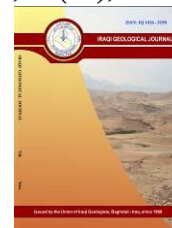




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Application of Velocity Deviation Technique for Pore System Analysis in the Hartha Formation, Gharraf Oil Field, Southern Iraq

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Abstract

The study's main objective is to determine the pore types of the Hartha Formation in the southern Iraqi Gharraf oil field. The study integrates velocity deviation analysis, secondary porosity evaluation, and conventional log data, collected from three wells distributed across the study area. In addition, shale volume was quantitatively estimated to enhance the accuracy of the lithological interpretation. The velocity deviation log was generated from the difference between the measured sonic velocity and the synthetic neutron-derived velocity estimated using the Wyllie Equation. The results revealed a significant relationship between the increasing and decreasing trends of velocity deviation and secondary porosity within the studied wells. This relationship reflects variations in pore-system development and reservoir heterogeneity. Based on the velocity deviation log response, three main zones were identified. The near-zero deviation zone, characterized by small differences between actual and synthetic velocities, accounts for an average thickness of 66 m (35%) of the total formation thickness. This zone represents intervals with various intercrystalline, interparticle, and microporosities. The positive deviation zone represents an average of 63.8 m (30.6%) of the total formation thickness. This zone, which shows relatively high velocity values, represents intraparticle or moldic porosity, which has low permeability. The third zone is the negative velocity deviation zone, constituting about 34.3% of the total formation thickness and mainly occurring in the lower part of the formation. This zone is associated with increased density and resistivity, lower sonic velocity, higher synthetic neutron velocity, and elevated shale content, suggesting the effects of compaction, cementation, fractures, and shale-related influences on the pore system. These results reveal that the velocity deviation technique is a dependable indicator for pore-type differentiation in reservoir characterization, especially when integrated with conventional well logs. It provides valuable insights into pore-system heterogeneity and can support improved reservoir evaluation in carbonate formations.

Keywords: Hartha Formation; Secondary porosity; Velocity deviation; Fractures; Dolomatization

1. Introduction

More than 50% of the world oil reservoirs are found in carbonate rocks, that form significant hydrocarbon reservoirs, and a significant portion of natural gas. Despite their importance, their strong heterogeneity and complex pore structures, resulting from depositional conditions and diagenetic processes, make them more challenging to characterize than clastic reservoirs (Lucia, 2007; Schlumberger, 2013; Balaky et al., 2023). Unlike clastic reservoirs, carbonate rocks are characterized by a wide variety of pore types, including interparticle, intraparticle, moldic, vuggy, and fracture

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porosity, which may develop during depositional and post-depositional processes. The type, distribution, and connectivity of these pores strongly influence reservoir quality, particularly porosity and permeability (Choquette and Pray, 1970; Lucia, 1995). Because of the complexity of carbonate pore systems, identifying pore types has become an essential step in reservoir characterization. Traditional approaches for determining pore types depend mainly on core analysis, thin-section petrography, and scanning electron microscopy. Although these techniques provide detailed information about pore geometry, they are limited by the availability of core samples and their restricted vertical coverage within the reservoir. Thus, petrophysicists increasingly rely on well-log data to infer pore structures and evaluate reservoir properties in uncored intervals (Lucia, 1999; Tiab and Donaldson, 2015).

Recently, some studies have demonstrated that acoustic velocity information obtained from sonic logs can provide valuable insights into the internal structure of reservoir rocks. The propagation velocity of acoustic waves in porous media is controlled not only by porosity but also by pore geometry, pore connectivity, and the mechanical properties of the rock framework (Xu and Payne, 2009; Baechle et al., 2007; Al-Awsi et al., 2021). Therefore, integrating velocity data with petrophysical logs has become an important tool for evaluating pore systems and reservoir quality.

Among the numerous methods established to interpret acoustic velocity data in carbonate rocks, the Velocity Deviation technique has gained considerable attention. This technique is based on: comparing the measured acoustic velocity, obtained from well logs, with the theoretical velocity, predicted from established velocity–porosity relationships. The difference between the measured, and predicted velocities, referred to as velocity deviation, can provide important information about: pore types and rock fabric (Anselmetti and Eberli, 1999; Mashayekhi et al., 2025).

The Hartha Formation; is one of the important carbonate formations, in southern Iraq, and represents a significant hydrocarbon reservoir in several Iraqi oil fields. The formation mainly consists of: limestone, and dolomitic limestone, deposited in shallow marine environments, during the Late Cretaceous (Jassim and Goff, 2006). Diagenetic processes such as: dissolution and recrystallization have modified the original depositional fabric, and created complex pore systems, that strongly influence reservoir quality. In the Gharraf oil field, the Hartha Formation is considered a promising reservoir interval. However, understanding the nature of its pore systems remains essential for; accurate reservoir evaluation (Jassim and Goff, 2006; Aqrabi et al., 2010). Therefore, the current study aims to; identify pore types within the Hartha Formation in the Gharraf oil field, southern Iraq, using the Velocity Deviation technique.

