DX.DOI.ORG//10.19199/2023.169.1121-9041.047

Christoforos Benetatos*

* Politecnico di Torino, DIATI, Torino

Corresponding author:
christoforos.benetatos@polito.it

Preliminary statistical analysis of borehole and geological data from the Po plain

The Po Plain area in the north of Italy can be considered a natural geological and geophysical laboratory due to its complex geological evolution, particularly from the Miocene to today. Much of our understanding about the subsurface of the Po Plain is due to the large amount of data collected during the period of hydrocarbon exploration in Italy. In total more than 7000 wells have been drilled and thousands of km of seismic acquisition lines have been acquired. Furthermore, the study of the natural gas fields contributed with additional data facilitating the creation of detailed structural and stratigraphic models of the subsurface. The majority of the "original" data, including well logs, seismic and geological profiles existed in paper format thus posing challenges for their integration into modern models where digital data are incorporated to achieve a sound description of the subsoil. Livani et al. (2023) have collected and digitized a large number of "original" data and subsequently used them to recreate the overall subsurface architecture of the Po plain and extract the physical properties of the main geological units. In this study, we use the results of the work of Livani et al. and we perform a preliminary statistical analysis on them. We explore relationships between rock density and geological formations, we compare log data (GR, sonic) with lithologies and we investigate the lithological content for each of geological formations. Ultimately, we compare some of our results with previously published research.
Keywords: *Po plain, sonic log, lithology, P-wave velocity.*

1. Introduction

In Italy, hydrocarbon reservoirs are located along the Apennines, in foredeep basins, and off-shore, along the Adriatic foreland. Most of the gas accumulations were found in the Po Plain and the northern Adriatic Sea while oil accumulations were typically identified along the Southern Apennines and Sicily (Bertello *et al.*, 2010, Cazzini *et al.*, 2018). The distribution of hydrocarbon reservoirs onshore and offshore in Italy highlights the close connection between the evolution of the chain-foredeep-foreland system and the origin of reservoir rocks and traps for the accumulation of oil and gas (Casero, 2004; Casero and Bigi, 2013). Since the second half of the 20th century, the discovery and exploitation of numerous hydrocarbon reservoirs, primarily gas-bearing, have played a pivotal role in Italy's economic advancement. The Po Plain and the adjacent northern Adriatic Sea have emerged as the primary hosts for hydrocarbon fields in the nation, contributing to nearly 1/3 of the national gas production (Livani *et al.*, 2023). From the mid of the mid-20th century and once the gas reservoirs reached the end of their lifecycle, some of them have been converted into gas storage that are still active nowadays. Eni-Agip company performed large-scale exploration activities throughout the Po Plain and central and Northern Adriatic Sea acquiring a large volume of subsurface data that included 2D and 3D seismic surveys in local and regional scale and well-log data during the drilling of exploration or development wells. Most of the subsurface information coming from the wells is available in the form of well profiles (scale 1:1000) that include a substantial quantity of sedimentological, stratigraphic and structural information. In this study we use the well-log data present in the database of Livani *et al.*, 2023 in order to perform a preliminary statistical analysis using digitized well logs recordings, lithological and stratigraphic information.

2. Regional geology

The geological framework of the areas containing hydrocarbon reservoirs is the outcome of a complex tectono-stratigraphic evolution marked by a Mesozoic extensional phase, primarily accompanied by carbonate sedimentation (fig. 1). This was followed by a Cenozoic compressional phase associated with the deposition of thick turbidite sequences. The period extending from the Mesozoic through the Lower Paleogene was marked by the formation of important carbonate platform sequences, accompanied by deposits of platform margin and slope, primarily represented by carbonate breccias, and intra-platform basins that characterize the entire peri-Adriatic area. In more recent times the sedimentation in the foredeep was characterized by the deposition of thick clastic successions derived from the erosion of the mountain chains themselves. The Oligo-Miocene foredeep succession comprises a series of turbidite sequences associated with

If there are references to colour figures in the text, the articles are available in open-access mode on the site www.geam-journal.org different orogenic phases. From the Messinian to Pleistocene the basin accumulated thick turbidite sequences, reaching thicknesses of 7000-8000 meters, linked to the advancement of the Apennine front that led to the gradual filling of the Po Basin. (e.g. Casnedi *et al.*, 1982; Dondi *et al.*, 1982; Casero, 2004; Fantoni *et al.*, 2004; Fantoni & Franciosi, 2010; Ghielmi *et al.*, 2010 among others).

From a structural and stratigraphic perspective, the most common geological scenarios associated with hydrocarbon reservoirs in Italy are represented by:

1. Deep structures within carbonate successions, primarily linked to Mesozoic extensional phases or their subsequent tectonic inversion.
2. Anticlines within the Tertiary succession associated with south Alpine or Apennine-vergent thrusts connected to the structuring of the two orogenic mountain chains.
3. Gentle, very shallow anticlines developed between the Upper Pliocene and Quaternary.

Specifically, thermogenic oil and gas reservoirs are mainly associated with Mesozoic carbonate successions, while gas reservoirs are primarily linked to Oligo-Miocene foredeep clastic successions (thermogenic gas) and Plio-Pleistocene formations (biogenic gas).

3. *Data digitization*

The data used in this study are part of the database made available by Livani *et al.* (2023). Their database was created by the collection, digitization, and revision of geological and geophysical data (in raster format) that was derived from public sources. The fundamental source of well data was the VIDEPI project database (http://www.videpi.com) which is the outcome of the collaboration between the Ministry for Economic Development – DGRME, the Italian Geological Society and Assomineraria (the Italian petroleum and mining industry association, now Assorisorse). The main objective was to allow everyone easy access to all documentation related to Italian oil and gas exploration. This comprehensive database encompasses public well data, documents, mining permits, and concessions submitted to UNMIG, the National Mining Office for Hydrocarbon and Geothermal Energy under the Ministry for Economic Development, since 1957 (Benetatos *et al.*, 2019).

