

Comparative analysis of bulk and velocity-derived density data in deep wells in the Adriatic area (Italy)

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Abstract

This work is based on a systematic comparison between two datasets related to density data of geological formations crossed in 13 deep wells. The wells are located in the Adriatic area and reach depths of over 5000 meters. The main lithologies involved include sandstones, marls, clays, evaporite, and carbonate rocks. The first dataset concerns density values obtained from the analysis of sonic logs recorded along the wells, by applying the Gardner relation. The second dataset, on the other hand, refers to actually acquired density log measurements. Differences among the values in the two datasets have been calculated. The aim behind this work is to assess the reliability of rock densities estimated using the Gardner equation by comparing them to measurements obtained through density logs, despite many factors influencing the log density. This comparison of the densities obtained from various lithologies and geological formations leads us to draw, in this region, some initial considerations regarding the applicability and accuracy of Gardner formula, usually considered as standard reference, since the density log is generally available only within the reservoir. In the area we analyzed it is observed that the density values estimated from sonic velocities are underestimated for the Plio-Quaternary formations characterized by clayey-sandy lithologies by at least 0.1 g/cm^3 ; whereas, densities of the carbonate sequences are overestimated by the same extent. Noteworthy, the density estimates deviate from the real values especially for gypsum units, overestimating by a factor of approximately 0.3 g/cm^3 . The results we obtained emphasize differences in density values when using the Gardner formula and suggest the need for taking into account the possible errors in the specific geological context or instead lithologies, such as those explored in this study.

Keywords: Density; Sonic log; Deep wells; Adriatic Sea; Italy

1. Introduction

This work is based on the analysis of rock density values derived from sonic logs and from data directly acquired from density records, along 13 deep wells drilled in the Adriatic area (Fig. 1). The purpose is to evaluate the accuracy of rock densities estimated using the Gardner equation [Gardner et al., 1974] by comparing them to measurements directly acquired by density logs, notwithstanding numerous factors affecting log density, such as borehole condition and the presence of gas.

Several papers have been published in the last years about the analysis of sonic log records along deep wells both in the neighboring area [Montone and Mariucci, 2023a] and in other regions of Italy [Montone and Mariucci, 2015; Mariucci and Montone, 2016; Montone and Mariucci, 2020; Montone and Mariucci, 2023b].

Density is a fundamental physical property of rocks [Mavko et al., 2009] typically determined in a laboratory through the examination of core samples [Smeraglia et al., 2014; Trippetta et al., 2021] or from wireline logging acquisition. Unfortunately, density values are not frequently accessible, as core data are not very abundant especially in the more recent sequences and the density tool is often excluded from the logging string as its measurement is based on the use of a radioactive source. The density log is generally performed only within the reservoir, instead the sonic log is usually available throughout the entire well. Thus, in most wells, the velocity-derived density obtained from sonic measurements is the sole available source of information, and the Gardner formula is typically regarded as standard reference.

Density values are important to construct and to interpret seismological, gravity and magnetic models and to constrain finite element models and in order to perform the physics-based numerical simulations of the seismic wave propagation [Tiberti et al., 2005; Candela et al., 2015; Klin et al., 2019; Mancinelli, et al., 2019; Buttinelli et al., 2021]; and also to determine the vertical lithostatic stress magnitudes along the crust [e.g., Bonini, 2012; Musolino et al., 2019; Morawietz et al., 2020].

Along the wells, within each geological formation, from the detailed analysis of the sonic curve, intervals characterized by homogeneous sonic slowness were identified, and the average slowness was determined. Subsequently, the slowness value was used to compute the rock density of each interval by applying Gardner formula. For the same wells and for the same depth intervals the average density from measurements directly acquired during drilling was computed and compared with the sonic derived one. This allowed us to carry out a systematic comparison of the density results obtained for different lithologies and geological formations, which led us to reach some preliminary considerations on the applicability and goodness of Gardner's formula for this Italian area. Gardner's relation is a widely used empirical formula in geophysics to estimate the bulk density of homogeneous intervals within a sedimentary formation based on its seismic P-wave velocity, when direct density measurements are not available. It is important to note that this formula provides an estimation and may not always be highly accurate, as geological formations can vary in composition and properties. Certainly, this rule offers accurate density

