

Article

Groundwater Exploration in Carbonate Reservoirs Using Borehole Investigations: A Case Study from South Dobrogea, Romania

Bogdan Mihai Niculescu ^{1,*} , Maria Mădălina Bucur ^{2,*} and Adrian Talmaciu ²

¹ Department of Geological Engineering and Geophysics, Faculty of Geology and Geophysics, University of Bucharest, 6 Traian Vuia Street, 020956 Bucharest, Romania

² Doctoral School of Geology, Faculty of Geology and Geophysics, University of Bucharest, 6 Traian Vuia Street, 020956 Bucharest, Romania; adrian.talmaciu@s.unibuc.ro

* Correspondence: bogdan.niculescu@unibuc.ro (B.M.N.); maria-madalina.bucur@g.unibuc.ro (M.M.B.)

Abstract: The Late Jurassic–Early Cretaceous (J₃–K₁) transboundary aquifer is the most important groundwater body in southern–southeastern Romania, shared with Bulgaria and hosted in karstic–fractured carbonates. We conducted an integrated evaluation of this aquifer by analyzing three 700 m deep groundwater exploration–exploitation boreholes, which intercepted it in the Cernavodă area (South Dobrogea region). The evaluation was based on geophysical wireline logging, drilling information, and borehole production tests. A K-means clustering of the logging data was performed for lithology typing, formation boundaries identification, and the delineation of probable producing intervals associated with secondary porosity development. Petrophysical interpretation was carried out via depth-constrained (zonal) inversion, using multimineral models, the estimated formation boundaries, and variable uncertainties for the main input logs. The optimal interpretation models were correlated with borehole testing results to gain insight into the hydrogeological properties of the aquifer complex. The fractured–vuggy interval with the highest water-producing potential was identified in the lower section of the J₃-age *Rasova Formation* (639–700 m depth), comprising mainly undolomitized limestones. A southeast-to-northwest trend of increasing productivity of the boreholes, correlated with an increasing lateral dolomitization intensity within the *Rasova Formation*, suggests a highly heterogeneous character of the aquifer. The differences in productivity are due not only to local porosity variations but also to various degrees of pore space connectivity that are related to the amount of fracturing or karstification. The novel findings of this study have important practical implications for the optimal placement, design, and drilling program of future groundwater exploitation boreholes in the Cernavodă area and neighboring sectors.

Keywords: borehole pumping test; dolomitization intensity; geophysical wireline logging; karst–fractured aquifer; K-means clustering; petrophysical inversion; secondary porosity



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1. Introduction

It is estimated that carbonate reservoirs—limestones and dolomites—host more than half of the world’s oil and gas reserves [1] and also much of the known groundwater reserves. With respect to clastic reservoirs rocks, carbonates often have a highly heterogeneous structure, leading to various petrophysical interpretation difficulties and to uncertainties in predicting reservoirs’ quality over larger scales [2–4]. Carbonate reservoirs are very frequently fractured and can have multiple pore sizes (microporosity to megaporosity) and also multiple porosity types: primary/“matrix” porosity (the interparticle pore space) and secondary porosity (joints, fissures, fractures, channels, isolated or connected vugs/voids), with the secondary porosity usually being more important than the primary one [1–6].

The relationships between porosity and permeability in carbonates often exhibit significantly greater variability compared to clastic reservoirs. Their permeability depends not only on the pore volume but also on the pore-size distribution [3–5,7]. In addition to

fractures and fissures, the initial connectivity of carbonates can be greatly enhanced by diagenetic processes, like the dolomitization of limestones in the presence of magnesium-bearing waters. Occasionally, this process may increase the porosity by 12–13% [1,4], although other studies suggest that the initial porosity of pre-existing limestones may be preserved or even destroyed through dolomitization [8,9].

One of the most important aquifer systems in Romania is the deep groundwater body coded RODL06 (international designation EB088), which is hosted in a Late Jurassic–Early Cretaceous (J_3 – K_1) carbonate complex of the karstic–fractured type [10–18]. This trans-boundary complex of Oxfordian–Barremian limestones and dolomites is developed in the southern and southeastern parts of Romania (the Wallachian and South Dobrogea sectors of the Moesian Platform) and in the entire northern part of Bulgaria. The exploited groundwater is used for domestic purposes/the drinking water supply, industry, and agriculture. South of the study area, in northeastern Bulgaria (Dobrich district), the J_3 – K_1 aquifer has a geothermal character, with temperatures of 32–41 °C in Balchik, Cape Kaliakra, and Shabla areas, reaching even 45–52 °C in the Varna region and providing thermal energy for coastal resorts [13,14]. This groundwater body has a total area of 24,374 km², out of which 11,340 km² are within the Romanian territory, with approximately 4500 km² in the South Dobrogea sector [12]. Its thickness gradually decreases from southwest towards the northeast and east, varying from over 1000 m to 200–400 m [10], and the aquifer is confined (under pressure) over most of South Dobrogea’s area except the zone adjacent to Danube River [11,15]. The general flow direction is from southwest to northeast, and the discharge occurs mainly north of the Constanța port city, on the Black Sea coast [10]. Long-term isotopic monitoring studies conducted by Tenu et al. [10,16–18] have identified the main recharge area in the Pre-Balkan Platform in Bulgaria. The hydraulic transmissivity of the aquifer varies from hundreds m²/day to over 150,000 m²/day.

Despite the significant number of wells that have been drilled for groundwater or geothermal water extraction from the J_3 – K_1 aquifer and for monitoring the groundwater quality and quantity, there is a very limited amount of published data and research concerning the geophysical responses and petrophysical characteristics of the hosting carbonate reservoir, especially with regard to its hydrogeological properties. Given the potential, the great areal extension, and the importance of this aquifer on national and international scales, the present study aims to fill this significant knowledge gap.

We evaluate three deep groundwater exploration and exploitation boreholes from the Cernavodă town area (South Dobrogea region, Romania), which intercepted the J_3 – K_1 complex and provided a better understanding of this regional and highly heterogeneous reservoir. The boreholes were drilled vertically to a depth of 700 m to supply with fresh water the Cernavodă nuclear power complex and its additional facilities (Figure 1). Besides geological analyses carried out on cores and cuttings samples (particularly for the first borehole), a geophysical wireline logging program was conducted for the identification of probable water-bearing intervals (vugs, caverns, and fractures/fissures), porosity evaluation, detailed lithological characterization, and the delineation of the main sedimentary formations in correlation with the general geological framework of South Dobrogea. The interpretation approach that we utilized is the depth-constrained (zonal) inversion of the logging datasets based on distinct multimineral models, using as a control the lithological information from drill cores and cuttings. To improve and facilitate the rock typing and separation of the geological complexes, in addition to correlation between boreholes, we performed a cluster analysis of the joint logging datasets via a nonhierarchical *K*-means algorithm [3,19–22]. Because the formation boundaries (tops) were known with higher certainty only in the first borehole drilled, we used the parallelization of the electrofacies (specific combinations of geophysical log responses) [23–25] that resulted from cluster analysis to identify these boundaries in the other boreholes.

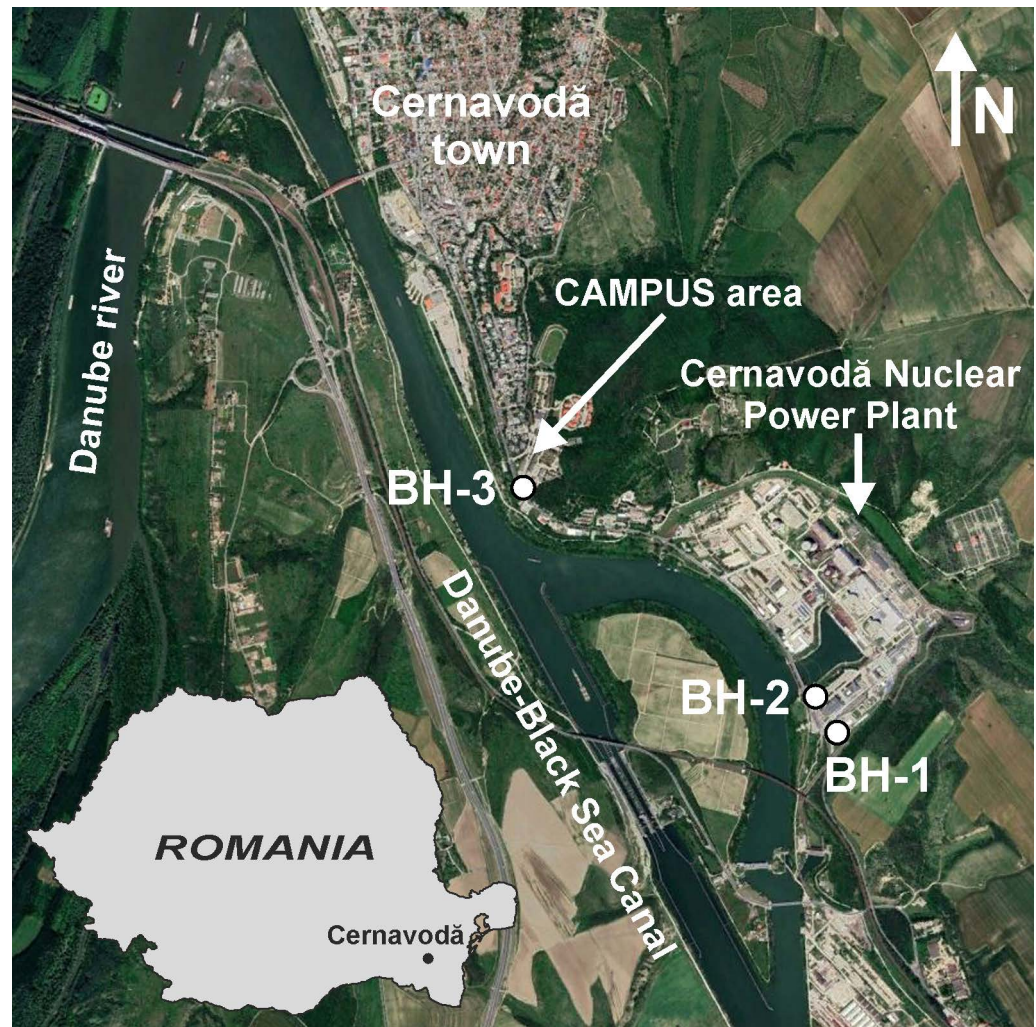


Figure 1. Location of the analyzed groundwater exploration–exploitation boreholes (BH-1, BH-2, and BH-3) in the Cernavodă area, South Dobrogea region, Romania.

