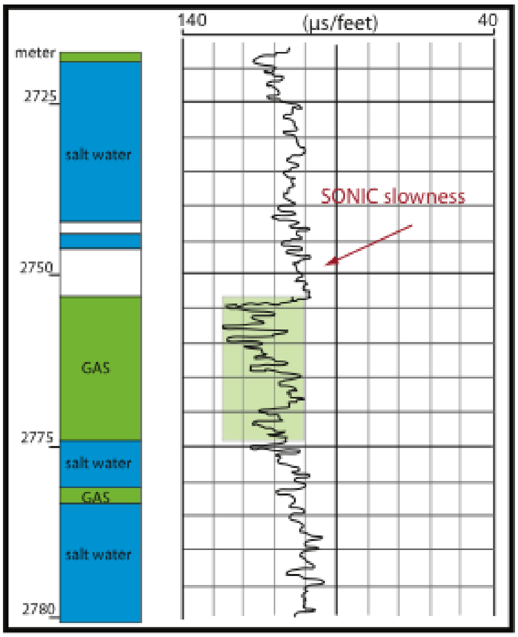

Figure 3. Effect of the gas presence on the sonic curve (slowness) along a well.

We have analyzed the available sonic logs, from 37 out of 64 wells, with a total length of more than 100 km. We have split each well into several intervals that correspond to zones of homogeneous values on the sonic log, assigning a quality value to each interval. Then we have associated these "homogeneous sonic intervals" to actual stratigraphic units; in the 27 wells where sonic log data were missing, we have estimated sonic values from those found in the nearest wells, in the same stratigraphic units and at similar depths.

We have estimated rock density following the empirical relationship between sonic velocity and density proposed by Gardner *et al.* (1974), based on borehole measurements:

$$\rho = d \cdot V_p^{\ f} \qquad (1)$$

where ρ is density in g/cm^3, Vp is the sonic velocity in km/s, d=1.74 and f=0.25

This rule, derived for sedimentary rocks, is valid for $1.5 < Vp < 6.1$ km/s. We have verified that, using different values of d and f coefficients (Castagna *et al.* 1993) associated to different lithologies, as reported in Table 7.10.1 of Mavko *et al.* (2009), density does not vary significantly. Taking into account the geological features of the study area and the recent consideration reported in Brocher (2005) and Mavko *et al.* (2009) we consider that the equation (1) provides a good estimation of densities for the stratigraphic sequence. Applying this velocity-density relation, we have obtained density values for each homogeneous sonic interval (in all the wells) and then associated them with each stratigraphic unit.

Based on the lithologies and time intervals, we have organized the ~40 stratigraphic units recognized in the wells into eight "lithogroups". The most recent is the Quaternary sedimentary sequence (SQ) composed of alluvial deposits, clays, silts and sands characterized by high water content and low compaction (e.g., alluvial sediments, Sabbie di Asti, Ravenna Fm.). The Pliocene group (PL) is mainly characterized by clay, silt and sand (e.g., Argille del Santerno, Portocorsini Fm. and Garibaldi Fm.); the Messinian group (ME) consists of sand, clay and sandstone with gypsum (e.g., Gessoso-Solfifera and Colombacci Fms.). The Flysch group (FL) consists of syn- and post-orogenic terrigeneous sequences (e.g., Marne di Gallare, Marnoso-Arenacea and Cervarola unit); the CA group is composed of the Meso-Cenozoic calcareous and marly sequences (e.g., Scaglia and Maiolica Fms.). The DO group mainly consists of Triassic dolomite; the Triassic Volcanic group (VU) and metamorphic basement (TT) complete the lithogroups.

In Fig. 2 we present four schematic stratigraphy columns (Po Plain, Po Plain-high zone, Adriatic and Apennines) with the average thickness of the lithogroups, showing the complex geological variability within the studied area. We do not include the VU and TT lithogroups because they are only occasionally present in the wells considered here.

4. Data and Results

We have organized *a priori* the wells into 15 groups mainly considering homogeneous geological and structural characteristics (Figs. 1 and 2) only to describe the results more easily. Besides the above criteria we have grouped the wells considering also: areal distribution, well data presence and easier viewing of diagrams (Fig. 4). This grouping has not been used for further considerations and models.

The diagrams in Fig. 4 show Vp versus depth for all wells, each Vp value is relative to a different thickness and plotted at the bottom depth. The wells all show Vp to be around 2 km/s at ground level, with the exception of well 8 (A2 group), which presents a lower velocity of 1.5 km/s, and the wells within the Apennines that start with velocities higher than 2 km/s (e.g., group A14, 3.5 km/s).