2. Location of the Study Area

The Gharraf oil field is located in Dhi Qar Governorate, southern Iraq, about 265 km southeast of Baghdad city and about 85 km north of Nasiriyah city (Fig. 1). The Gharraf oil field lies within the Mesopotamian Basin, in the Stable Shelf region (Jassim and Goff, 2006). It is situated within the Euphrates Subzone. This subzone is characterized by short, longitudinal anticlines trending from northwest to southeast. The Gharraf oil field represents a longitudinal anticline with its structural axis oriented in a NW–SE direction. The Gharraf oil field extends for approximately 24 km in length and 5 km in width.

3. Materials and Methods

The log data used in this study include Gamma Ray (GR), Density (RHOB), Neutron (NPHI), and Sonic (DT) logs obtained from three selected wells in the Gharraf oil field (Ga-D86P, Ga-G138P, and Ga-K136P). Before the petrophysical analysis, data quality control and environmental corrections were

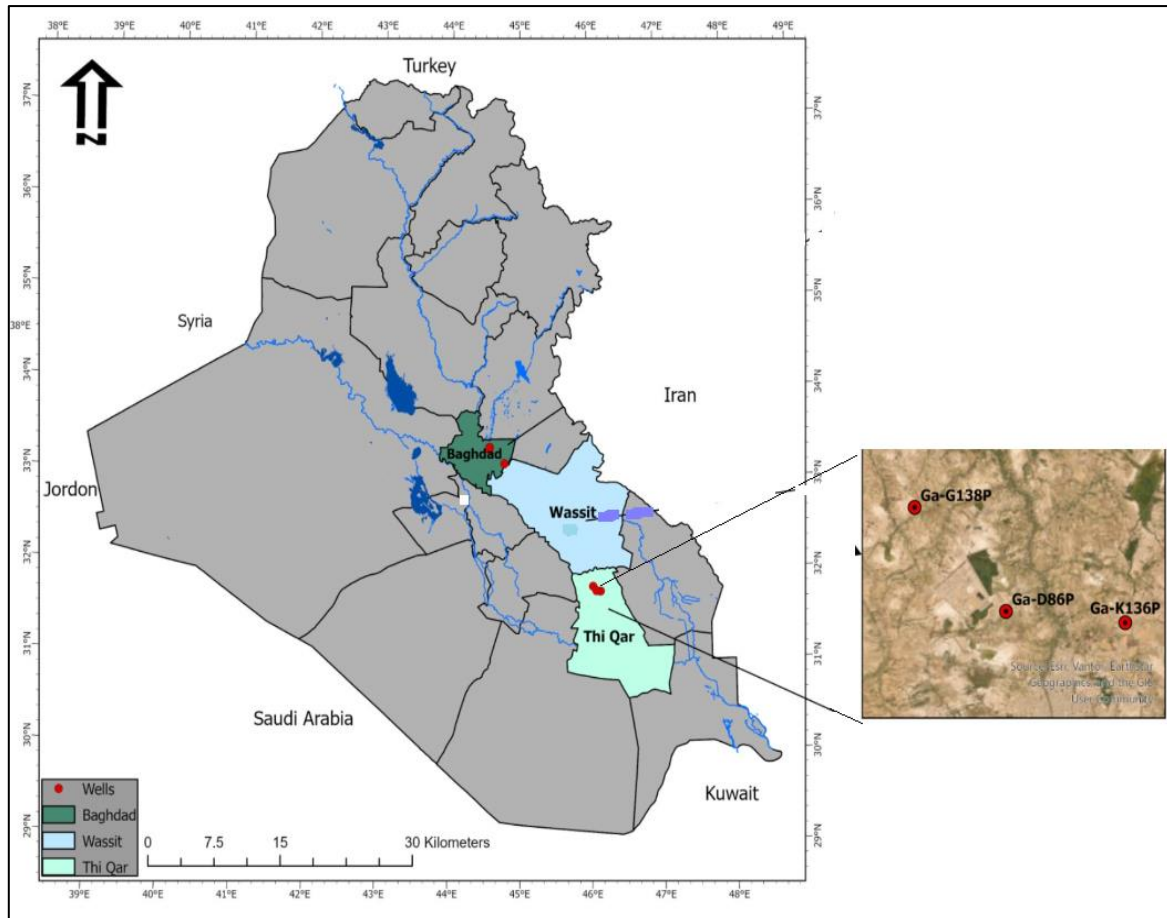


Fig. 1. Location map illustrating the studied wells

performed to eliminate the effects of borehole conditions on the log readings using Interactive Petrophysics software (IP v3.5, 2009). The corrected log data were subsequently used as input for the petrophysical evaluation of the Hartha Formation in the studied wells. The shale volume was estimated from the gamma ray log, while the lithology of the studied intervals was identified using the neutron–density cross-plot. The actual compressional wave velocity (V_p), defined as the reciprocal of the sonic interval transit time ($1/\Delta t$), was calculated. In addition, porosity values derived from the neutron log (NPHI) were converted into synthetic velocity values using Wyllie’s time-average equation (Wyllie et al., 1956), and their relationship was extracted. Finally, the velocity deviation log was obtained by calculating the difference between the actual and synthetic velocities. Variations in these deviations were subsequently analyzed to identify the pore types within the study area.