In this way, the geophysical logs inversion was depth-constrained in addition to the lithological controls to minimize the data fitting errors and optimize the interpretation models. Finally, the relationships between several parameters of the log interpretation models and the results of groundwater production tests are presented and discussed to highlight significant particularities of the analyzed aquifer complex, with practical implications upon the drilling of future groundwater extraction boreholes.

2. Geological and Tectonic Setting

The South Dobrogea Platform unit is situated in the southeastern part of the larger Dobrogean sector of the Moesian Platform. The unit is delimited by the NW–SE-trending Capidava–Ovidiu crustal fault (and the Central Dobrogea tectonic unit) to the north, the Black Sea shelf to the east, the NW–SE-trending Intramoesian crustal fault (and the Romania–Bulgaria state border as a formal boundary) to the south, and the NNE–SSW-trending Danube fault to the west [26,27].

The basement of the South Dobrogea unit consists of three metamorphic groups of the Archean to Late Proterozoic (Vendian) age. The overlying platform cover was deposited in five major marine transgression–regression cycles: Cambrian–Carboniferous, Permian–Triassic, Middle Jurassic–Late Cretaceous, Eocene–Oligocene, and Middle Miocene–Late Pliocene, alternating with exondation periods and followed by continental Quaternary sediments [26–28].

The Middle Jurassic–Late Cretaceous deposits, which host the J_3 – K_1 groundwater body, are extended over the entire area of South Dobrogea and range in age from Bathonian to Santonian–Campanian. The Jurassic sequence comprises limestones, dolomitic limestones, and dolomites, with minor epiclastic intercalations. The Cretaceous sequence was formed in three stages: Berriasian to Barremian—evaporites and polychrome shales with extensions limited to the northern part of South Dobrogea, followed by shallow-marine shelf carbonates; Aptian—mostly continental fluvial and lacustrine deposits, with alteration products indicative of a tropical–subtropical climate, and subordinate clastics and carbonates developed in a marine littoral facies only in the western part of South Dobrogea; Albian to Senonian—clastic deposits, followed by chalk sedimentation [27,28].

The arrangement of Mesozoic and Cenozoic formations in South Dobrogea is complex, owing to the presence of numerous vertical and subvertical faults (Figure 2) [10,26,29]. These faults have divided the area into tectonic blocks that underwent either uplift or subsidence (Figure 3). The faulting events occurred after the accumulation of J_3 – K_1 carbonate deposits and continued throughout the Cretaceous and Paleogene periods. Most of these blocks had ceased their movement before the deposition of Sarmatian (late Middle Miocene) formations, which exhibit a plate-like structure with an eastward inclination. The fault system with a WNW–ESE orientation (Cernavodă–Constanța, Rasova–Costinești, North Mangalia, and Mangalia faults) is newer, continuous, and runs parallel to the prominent Capidava–Ovidiu crustal fault [10,11,27]. These tectonic lineaments interact with an older fault system that is oriented NNE–SSW [10,11,27], resulting in the formation of 31 tectonic blocks of various sizes. The NNE–SSW fault system extends eastward into the continental shelf of the Black Sea.

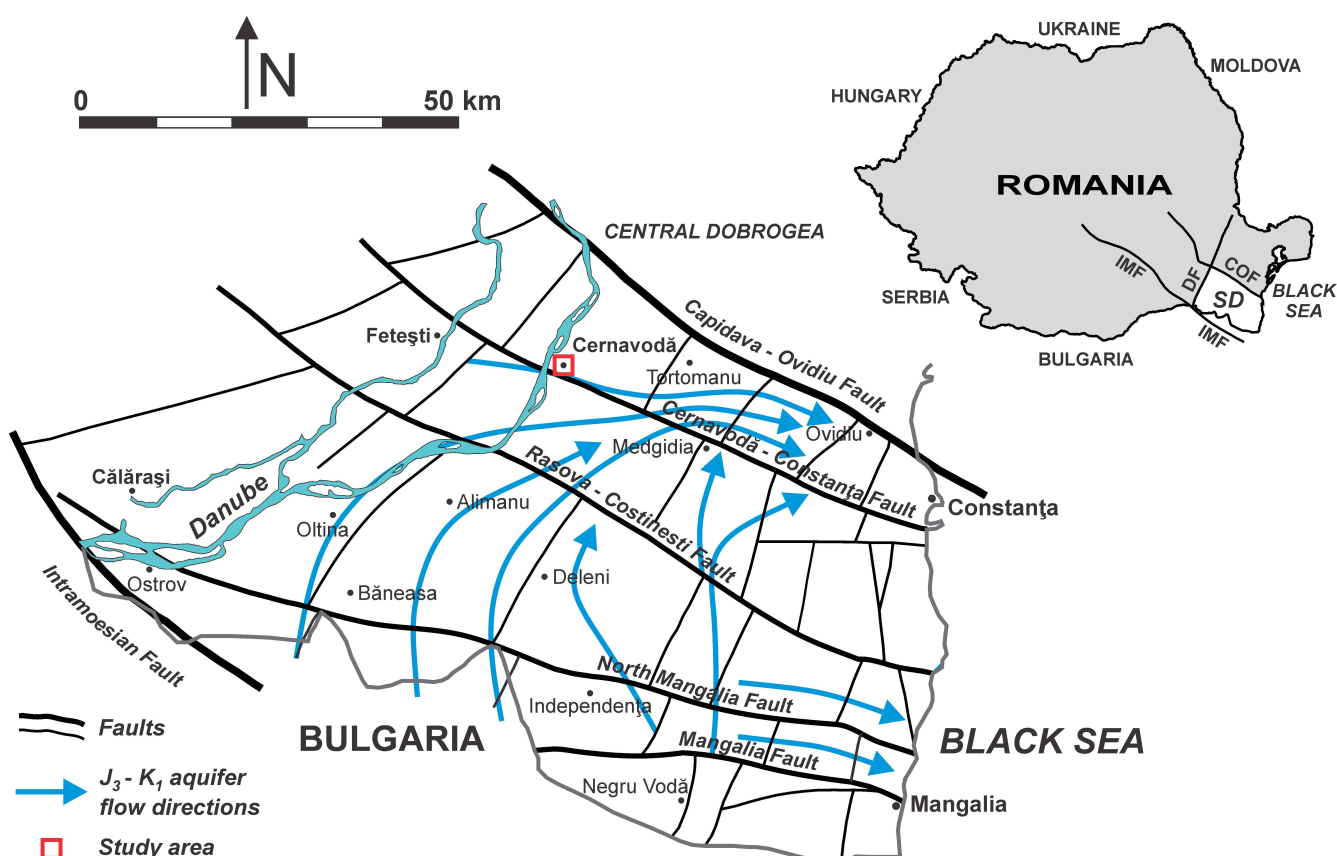


Figure 2. Tectonic map of South Dobrogea (SD) showing the main fault systems and the general groundwater flow directions within the J_3 – K_1 aquifer. COF—Capidava–Ovidiu fault, DF—Danube fault, IMF—Intramoesian fault (based on [10,29]).

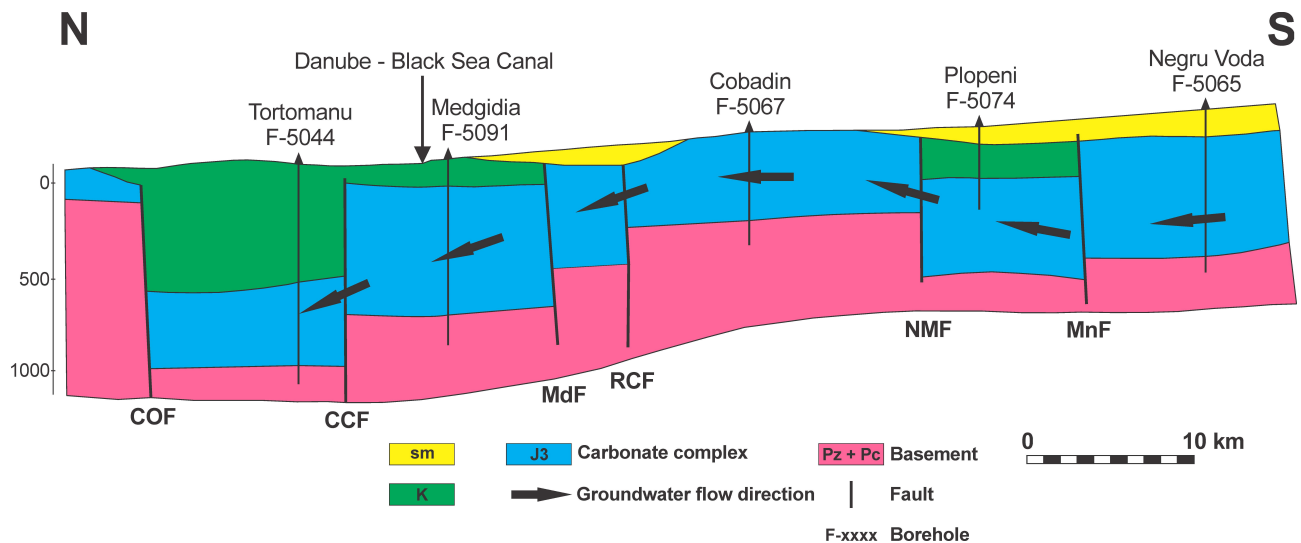


Figure 3. Geological cross-section in N-S direction through South Dobrogea, illustrating the arrangement of tectonic blocks. COF—Capidava–Ovidiu fault, CCF—Cernavodă–Constanța fault, MdF—Medgidia fault, RCF—Rasova–Costinești fault, NMF—North Mangalia fault, MnF—Mangalia fault, sm—Sarmatian (prevailing oolitic limestones), K—Cretaceous (detrital and carbonates).