A brief description of each group is presented below (see Fig. 4 and also Fig. 2). Group A1 has Vp ≤ 4.5 km/s up to a depth of 4000 m. A rapid increase in Vp below 6000 m, from 4 km/s to greater than 6 km/s, is recognizable for the deep well 7. Group A2 (just one well) has a variable trend with a low velocity zone at a depth of about 5 km (from 6.5 to 3 km/s), due to the Triassic volcanic units (VU) underlying the Triassic Dolomia Principale Fm (DO). Wells in group A3 have different trends: in well 9, the increase of Vp with depth is more rapid than in wells 10 and 11. The maximum Vp value is slightly higher than 5 km/s around 2700 m, but in general the velocity is less than 5 km/s up to 4000 m. Group A3 includes wells close each other but with different geological characters: from the top down to 2000 m depth, well 9 has FL lithogroup (with Vp higher) while wells 10 and 11 have SQ and PL lithogroups (with Vp lower). In particular, the Vp trend of well 11, characterized by small velocity inversions around 3000 m, is related to gas presence as evidenced in the well log. Group A4, located in an area of deep Plio-Pleistocene fill, shows a small increase of Vp with depth, which is less than 5 km/s up to 6500 m. The Vp trend is in agreement with the well stratigraphy characterized by sand and clay sequence. The maximum value of Vp in group A5 is about 5 km/s at depths >4600 m to 5000 m associated to the boundary between Flysch and Calcareous lithogroups. Velocities of group A6 clearly define the different depths (from about 2500 to 5500 m) of the top of the Scaglia and Maiolica Fms. (belonging to CA lithogroup) with Vp around 4.3 km/s and 5km/s, respectively, and the Triassic dolomite top (DO lithogroup) with Vp around 6 km/s. Group A7 shows a quick increase in Vp up to about 4.5 km/s, from

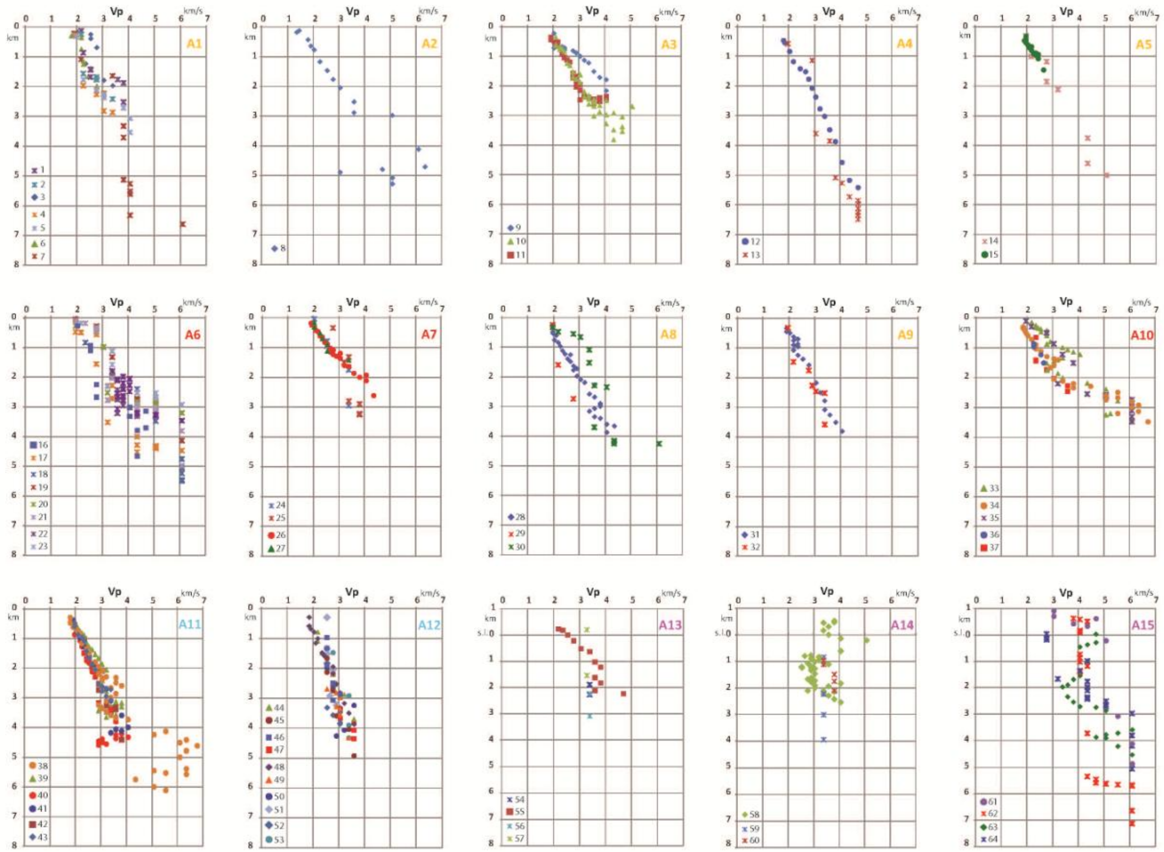

Figure 4. P-wave velocity (Vp) versus depth of all the study wells grouped as in Figure 2. Diagram labels: Po Plain in orange, Po Plain-high zone in red, Adriatic in cyan and Apennines in purple. Each data point is relative to a different rock thickness and plotted at the bottom depth of the interval. Plain symbols refer to direct sonic log data, star and cross symbols to indirect data (retrieved from the nearest wells).