The well-log database of Livani *et al.* comprises digitized data from 160 wells (originally in raster format) located in the Po plain area and the northern Adriatic Sea (fig. 2). The master logs at a 1:1000 scale include a standard set of logs that offer information on lithology, stratigraphy, and fluid saturation. The primary dataset comprises a Spontaneous Potential (SP) log, employed for lithological characterization and stratigraphic correlations, and a Resistivity (Res) log for identifying hydrocarbon-bearing layers. Supplementary data pertains to lithological characteristics (e.g., cuttings and lithological classifications along

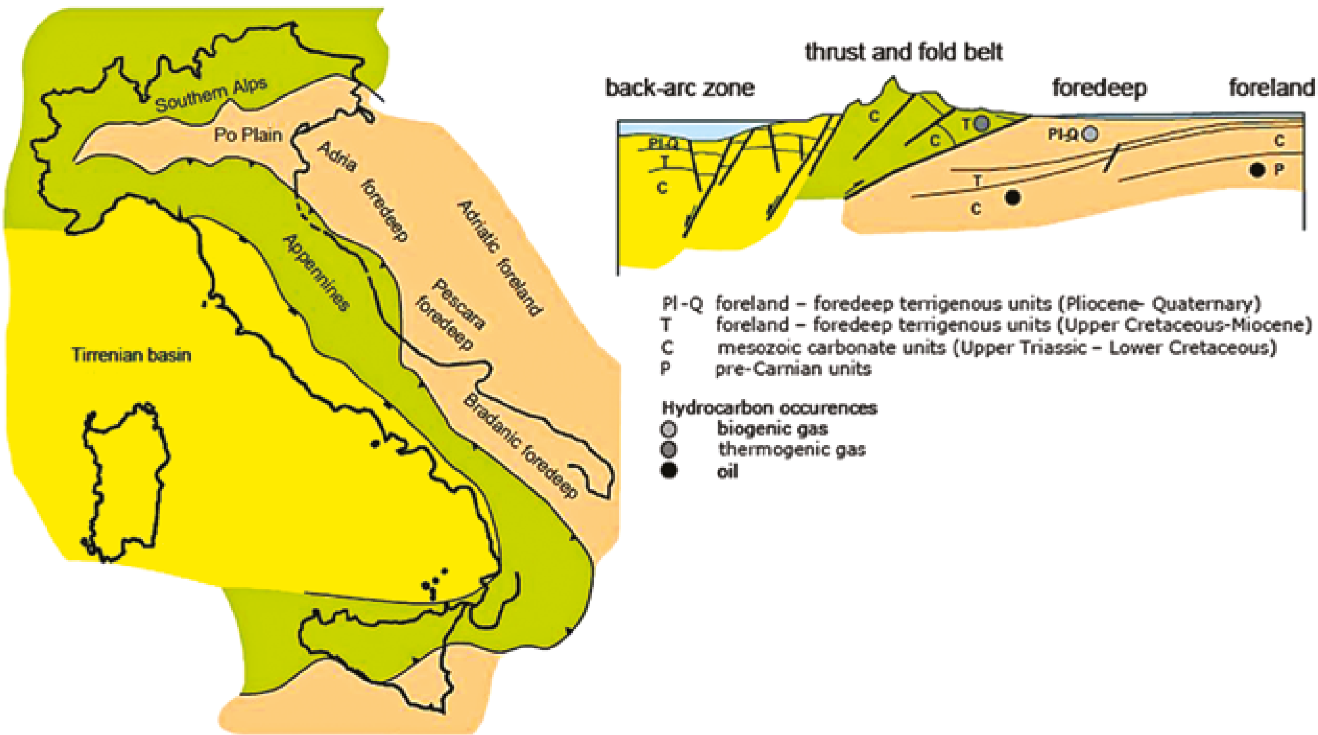

Fig. 1 – Location scheme of the principal gas and oil reservoirs in the Italian geological context (fig. mod. from Bertello *et al.*, 2008).

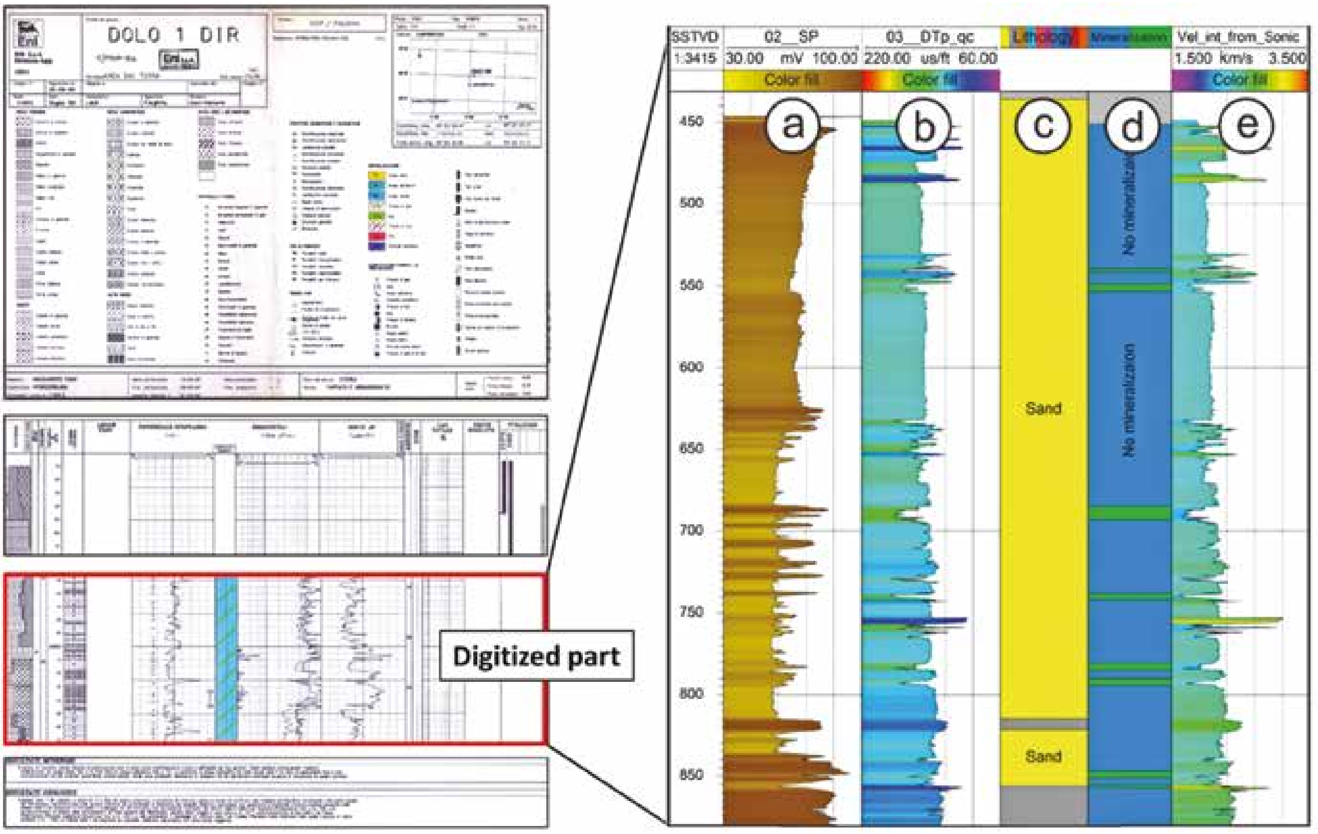

Fig. 2 – (Left) Typical example of well profile (scale 1:1000) from the Po plain area. (Right) Example of a typical logset of the wells in the database. a) Spontaneous Potential log, b) Sonic log, c) Lithological log, d) Mineralization log, e) Sonic velocity log.