Previous geological studies based on outcrop samples and drill core data have shown that in the Cernavodă tectonic block, the Jurassic and Cretaceous formations are directly overlaid by Quaternary deposits. The following general lithostratigraphic succession has been outlined:

- (1) *Quaternary*—Holocene–Pleistocene loessoid deposits with paleosols intercalations, which unconformably cover the Cretaceous formations. Usually, a 2–3 m thick level of reddish shales and reworked gravels (early Pleistocene) is present at the base of these loessoid deposits. The thickness of the Quaternary deposits ranges from 10 to 45 m.
- (2) *Gherghina Formation*—Middle–Late Aptian [30,31]. Continental fluvial–lacustrine deposits of 5–30 m thickness, consisting of polychrome kaolinitic shales with calcareous concretions in the upper part and sands, gravels, and conglomerates with a reddish shaly or silty matrix at the base of the unit. The continental deposits may change laterally and/or vertically into shallow marine facies with marlstones, siltstones, and sandstones with marly intercalations.
- (3) *Cernavodă Formation*—late Berriasian–Valanginian [30–33]. A shallow marine calcareous unit of 20–40 m thickness, discordantly overlaid by the Gherghina Formation and separated into two subunits in the study area: (a) the *Aliman Member* (Valanginian) at the upper part, unconformable and transgressive, consisting of calcirudites and calcarenites with numerous macro- and microfossils and intercalations of algal stromatolites; (b) the *Hinog Member* (late Berriasian) at the base, comprising conglomerates, sandy shales, argillaceous limestones, oolitic limestones, and biostromes, with gastropod fauna.
- (4) *Amara Formation*—Late Jurassic (late Tithonian)–Early Cretaceous (early–middle Berriasian) [31,33]. This unit of over 300 m thickness includes siliciclastic, carbonate, and evaporitic deposits and comprises two subunits in the study area: (a) the *Zăvoaia Member* (early–middle Berriasian) at the upper part, consisting of a 40–60 m thickness sequence of polychrome (reddish-violet, greenish) shales, marlstones, and oolitic and micritic limestones, overlying a marine carbonate sequence of up to 50–60 m thickness, which includes bioclastic limestones, detrital limestones, oolitic limestones, and calcareous sandstones, with intercalations of marlstones and argillaceous limestones. The rich fossil microfauna and microflora collected from the upper part of the *Zăvoaia Member* indicates a deposition in a continental–lacustrine and lagoonal, even littoral, environment and allowed a parallelization with the Purbeckian facies; (b) the *Cireșu Member*, representing an evaporitic sequence of 180–200 m thickness, consisting of massive gypsum and anhydrite, with intercalations of gypsiferous shales

and marlstones, oolites, and micritic limestones of variable thicknesses. Secondary gypsum frequently appears deposited in the fissures or the bedding planes of the argillaceous rocks, and the gypsiferous shales adjacent to massive gypsum intervals show microfolds related to the hydration of anhydrite. The very scarce fossil microfauna are limited to species adapted to hypersaline conditions. This sequence is indicative of a lagoonal depositional environment in a warm and arid climate.

- (5) *Rasova Formation* (Oxfordian–Tithonian) [31,33]. The unit has a thickness of over 500 m and consists of dolomites (dolomicrites, dolosparites), dolomitic limestones, micritic limestones, and oosparites, with scarce fossil macro- and microfauna. Locally, the dolomites have a laminated appearance, with gray–yellowish bands alternating with greenish bands of more intense dolomitization. Marlstones, argillaceous limestones, and calcareous breccia levels appear as intercalations. Fractures/fissures and karstic dissolution voids are very frequent in this carbonate sequence, together with a porosity related to the dolomitization of limestones. These voids can be small and uniformly distributed or larger and irregular, forming channel systems. Likely, this occurs on a large scale, leading to an extended karst network within the Late Jurassic carbonates.

3. Borehole Data

The 700 m deep groundwater exploration–exploitation boreholes analyzed in this study, denoted BH-1, BH-2, and BH-3, were drilled within the site of the Cernavodă nuclear power complex (BH-1, BH-2) and in the Campus residential district of Cernavodă town (BH-3), on the northern bank of the Danube–Black Sea Canal. The distance between BH-1 and BH-2 is 203 m and the distance between BH-2 and BH-3 is 1645 m. The drilling with fresh water-based fluids and the geophysical investigation were carried out by the Romanian company Foradex S.A.—București (now Foraj București S.A.). The diameters of the intermediate and final sections of the boreholes are 12.25 in. and 8.5 in., respectively.

3.1. Geological Investigations

The BH-1 borehole provided the most complete information about the crossed geological sequence, based on lithological–petrographic and micropaleontological analyses performed on extracted drill cores (60 m total core recovery) and drill cuttings (over 600 samples). For BH-2 and BH-3, fewer drill cuttings were available, resulting in uncertainties regarding the boundaries between the main geological formations. The laboratory analyses results obtained for BH-1 allowed the synthetic lithostratigraphy of the deposits from Cernavodă drilling sites area to be established. Certain units were assigned unconventional terminology, but they were correlated with the known general lithostratigraphic succession.

Based on drilling data analyses, the geological succession of the Cernavodă section crossed by the BH-1 borehole was reported as follows:

Quaternary Continental Deposits (“Q”): 0–25 m

Loess deposits, overlying rock debris with altered limestone fragments (Berriasian–Valanginian), and reworked elements from the underlying Aptian gravels. At the base of the debris layer, there are shales and sandy shales with freshwater lacustrine fauna.

Early Cretaceous Continental Deposits (“CD”): 25–30 m

Quartz sands and gravels, with intercalations of kaolinitic shales. The microfossil content indicates a Middle–Late Aptian age, and these deposits were considered to represent the *Gherghina Formation*.

Carbonate Complex I (“CC-I”): 30–45 m

The deposits consist primarily of carbonates and include bioclastic limestones with recrystallizations, detrital limestones, oolitic limestones, argillaceous limestones, marlstones, and calcareous sandstones. The rich marine microfauna suggest a late Berriasian–early Valanginian age. This carbonate complex was assigned to the *Cernavodă Formation*.

Polychrome Marlstones and Shales Complex (“PMSC”): 45–100 m

Greenish or violet marlstones and shales with intercalations of detrital limestones, calcareous sandstones, oolites, argillaceous limestones, and silty shales. They contain rich

brackish and freshwater microfauna of an early–middle Berriasian age, characteristic for the Purbeckian facies. This mainly argillaceous complex was assigned to the upper part of the *Zăvoaia Member—Amara Formation*.

Carbonate Complex II (“CC-II”): 100–161 m

Predominantly bioclastic limestones, oolites, argillaceous limestones, and marlstones. The abundant marine-type microfauna collected from this carbonate sequence indicate an early Berriasian age, and the complex is considered the lower part of the *Zăvoaia Member—Amara Formation*.

Evaporite Complex (“EC”): 161–363 m

Gypsum and anhydrite, gypsiferous shales, and marlstones, with thin intercalations of oolites and argillaceous limestones. The very sparse microfauna encountered are representative for the late Tithonian age, and this complex was assigned to the basal *Cîrșu Member—Amara Formation*.

Dolomite Complex (“DC”): 363–700 m

Dolomites, limestones partially affected by dolomitization, hard micritic limestones, and thin intercalations of marlstones or argillaceous limestones. The process of dolomitization of the pre-existing limestones is not uniform, as it is more intense in the upper part of the complex. The scarce microfossil content indicates a Kimmeridgian–early-to-middle Tithonian age. The *Dolomite Complex* corresponds to the *Rasova Formation* and represents the main exploration objective of the analyzed boreholes.

3.2. Geophysical Investigation Program

The phases of the open-hole wireline logging program carried out in the Cernavodă groundwater exploration boreholes are presented in Table 1. The investigation was performed using Robertson Geologging equipment and included conventional (standard) electrical logs, nuclear logs—total gamma ray and dual-spacing (compensated) thermal neutron, compensated sonic velocity logs, caliper, and borehole temperature logs. The main recorded curves (channels), at a depth sampling step of 0.1 m, are presented in Table 2. Not all logs were acquired over the entire depth of the boreholes.

Table 1. Phases of the geophysical investigation program carried out in the groundwater exploration boreholes drilled in Cernavodă town area.

	BH-1	BH-2	BH-3
WGS 84 coordinates	44°18′56.79″ N 28°03′24.30″ E	44°19′02.94″ N 28°03′21.04″ E	44°19′33.55″ N 28°02′20.29″ E
Surface elevation *	15.3 m	14.2 m	16.1 m
Investigated interval	16.4–702.6 m	12.1–700.5 m	108.9–699.8 m
Run I	16.4–154.2 m	12.1–546.4 m	108.9–549.9 m
Run II	127.5–471.7 m	542.3–700.5 m	536.2–699.8 m
Run III	460.4–599.9 m		
Run IV	600.0–702.6 m		

* Referenced to Black Sea level.

Table 2. Geophysical well logs recorded in the groundwater exploration boreholes drilled in Cernavodă town area.