around 2100 to 2600 m; some velocity variations at greater depth are related to the succession of different lithologies. Groups A8 and A9 have similar trends of Vp. Wells in A8 have the maximum value of about 4.5 km/s up to 4300 m, except in a short interval that arrives at a velocity of 6 km/s around 4200 m. A low velocity zone can be identified at about 3000 m associated to the sequence of different lithologies as group A7. Group A9 has a homogeneous trend with Vp a little higher than 4 km/s from about 3500 to 3800 m. The trend variability is related to the succession of sand and clay in the crossed stratigraphic units. Velocities of group A10, located in a structural high zone, rapidly increase up to 6.8 km/s below 3000 m; the velocity variations observable around 1500 m (wells 33 and 34) are related to the boundary between two different units belonging to the Flysch lithogroup: the upper one with a more arenaceous composition with respect to the lower which is mainly clayey. Group A11 shows variable Vp, particularly evident at depth. Within well 38, Vp is 5.5 km/s around 4000 m and reaches a maximum value of 6.8 km/s around 4500 m; it then decreases to about 5.5 km/s. The two main velocity decreases occur at around 5400 and 5600 m in correspondence of the boundaries Dolomite (DO) - Volcanic (VU) lithogroups and Dolomite (DO) - Metamorphic (TT) lithogroups, respectively. The maximum Vp value of all the other wells is slightly more than 4 km/s from around 3800 m. Well 40 also shows a low velocity zone (from 4 to 2.9 km/s) around 4500 m related to lithological variations within the stratigraphic unit. It is worth pointing out the marked differences among the neighboring groups A10, A11, and A12 that show the changes from the inner Po Plain to the coast and offshore. As already mentioned, the groups located in the Apennines have higher Vp values than the other groups, starting from the ground level. A13 mostly has maximum velocities around 3.5 km/s up to 3000 m, with an exception of ~4.5 km/s starting from about 2000 m. Group A14 has an unusual trend, with a velocity inversion around 1000 m (below the ground) from a maximum Vp a little higher than 5 km/s to almost 2.5 km/s related to a frequent succession of different lithologies. Also in group A15 there are peculiar velocity inversions found at several depth intervals with the maximum Vp a little more than 6 km/s at different depths, from around 3000 m to more than 7000 m. The velocity variation (well 63) at 2000 m is inside the Marnoso Arenacea Fm (Flysch lithogroup); at depth around 4000 m the variation is related to the boundary between calcareous and marly formations (both belonging to CA group). Minor Vp variations are related to tectonic contacts and gas pockets, especially in the first 2000 m.

In summary, Vp generally increases with depth and in correspondence of stratigraphic boundaries through steps not always considerable. Some low velocity zones have been recognized, as for instance at depth >3 km (depending on well location) where an inversion of Vp is evident in some wells. These velocity zones can be linked first to different lithologies, then to the occurrence of gas (Fig. 3) and finally to the presence of main faults characterized, for instance, by layers with microcrystalline calcite. In general, in wells located in the belt or on structural highs, Vp rapidly increases with depth, whereas in wells from the Adriatic offshore, or where thick Plio-Pleistocene sediments are present, a slow rise has been found. In particular, on structural highs an increase in Vp is observed between 2500-4500 m related to the different position at depth of the top of the carbonate multilayer (i.e., diagram A6 along the Ferrara-Romagna arc). Depending on the area, at ~4000 m depth, Vp is equal or slightly greater than 4 km/s; Vp values of around 6 km/s are reached only along the Apennine belt or in structural highs.

We have plotted the empirical cumulative distribution of Vp, and derived density, obtained in the different wells and assembled it for the lithogroups (Figs 5 and 6) to define the variability of these parameters within each group. Table 2 shows Vp and density values at the 50°, 10° and 90° percentiles for each lithogroup. Taking into account the median values and the range between the 10° and 90° percentiles, with the exception of minor representative groups like TT and VU, Vp are more homogeneous for those groups with less internal variability in composition (Fig. 5). This can be observed in SQ, DO and ME groups, whereas in the carbonate sequence (CA) or in the Pliocene sequence (PL), composed of different lithologies and content of fluids, the variability is higher.