the wellbore). Occasionally, Sonic log registrations useful for the calculation of seismic sonic velocities were also available. The digitization procedure was performed manually, with a variable sampling step, or by a semi-automatic method of line recognition and the logs were resampled in steps of 0.5 m.

3.1. Results of the digitization process

The digitization process and the subsequent data analysis led to a variety of stratigraphic, lithological and geophysical results. For the large-scale stratigraphy analysis, the digitized logs, in particular SP and GR were used to perform stratigraphic correlation between the wells at the regional scale. They provided insight into the subsurface stratigraphy by identifying units showing different lithological properties and defining horizons that divide the geological succession into different parts based on their mechanical properties. The main recognized units were (Livani *et al.*, 2023):

1. Recent clastic deposits of the Po Plain and the Adriatic Sea (hereafter called "**Alluvium**")
2. Late Pliocene-Pleistocene sand-rich sequences (eg. Sand of the Asti Fm, hereafter called "**Pleistocene**")
3. Late Miocene-late Pliocene clastic deposits (e.g. Argille del Santerno Fm./P.to Corsini Fm./P.to Garibaldi Fm., hereafter called "**Pliocene**")
4. Early-late Miocene marly sequences (e.g. Marne di Gallare, hereafter called "**Miocene**")
5. Triassic to Eocene carbonate units (hereafter called "**Triassic**")
6. Varyscan crystalline basement

The adopted names chosen for the 5 main recognized units are used hereafter for the sake of simplicity. The Varyscan crystalline basement is intercepted for very few meters only by 5 wells and since it does not belong to the sedimentary fill of the Po Plain it will not be mentioned or used in the analysis here below.

The lithological analysis was performed by evaluating the information coming from the cuttings description of each well. The cuttings description compiles data acquired during mud logging, involving rock fragments brought to the surface as a result of drilling fluid circulation within the borehole. These mud logging observations were integrated with SP and GR logs, as well as lithological data obtained from core sample analyses recorded in the well profile. This combined dataset was used to establish the lithological characteristics throughout the entire well. Livani *et al.*, 2023 were able to identify 9 macro-lithologies that are (Livani *et al.*, 2023):

Gravel – Sand – Cemented sands – Shale – Sand/Shale alternances – Conglomerates – Marls – Dolomites – Limestone

Within each macro-lithology group, there are also similar lithologies included alongside the primary one. This decision was made to simplify the classification process. For example, the "Sand" macro-lithology group includes also reported lithologies such as "Sand prevalent", "Fine sand", "Sand and shaly sand" and so on.

The geophysical/geomechanical outcome of the digitization process was the calculation of sonic slowness time (μsec/ft) that was later converted to sonic P-wave seismic velocities (m/sec) for all the wells having available registrations of the sonic log. Seismic velocity information along the wellbore is of particular importance since it can be used for the calculation of mechanical properties necessary for geomechanical simulations (e.g. Benetatos *et al.*, 2015, 2017, 2020) during the injection of various types of fluids in the subsurface such as natural gas, CO_2 or H_2. The sonic transit times varied from a maximum of almost 200 μsec/ft for the most superficial geological layers to a minimum of almost 40 μsec/ft for the deepest formations.

4. Preliminary statistical analysis

In this study, we used the results of the digitization and log analysis presented in par. 3 in order to investigate the relationship between lithologies, geological formations and seismic velocities. The first observation that we can extract from the well data of the database is the depth range that they cover inside the Po Plain's subsurface. The bottom hole depth, that is the maximum drilled depth of a well expressed in meters True Vertical Depth Sub Sea (m TVDss) is presented in fig. 3. Most of the wells (almost 90 wells) sample the range down to almost 2500 m, covering very well the upper portion of the basin, some wells arrive to the middle part while very few wells sample the deeper parts of the basin.

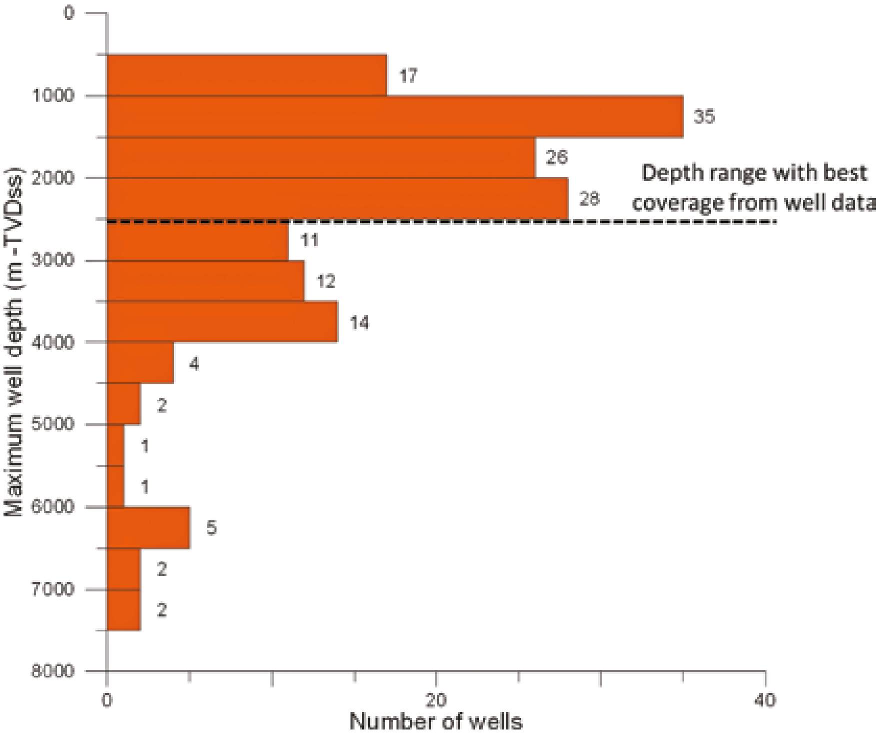

Fig. 3 – Histogram of the bottom hole depth of the wells present in the database.