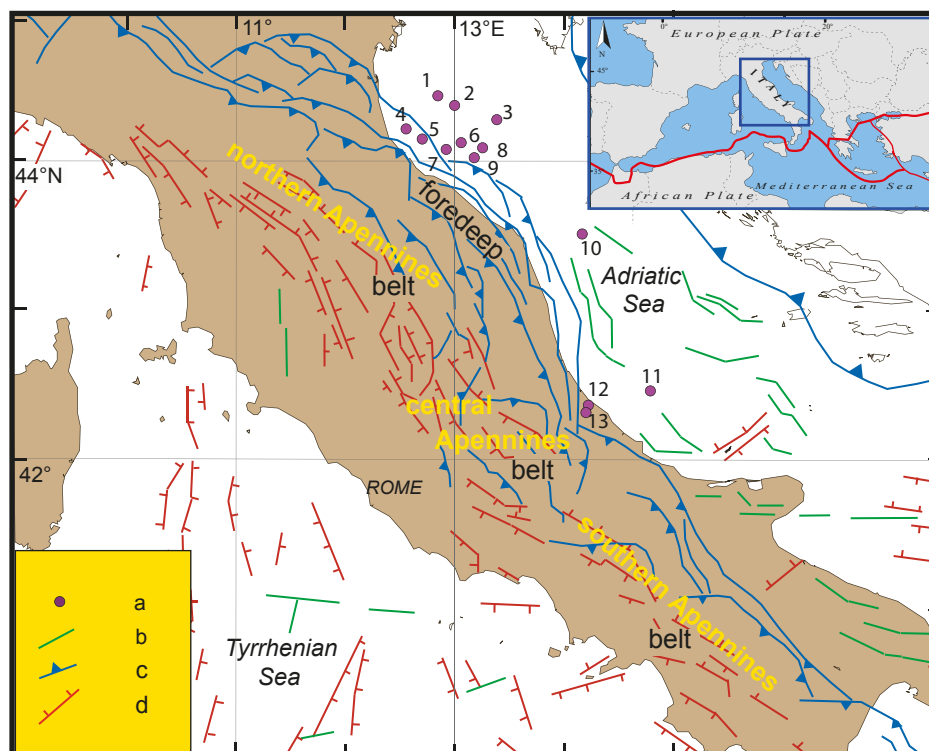


Figure 1. Tectonic setting of the Apennines. Legend: a) deep wells from 1 to 13; b, c and d) strike slip, thrust and normal faults simplified from Meletti et al. [2000].

predictions, even though employing the Nafe-Drake curve [Ludwig et al., 1970] results in values approximately 0.1 g/cm^3 lower, as noted by Brocher [2005]. Moreover, it exhibits a more significant deviation from the Nafe-Drake curve when V_p falls below 2 km/s.

A discrepancy between the density values derived from the application of Gardner's formula and the actual density values had already been highlighted by Gardner himself [Gardner et al., 1974] and by other authors later [Brocher, 2005]. In particular, it had been clearly demonstrated the inapplicability of Gardner's formula concerning evaporitic rocks. Evaporite rocks are sedimentary rocks that form as a result of the evaporation of water containing dissolved minerals. These rocks can include i) halite (rock salt), composed mainly of sodium chloride; ii) gypsum or anhydrite, composed of calcium sulfate; and iii) carbonates, while not exclusively considered evaporite rocks, some carbonate minerals like calcite and dolomite can be found in evaporite deposits.