3.1. Lithology Identification

The neutron-density cross plot was used to identify lithology in the studied wells. This method is one of the most important and commonly used for lithological identification. Cross plot features three diagonal lithology lines; sandstone, limestone, and dolostone, each marked with corresponding porosity values expressed as percentages. In this cross plot, the neutron porosity reading, is represented on the x-axis, while the bulk density readings are on the y-axis. The color scale, typically, indicating the Gamma Ray (GR), is displayed on the z-axis. Log readings at specific depths are; plotted on the cross plot. The position of these plotted readings relative to the lithology lines serves as an indicator of both; lithology and porosity.

3.2. Velocity Deviation Log

The Velocity Deviation Log (VDL) is used to identify pore types, and infer permeability trends by integrating density, neutron, and sonic logs. The method follows the Anselmetti and Eberli (1999) approach, where synthetic velocities (based on porosity logs) are compared with actual sonic velocities to compute deviation values. In this study, synthetic velocity is calculated from the porosity values measured by the neutron-porosity log (due to the uncertainty of the density log, which is highly sensitive to borehole wall conditions). The neutron-porosity values are converted to synthetic velocity by applying the following time-average equation (Wyllie et al., 1956).

$$\frac{1}{V_{rock}} = \left[\frac{1 - \Phi}{V_m} \right] + \left[\frac{\Phi}{V_f} \right], \quad (1)$$

Where: V_{rock} is the required velocity (synthetic velocity), Φ is the neutron porosity (NPHIc), V_m is the velocity of the rock matrix (6530 m/s for limestone), and V_f is the velocity of interstitial fluids (1500 m/s for water) (Anselmetti and Eberli, 1999).

The actual sonic velocity (V_p), which represents the reciprocal of the sonic interval transit time ($1/\Delta t$), was calculated by following the Schlumberger (1972) equation:

$$V_{actual} (V_p) = 1000000 / (DT) \text{ (m/sec.)}, \quad (2)$$

The velocity deviations are obtained by subtracting the synthetic velocity from the actual velocity values calculated from the sonic log.

$$Velocity\ Deviation(VD) = Actual\ sonic\ velocity - synthetic\ velocity, \quad (3)$$

The velocity deviations can be plotted as a normal log in plots of deviation vs. depth. The best graphical displays were made by filling the deviations with respect to the zero-deviation line. The velocity deviation log represents the velocity difference resulting from two types of porosity logs (sonic and neutron logs), which can be a negative or positive number. Positive velocity deviations show zones where velocity is higher than expected from the porosity values, such as zones where frame-forming pore types dominate. Zero deviations mark intervals where the rock lacks a rigid frame. Negative velocity deviations show zones in which sonic log velocities are unusually low (Anselmetti and Eberli, 1999; Mashayekhi et al., 2025). By checking the velocity deviations continuously, diagenetic zones can be identified that are characterized by different pore types (Akintorinwa et al., 2008; Ebrahim et al., 2023).

4. Results and Discussion

4.1. Lithology Identification

As illustrated in the neutron–density cross-plots (Fig. 2), the distribution of data points from the Hartha Formation in wells Ga-K136P and Ga-G138P suggests that the main lithology is limestone and dolomitic limestone. Most data points from these wells cluster along the limestone line and between the limestone and dolomite lines. In contrast, well Ga-D86P shows that most data points shift towards the dolomite line, suggesting a higher degree of dolomitization within this well. This enhanced dolomitization is interpreted to be related to early diagenetic processes driven by Mg-rich fluids, commonly associated with restricted shallow-marine conditions (Warren, 2000). In addition, there are some points in all wells scattered as outliers, indicating shale content, which increases more in well Ga-D86P.