Figure 4 illustrates the depth range covered by the primary stratigraphic units. The boundary

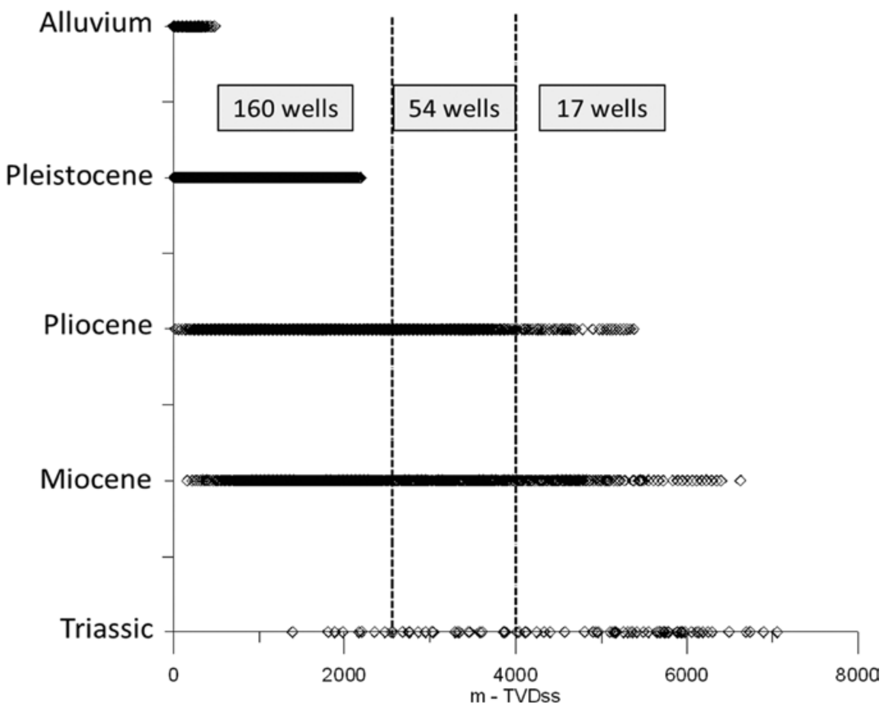

Fig. 4 – Graphs indicating the depth intervals covered by each of the stratigraphic units. The vertical dashed line corresponds to the depth limit that indicates the best well data coverage (maximum number of wells intercepting these depths).

at 2500 meters indicates that the available well data effectively cover the Alluvium, Pleistocene, and a significant portion of the Pliocene and Miocene deposits, with all wells (160) sampling these depths. However, the well data coverage decreases when examining the intermediate parts of the Pliocene and Miocene, with 54 wells sampling this interval while the deeper parts of those stratigraphic intervals and the largest part of the Triassic deposits are sampled by 17 wells only.

The definition of the lithological logs was one of the main objectives during the digitization and analysis part of the geological profiles. Lithologies were recognized in all the wells based on the available information from the well cuttings and in some cases from core analysis. Figure 5 shows an overall histogram with the lithologies from all the wells while in fig. 6 are presented separate histograms showing the abundance of these lithologies inside each of the 5 main stratigraphic units.

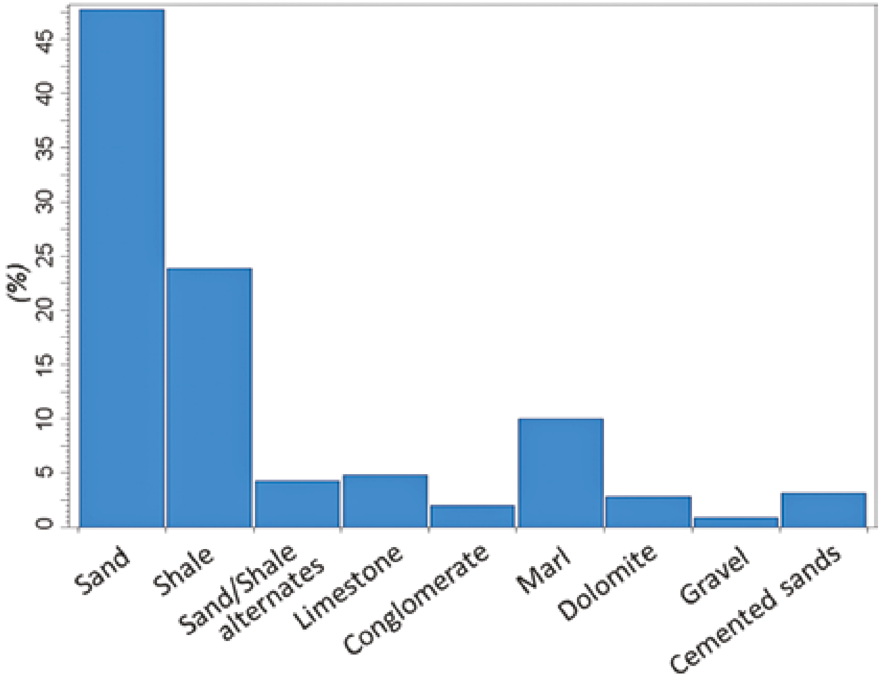

Fig. 5 – Histogram showing the distribution of the 9 macro-lithological groups at the wells position.