The 13 wells are located along the Adriatic foredeep of the Italian peninsula (Fig. 1). The Adriatic foredeep is a geologically significant and dynamic region within the broader context of the Mediterranean tectonic plate boundary. This geological feature is primarily associated with the convergence of the African and Eurasian tectonic plates, which has shaped Italy's complex geology and tectonics. The Adriatic foredeep is essentially a long, narrow depression that extends along the eastern side of the Italian Peninsula, running parallel to the Apennine belt. This basin is a product of tectonic compression, where the African plate is colliding with the Eurasian plate. The ongoing collision has led to the subduction of the Adriatic microplate beneath the Apennines, resulting in the formation of the foredeep. One of the most characteristic features of the Adriatic foredeep is its sedimentary fill. Over millions of years, as the African plate pushes against the Eurasian plate, it has caused the deposition of a thick sequence of sedimentary rocks within the basin. Furthermore, the sedimentary deposits within the Adriatic foredeep have made it a resource-rich area, with significant hydrocarbon reserves. Oil and gas exploration and production have been ongoing in this region for many years.

The analyzed wells cross a sedimentary sequence characterized by Plio-Quaternary deposits primarily composed of alternating layers of clays and sandstones; Messinian evaporite formation and Jurassic-Miocene mainly calcareous rocks (Fig. 2).

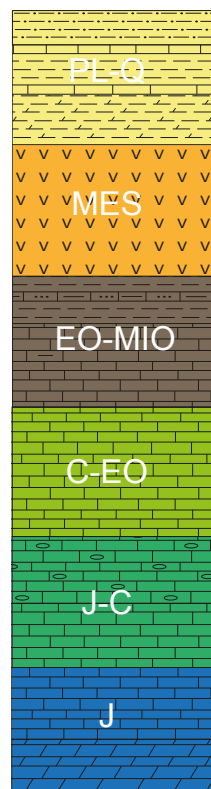


Figure 2. Scheme of the litho-stratigraphic groups. 1) PLQ, Plio-Quaternary formations. 2) MES, Messinian “Gessoso-Solfifera” formation. 3) EO-MIO, terrigenous units of Eocene-Miocene. 4) C-EO, Cretaceous-Eocene formations. 5) J-C, Jurassic-Cretaceous formations. 6) J, Jurassic formations.

After a brief description of the methodology used, we will describe the results obtained by comparing the dataset of densities derived from the Gardner formula with those obtained directly from density logs. Finally, the conclusions of this work, albeit preliminary, serve as a significant starting point for potentially calibrating the Gardner relationship in more localized geological contexts, such as the one analyzed in this study.

2. Method

We have analysed sonic and density log data from 13 deep wells located in the Adriatic Sea, offshore and along the coast of Italy, using both plot of “composite logs” of 1:1000 scale and digital logs, investigating a depth range from 750 to 5200 m.

From the stratigraphic logs of the study wells we have identified the main formations and gathered them into six groups according to lithologies and age, in order to discuss the geophysical characters inferred from well logs jointly to the main lithologies of each group.

Here is a brief description of the litho-stratigraphic groups (Fig. 2). The Plio-Quaternary successions of the Adriatic foredeep, mainly composed by alternating clays and sands form the PLQ group, e.g., Santerno, Porto Corsini and Porto Garibaldi formations. The MES group is relative to the Messinian Gessoso-Solfifera formation, characterized by evaporitic facies (gypsum and anhydrite) and clay intervals. The EO-MIO group includes the marly, clayey-marly, and marly-calcareous lithofacies of Eocene-Miocene age, belonging to the formations Schlier, Bisciaro and Scaglia Cinerea of the Umbria-Marche sequence (between central and northern Apennines). The C-EO group refers to the Scaglia formation, a succession of marly limestone from Cretaceous to Eocene. The whole pelagic sequence from Jurassic to Cretaceous, forms the J-C group and includes the following formations: Marne a Fucoidi, Maiolica, Aptici, Diaspri, Marne a Posidonia, Rosso Ammonitico, Corniola. The calcareous-dolomitic succession of the Calcare Massiccio formation is the group J.

From the sonic records we have inferred the P-wave velocity in each homogeneous depth range, assigning a slowness value accurately hand-picked and/or through an average computed from the digital logs, and a related quality rank to evaluate the reliability of the value.

