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Modified Gardner equation for evaluation of rock density basing on velocity data for Dnipro-Donets depression

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SUMMARY

Being an important parameter for geophysical data interpretation, density is often poorly studied for many basins, both by core and log data. This is the case for Dnieper-Donets basin. Multiple projects on joint gravity and seismic inversion allowed authors to investigate interrelationship between P-wave velocity and density using Gardner equation, thus allowing to use sonic logs and VSP velocities to calculate formation density. Studies showed that Gardner coefficients differ much from the average values published in classic paper by Gardner et al. (1974). The paper presents modified Gardner equation, refined for productive Carboniferous and Devonian formations of Dnieper-Donets basin.

Introduction

Density of the rocks is one of the important parameter used for understanding of lithological section but is more important for estimation of hydrocarbon reservoir properties, such as porosity or saturation. Traditionally density estimation is important for amplitude of seismic data inversion and interpretation. But with recent advances in gravity data inversion (e. g. Petrovskyy et al. 2005), preliminary estimation of formation density is first and an important step for building of realistic subsurface 3D density model. The latter can provide essential information for delineation of hydrocarbon reservoirs, thus to improve well planning and reduce risks of exploration process and drilling of the dry wells.

The main sources of density information are density logs and core data. As core data along do not provide continuous information needed for 3D spatial modelling and inversion, core data usually used only for calibration of petrophysical relationships. As to the well log data, for Dnieper-Donets basin (DDB) density logs are rare and mostly available only for old key wells, drilled 20-40 years ago. The latter are often corrupted hardly by well bore rugosity, making corrections challenging and data themselves mostly unsuitable for subsurface characterization.

In the situation when density logs are absent, traditionally, density is recalculated from interpreted lithology or velocity data using core data for relationships calibration. Densities based on lithology usually suffer from lack information about rocks mineral composition. Also it is often common to see that lithology-based densities do not reflect adequately compaction trends, depth and PT conditions. Instead, as velocity is sensitive to all of these parameters, velocity-based density estimation usually gives better results. Relationships for velocity-density conversions are empirical ones and are based on core measurements of mentioned parameters. The classical paper is Gardner et.al. (1974). Still as multiple research show (e.g. Wang Z. 2000; Nwozor et al. 2017), the coefficients of the velocity to density equation may vary for the same rock types for different basins. Results of multiple projects of joint inversion of gravity, seismic and well data to build 3D density models of HC prospects in DDB, allowed authors to specify Gardner's coefficients for rocks of different lithology and saturation type for this basin.

Method

General Gardner's equation (Gardner et. al., 1974) for bulk density estimation from seismic velocity is as follows:

$$\rho = \alpha * {V_p}^b,$$

where: ρ – bulk density, g/cm^3; V_p – P-wave velocity, m; α and b – empirical coefficients, calibrated basing on measurements of velocity and density on core. The average values of the coefficients for sedimentary rocks are a=0.31; b=0.25, which characterize approximately a mid-line for averaged several lithologies including shale, sandstone, limestone and dolomite. In practice, these coefficients vary depending on many factors. The dominating ones are rock lithology, porosity and saturation type. Other factors affecting rock bulk density, velocity and subsequently, Gardner's relationship coefficients include presence of microfractures, cracks, and pore geometry, reservoir depth and pressure, compaction and cementation, mineralogy, frequency. The number and variety of influencing factors are the reasons that velocity-density relationships are hard to be described by theoretical functions, so the empirical ones used. And, as mentioned above, even the latter differ for different basins.

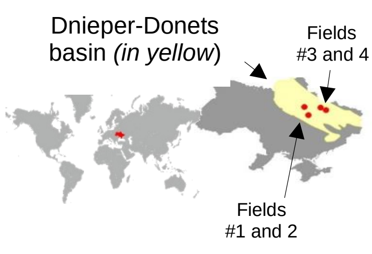

***Figure 1** Location of the investigated areas*

The research is based on the legacy core data of 67 wells from the four gas fields of Dnieper-Donets basin: two located close to the central part (CP) of the depression and two on its Northern Flank (NF) (Figure 1, Table 1). The age of studied rocks is mostly Carboniferous. Depth intervals vary from 1771 to 6390 meters. Limited number of data for Devonian sequence were included to study. Core data included laboratory density measurements in standard conditions. Thus, rock density by core was corrected for in-situ fluid density. Still corrections for in-situ fracture opening, pressure influence on matrix etc. could not be made. No velocity measurements on core were done. Thus in this particular case Gardner's coefficients were determined by adjusting density recalculated from sonic log to the core data.