Mnemonic	Measured Parameter	Description
GR	I_{γ} (cps)	Total natural gamma ray intensity
CAL	d (inch)	Caliper (true diameter of the borehole)
SHN	$\rho_{A,16}$ (Ω m)	Short normal (16 inch spacing) apparent resistivity
LONG	$\rho_{A,64}$ (Ω m)	Long normal (64 inch spacing) apparent resistivity
SP	ΔV_{SP} (mV)	Spontaneous electrical potential (voltage) variation
NEAR	$I_{n,Near}$ (cps)	Intensity of neutron flux at Near (short spacing) detector
FAR	$I_{n,Far}$ (cps)	Intensity of neutron flux at Far (long spacing) detector
DT	Δt (μ s/ft)	Compensated sonic interval transit time (<i>P</i> -wave slowness)
TEMP	T ($^{\circ}$ C)	Borehole temperature

The nuclear log data were provided in counts per second (cps), so for the Dual Neutron tool only the short-spaced (Near detector) and long-spaced (Far detector) raw count rates were available, instead of a neutron porosity curve. The total gamma ray logs, though not expressed in standard American Petroleum Institute (API) units, are still adequate for the delineation of lithological complexes, clay volume estimation, and multimineral petrophysical interpretation. The unfocused Electric Log tool employed for the resistivity logging had an operating range of 1–10,000 Ω m, but is not ideally suited for the investigation of high-resistivity carbonate formations, as $\rho_{A,16}$ and $\rho_{A,64}$ measurements are sometimes adversely affected by the borehole influence (diameter variations, mud resistivity). A focused resistivity logging device (*Laterolog/Guard Log* type) was not available for the investigations.

The data channels were edited to remove invalid start and end readings, a five-point (0.5 m) moving average smoothing filter was applied to the nuclear logs, and single composite logs were created through the optimal splicing (merging) of the individual segments recorded over different depth intervals (Figures 4–6). Due to the limited quantitative usefulness of the SP in carbonate formations and the uncertainty of baseline shifts over the borehole sections drilled in different stages, the SP log segments were not merged.

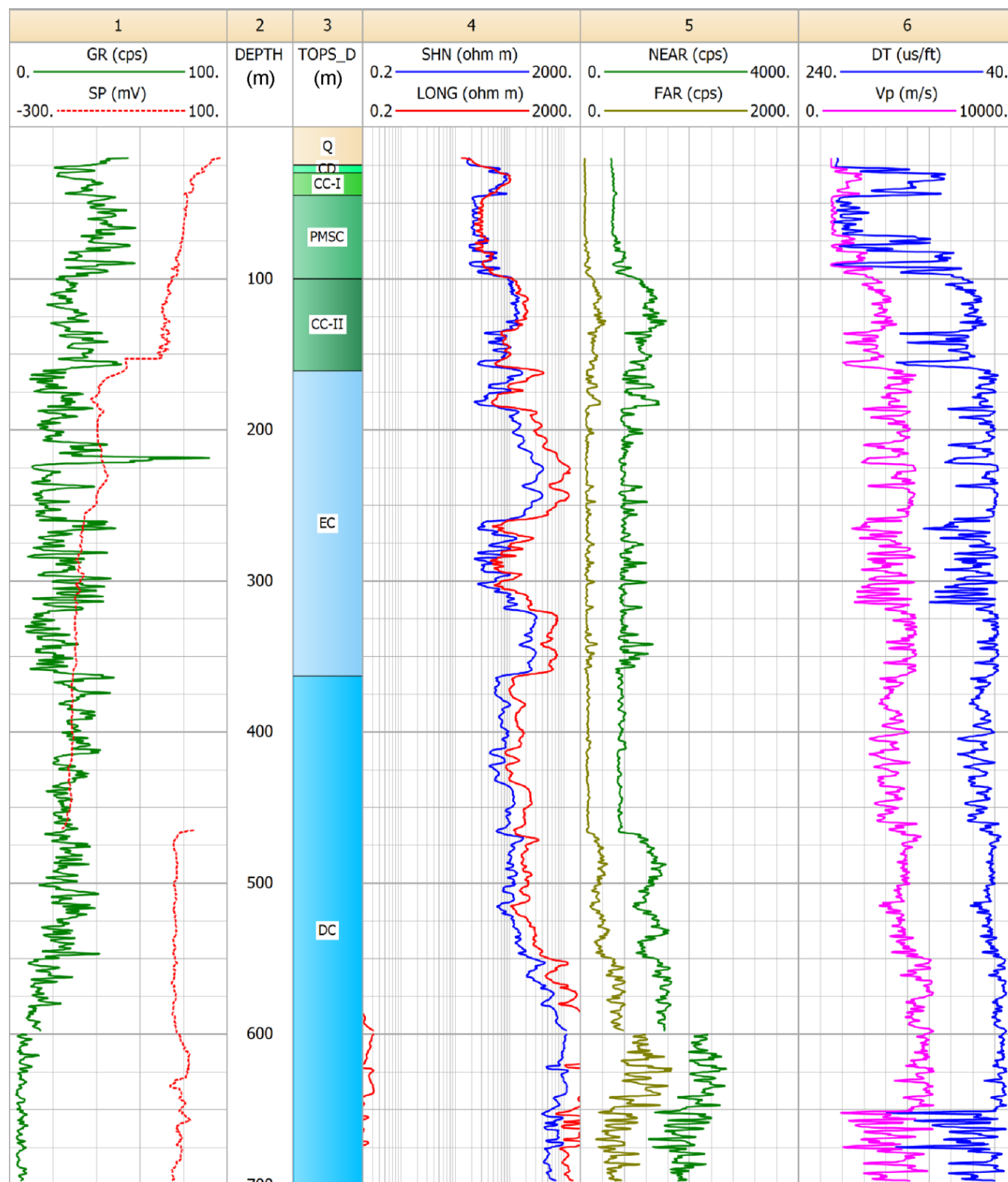


Figure 4. Geophysical wireline logs recorded in BH-1 borehole: track 1—total gamma ray(cps) and SP (mV); track 2—measured depth (m); track 3 (TOPS_D)—formation boundaries (tops) reported from drilling data and geological analyses (m); track 4—short normal and long normal apparent resistivities [Ω m]; track 5—short-spacing and long-spacing neutron count rates (cps); track 6—compensated sonic interval transit time (μ s/ft) and P -wave velocity (m/s). Caliper log and borehole temperature data were not available for BH-1.

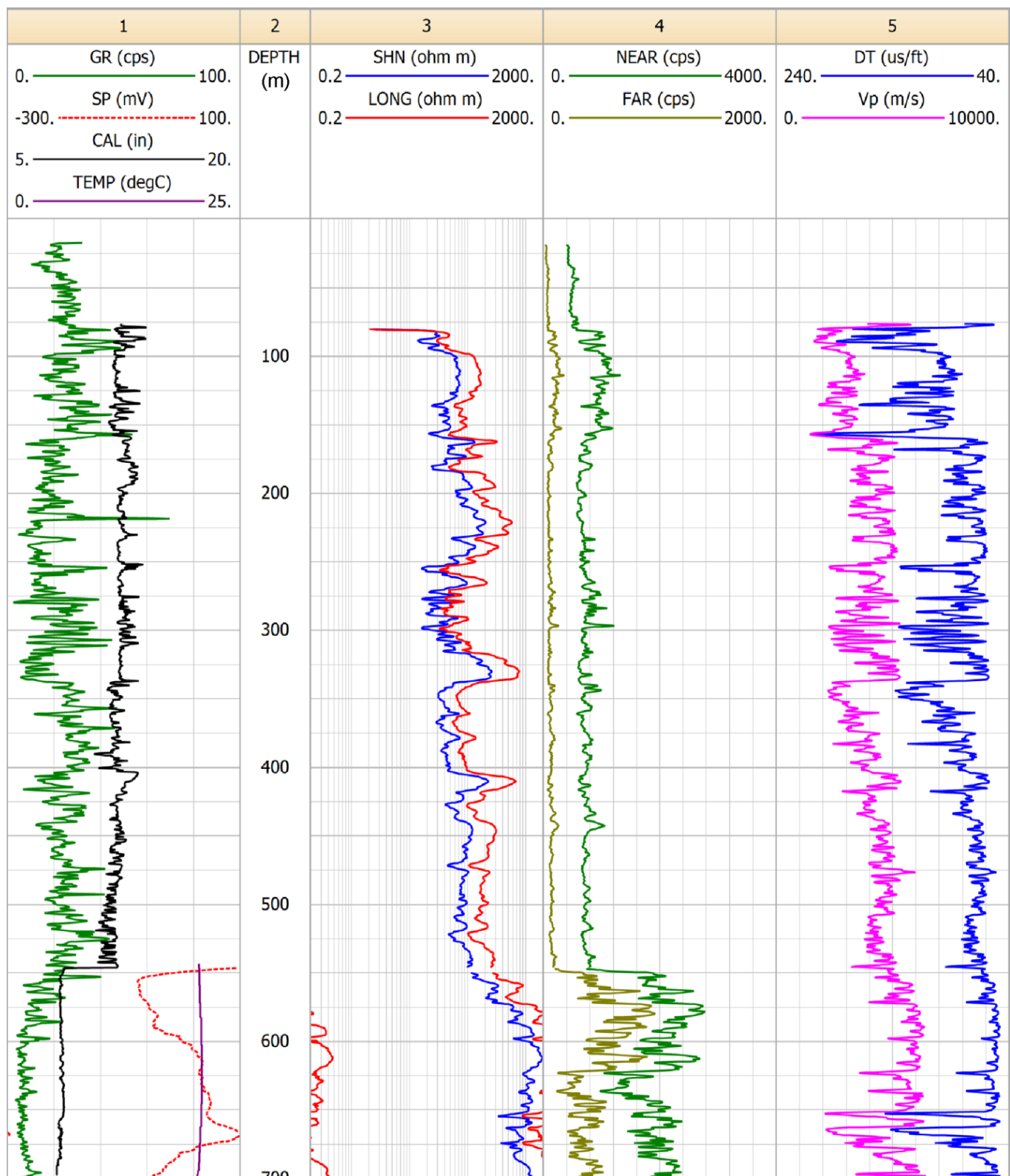


Figure 5. Geophysical wireline logs recorded in BH-2 borehole: track 1—total gamma ray (cps), SP (mV), caliper (in), and borehole temperature (°C); track 2—measured depth (m); track 3—short normal and long normal apparent resistivities (Ω m); track 4—short-spacing and long-spacing neutron count rates (cps); track 5—compensated sonic interval transit time (μ s/ft) and P -wave velocity (m/s). Note the change in borehole diameter at 546 m depth.