For each homogeneous interval of the sonic record, we have estimated a density value (velocity-derived density) using the empirical formula by Gardner et al. [1974]:

$$d = 0.23V^{0.25} \quad (1)$$

where d is density in g/cm^3 and V is sonic velocity in feet/s.

Then, we have analyzed digital density logs [except for one well with no digital data] and have computed the mean values (directly measured density) for the same intervals of the sonic logs. Also in this analysis, we assigned a quality rank to each value. In Fig. 3 an example of three homogeneous log intervals and the related average values is shown. The slowness value was used to compute the density of each interval with the Gardner formula. In the same interval, average density from density log was computed, and compared with the sonic derived one.

Afterwards we have compared the two datasets, results of velocity-derived density and density directly measured (Fig. 4a-d), to investigate the differences between them and the possible reasons.

The quality rank assigned to each value allowed us to discard the worst data before comparing and discussing the results. Discarded data are those relative to depth intervals, although short, where a reliable mean value of a log is difficult to infer. Often this occurs where lithologic succession is composed by thin layers with very different characters or in fractured rocks. Of course, we also removed depth intervals with a gap in one of the logs.

By comparing well stratigraphy and logs, we have associated sonic and density values to the main litho-stratigraphic groups identified in the wells.

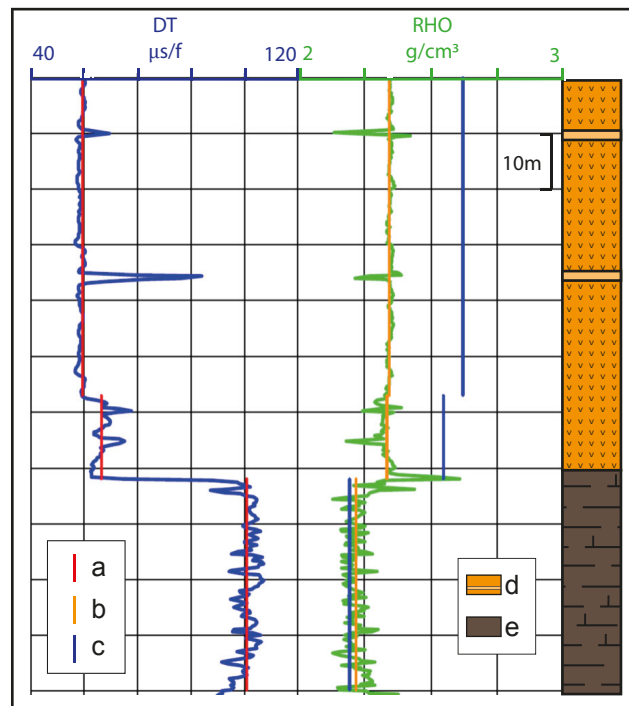


Figure 3. Example of three different homogeneous intervals recognized in the sonic (DT, on the left) and density (RHO, on the right) logs. a) average slowness values; b) average density values; c) average velocity-derived density values; d) gypsum and anhydrites with two clay levels (Gessoso-Solfifera fm., Late Messinian); e) marls (Schlier fm., Early Messinian).

3. Data Analysis

Density data distribution with depth of the litho-stratigraphic groups is plotted in Fig. 4 for both density datasets; circles and squares indicate velocity-derived and density log, respectively. In general, a common trend of density increasing with depth is observed.

The minimum and maximum values of density in the study area, without considering the method used to infer density, are around 2 g/cm^3 and more than 2.8 g/cm^3 . The lowest value refers to clay and sands of PLQ group at 1000 m depth, for velocity-derived density, and the highest is relative to dolostones of J group at about 4800 m from density log.

Considering the different litho-groups, at a first glance to the diagram (Fig. 4a), we can consider typical ranges of density values. PLQ ranges from 2.0 to 2.45 and from 2.1 and 2.55 g/cm^3 for velocity-derived and density log data, respectively (Fig. 4b). The variability is due to the lithology successions that characterize the group and their compaction with depth but is also partially due to the different method used to derive density. Indeed, looking in detail Fig. 4b, the difference between velocity-derived density and density log values is quite evident. Density estimated from sonic log (circles in Fig. 4) seems almost always lower than that measured by density log (squares).