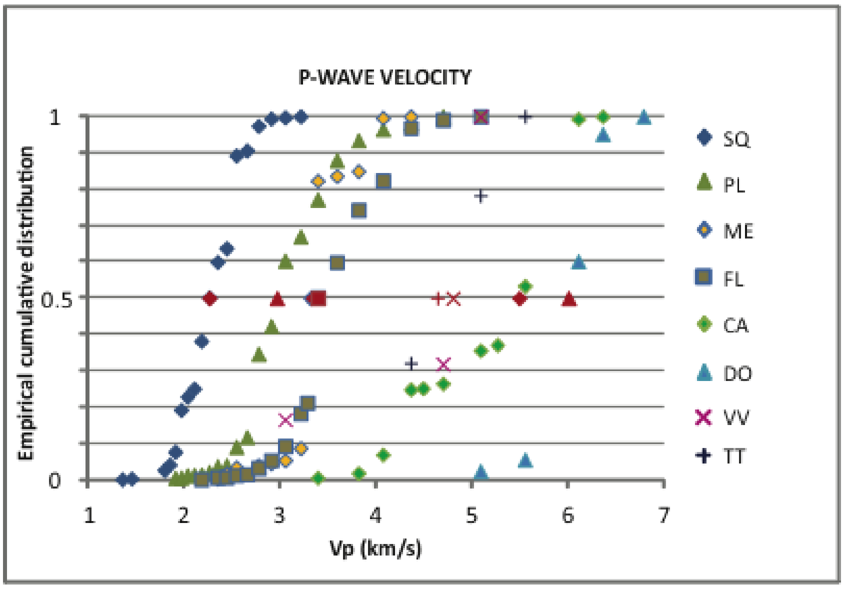

Figure 5. Cumulative curves of P-wave velocity (Vp) values within each lithogroup (see text for lithogroup description). The median velocity values (50° percentile) and their variability (10°-90° percentile) for each lithogroup are shown in Table 2.

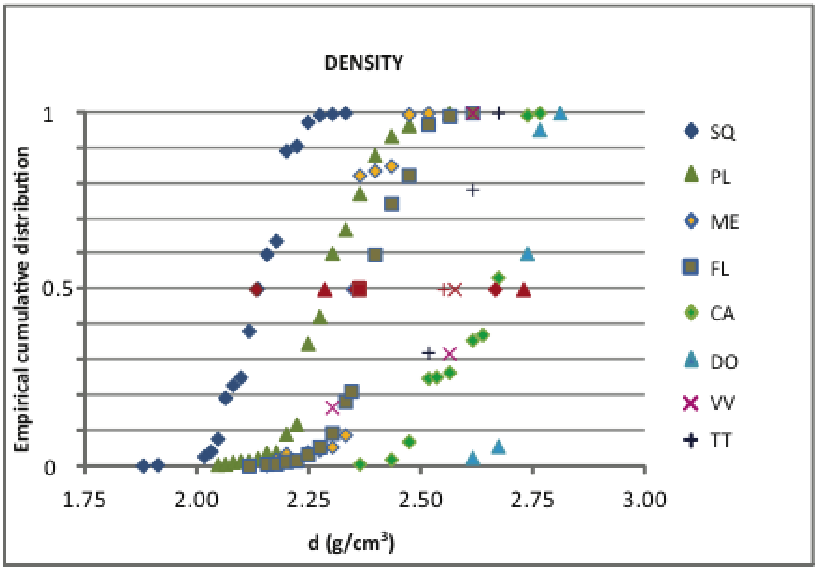

Figure 6. Cumulative curves of density values, derived from Vp, within each lithogroup (see text for description). The median density values (50° percentile) and their variability (10°-90° percentile) for each lithogroup are shown in Table 2.

Table 2. Vp and density values for lithology groups

lithogroup	V	D
SQ	**2.26** (1.92-2.60)	**2.13** (2.05-2.21)
PL	**2.96** (2.56-3.67)	**2.28** (2.21-2.41)
ME	**3.31** (3.21-3.90)	**2.35** (2.33-2.44)
FL	**3.39** (3.06-4.21)	**2.36** (2.30-2.49)
CA	**5.48** (4.11-5.99)	**2.66** (2.48-2.73)
DO	**6.00** (5.59-6.31)	**2.73** (2.68-2.76)
VU	**4.79** (3.05-5.02)	**2.57** (2.30-2.60)
TT	**4.63** (4.35-5.32)	**2.55** (2.51-2.64)

V: P-wave velocity (km/s); D: density (g/cm^3). In bold the median value and in brackets 10°-90° percentile of the cumulative distribution. For lithogroup label and description see text.

Fig. 7 shows the relationship between Vp and depth within each lithogroup. Note that the great variability in Vp and density (Figs 7 and 8) within the same lithogroup is relative both to the depth and other factors (e.g., variations in composition or fluid content) as also discussed below. On the contrary, where the lithology is prevalently the same, Vp value is constant at different depths: for instance, we have observed that a uniform DO sequence shows the same sonic velocity for the whole stratigraphic interval. As density is derived from Vp, we are not able to highlight density variations due to factors affecting it in a different way than Vp. Principally group FL exhibits significant variability at the same depth as a result of its various lithologies with different characters: that mainly occurs in the Apennine wells, where the FL lithogroup is the major component in the first few kilometers (Fig. 2). Of course for some lithogroups (i.e., VU and TT), data are sparse and not representative, even if we expect a low variability, as they are usually found at comparable depth (Figs 7 and 8).