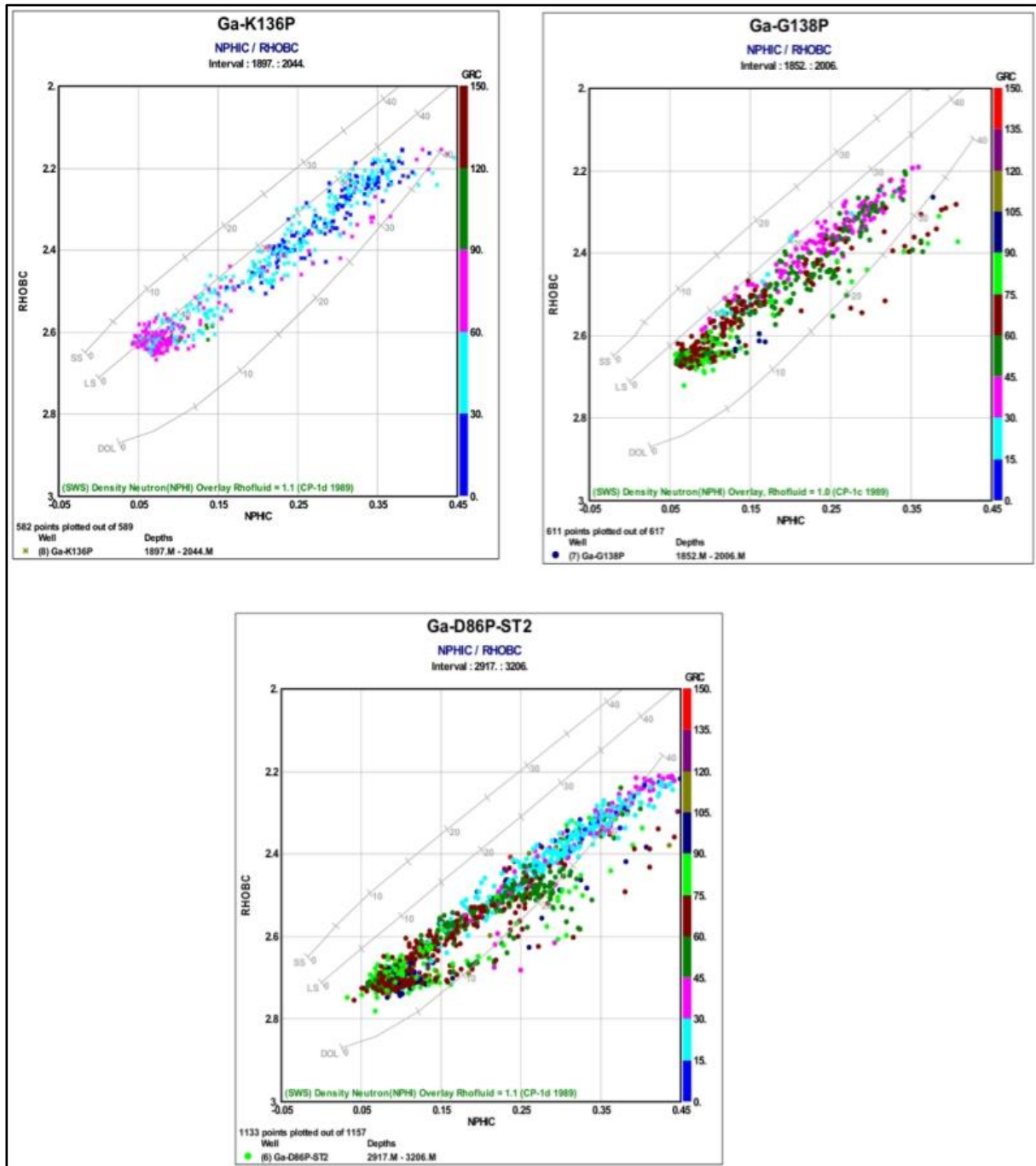


Fig. 2. Neutron –Density cross plots for the studied wells

4.2. Velocity Porosity Relation

The cross-plot of synthetic velocity (V_{syn}) versus neutron porosity (NPHIC) reveals an inverse relationship with a high coefficient of correlation of 0.96 (Fig. 3). Some data points from the studied wells align with the theoretical regression line, representing the dominance of primary porosity within certain depth intervals of the formation. Other data points scatter around the regression line, reflecting the effects of diagenetic processes, pore types, pore structure, and rock fabric on seismic velocity.

Points above the regression line indicate rocks with higher velocities than expected for a given porosity, which can be attributed to increased compaction, cementation, or dolomitization—all of which

increase the stiffness of the rock framework (red and blue points for Ga-D86P and Ga-G138P wells, respectively).

In contrast, points below the regression line represent lower velocities than expected, due to poor cementation or the effect of secondary porosity, which increases porosity without increasing elastic stiffness (Wyllie et al., 1956) (green points of the Ga-K136P well).