A peculiar feature is shown by MES group (Fig. 4c), where the difference between the two methods is sometimes stronger and deserves a thorough discussion: the velocity-derived densities are much higher than those from density logs. The succession that characterizes this group is formed by evaporitic facies (gypsum and anhydrite) and clay intervals producing clear responses in the geophysical logs (Fig. 5). The large difference between velocity-derived and measured density is due to the properties of the evaporitic rocks. For instance, where gypsum prevails the formula used to estimate density from sonic log does not work properly. Gypsum is characterized by lower densities with respect to the ones predicted by the sonic velocities.

The variety of different lithologies of the formations included in the EO-MIO group (Fig. 4c) makes the range of density values much larger, between 2.17 and 2.7 and 2.15 and 2.65 g/cm^3 , for velocity-derived and density log data, respectively. In this case the values estimated from sonic logs are generally slightly higher than the measured density. The same happens in the C-EO group (Fig. 4d), with few exceptions, although here the variability is lower, from 2.4

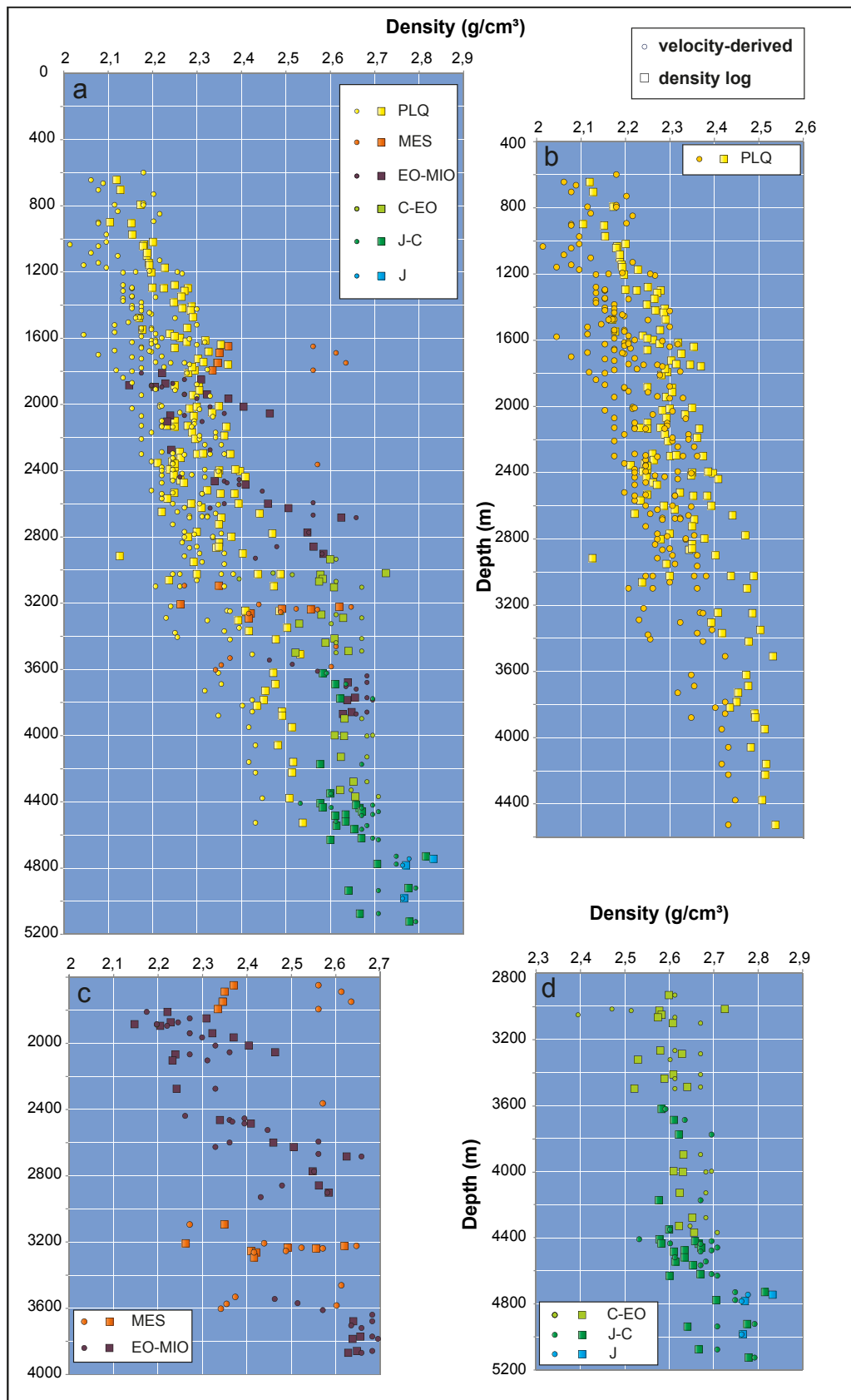