The principal stress field in the lithosphere lies in approximately horizontal and vertical planes as evidenced from the orientation of fault planes, earthquake focal mechanisms, and deep in situ stress measurements (e.g., Anderson 1951; McGarr & Gay 1978; Zoback & Zoback 1980; Zoback 1992; Chang *et al*. 2010).

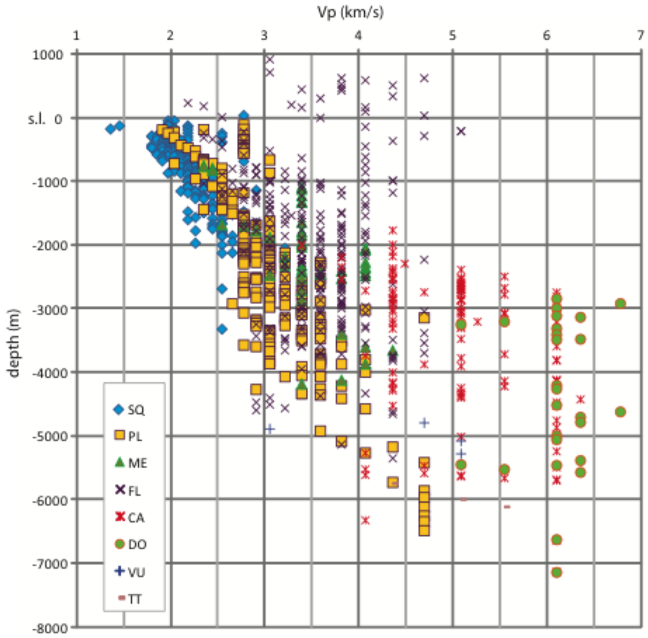

Figure 7. P-wave velocity (Vp) versus depth for the identified lithology groups (see text for lithogroup description).

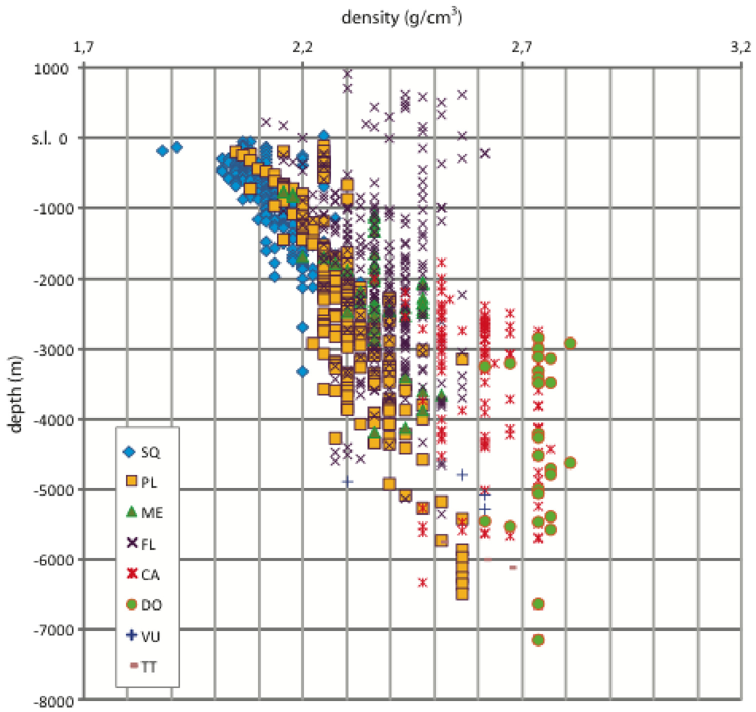

Figure 8. Density (derived from Vp) versus depth for the identified lithology groups (see text for lithogroup description).

In particular along the Po Plain and the Apennines, the inversion of several earthquake focal mechanisms enables us to confidently approximate that the three principal stresses are perpendicular to each other with one being in a vertical orientation (e.g. Frepoli & Amato 2000; Selvaggi et al. 2001; Boncio & Bracone 2009). The magnitude of the vertical stress (Sv) is usually estimated from the lithostatic pressure (e.g., Cornet & Rockel 2012); Fig. 9 shows the magnitude of Sv calculated at various depths in the 37 selected wells, from the cumulated weight of overburden. The trends are similar and quite regular but there are evident differences among the values from the Apennines (purple color) and the Po Plain and Adriatic Sea (cyan color). In this paper, we do not consider pore pressure influence, although at least occasionally pore pressure may be much higher than hydrostatic in some wells from the Po Plain.