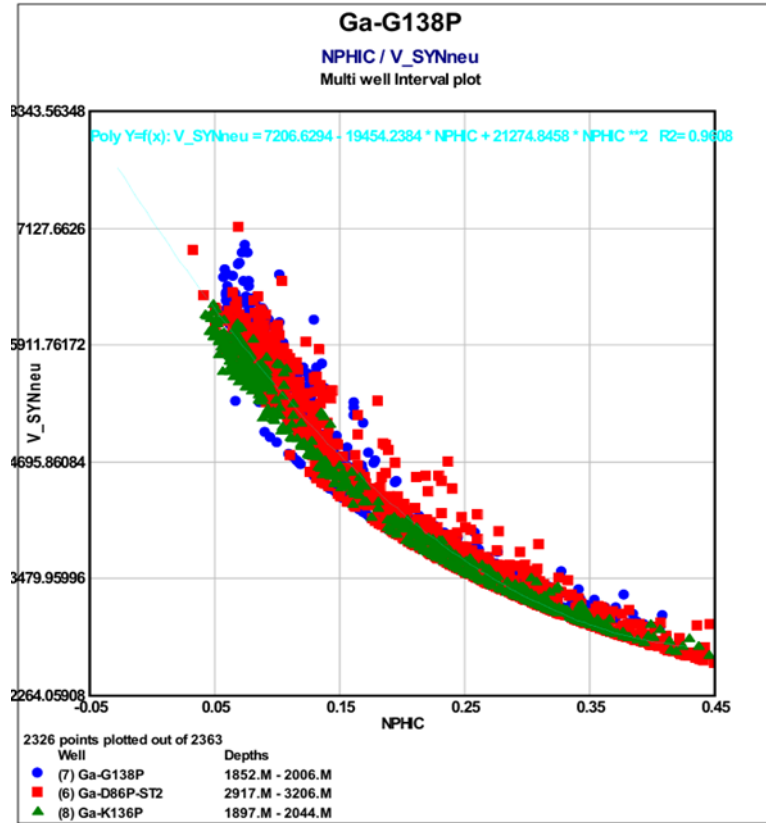


Fig. 3. Neutron Porosity- Synthetic Velocity Crossplot for the studied wells

4.3. Velocity Deviation Log

To identify the pore types of the Hartha Formation in the studied wells, the velocity deviation logs were integrated and compared with secondary porosity curves. This was achieved by using velocity logs derived from both sonic and neutron logs, in addition to porosity logs, resistivity logs, and the shale volume log (Figs. 4, 5, and 6). Based on the results obtained from the velocity deviation logs, three zones can be identified: zones with near-zero deviation, which have a low velocity deviation (± 500 m/s), positive deviation zones, and negative velocity deviation zones. The results were interpreted based on the methodology and interpretations applied by Anselmetti and Eberli (1999) for carbonate formations.

In the studied wells, a zone of small positive and negative velocity deviations (± 500 m/s) was observed across various depth intervals. This zone represents approximately 90 m (58%) of the total formation thickness in well Ga-G138P, 29 m (20%) in well Ga-K136P, and 79 m (27%) in well Ga-D86P (Fig. 7). This zone is characterized by intercrystalline porosity, microporosity, and interparticle porosity, all of which are formed after deposition. Such porosities generally have good connectivity and contribute to high permeability (except micropores, which reduce permeability). In these areas, diagenic processes are mild, leading to an increase in primary porosity and a decrease in secondary porosity. The relatively high proportion of this zone in Ga-G138P suggests that this pore system represents a dominant pore system within the formation at this location.

Zones with large positive velocity deviation and positive secondary porosity represent approximately 4.5 m (3%) of the total formation thickness in well Ga-G138P, 72 m (49%) in well Ga-K136P, and 115 m (40%) in well Ga-D86P (Fig. 7).