Figure 4. Density values vs depth in the 13 wells analysed. Circle is velocity-derived density, square is density log. Values are plotted at the upper depth of the interval to which they refer. Colours stand for the different litho-groups (see Fig. 2 and text for details): PLQ, Plio-Quaternary formations; MES, Messinian “Gessoso-Solfifera” formation; EO-MIO, terrigenous units of Eocene-Miocene; C-EO, Cretaceous-Eocene formations; J-C, Jurassic-Cretaceous formations; J, Jurassic formations.

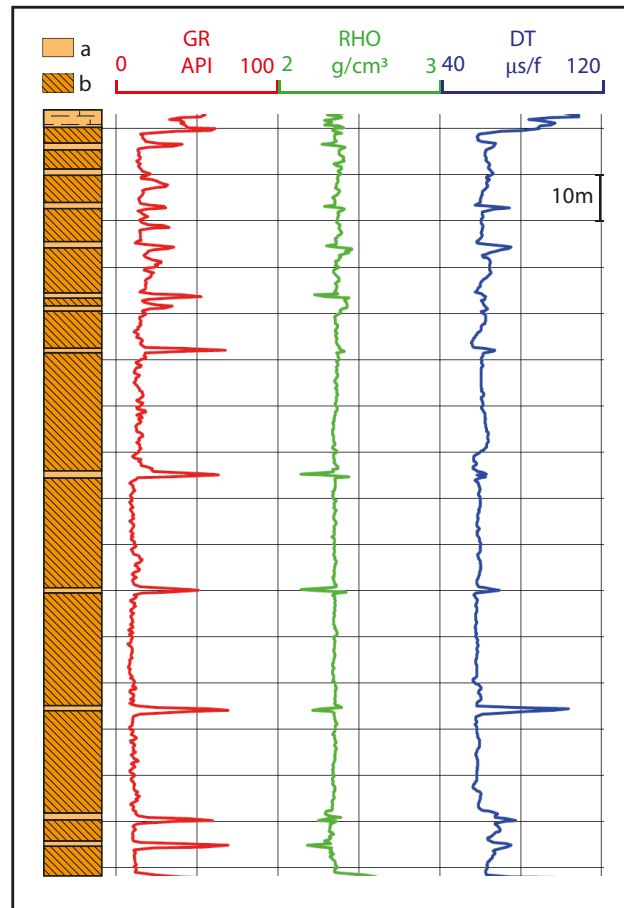


Figure 5. Example of log responses in a succession of different lithologies characterizing the Gessoso-Solfifera formation. a) clayey intervals; b) evaporitic levels. On the right, some geophysical logs: GR, gamma-ray (red); RHO, density (green); DT, sonic (blue).

to 2.71 and from 2.52 to 2.73 g/cm³, for velocity-derived and density log data, respectively. Similar behavior is shown by data of the J-C group (Fig. 4d) with values ranging from 2.5 to 2.79 and 2.57 to 2.82 g/cm³ for velocity-derived and density log data, respectively. Density values of the J group, relative to dolomite or calcareous-dolomite lithofacies, are defined by few data that do not show relevant differences between the two methods, with values from more than 2.75 up to about 2.85 g/cm³ for both datasets (Fig. 4d).