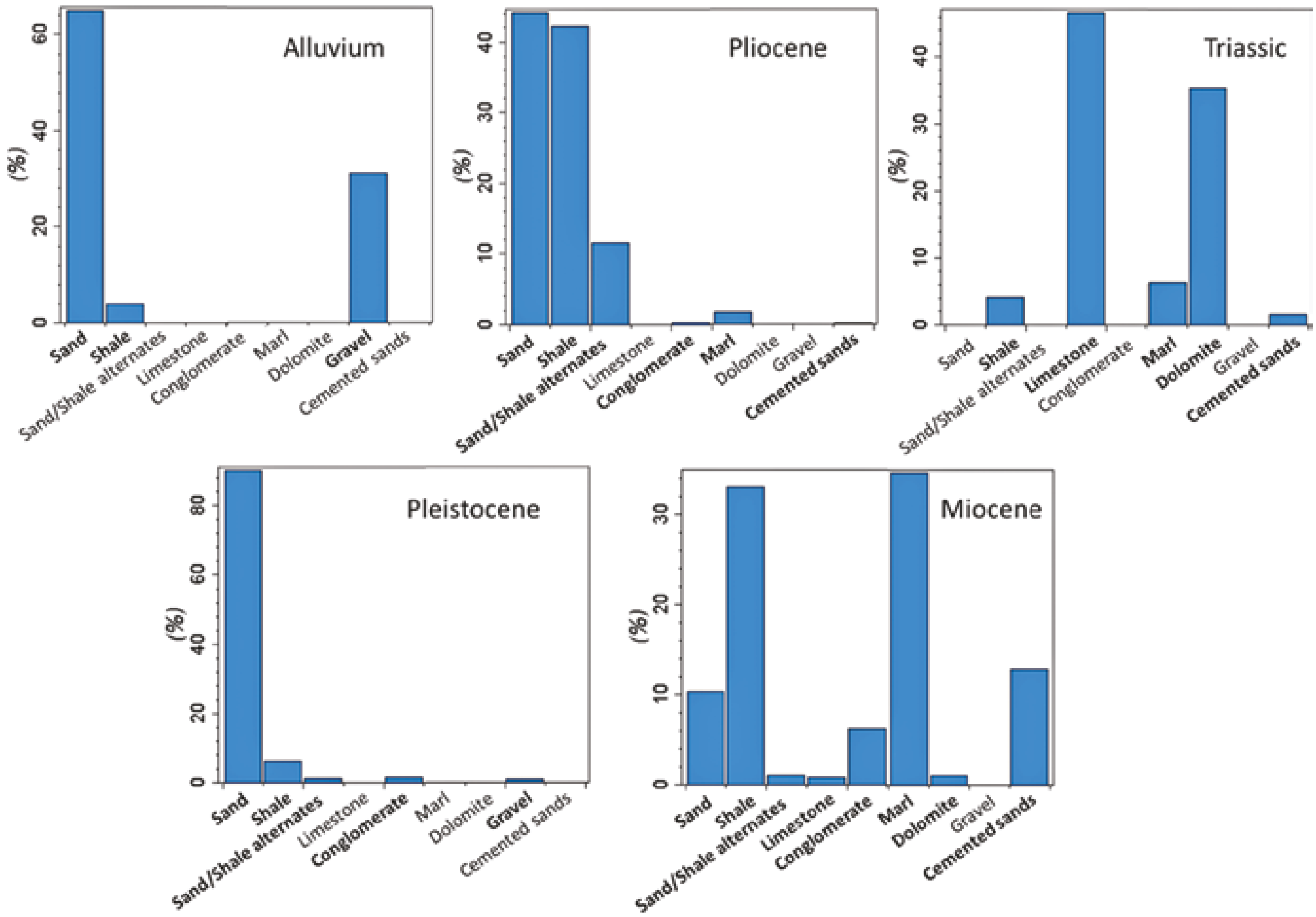

Fig. 6 – Histograms showing the lithological content for each stratigraphic zone.

From the histograms of fig. 6 we can note the prevalence of sand in the Alluvium and Pleistocene deposits; sand is strongly linked to the deposition of turbiditic deposits in a large part of the basin. During the Pliocene period, the shale content significantly increased due to the deposition of the Argille del Santerno Fm. During the Miocene period, we observe a variety of lithological types that include significant percentages of marls, conglomerates and cemented sands. In the portion of the wells belonging to the Triassic period we observe mostly limestones and dolomites linked to the carbonate platform.

The digitization of the sonic logs (Sonic) offers valuable information regarding the sonic seismic velocities and their variation with depth for the Po Plain area. Figure 7 displays graphs illustrating the fluctuations in P-wave sonic velocities at different depths for the identified macro-lithological units. This figure reveals that limestones and dolomites maintain relatively constant velocities regardless of depth. In contrast, lithologies like marls and cemented sandstones exhibit a distinctive behavior: a cessation in velocity increase that occurs at approximately 4 km depth, followed by a consistent trend at greater depths. More information regarding the velocity variations for each macro-lithological group can be found in Benetatos *et al.*, (2019).