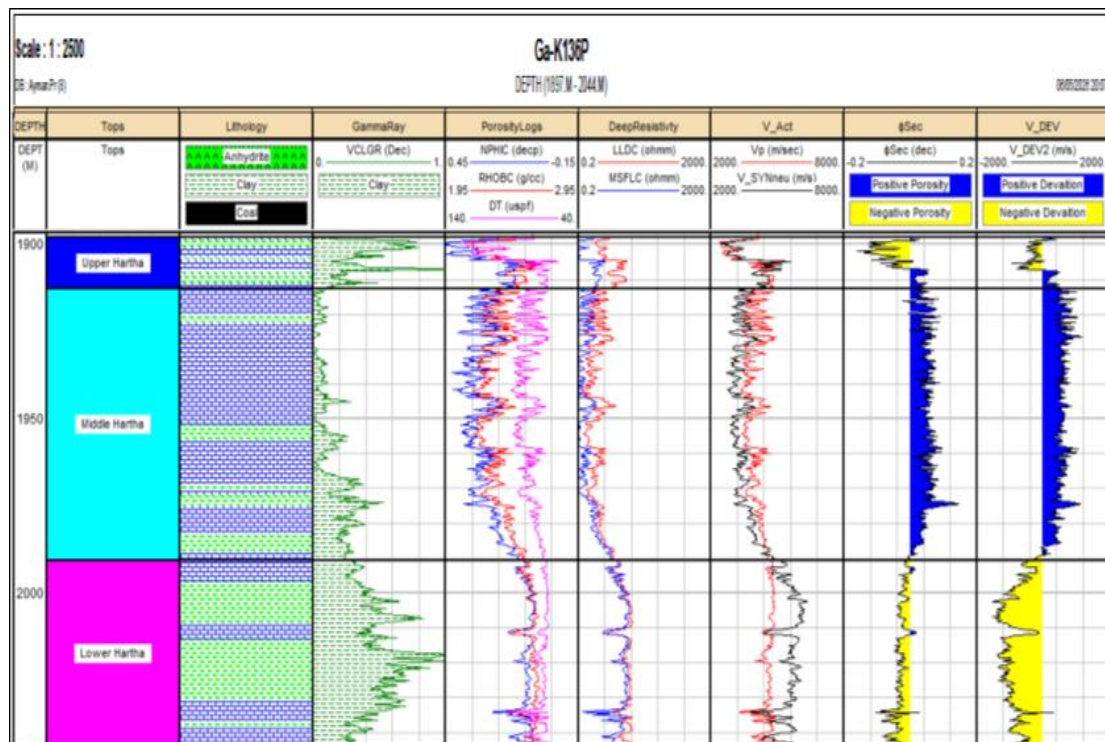


Fig. 4. Velocity deviation , secondary porosity, and Well log responses in Well Ga-K136P

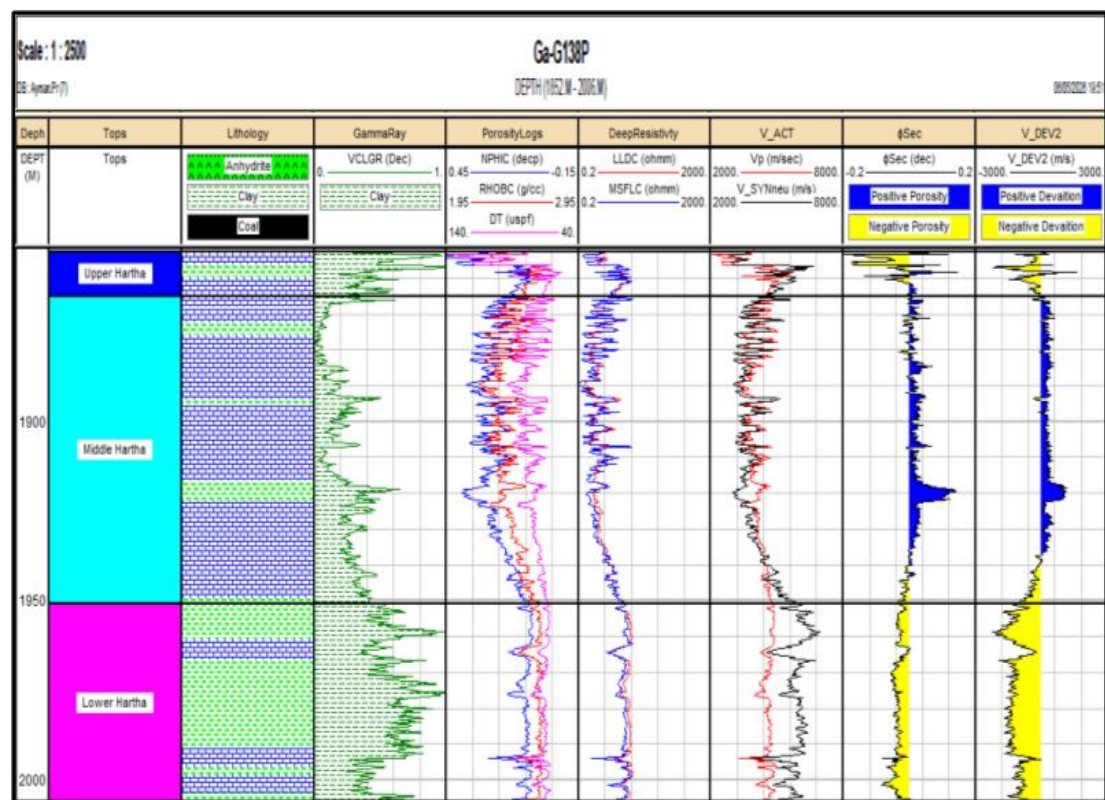


Fig. 5. Velocity deviation , secondary porosity, and Well log responses in Well Ga-G138P