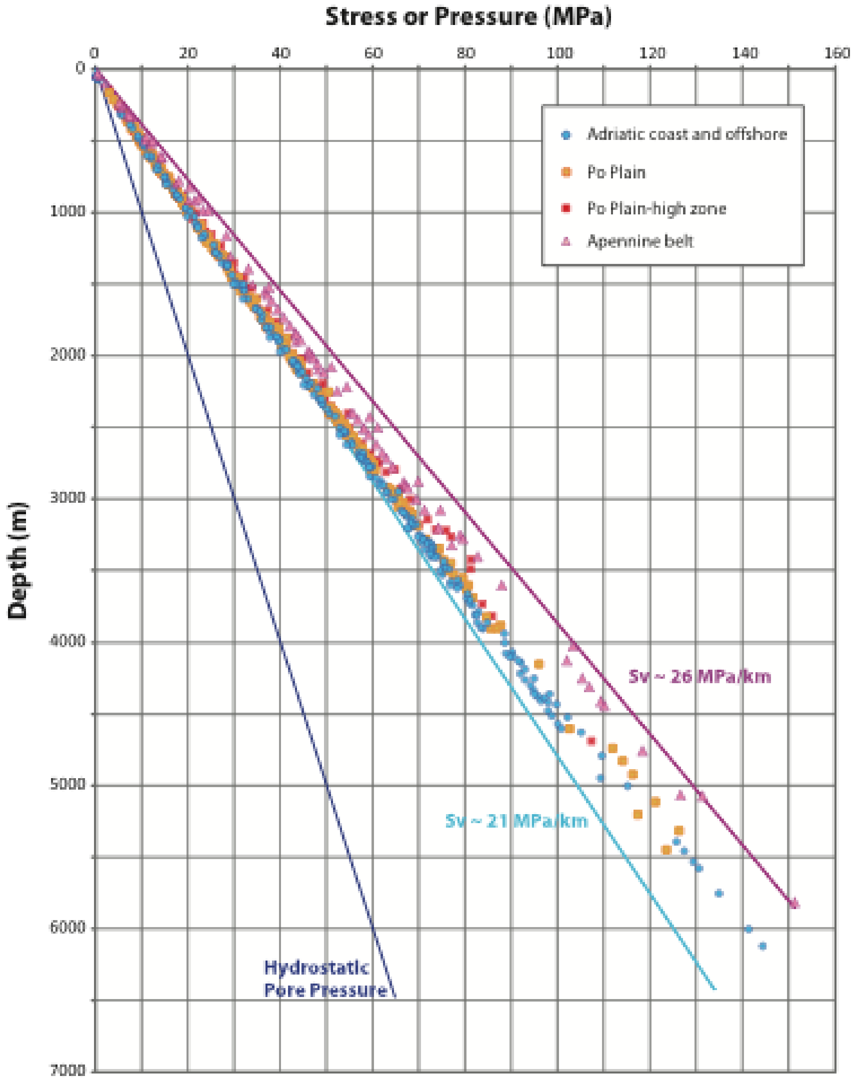

Figure 9. Vertical stress (Sv) magnitude (estimated from the lithostatic pressure) with depth in 37 wells (grouped following Fig. 2). Depth refers to ground level for on-land wells and sea level for offshore wells. The lithostatic gradient ranges from ~21 MPa/km (cyan line) in the Adriatic wells to ~26 MPa/km (purple line) in the Apennines.

5. Discussion

Different values of lithostatic gradient are generally applied for various geological areas and depths. For example, some authors assume a regional lithostatic gradient of 25 MPa/km, corresponding to an overburden mean density of 2.5 g/cm^3 for the upper crust, and then transition to higher gradients (e.g., 27–28 MPa/km) at greater depths (e.g., Hurd & Zoback 2012).

Our data (Fig. 9) support significant differences at the same depths in the Apennine belt, Po Plain and Adriatic. Along the Apennine belt we infer a regional maximum lithostatic gradient of around 26 MPa/km (purple data); in the area of the Po Plain (yellow data) and Adriatic (cyan data), we measure values of ~22 MPa/km and 21 MPa/km (minimum), respectively.

A value of 2.67 g/cm^3 (Harkness 1891) is commonly adopted as the mean density of upper continental crust characterized by crystalline and granitic rocks. However, crystalline rocks represent roughly only 25% of the upper continental crust, with the remaining 75% consisting of sedimentary units made up of about 65% shale, 20–25% sandstone (both 2.0–2.7 g/cm^3), and 10–15% carbonate rock (2.5–2.9 g/cm^3). Considering these proportions, mean continental crustal density should be about 2.6 g/cm^3 (Hinze 2003). In New Zealand, a recent study by Tenzer *et al.* (2011), performed in order to generate a digital density model, shows that the mean density of the New Zealand rock catalog is around 2.45 g/cm^3, i.e., considerably lower than the values normally used. Direct well log data are sparse. For example, in rocks with granitic composition retrieved from the SAFOD Pilot Hole (775-2150m depths) a mean density of 2.6 g/cm^3 was measured. For sedimentary rocks, an average overburden density of 2.3 g/cm^3 seems to be more appropriate (Zoback *et al.* 2003; Boness & Zoback 2004; Brocher 2005).