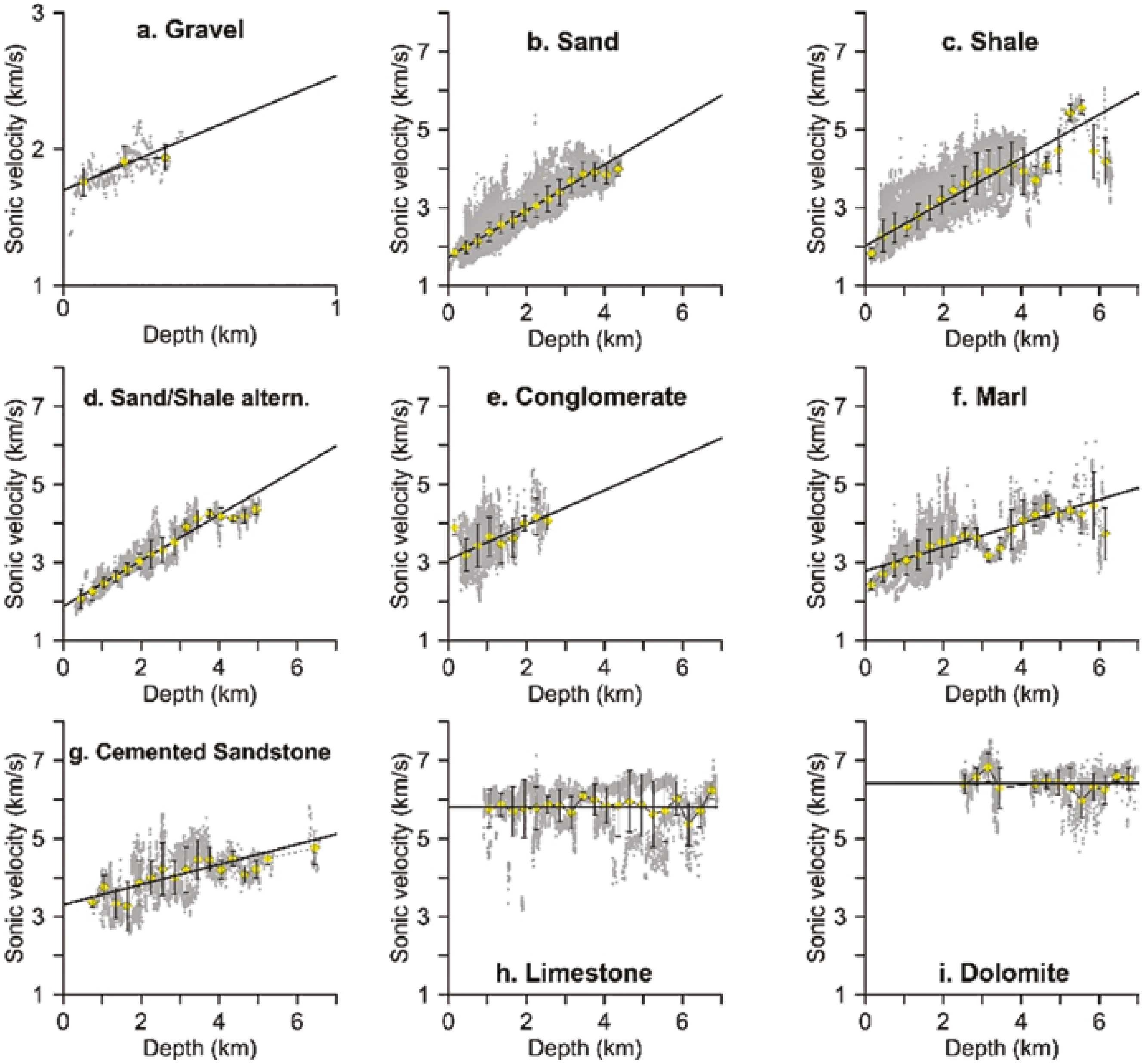

Fig. 7 – Relations between sonic velocities and depth for each lithological type recognized at the well profiles. The black line corresponds to the simple linear regression. The yellow points with the corresponding black upper and lower bounds correspond to the average values and standard deviation of the sonic velocities for 300 m intervals (fig. from Benetatos *et al.*, 2023).

The sonic velocities of the primary stratigraphic units were compared with those documented in the work of Montone and Mariucci (2020). The findings are outlined in Table 1 and represented in fig. 8. In those cases where the velocity values of a specific lithological composition are more appropriate for comparison purposes than those of the entire stratigraphic unit, such values have been utilized in the table. In some cases, merging the velocity results from two stratigraphic units was necessary in order to perform a more accurate comparison with the results of the other researchers.

5. Conclusions

The discovery and exploitation of numerous hydrocarbon resources in the Po Plain basin led to large-scale exploration activities, in particular by Eni-Agip company. The investigated area comprises the Po Plain and at the central

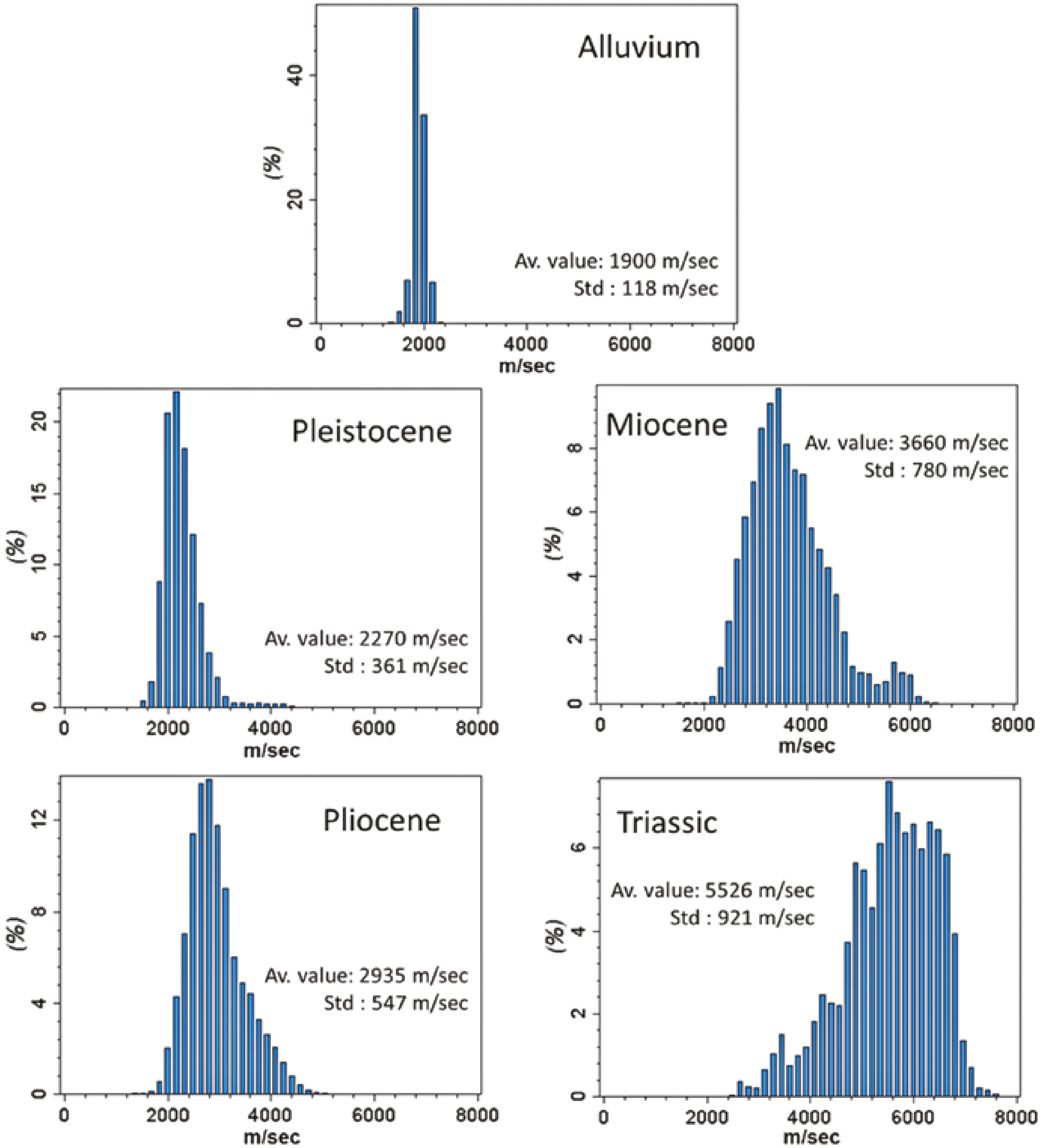

Fig. 8 – Histograms indicating the distribution of the sonic P-wave velocities for each stratigraphic unit.