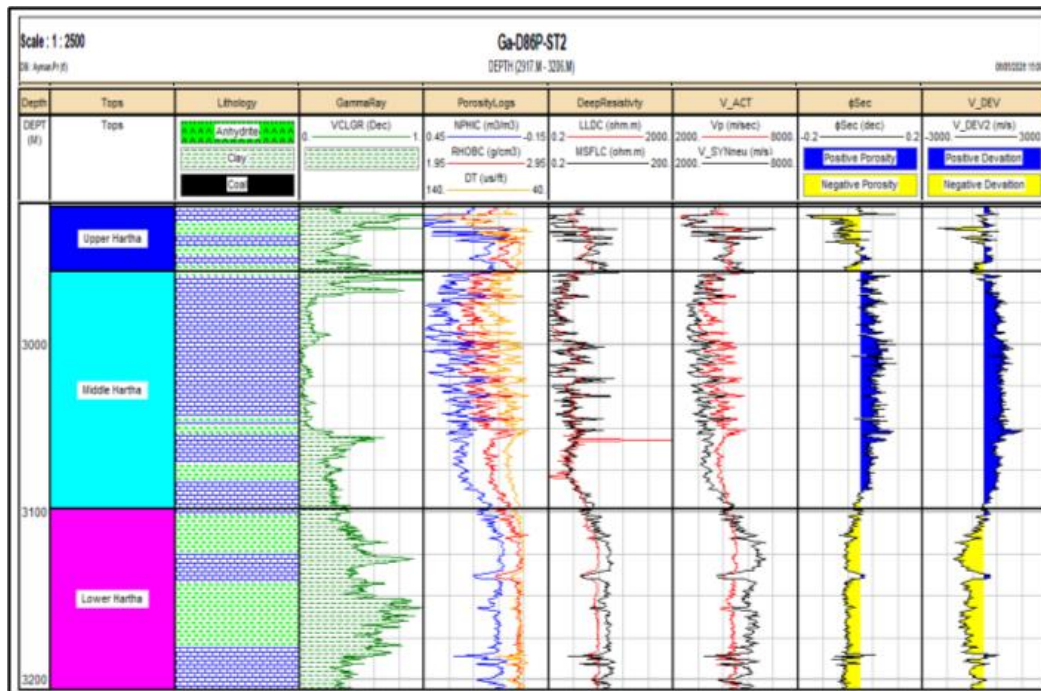


Fig. 6. Velocity deviation , secondary porosity, and Well log responses in Well Ga-D86P

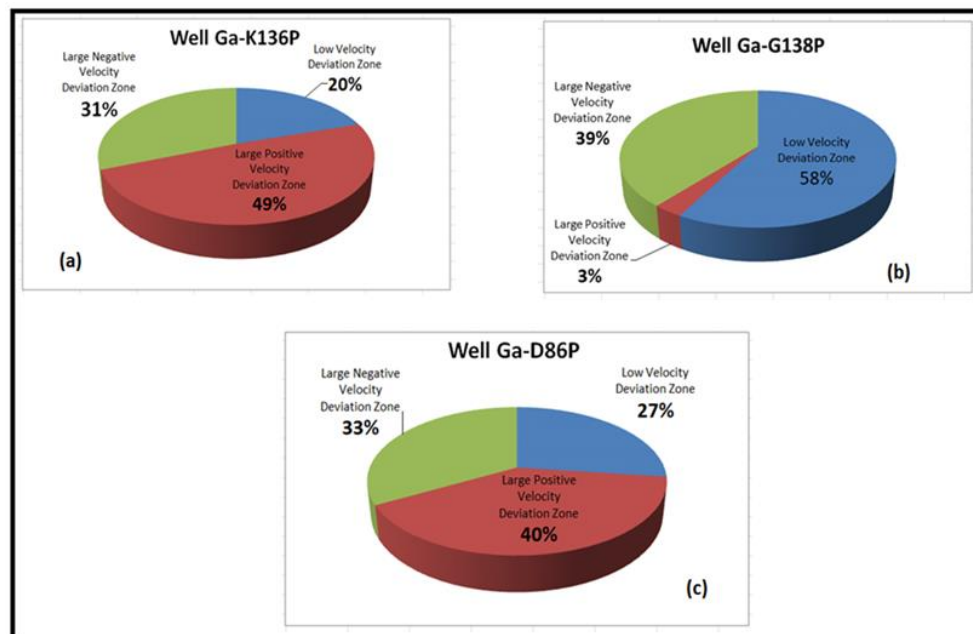


Fig. 7. Pie charts of the porosity types distribution in the studied wells of the Hartha Formation a) Well Ga-K136P; b) Well Ga-G138P; c) Well Ga-D86P

Zones with positive velocity deviation indicate relatively high velocities that are associated with porosities having a framework fabric, such as moldic, intra-skeletal, or isolated porosity. In moldic porosity, positive deviation reflects strong diagenetic variations, including dissolution or precipitation of soluble materials in the form of pore-filling cements (Anselmetti and Eberli, 1999). In general, positive deviations are indicative of a dense and cemented matrix with little or no connectivity between pore spaces, which results in low permeability (Anselmetti and Eberli, 1999). The relatively high proportion of this zone in the Ga-K136P well suggests that this pore system represents a dominant pore system within the formation at this location.