For single wells, we have derived from Vp the crustal mean densities for the study area, and we find very different values when moving from the Apennine belt to the plain, as already seen in terms of lithostatic gradient. Along the Apennines density values vary from 2.65 to 2.33 g/cm^3; in the Po Plain, the mean density is around 2.25 g/cm^3 and in the Adriatic area the mean density reaches the lowest value of 2.13 g/cm^3. Our results along the belt are slightly smaller than the 2.7 g/cm^3 inferred in central Italy (Umbria - Marche Apennines) by other authors (Federico & Pauselli 1998; Pauselli *et al.* 2010). Unfortunately we do not have sufficient data to perform a detailed comparison. However, our results (Table 2) are in good agreement with those found in analogous lithological formations (Umbria Marche area) - consisting of flysch, carbonate and dolomite-evaporite sequences - both for density and Vp values (Barchi *et al.* 1998; Bally *et al.* 1986; Pauselli & Federico 2003).

Using the limited amount of data recovered by a mud leak-off test in a vertical well from our dataset (group A6) (Fig. 2), Carminati *et al.* (2010) computed at 2836 m, a value of 53 MPa for the minimum stress and around 68 MPa for the overburden pressure (Sv), assuming an average density of 2.45 g/cm^3. The Sv value is quite similar to what we find at the same depth in a similar well. Although slightly smaller, our estimated Sv lying between 60 and 65 MPa shows that at this depth the tectonic regime is probably strike-slip or extensional.

Considering the lithogroups previously identified, we observe that the P-wave velocity and derived density values (Figs. 7 and 8) change with depth (as expected). However, inside the same identified lithogroup, Vp and then density are also related to different petrophysical properties, such as intrinsic porosity and fluid content, and acquired properties, such as degree of fracturing or cataclasite development. This is evident for the dolomite-evaporite group (DO), where Vp changes from >5 to ~6.8 km/sec with a median value of 6 km/s (Fig. 5 and Table 2). This observation also has been highlighted in some deep wells located in central Italy (Trippetta *et al.* 2010).

For example, in the Monte Civitello 1 well, the stratigraphic log indicates that at depths between about 2900 and 4600 m, "evaporite strata" alternate in a sequence of dolostones and anhydrites, whereas at greater depths from 4800 to 5400 m, dolostones are predominant. Along this well, the sonic log records an average Vp of 6.3 km/s and 6.7 km/s for the shallow and deeper sequences, respectively. The higher value of Vp in the deeper sequence appears to be correlated with the higher proportion of dolostone at that depth, which is also consistent with the values obtained in laboratory tests on the same lithology. Low Vp (around 6-6.3 km/s) seems consistent with the presence of anhydrites, while Vp<6 km/s could be related to a gypsum-dolostone unit (Trippetta *et al.* 2010).

Based on achieved data, we have constructed a velocity model for the investigated area (Table 3). We have identified two tectonic areas, the Apennines (AP) and Po Plain (PP) zones, to highlight the variation in P-wave velocity. Moreover, following the great geological differences within the Po Plain, we have also distinguished (Pa) and (Pb) sub-areas. The Pa area corresponds to the Po Plain structural high zones characterized by thin Plio-Pleistocene sediments and/or the shallow depth of the carbonate multilayer, as for instance in groups A6, A7 and A10 (see Fig. 2); the Pb area is characterized by a thick Plio-Pleistocene sequence, also up to 6 km, and/or a deep top of the carbonate sequence (e.g., groups A1, A2, A3, A4, A5, A8, A9, A11 and A12 in Fig. 2).

Our five-layer Vp model (Table 3) is based on robust data from depths of 0 to 5 km; we have not included data from below 5 km because there are only a few of them and they are probably not representative. Moreover, we highlight that the Apennine data (AP) are less constrained than Po Plain data, but they can contribute to the characterization of this region and can be used for comparison with the other area. In our model we recognize an important velocity increase at 4 km depth, with values changing from 3.7 to 4.8 km/s for the Po Plain and from 4.7 to 6 km/s for the Apennine belt. Although the Apennine model is less consistent than the Po Plain model, the strong lateral velocity contrast between the two adjacent areas is highlighted. This is most evident in the upper 1 km (AP 3.8 km/s and PP 2.2 km/s) and also below 4 km depth (AP 6 km/s and PP 4.8 km/s). Finally, if we consider Pa and Pb, we observe further important differences inside the Po Plain that are quite evident below 1 km (Pa 3.2 km/s and Pb 2.5 km/s), and even more marked below 3 km (Pa 4.9 km/s and Pb 3.4 km/s).

Comparing our Vp model with those of recent researches (Table 3), we find interesting points to discuss. For example, some authors (Bragato *et al.* 2011; Vuan *et al.* 2011) propose a velocity model for the Po and Venetian plains based principally on geophysical information from oil exploration and deep seismic soundings and secondarily on geological data, with a very low value of Vp (≤ 2.2 km/s) for the first 3 km. This latter value is not comparable with our results observed either in the entire PP area or in the two sub-areas Pa and Pb separately. Moreover, according to the research mentioned above (see Table 1; Vuan *et al.* 2011), very low values of density correspond to these Vp values (i.e., between 1.6 and 1.7 g/cm^3), which could be related only to alluvial sediments and may not be reliable to a depth of 3 km. Also at greater depths (around 4 km), higher Vp values seem to be correlated to very low density (2.1 g/cm^3).