Tab. 1 – P-wave sonic velocity (km/s, mean and standard deviation) compared to other studies. Units are: Q, Quaternary; PL, Pliocene; MIO-PL, Miocene-Pliocene; FMA, Marnoso Arenacea Formation; EO-MIO, Eocene-Miocene; C-EO, Cretacic-Eocene; J-C, Jurassic-Cretacic; J, Jurassic; TR, Triassic; V, Verrucano. (Table mod. from Montone and Mariucci, 2020).

<table>
<tr><th colspan="2">This study</th><th>Montone and Mariucci (2020)</th><th>Lithostratigraphic units from Porreca et al.</th><th>This study</th><th>Porreca et al. (2018)</th><th>Latorre et al. (2016)</th><th>Scisciani et al. (2014)</th><th>Bigi et al. (2011)</th><th>Mirabella et al. (2011)</th><th>Barchi et al. (1998)</th><th>Bally et al. (1986)</th></tr>
<tr><th>UNIT</th><th>vel. (km/sec)</th><th>vel. (km/sec)</th><th></th><th>vel. (km/sec)</th><th>vel. (km/sec)</th><th>vel. (km/sec)</th><th>vel. (km/sec)</th><th>vel. (km/sec)</th><th>vel. (km/sec)</th><th>vel. (km/sec)</th><th>vel. (km/sec)</th></tr>
<tr><td>Q</td><td>2.3 ± 0.3</td><td>2.2 ± 0.1</td><td rowspan="2">Plio-Pleistocene</td><td rowspan="2">2.6 ± 0.6</td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2">3.6</td><td rowspan="2"></td><td rowspan="2">2.0</td><td rowspan="2">2.3-2.5</td><td>2.0</td></tr>
<tr><td>PL</td><td>2.9 ± 0.5</td><td>3.4 ± 0.6</td><td>2.6</td></tr>
<tr><td>MIO-PL</td><td>3.7 ± 0.8</td><td>4.0 ± 0.5</td><td rowspan="2">Miocene Turbidites</td><td rowspan="2">3.4 ± 0.6</td><td rowspan="3">4.0</td><td></td><td rowspan="2">4.0</td><td>3.6</td><td></td><td></td><td rowspan="2">3.4-4.0</td></tr>
<tr><td>FMA</td><td></td><td>4.0 ± 0.3</td><td>3.9</td><td></td><td>4.0</td><td>4.0</td></tr>
<tr><td>EO-MIO</td><td></td><td>4.8 ± 0.5</td><td>Marly group</td><td>3.7 ± 0.8</td><td rowspan="4">5.7</td><td rowspan="2">5.0</td><td>4.5</td><td rowspan="4">5.6</td><td>4.0</td><td>3.4</td></tr>
<tr><td>C-EO</td><td>5.5 ± 0.9</td><td>5.8 ± 0.3</td><td>Scaglia group</td><td>5.7 ± 0.8</td><td rowspan="3">5.8</td><td>5.8</td><td rowspan="3">5.5</td><td>4.5</td></tr>
<tr><td>J-C</td><td></td><td>5.9 ± 0.4</td><td>Carbonate multilayer</td><td></td><td>5.5</td><td>6.1</td><td>5.2</td></tr>
<tr><td>J</td><td></td><td>6.3 ± 0.4</td><td>Calcare Massiccio Fm.</td><td></td><td>6.8</td><td>6.4</td><td>6.0</td></tr>
<tr><td>TR</td><td></td><td>6.3 ± 0.3</td><td>Evaporites</td><td></td><td>6.4</td><td>6.3</td><td>6.0</td><td>6.0</td><td>6.1</td><td>6.1</td><td>6.4</td></tr>
<tr><td>V</td><td></td><td>4.9 ± 0.2</td><td>Basement s.l. phyllites</td><td></td><td>5.1</td><td>5.3</td><td>5.5</td><td></td><td>5.1</td><td>5.0</td><td>3.9</td></tr>
<tr><td></td><td></td><td></td><td>Crystalline basement unit</td><td></td><td></td><td>5.8</td><td>6.0</td><td></td><td>6.0</td><td>5.5</td><td></td></tr>
</table>

and northern Adriatic Sea. These activities resulted in the accumulation of a large volume of data related to the basin's subsurface that includes 2D and 3D seismic surveys at the local and regional scale and well-log data. The digitization of a large part of that dataset, performed by Livani *et al.* (2023), has provided a lot of information in a digital format for further analysis. This dataset encompasses a large range of geological and stratigraphic data, offering valuable insights into lithology, stratigraphy and geophysical properties of the Po Plain, providing a useful data pool to many other researchers.

The preliminary statistical analysis conducted in this study provides a first insight into the relationships between lithologies, geological formations, and seismic velocities in the Po Plain area. It is evident that the distribution of lithologies across the different stratigraphic units is linked to the complex geological history of the region. Furthermore, the analysis of sonic log data offered the possibility to calculate the seismic velocities, revealing their different characteristics and trends with depth, and to link them to lithologies. The velocity data also provided critical information for geomechanical simulations during subsurface operations (Benetatos *et al.*, 2023), offering the basis for further geological and geophysical studies.

References

Bally, A., Burbi, L., Cooper, C. & Ghelardoni, R. (1986). Balanced sections and seismic reflection profiles across the central Apennines. Mem. Soc. Geol. Ital. 35, 257-310.

Barchi, M. *et al.* (1998). The structural style of the Umbria-Marche fold and thrust belt. Mem. Soc. Geol. Ital. 52, 557-578

Benetatos, C. Rocca, V., Sacchi, Q. Verga, F., (2015). How to Approach Subsidence Evaluation for Marginal Fields: A Case History. Open Petrol. Eng. J., 8, 213-234.

Benetatos, C., Codegone, G., Deangeli, C. Giani, G.P. Gotta, A., Marzano, F. Rocca, V., Verga, F., (2017). Guidelines for the Study of Subsidence Triggered by Hydrocarbon Production. GEAM, 152, 85-96.