The lower part of the Hartha Formation is characterized by negative velocity deviation ($V_{DL} < -500$ m/s) in all studied wells. According to Anselmetti and Eberli (1999), three main factors can explain negative deviations: borehole washout, free gas content, and fracture porosity. Conventional logs were used to confirm the cause of negative deviation in the studied wells. In the absence of caliper logs, borehole washout is indicated by low density readings, increased sonic transit time, and reduced resistivity. Free gas zones can be recognized by low density and low neutron porosity readings, reflecting the low density and hydrogen content of gas. In the absence of these indicators, as shown in this study, large negative velocity deviations are attributed to secondary fracture porosity. In fractured rocks, the sonic-derived velocity (V_p , actual velocity) decreases sharply, while the neutron-derived velocity (synthetic velocity) remains unaffected due to limited porosity within fractured zones. This results in a negative difference between synthetic and actual velocity (Larki et al., 2024).

At intervals of negative velocity deviation, an increase in shale volume is observed, indicating that shale contributes alongside secondary porosity (fractures and vugs) to the negative velocity deviation. These intervals are characterized by high resistivity and bulk density, low actual sonic velocity relative to synthetic neutron velocity, and high neutron porosity. This combination shows how the observed log response is affected by shale, secondary porosity, and a dense carbonate matrix. Therefore, shaly, densely layered carbonate zones (limestone or dolomitic limestone) might be understood as negative velocity deviation intervals. A compacted and cemented carbonate matrix is indicated in these zones by high resistivity and bulk density, whilst the presence of shale is indicated by a strong neutron response. The effect of secondary porosity, especially cracks and vugs, is suggested by the low real sonic velocity and negative velocity deviation.

Fig. 8 displays: the relationship between; velocity deviation and secondary porosity (Φ_{Sec}), in the studied wells. The plot shows, a nonlinear polynomial positive trend, indicating, that as velocity deviation increases, secondary porosity also increases. The correlation coefficient ($R^2 = 0.7182$) suggests a strong relationship, consistent with previous studies on carbonate reservoirs (Anselmetti and Eberli, 1999; Weger et al., 2009; Ebrahim et al., 2023). These studies; confirm that pore geometry significantly influences sonic velocity behavior in carbonate rocks.

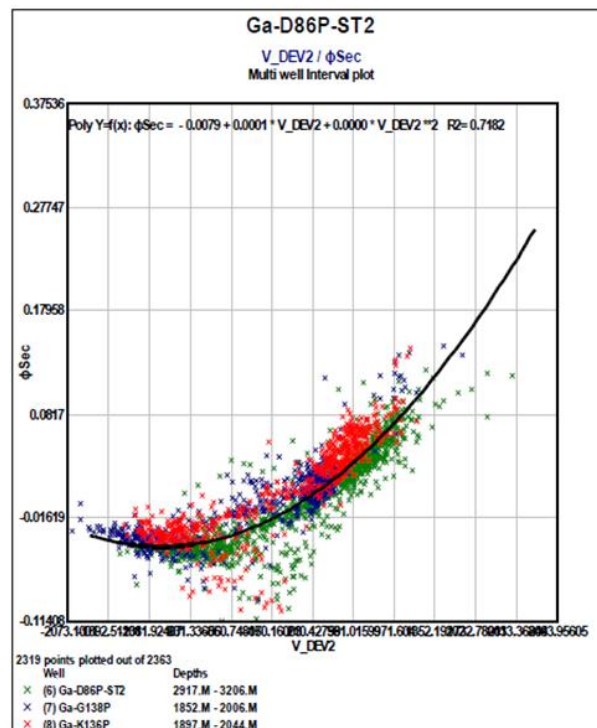


Fig. 8. Phi Secondary- Synthetic Velocity Crossplot for the studied wells

5. Conclusions

The current study reveals; combining the velocity deviation technique with traditional log data provides a reliable method for identifying pore types within the Hartha Formation in the Gharraf oil field. The methodology, based on; subtracting the synthetic neutron-derived velocity from the actual sonic-derived velocity, and charting the difference compared with depth to generate the velocity deviation log, allows for the characterization of predominant pore types in the formation.

Velocity deviation trends are closely correlated with changes in secondary porosity as The results demonstrate that. The formation can be divided to three main zones, were identified across the studied wells: the first; near-zero deviation zones, second zone; positive deviation zones; and third zone is negative deviation zones. The near-zero and positive deviation intervals, which represent the upper part of the Hartha Formation, there zones are characterized by lower density, lower resistivity, high reading of neutron porosity, and reduced shale content. These features reflect the dominance of primary porosity with contributions from dissolution-related secondary porosity.

In comparison, the lower part of the Hartha Formation is distinguished by negative deviation zones, which conform to weak reservoir conditions. In these intervals, compaction, cementation, and the presence of shale reduce pore connectivity, thereby decreasing reservoir quality.

Generally, the study confirms that the integration of the velocity deviation technique with conventional log data provides a reliable and effective approach for identifying pore types and evaluating reservoir heterogeneity within the Hartha Formation in the Gharraf oil field.

Declaration of Competing Interests

We declare that we have no competing financial interests or personal relationships that could influence the work reported in this study.

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