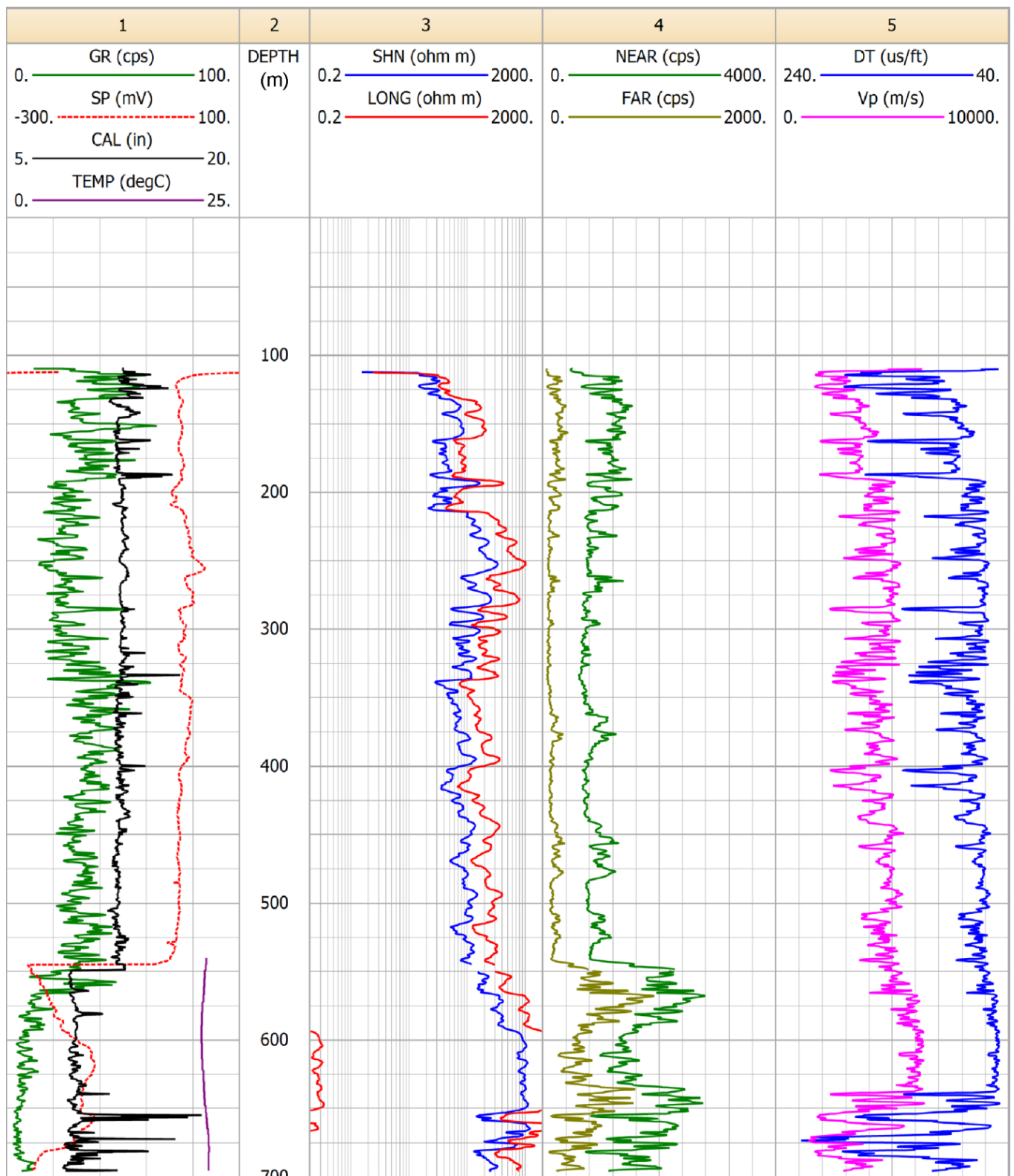


Figure 6. Geophysical wireline logs recorded in BH-3 borehole: track 1—total gamma ray (cps), SP (mV), caliper (in), and borehole temperature (°C); track 2—measured depth (m); track 3—short normal and long normal apparent resistivities (Ω m); track 4—short-spacing and long-spacing neutron count rates (cps); track 5—compensated sonic interval transit time (μ s/ft) and P -wave velocity (m/s). Note the change in borehole diameter at 549 m depth.

4. Data Processing and Interpretation

The wireline logs recorded in the BH-1, BH-2, and BH3 boreholes were processed and interpreted to achieve the following goals: (a) porosity evaluation from the neutron and sonic logs to assess the most appropriate sonic porosity transform and to identify the intervals with significant secondary porosity, i.e., the potential water-producing horizons; (b) correlation of the main geological formations (complexes) between the boreholes and an improved delineation of the formation boundaries using multivariate statistical classification via cluster analysis; (c) depth-constrained logging data inversion based on optimal multiminerall models, for a comprehensive evaluation of the formations lithology, true porosity, and groundwater resistivity/salinity.

The multivariate analyses and the logging data inversion were conducted over the intervals with complete log coverage: 25–697 m in BH-1, 80–698 m in BH-2, and 112–696 m in BH3.

4.1. Neutron Porosity Evaluation

The dual-detector neutron tool significantly reduces the adverse borehole effects, and the ratio of count rates between the detectors ($Ratio = I_{n,Far}/I_{n,Near}$) is proportional to the neutron (apparent) porosity ϕ_N , i.e., the formation hydrogen index. The primary calibration of the tool (experimentally derived relations between the counts ratio and the decimal logarithm of ϕ_N relative to a limestone matrix) was performed by the manufacturing company in water-filled boreholes with standard diameters. The calibration transforms $Ratio$ [dec.] $\rightarrow \phi_N$ [%] were provided as sets of coefficients of the polynomial Equation (1)

$$\phi_N(Ratio) = a + b \text{ Ratio} + c \text{ Ratio}^2 + d \text{ Ratio}^3 \quad (1)$$

with a , b , c , and d taking particular values for each reference borehole diameter. We have elaborated and utilized a MATLAB code to compute the limestone-based ϕ_N (NPHI curves) for arbitrary borehole diameters, provided by the CAL curve, through interpolation between the reference ϕ_N values calculated with Equation (1). In carbonate formations, ϕ_N corresponds to the total porosity (ϕ_t), i.e., the sum of the primary (interparticle) and secondary (vug and fracture) porosities. The code for ϕ_N computation is presented in Appendix A.

4.2. Sonic (Acoustic) Porosity Evaluation

The sonic porosity (ϕ_s) was computed using the Raymer et al. [34] transit time–porosity transform and the Raiga-Clemenceau et al. [35] acoustic formation factor equation, assuming a limestone lithology as a reference. The resulting ϕ_s (SPHI curves in Figures 7 and 8) were evaluated by comparison with the computed limestone neutron porosity ϕ_N .

The empirical Raymer et al. transform operates over the entire porosity range. For the lower (0 to 0.37) and upper (0.47 to 1) ranges, ϕ (i.e., ϕ_s) results from Equations (2) and (3)

$$\frac{1}{\Delta t_1} = \frac{(1 - \phi)^2}{\Delta t_{ma}} + \frac{\phi}{\Delta t_f} \quad (\phi < 0.37) \quad (2)$$

$$\Delta t_2 = \sqrt{\frac{\delta \phi \Delta t_f^2}{\delta_f} + \frac{\delta(1 - \phi) \Delta t_{ma}^2}{\delta_{ma}}} \quad (\phi > 0.47) \quad (3)$$

where Δt_1 and Δt_2 are measured or predicted P -wave transit times; ϕ is the fractional porosity, δ is the bulk density of the formations; Δt_{ma} and δ_{ma} are the P -wave transit time and the density of the rock matrix; and Δt_f and δ_f are the P -wave transit time and the density of the pore fluid (mud filtrate). The commonly adopted parameter values are $\Delta t_{ma} = 56 \mu\text{s}/\text{ft}$ and $\delta_{ma} = 2.65 \text{ g}/\text{cm}^3$ for quartz sands/sandstones; $\Delta t_{ma} = 49 \mu\text{s}/\text{ft}$ and $\delta_{ma} = 2.71 \text{ g}/\text{cm}^3$ for limestones; $\Delta t_{ma} = 44 \mu\text{s}/\text{ft}$ and $\delta_{ma} = 2.86 \text{ g}/\text{cm}^3$ for dolomites; $\Delta t_f = 189 \mu\text{s}/\text{ft}$ and $\delta_f = 1.0 \text{ g}/\text{cm}^3$ for freshwater mud filtrate; and $\Delta t_f = 185 \mu\text{s}/\text{ft}$ and $\delta_f = 1.1 \text{ g}/\text{cm}^3$ for saltwater mud filtrate [6,7,34,36].

For the intermediate porosity range (0.37 to 0.47), a linear interpolation between Δt_1 and Δt_2 is used—Equation (4) or the simplified Equation (5):

$$\Delta t = \frac{0.47 - \varphi}{0.1} \Delta t_1 + \frac{\varphi - 0.37}{0.1} \Delta t_2 \quad (4)$$

$$\Delta t = \frac{0.47 - \varphi}{0.1} \Delta t_1 + \frac{\varphi - 0.37}{0.1} \Delta t_f \quad (5)$$

Equations (2) and (5) allow for the estimation of sonic porosities of up to 0.47 without density log data, which were not available in the analyzed boreholes.

The Raiga-Clemenceau et al. transit time–porosity transform is given by

$$\frac{\Delta t_{ma}}{\Delta t} = (1 - \varphi)^x \quad (6)$$

The sonic porosity is obtained from the measured Δt :

$$\varphi = \varphi_s = 1 - \left(\frac{\Delta t_{ma}}{\Delta t} \right)^{1/x} \quad (7)$$

where x is a lithology-dependent exponent. The parameters in Equations (6) and (7) for the typical reservoir lithologies are $\Delta t_{ma} = 55.5 \mu\text{s}/\text{ft}$ and $x = 1.60$ for quartz sands/sandstones; $\Delta t_{ma} = 47.6 \mu\text{s}/\text{ft}$ and $x = 1.76$ for limestones; and $\Delta t_{ma} = 43.5 \mu\text{s}/\text{ft}$ and $x = 2.00$ for dolomites.