4. Discussion and Conclusions

This work compares the density values derived from the sonic logs recorded along deep wells with those directly measured in the wells. Data from 13 deep wells, located along the Adriatic margin, both onshore and offshore the Italian peninsula, were analyzed. Density measurements fall within a depth range of 750 to 5200 m. From the detailed analysis of the sonic log curves along the wells, within homogeneous intervals density measurements were derived using the specific Gardner formula for those rocks and grouped based on the crossed lithologies. Comparing these values with those directly obtained from the density log allowed for the identification of some systematic correlations in the density value variations.

To verify these possible correlations, we calculated the differences between the values estimated from sonic log data using Gardner's relation and those directly measured by the density logs (Fig. 6). This allowed us to draw a graph in which, for the various litho-groups identified, data that most deviate from each other are highlighted. The negative differences point out that the formula used to infer densities from sonic velocities, underestimates the density value; the positive differences, on the contrary, indicate an overestimation, the real values are lower than the estimated ones.

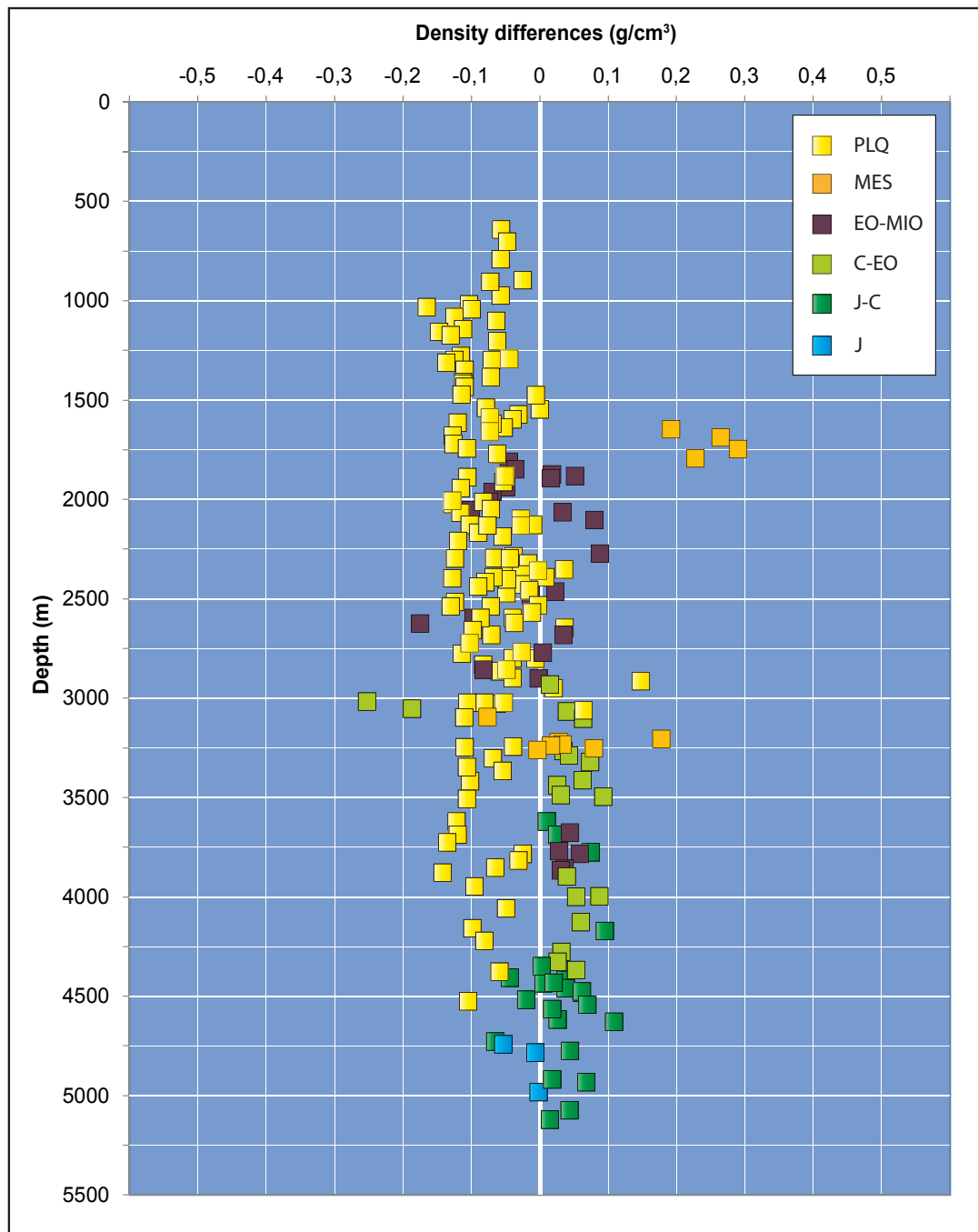


Figure 6. Differences of density values (estimated-measured) for each interval selected in each well, between the velocity-derived value, estimated using Gardner’s formula [Gardner et al., 1974], and the value measured from the density log. Values are plotted at the upper depth of the range to which they relate. Colours represent the different litho-groups (see text for details).

Brocher [2005] already highlighted some discrepancy between the values obtained from the Gardner formula and those derived from the Nafe-Drake curve [Ludwig et al., 1970]. In particular, a more or less constant overestimation of approximately 0.1 g/cm^3 was observed.

In light of the results we obtained (Fig. 6), the first evidence is the great difference among data of MES group, probably due to the presence of evaporitic rocks, whose density cannot be correctly estimated from sonic data using the Gardner formula, as Gardner et al. [1974] also stated. Evaporites, unlike all the other sedimentary rocks have physical properties that are not correctly represented by that formula. Specifically, among the evaporite rocks, gypsum displays estimated density values significantly overestimated compared to their true values obtained from