Sonic logs for 42 wells were used in the study. For the wells, containing both sonic log and density by core direct calibration was done. For some wells we also minimized difference of the mean values by sonic density and by core density. Density logs for four wells were available, still only one from the central part of the DDB had acceptable quality to be used for calibrations.

Field	Number of wells with sonic log	Number of wells with core data	Cored interval, m		Age of rocks	Number of samples		
			top	bottom		Clay	Sandstone	Limestone
Field #1, CP	7	7	3281	4511	C	207	191	208
			5437	5950	D	6	653	81
Field #2, CP	8	11	3459	6390	C	-	1234	53
Field #3, NF	1	5	1771	3814	C	389	310	37
Field #4, NF	26	44	1795	4630	C	540	1371	183

Table 1 *Number of core data used for calibration of Gardner's coefficients*

To take into account the rocks lithology, we modified Gardner's equation by introducing weighted sum of the coefficients a and b for clay, sand and carbonate:

$$\rho = (K_c * a_c + K_s * a_s + K_{cl} * a_{cl}) * V^{(K_c * b_c + K_s * b_s + K_{cl} * b_{cl})},$$

here K_c, K_s, K_{cl} – the coefficients of carbonate, sand and clay content (calculated from the well interpretation data); a_c, a_s, a_{cl} – the coefficients in Gardner's equation for carbonaceous rocks, sandstones and clay relatively; b_c, b_s, b_c – Gardner's exponents for carbonaceous rocks, sandstones and clay respectively; V – velocity by sonic log, m/s. For known producing intervals, analogical coefficients were introduced for gas-saturated rocks.

Results

Resulting modified Gardner coefficients for DDB are illustrated in Table 2 and Figure 4, and velocity-density curves on Figure 2. Quality of density fit by core and log data is illustrated on Figures 3 and 5.

Rock type	Gardner's coefficient (a)					Gardner's exponent (b)				
	Field #1, CP		Field #2, CP	Field #3, NF	Field #4, NF	Field #1, CP		Field #2, CP	Field #3, NF	Field #4, NF
	C	D_3fm	C	C	C	C	D_3fm	C	C	C
Clay	0.335	0.3116	0.34	0.34	0.34	0.2515	0.2549	0.25	0.2515	0.2515
Sandstone	0.23	0.311	0.233	0.225	0.225	0.2826	0.2533	0.28	0.2826	0.2826
Limestone	0.31	0.3079	0.272	0.272	0.272	0.243	0.2486	0.26705	0.26705	0.26705

Table 1 *Modified Gardner's coefficients of velocity - density relationship for different areas of Dnipro-Donets depression*