4.3. Cluster Analysis

For the multivariate cluster analysis of the wireline logging datasets, we used an unsupervised K -means algorithm [19–22] to assign individual data points to electrofacies of physical properties, which could be correlated to the main geological formations (lithologies) or to specific geological facies [23–25]. The number of clusters (K) utilized for partitioning the data is user-imposed. The algorithm partitions a set of N data points into distinct K domains ($K < N$) so that the data dispersion within each domain is minimal, i.e., the data are as “similar” as possible. The steps involved in the cluster analysis are as follows:

1. Define the number of clusters;
2. Randomly initialize the cluster centroids (seed points);
3. Assign data points to the cluster with the closest centroid;
4. Recalculate the cluster centroids based on the data in each cluster;
5. Repeat steps 3 and 4 until convergence is achieved, i.e., the cluster centroids stabilize and the allocation of data points to clusters remains unchanged.

The clustering solution is obtained by iteratively minimizing the objective function F from Equation (8), which represents the total within-cluster variation (the sum of squared distances between the data points and the related centroid given by Equation (9))

$$F(x_i, \mu_j) = \sum_{j=1}^K \sum_{i \in C_j} \|x_i - \mu_j\|^2 \quad (8)$$

$$\mu_j = \frac{1}{n_j} \sum_{i \in C_j} x_i \quad (9)$$

where x_i is a data point, C_j is a current cluster, μ_j is the mean value assigned to cluster C_j (the centroid of the cluster), and n_j is the number of data points in cluster C_j . The logging data were standardized (normalized) before clustering by subtracting the mean and dividing by the standard deviation of each log to ensure a consistent range for all the logs. The ρ_A input data were represented by the decimal logarithm of the SHN and LONG curves.

To determine the appropriate number of clusters, we performed a preliminary multi-borehole analysis by simultaneously utilizing all the logging datasets (GR, SHN, LONG,

NPHI, and DT curves) with a relatively large value of K ($K = 10$). We defined cluster randomness through the ratio h_a/h_r [37,38], where h_a is the average thickness of a cluster layer, i.e., the average number of depth levels per cluster, and h_r is the theoretical average random thickness of a layer, calculated assuming the clusters to be assigned randomly at each depth level. The h_r is given by

$$h_r = \sum \frac{p_j}{1 - p_j} \quad (10)$$

where p_j is the proportion of depth levels assigned to the j -th cluster [37,38]. Higher values of the ratio correspond to less random clusters, i.e., more structured logging data. We employed the plot of cluster randomness ratio as a function of the number of clusters and identified a likely range for K around the inflection point where the ratio ceased to decrease significantly.

4.4. Quantitative Log Interpretation

The interpretation of the wireline logging datasets was carried out with a probabilistic inversion algorithm included in the *Mineral Solver* module from the *Interactive Petrophysics*TM (version 4.6) log analysis software [38]. The algorithm solves for mineralogy, porosity, and fluid saturations by considering the linearized response equations of the logging tools, the volumetric endpoint parameters (theoretical logging tools responses for 100% content of a particular mineral or fluid), and the likely uncertainties associated with the measured logs.

Given a set of m measured logs $X_1, X_2, \dots, X_m$ and a petrophysical interpretation model $\mathbf{V} = [V_1, V_2, \dots, V_p]$ with p parameters (the unknown solid and fluid volume fractions of the formations), the optimal solution vector is obtained by iteratively minimizing the normalized fitting error $E(\mathbf{V})$ from Equation (11)

$$E(\mathbf{V}) = \frac{\sum_{j=1}^m |X_j(\mathbf{V}) - L_j(\mathbf{V})|}{\sigma_j} \rightarrow \text{minimum} \quad (11)$$

where $L_1, L_2, \dots, L_m$ are theoretical (reconstructed) log responses corresponding to a particular model vector in an arbitrary iteration and $\sigma_1, \sigma_2, \dots, \sigma_m$ are user-defined uncertainties (confidence weights) associated with the measured logs. Smaller σ values imply a high degree of confidence (accurate log readings, good borehole conditions) and a higher weighting factor for a particular log response equation, whereas larger σ values stand for a decreased confidence (errors affecting the logs, poor borehole conditions) and a lower weighting factor.

A volumetric constraint (unity equation) $V_1 + V_2 + \dots + V_p = 1$ is imposed for the components of the solution vector, as well as physical constraints like $0 \leq V_k \leq 1, k = 1, \dots, p$. Starting with an approximate solution $\mathbf{V}^{(0)} = [V_1^{(0)}, V_2^{(0)}, \dots, V_p^{(0)}]$, the inversion algorithm computes a series of model correction vectors $\Delta\mathbf{V} = [\Delta V_1, \Delta V_2, \dots, \Delta V_p]$ in each iteration and updates the current model, i.e., $\mathbf{V} = \mathbf{V}^{(0)} + \Delta\mathbf{V}$. The model optimization continues until the data misfit (14) is minimized and convergence is reached (the computed solid and fluid volume fractions do not change significantly between iterations). We used a general interpretation model $\mathbf{V} = [V_{\text{quartz}}, V_{\text{calcite}}, V_{\text{dolomite}}, V_{\text{gypsum}}, V_{\text{anhydrite}}, V_{\text{clay}}, V_{\text{water}} = \phi]$, where the particular components of $\mathbf{V}$ at each level are depth-zoned according to the identified formation boundaries.

As main inputs for the inversion algorithm, we utilized the GR, DT, and NPHI curves to evaluate the clay volume, porosity, lithology, and LONG curves—approximating the true resistivity of the water-saturated formations ρ_o —to estimate water resistivity (ρ_w) and calibrate the water saturation (S_w) to unity in the porous permeable aquifer sections. The Poupon–Leveaux (“Indonesia”) [3,39] model was used for S_w computation, with a saturation exponent set to $n = 2$. Generic values suitable for carbonates $a = 1$ and $m = 2$

were used for the tortuosity factor and the cementation exponent in the formation factor F expression (12) [6,7,40]:

$$F = \frac{\rho_o}{\rho_w} = \frac{a}{\phi^m} \quad (12)$$

The adopted $m = 2$ average cementation exponent balances the characteristic values for fractured carbonates (average $m = 1.4$) with those representative for vuggy ($m = 2.1$ – 2.6) or moldic porosity ($m \geq 3.0$) [1,41].

We derived the probable ρ_w (and thereby the water salinity) by computing synthetic resistivity logs corresponding to water-saturated formations, i.e., $\rho_o = a/\phi^m \rho_w$. The ρ_w values were adjusted until $S_w \approx 1$, and a match between the ρ_o logs and the measured $\rho_{A,64}$ logs was obtained in the reservoir intervals. The average wet clay parameters necessary for porosity–lithology evaluation and S_w correction in the shalier intervals were estimated statistically from multiborehole (joint wireline logging datasets) histograms and crossplots: $I_{\gamma, \text{clay}} = 90$ cps, $\phi_{N, \text{clay}} = 0.40$ – 0.45 , $\Delta t_{\text{clay}} = 90$ – 110 $\mu\text{s}/\text{ft}$, and $\rho_{\text{clay}} = 20$ Ω m. The background gamma ray radioactivity corresponding to the cleanest carbonate sections was selected: $I_{\gamma, \text{clean}} = 5$ cps. We employed the following matrix and fluid (mud filtrate) parameters for the neutron and sonic logs: $\phi_{N, \text{quartz}} = -0.02$, $\phi_{N, \text{calcite}} = 0$, $\phi_{N, \text{dolomite}} = 0.01$, $\phi_{N, \text{gypsum}} = 0.6$, $\phi_{N, \text{anhydrite}} = -0.02$, $\Delta t_{\text{quartz}} = 55.5$ $\mu\text{s}/\text{ft}$, $\Delta t_{\text{calcite}} = 47.6$ $\mu\text{s}/\text{ft}$, $\Delta t_{\text{dolomite}} = 43.5$ $\mu\text{s}/\text{ft}$, $\Delta t_{\text{gypsum}} = 52$ $\mu\text{s}/\text{ft}$, $\Delta t_{\text{anhydrite}} = 50$ $\mu\text{s}/\text{ft}$, $\phi_{N, \text{fluid}} = 1$, and $\Delta t_{\text{fluid}} = 189$ $\mu\text{s}/\text{ft}$ [6,32]. For the lithology–porosity logs, on the intervals with good hole conditions and a sonic response unaffected by attenuation (abnormally high Δt values), we used $\sigma_{GR} = 5$ cps, $\sigma_{NPHI} = 0.02$, and $\sigma_{DT} = 3$ $\mu\text{s}/\text{ft}$ as default uncertainties.

5. Results and Discussion

5.1. Quick-Look Analysis

A common feature observed on the BHC (*Borehole Compensated Sonic*) logs from the analyzed Cernavodă boreholes is represented by abnormally high compressional transit time readings at certain depths, with Δt reaching 210–220 $\mu\text{s}/\text{ft}$ and exceeding the mud filtrate transit time (Figures 4–6). Within the carbonate formations, especially in the final 8.5 in. borehole sections within the *Dolomite Complex* (≈ 635 – 700 m depth), we attribute this to a cycle-skipping effect caused by the P -wave attenuation in horizontal–inclined fractures/fissures or in karstified zones with a vuggy porosity [6]. In this case, the first arrival of the P -wave is too weak to trigger the receivers of the sonic tool, which record only later arrivals of higher amplitudes.