the density log, by at least 0.3 g/cm^3 . In this specific case, the density log records a very precise gypsum density value of 2.35 g/cm^3 , as visible in Figure 4c at depth between 1600 and 1800 m.

Along the analysed wells we have many levels mainly of gypsum within the Gessoso-Solfifera formation and their low density produces the high differences (Fig. 6). When estimating density, we are aware of this problem and avoid discussing density values of evaporitic levels. Here we wanted to define the error affecting the value of velocity-derived densities in this kind of lithology. When, instead, in the Gessoso-Solfifera formation (MES), there are levels characterized by a higher percentage of anhydrite compared to gypsum, the density value obtained using the Gardner formula is entirely comparable to the direct density value, which is approximately 2.6 g/cm^3 .

On the other hand, for carbonate densities, Gardner's values are overestimated by approximately 0.1 (Fig. 6), consistent with what Nafe-Drake had already suggested [Ludwig et al., 1970]. The highest density values (up to 2.8 g/cm^3) are observed in dolomitized limestones, calcareous dolomites, and dolomites, and the results are consistent for both datasets, such as for instance in the J and J-C formations at greater depths (Fig. 4d).

Nevertheless, typical trends are evident: the clayey-sandy formations of Plio-Quaternary (PLQ group) seems to be always underestimated, whereas all the other formations of the Umbria-Marche marine Meso-Cenozoic sedimentary sequence (C-EO, J-C) are slightly overestimated. Even if the differences are small, it is useful to know that the error from the estimation is only in one direction and could help in the interpretation of this kind of data, when no direct density measurements are available. Other differences lie within small values that could also be considered within the error of measurements, at least in some cases.

Certainly, the data presented here are relatively limited, focusing on a specific region. However, we consider this to be a preliminary assessment that can potentially be integrated with data from other regions in Italy where both sonic and density logs can be compared.

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