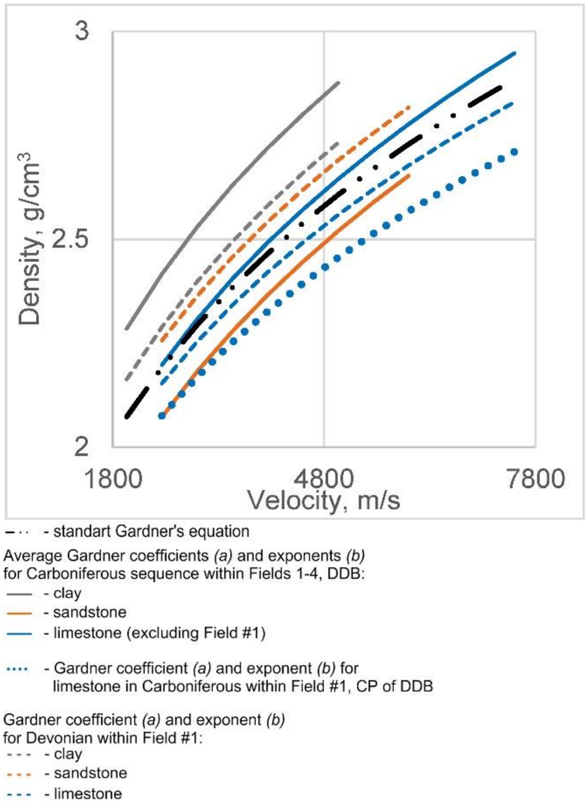

***Figure 2** Velocity-density relationships in rocks of different lithology for Dnieper-Donets basin*

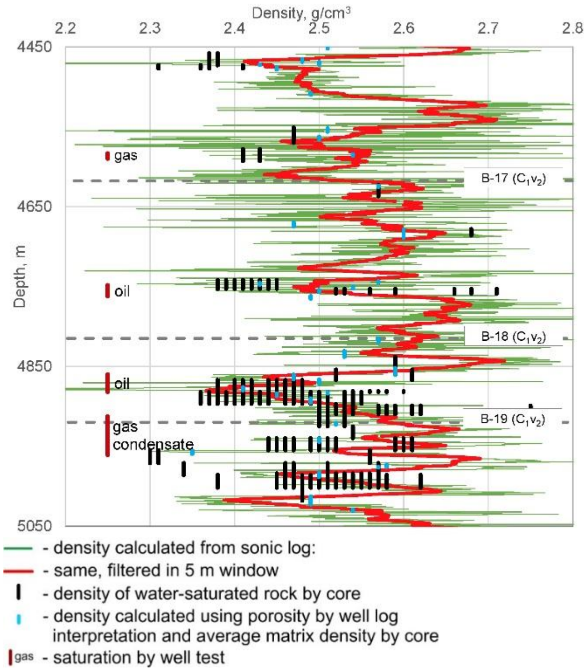

***Figure 3** The example of density curve calibration on core data for key well of the Field #2, CP of DDB*

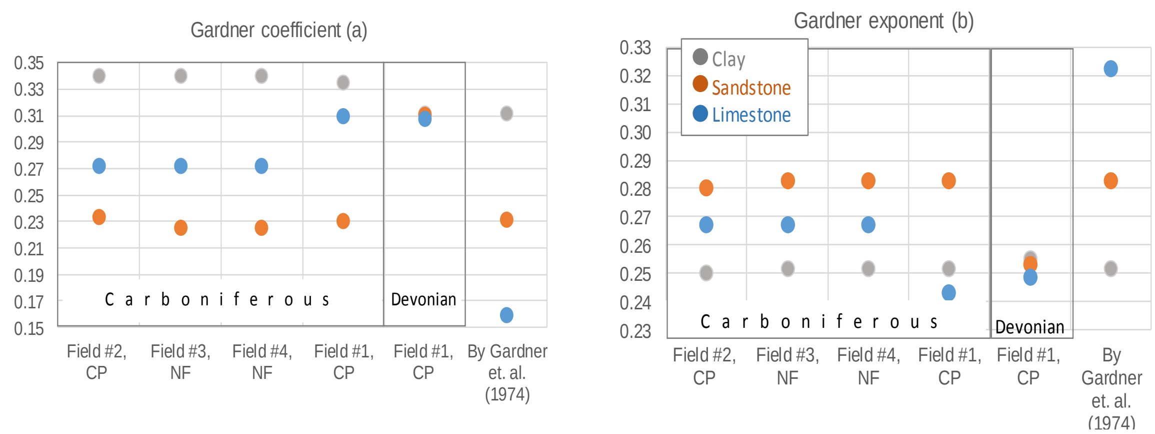

***Figure 4** Comparison of the Gardner's coefficients, obtained for different areas of DDB*

Conclusions

As seen from the Figure 4 values of Gardner's coefficients, estimated within four different areas of Dnieper-Donets basin are close. The exception is only carbonates of the Field #1, which are producing and overpressured only within this area. Another influencing factors are fractured type of the reservoir here and facial difference of carbonates from other areas. Also one should note that major difference with original Gardner's coefficients, presented by Garner et.al. (1974) also occur for carbonates. In spite of difference for clastic rocks between original and modified coefficients is less significant, but it gives a constant shift (error) in density estimation up to several g/cm^3.