Correlated with the very high Δt values, additional indications for the presence of fractures or fluid-filled caverns in the lower part of the *Dolomite Complex* are (a) significant increases in the borehole diameter (up to 18 in.) on several depth intervals, as seen on the CAL log from BH-3; (b) strong decreases in the recorded ρ_A values, from 1200–2000 Ω m (SHN curves) or 3100–4700 Ω m (LONG curves) in the most compact carbonate intervals to 100–400 Ω m (SHN curves) or 300–900 Ω m (LONG curves); (c) local increases in the computed ϕ_N values, from about 0.03 in the tightest intervals to 0.22–0.23 (BH-1 and BH-2 boreholes) and up to 0.44 (BH-3 borehole).

Figure 7 shows the frequency distribution (stacked histograms) of the sonic porosities computed using the Raymer et al. and the Raïga-Clemenceau et al. $\Delta t \rightarrow \phi_S$ transforms, assuming a standard limestone matrix. Additionally, the frequency distribution of computed limestone ϕ_N values is included for comparison.

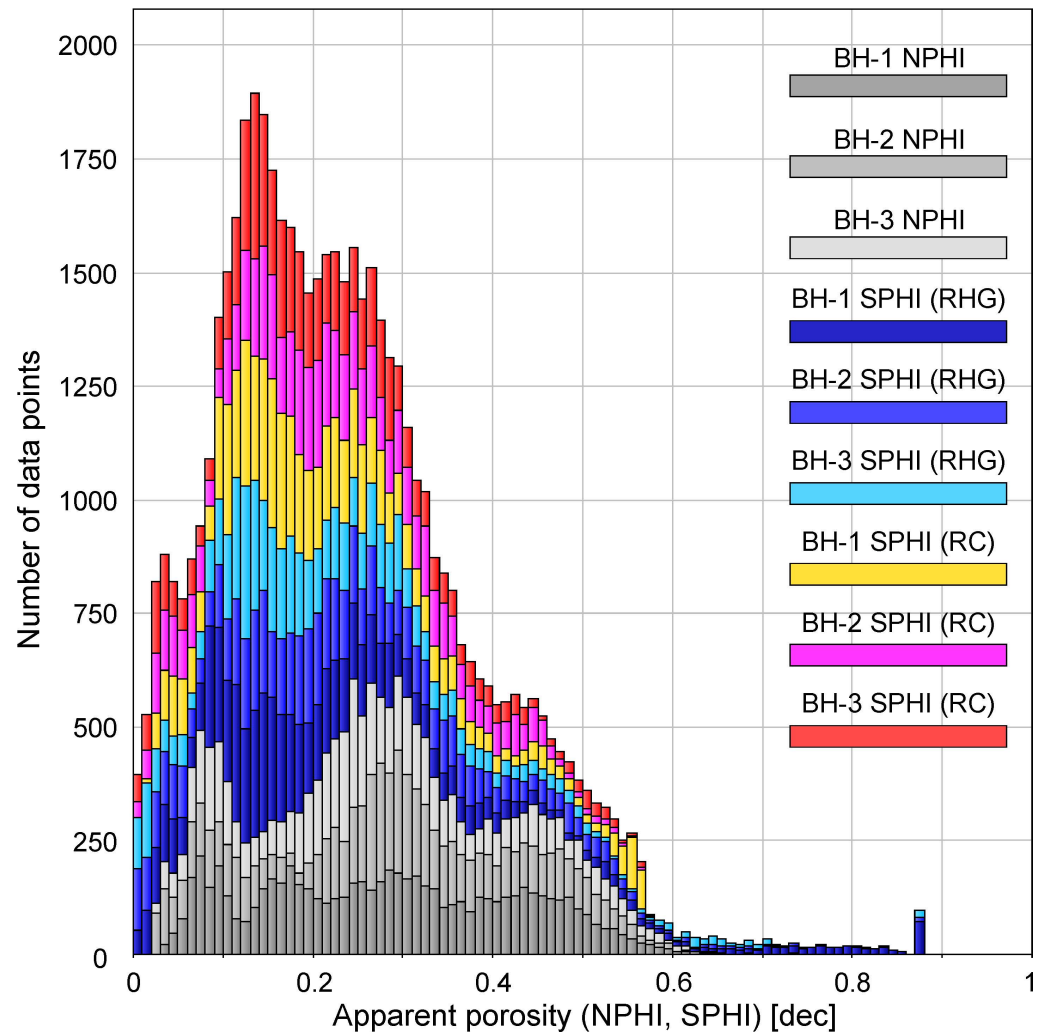


Figure 7. Stacked histograms of the computed neutron (NPHI) and sonic (SPHI) apparent porosities referenced to a limestone matrix for the Cernavodă boreholes (25–698 m overall depth interval). RHG—Raymer–Hunt–Gardner sonic porosity transform, RC—Raiga–Clemenceau sonic porosity transform.

It is evident that the range of ϕ_S variation derived from the Raiga–Clemenceau et al. transform better matches the ϕ_N range for all the analyzed boreholes, whereas the Raymer et al. transform occasionally leads to unrealistically high ϕ_S values. Considering that Equations (6) and (7) are also independent of Δt_f (a common source of uncertainty), we have selected the Raiga–Clemenceau et al. transform as the most suitable for ϕ_S evaluation in the studied boreholes and, in addition, as the sonic log response equation in the logging data inversion algorithm.

Figure 8 (tracks 3, 4, and 5) displays an overlay of the ϕ_N and ϕ_S apparent porosity curves computed for a standard limestone matrix. For reference, the BH-1 borehole formation boundaries as reported from cores and cuttings analyses are shown in track 2.

For all boreholes, the superposition of ϕ_N and ϕ_S in various depth intervals within the Cretaceous deposits and the *Dolomite Complex* indicates mostly clean limestones with primary porosity and validates the utilized $I_{n, Far}/I_{n, Near} \rightarrow \phi_N$ and $\Delta t \rightarrow \phi_S$ transforms. The *Evaporite Complex* is clearly delineated by very large separations $\phi_N > \phi_S$ exceeding 0.50 ($\phi_N - \phi_S \geq 50\%$ equivalent limestone porosity), due to the neutron log response to the crystallization water of gypsum. In the carbonate formations, especially near the boreholes' terminal depth within the *Dolomite Complex*, large inverse separations $\phi_S > \phi_N$ ($\phi_S - \phi_N = 0.30\text{--}0.43$) are diagnostic for intervals with a fluid-filled secondary poros-

ity (karstic dissolution voids or fractures). This effect appears more significant in the BH-3 borehole (below 638 m depth) and of lesser magnitude in BH-1 and BH-2 (below 651 m depth).

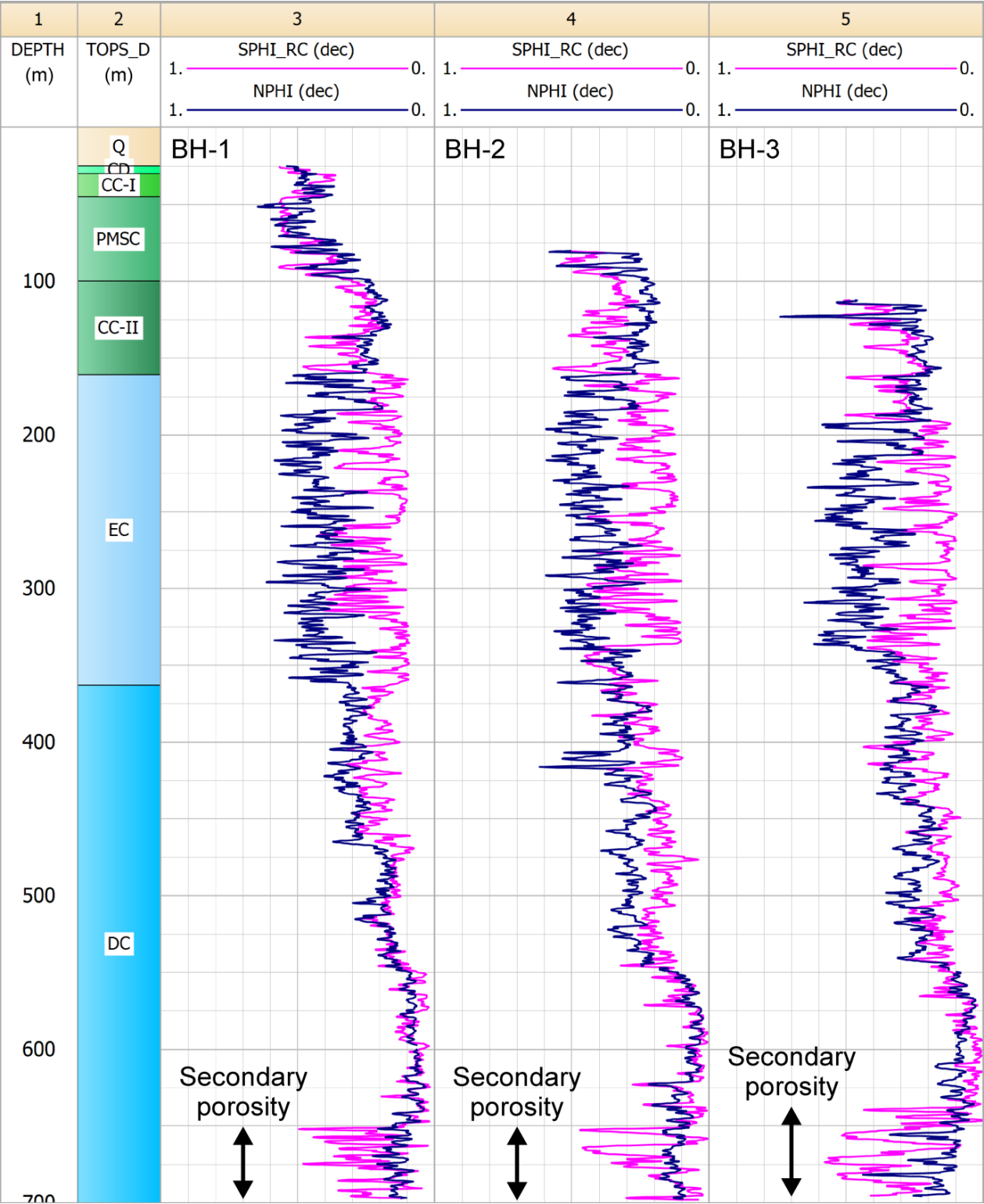


Figure 8. Overlay of neutron (NPHI curves) and sonic (SPHI_RC curves—Raiga-Clemenceau transform) apparent porosities computed assuming a standard limestone matrix for the Cernavodă boreholes (tracks 3, 4 and 5). Track 2 (TOPS_D)—formation boundaries (tops) in BH-1 borehole reported from drilling data and geological analyses (m).