More recently Malagnini *et al.* (2012), using data retrieved from seismic profiles and local geology, defined a 1D velocity structure for the shallow crust beneath the Po Plain. Evidence is presented for a sudden change in Vp at a depth of 2 km, from 2.6 to 3.8 km/s, and another minor Vp contrast at 4 km depth (Table 3). With respect to our

PP Vp model, we find comparable results although we use different methods and data. Nevertheless, if we consider the results from the Pa and Pb models, we think that applying a more complex model in this region would produce a better definition of seismic behavior.

Table 3. Velocity model

<table>
<tr><th rowspan="2">Depth (km)</th><th colspan="4">Vp - This work</th><th colspan="2">Other Authors</th></tr>
<tr><th>AP</th><th>PP</th><th>Pa</th><th>Pb</th><th>V</th><th>M</th></tr>
<tr><td>0-1</td><td>3.8</td><td>2.2</td><td>2.4</td><td>2.1</td><td>1.5</td><td>1.9</td></tr>
<tr><td>1-2</td><td>3.5</td><td>2.7</td><td>3.2</td><td>2.5</td><td>1.8</td><td>2.6</td></tr>
<tr><td>2-3</td><td>3.7</td><td>3.3</td><td>3.7</td><td>3.0</td><td>2.2</td><td rowspan="2">3.8</td></tr>
<tr><td>3-4</td><td>4.7</td><td>3.7</td><td>4.9</td><td>3.4</td><td>3.5-4.2</td></tr>
<tr><td>4-4.5</td><td rowspan="2">6.0</td><td rowspan="2">4.8</td><td rowspan="2">5.7</td><td rowspan="2">4.3</td><td rowspan="2">4.8</td><td>4.4</td></tr>
<tr><td>4.5-5</td><td>4.9</td></tr>
</table>

Vp: P-wave velocity (km/s); AP: Apennines; PP: Po Plain; Pa: Po Plain structural high zone; Pb: Po Plain other zones. V: Po Plain from Vuan *et al.* (2011); M: Po Plain from Malagnini *et al.* (2012).

6. Conclusions

In order to infer the *in situ* P-wave velocity at depth, we have selected 64 deep wells located in different regions of the Po Plain, Adriatic coast and northern Apennine belt (Table 1); for 37 of these wells, sonic logs have been also analyzed.

We have used the sonic log drilling data (slowness) to determine the velocity of elastic waves (Vp) through the stratigraphic units.

We have estimated rock densities following an empirical relationship between sonic velocity and density for sedimentary rocks as proposed by Gardner *et al.* (1974).

According to lithology and age interval information, we have organized the ~40 stratigraphic units crossed by the deep wells, into eight lithogroups. P-wave velocity values and consequently density are observed to change within each identified lithogroup. This is due to a range of petrophysical conditions, such as intrinsic porosity and/or fluid content, but also to the acquired properties, such as in highly fractured or cataclasite zones.

Within the Po Plain (Figs. 2 and 4), we do not find Vp < 2 km/s at ground level with the exception of one well (Vp ~1.5 km/s); whereas the wells along the Apennines start with velocities much higher than 2 km/s. A relationship of 2.0<Vp<2.6 km/s is associated mainly with the Quaternary sediments of the Po Plain in the upper 1 km. Vp increases with depth, although with different gradients. However, some velocity inversions have been recognized (i.e., at depths greater than 3 km). These velocity variations are often related to different lithologies although sometimes they are due to fluid presence or different petrophysical properties. In general, for wells located in the Apennine belt or in structural high zones, P-wave velocities rapidly increase with depth, whereas in the Adriatic offshore, or where a huge amount of Plio-Pleistocene sediments is present, we observe a low increase of velocity. In general, Vp velocity at a depth of ~4000 m is equal to or slightly greater than 4 km/s; Vp around 6 km/s is reached only along the Apennine belt or structurally high zones.

Sv has been estimated by the integration of derived rock densities from the surface to the bottom of each well. The lithostatic gradient gradually changes in the various study zones from a maximum of 26 MPa/km in the Apennine belt to a minimum of 21 MPa/km in the Po Plain and Adriatic region. Consequently, moving from the Apennine area to the Adriatic coast, values of lithostatic pressure from 130 to 105 MPa have been found for instance at a depth of 5 km.

According to the Apennine stratigraphic sequences, the estimated density ranges from 2.65 to 2.33 g/cm^3; in the Po Plain the mean density is around 2.25 g/cm^3; and in the Adriatic the lowest value is 2.13 g/cm^3. Similarly, we have identified for the main lithological groups their median Vp and density values (Table 2).

Although we think that a 2D model does not constrain the complicated and uneven tectonics well, on the basis of this paper we have tried to summarize a crustal velocity model for the Po Plain (PP) and Apennine belt (AP) identifying five distinct layers (Table 3). The data obtained in this paper can be used for more realistic 3D models in future integrating other geological and geophysical information.

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