Benetatos, C., Codegone, G., Marzano, F., Peter, C., Verga, F., (2019). Calculation of Lithology-Specific p-Wave Velocity Relations from Sonic Well Logs for the Po-Plain Area and the Northern Adriatic Sea; Offshore Mediterranean Conference and Exhibition 2019, OMC: Ravenna, Italy, 2019; p. 148084.

Benetatos, C., Codegone, G., Ferraro, C., Mantegazzi, A., Rocca, V., Tango, G., Trillo, F., (2020). Multidisciplinary Analysis of Ground Movements: An Underground Gas Storage Case Study. Remote Sens., 12, 3487. https://doi.org/10.3390/rs12213487

Benetatos, C., Catania, F., Giglio, G., Pirri, C.F., Raeli, A., Scaltrito, L., Serazio, C., Verga, F., (2023). Workflow for the Validation of Geomechanical Simulations through Seabed Monitoring for Offshore Underground Activities. J. Mar. Sci. Eng., 11, 1387. https://doi.org/10.3390/jmse11071387

Bertello, F., Fantoni, R., Franciosi, R., (2008). Overview of the Italy's Petroleum Systems and Related Oil and Gas Occurrences. CD Extended Abstract & Exhibitor's Catalogue, 70th EAGE Conference & Exhibition, A018, pp. 1-4

Bertello, F., Fantoni, R., Franciosi, R., Gatti, V., Ghielmi, M., Pugliese, A., (2010). From thrust-and-fold belt to foreland: hydrocarbon occurrences in Italy. In: Vining, B.A., Pickering, S.C.(Eds.) Petroleum geology: from mature basin to new frontiers. Proceedings of the 7th Petroleum Geology Conference, pp. 113-112. doi: 10.1144/0070113.

Bigi, S., Casero, P. & Ciotoli, G., (2011). Seismic interpretation of the Laga basin; constraints on the structural setting and kinematics of the Central Apennines. J. Geol. Soc. London 168, 179-190, https://doi.org/10.1144/0016-76492010-084

Casero, P., (2004). Structural setting of petroleum exploration plays In Italy. Special Volume of the Italian Geological Society for the IGC 32 Florence-2004, pp. 189-199.

Casero, P., Bigi, S., (2013). Structural setting of the Adriatic basin and the main related petroleum exploration plays. Marine and Petroleum Geology, vol. 42, pp. 135-147. https://doi:10.1016/j.marpetgeo.2012.07.006

Casnedi, R., Crescenti, U., Tonna, M. (1982). Evoluzione della avanfossa adriatica meridionale nel Plio-Pleistocene, sulla base di dati di sottosuolo. Memorie della Società Geologica Italiana, vol. 20, pp. 243-260

Cazzini, F., Dal Zotto, O., Fantoni, R., Ghielmi, M., Ronchi, P., Scotti, P., (2015). Oil and gas in the Adriatic foreland, Italy. Journal of Petroleum Geology, vol. 38 (3), pp. 255-279. doi:10.1111/jpg.12610

Cazzini F., Dal Zotto O., Fantoni R., Ghielmi M., Ronchi P., Scotti P., (2018). Oil and gas in the Adriatic foreland, Italy. Journal of Petroleum Geology, 38(3), 255-279.

Dondi, L., Mostardini, F., Rizzini, A. (1982). Evoluzione sedimentaria e paleogeografica nella Pianura Padana. In: Cremonini G., Ricci Lucchi F. (Eds.), Guida alla Geologia del margine appenninico-padano. Guide Geologiche Regionali, Società Geologica Italiana, pp. 47-58

Fantoni , R., Bersezio, R., Forcella, F., (2004). Alpine structure and deformation chronology at the Southern Alps-Po Plain border in Lombardy. Bollettino della Società Geologica Italiana, vol. 123, pp. 463-476

Fantoni, R., Franciosi, R., (2010). Mesozoic extension and Cenozoic compression in Po Plain and Adriatic foreland. Rendiconti Lincei – Scienze Fisiche e Naturali, vol. 21 (1), pp. 197-209. doi: 10.1007/s12210-010-0102-4

Ghielmi, M., Minervini, M., Nini, C., Rogledi, S., Rossi, M., Vignolo, A., (2010). Sedimentary and tectonic evolution in the eastern Po-Plain and northern Adriatic Sea area from Messinian to Middle Pleistocene (Italy). Rendiconti Lincei Scienze Fisiche e Naturali, vol. 21, pp. S131-S166. doi: 10.1007/s12210-010-0101-5.

Latorre, D., Mirabella, F., Chiaraluce, L., Trippetta, F. & Lomax, A., (2016). Assessment of earthquake locations in 3-D deterministic velocity models: a case study from the Altotiberina near fault observatory (Italy). J. Geophys. Res. 121, 8113-8135, https://doi.org/10.1002/2016JB013170

Livani, M., Petracchini, L., Benetatos, C., Marzano, F., Billi, A., Carminati, E., Doglioni, C., Petricca, P., Maffucci, R.,Codegone, G., *et al.*(2023). Subsurface Geological and Geophysical Data from the Po Plain and the Northern Adriatic Sea (North Italy). Earth System Science Data Discussions 2023, 1-41, doi:10.5194/essd-2023-65.

Mirabella, F., Brozzetti, F., Lupattelli, A. & Barchi, M.R., (2011). Tectonic evolution of a low-angle extensional fault system from restored cross sections in the Northern Apennines (Italy). Tectonics 30, TC6002, https://doi.org/10.1029/2011TC002890

Montone, P., Mariucci, M.T., (2020). Constraints on the Structure of the Shallow Crust in Central Italy from Geophysical Log Data. Sci Rep 10, 3834. https://doi.org/10.1038/s41598-020-60855-0

Porreca, M. *et al.*, (2018). Seismic reflection profiles and subsurface geology of the area interested by the 2016-2017 earthquake sequence (Central Italy). Tectonics 37, 1116-1137, https://doi.org/10.1002/2017TC004915

Scisciani, V. *et al.*, (2014). Positive inversion tectonics in foreland fold and thrust belts: a reappraisal of the Umbria-Marche northern Apennines (Central Italy) by integrating geological and geophysical data. Tectonophysics 637, 218-237, https://doi.org/10.1016/j.tecto.2014.10.010