Interesting fact is closeness of Gardner's coefficients for sandstones and shales for fields, located in the central part and within the Northern Flank of the DDB, in spite of the big difference in burial depth: 4-

5 kilometres vs. 2-3 kilometres. Probable explanation is that in both parts sediments reached maximum compaction and not much influenced by cracks.

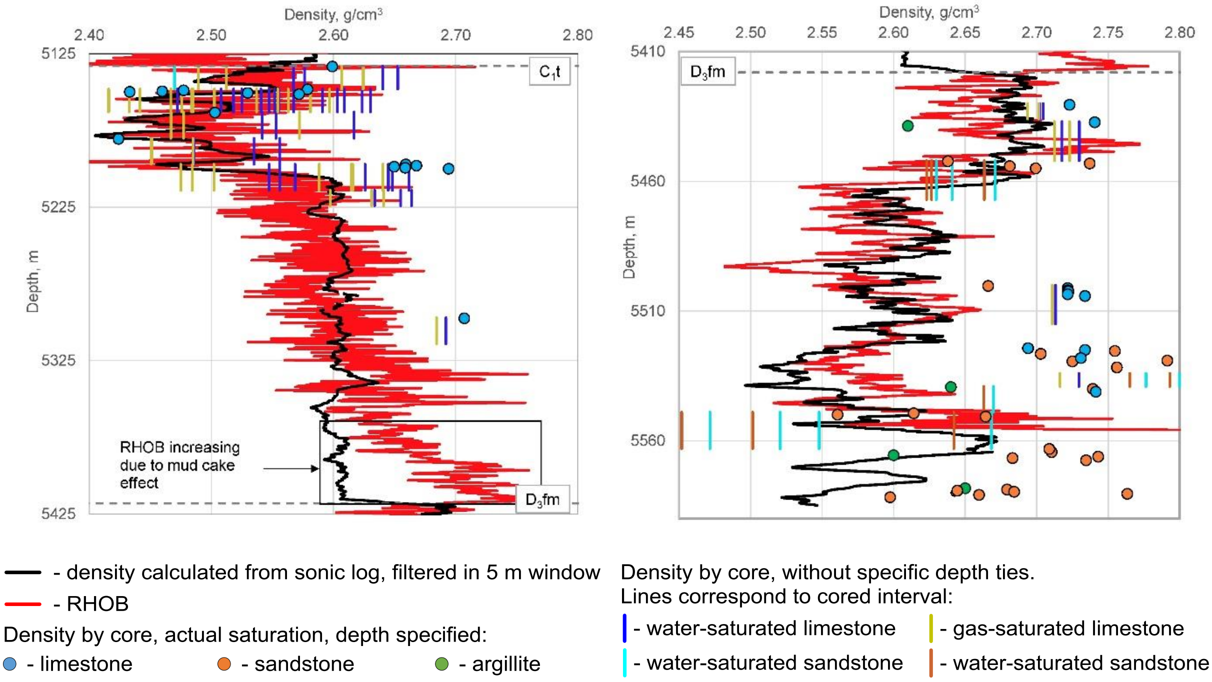

Figure 5 *The example of density calibration on core data and RHOB for exploration well of the Field #1, CP of DDB, for producing carbonates of Lower Carboniferous (left) and Famennian rocks of Devonian (right)*

Proximity of coefficients for different lithotypes of Devonian may be caused both by data lack and/or quality of core petrophysics and logs, and evidently require further refinement basing on larger dataset.

For Carboniferous obtained correlations provide reliable and valuable estimates of densities from acoustic velocities, or vice versa. This is valuable information both for evaluation of seismic reflectivity, AVO effects, geomechanical modelling, as well as for 3D density modelling basing on joint inversion with seismic and well data, all of mentioned aimed to reduce exploration risks. Resulting modified Gardner's relationships between velocity and density for rocks with different lithological composition are to be used as the basis for creating 3D density model of prospects and known hydrocarbon fields in the DDB where significant amount of complex oil and gas fields are concentrated.

Acknowledgment

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