5.2. Cluster Analysis Results

We conducted a preliminary multiborehole cluster analysis with a number of clusters (K) ranging from 2 to 10, using the logging datasets from all three boreholes simultaneously. The results shown in Figure 9 suggest that a significant decrease in the cluster randomness ratio, indicating more randomness in data grouping, starts at $K = 6$ or 7. Beyond this range, only a marginal reduction and a stabilization of the ratio are observed. Considering the main geological units—formations and members—crossed by the Cernavodă boreholes and the wireline logs coverage in each borehole, it can be assumed that data partitioning into six or seven clusters is representative for the existing contrasts in lithology and physical properties.

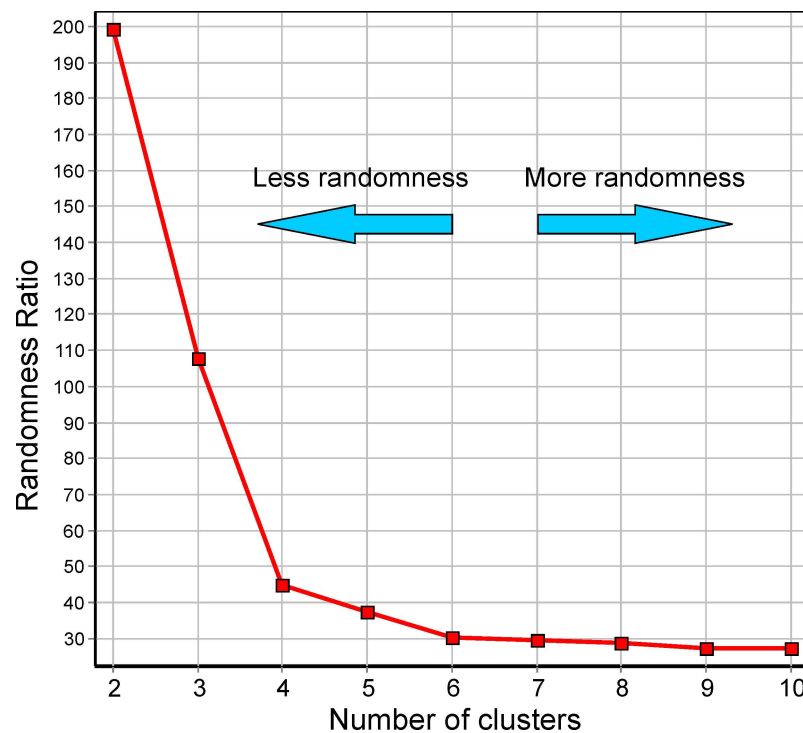


Figure 9. Cluster randomness plot used for selecting a representative number of clusters (K) for the multivariate analysis of the wireline logging datasets recorded in the Cernavodă boreholes.

Figure 10 displays the multiborehole (joint datasets) clustering solutions obtained for $K = 6$ and $K = 7$, respectively. Table 3 presents depth estimates for the boundaries of the main geological complexes, derived from analyzing the continuity and similarity of clusters between the boreholes. Both the six-cluster and the seven-cluster solutions provided clear and detailed electrofacies typing and delineation, with a close match between the formation boundaries reported from drilling data and the boundaries estimated from clustering in the case of the BH-1 borehole (tracks 2 and 3 in Figure 10a—left and Figure 10b—left). The use of BH-1 as a depth calibration (reference) borehole to assess the accuracy of formation boundaries estimation through clustering allowed for the validation of the formation boundaries estimated for the BH-2 and BH-3 boreholes.

Table 4 presents the statistical parameters of the $K = 6$ and $K = 7$ clustering solutions obtained for the analyzed boreholes (cluster/electrofacies numbers are sorted in ascending order of the I_γ log response). Compared with the six-cluster solution (Figure 10a), the seven-cluster solution (Figure 10b) provided additional details within the main groundwater exploration target from the Cernavodă area—the Dolomite Complex. This complex is well defined by the predominance of electrofacies #4 and #5 (moderate I_γ , ρ_A , ϕ_N , and Δt mean values) in its upper part and of electrofacies #2 (lowest I_γ , ϕ_N , and Δt mean values; highest ρ_A mean values) in its lower part, corresponding to the cleanest and tightest carbonates on the intervals 550–697 m in BH-1, 556–698 m in BH-2, and 553–696 m in BH3.

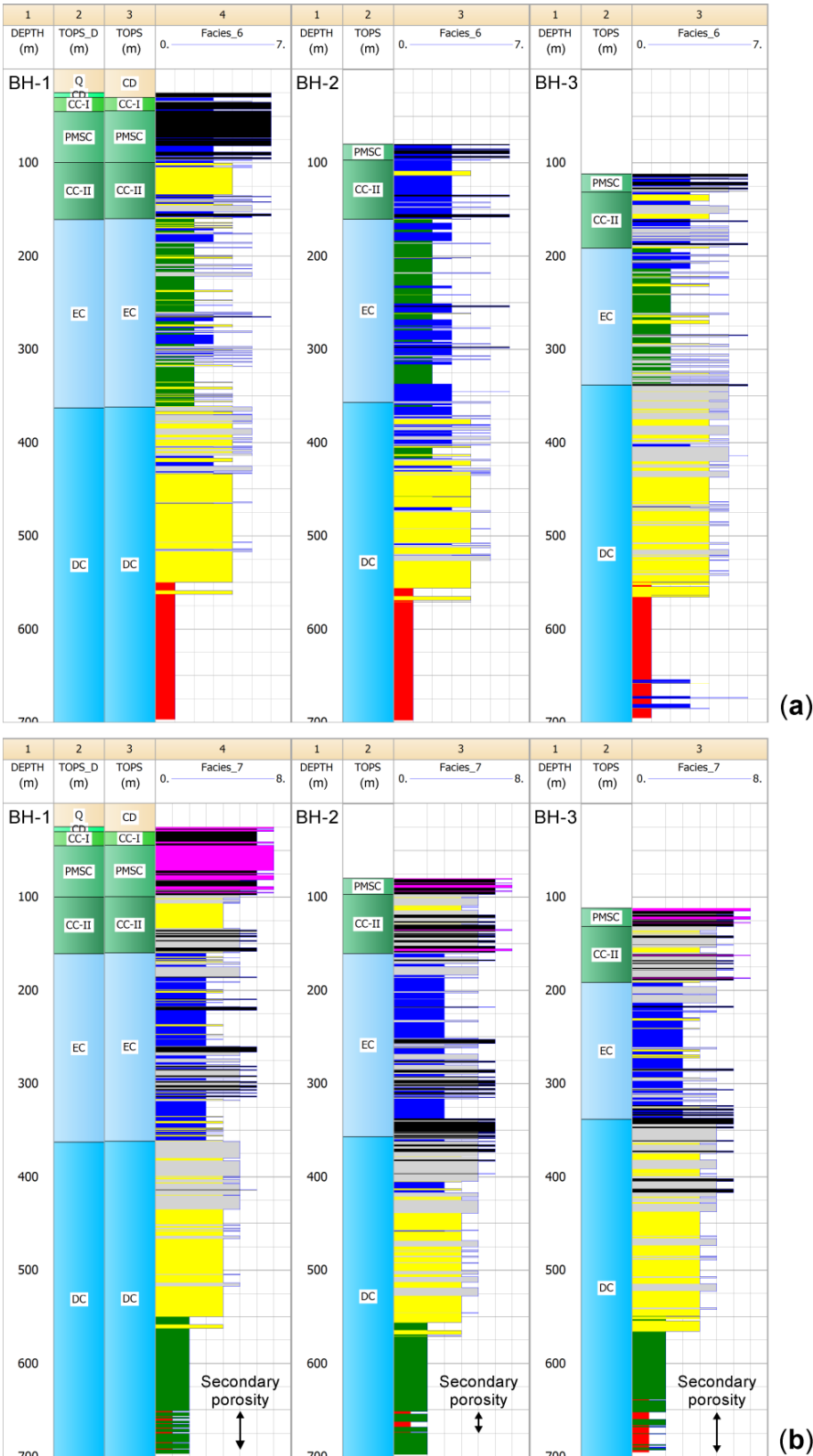


Figure 10. Results of the K-means cluster analysis of the wireline logging datasets recorded in the Cernavodă boreholes: (a) clustering solution obtained for $K = 6$; (b) clustering solution obtained for $K = 7$. TOPS_D—formation boundaries reported from drilling data and geological analyses (m); TOPS—formation boundaries estimated from cluster analysis (electrofacies correlation) (m).

Table 3. Estimation of the likely formation boundary depths for the Cernavodă boreholes, based on multiborehole cluster analysis results. The formation boundary depths reported from drilling data for the BH-1 borehole are provided for comparison.

Formation Boundaries	BH-1		BH-2	BH-3
	Reported (m)	Estimated (m)	Estimated (m)	Estimated (m)
Q/CD	25.0			
CD/CC-I	30.0	29.9		
CC-I/PMSC	45.0	44.7		
PMSC/CC-II	100.0	99.6	97.2	131.7
CC-II/EC	161.0	160.0	160.6	191.8
EC/DC	363.0	361.8	357.0	338.5

Q—Quaternary Continental Deposits, CD—Early Cretaceous Continental Deposits (K_{ap23}), CC-I—Carbonate Complex I ($K_{be3-val}$), PMSC—Polychrome Marlstones and Shales Complex (K_{be12}), CC-II—Carbonate Complex II (K_{be1}), EC—Evaporite Complex (J_{ti3}), DC—Dolomite Complex ($J_{ki-ti12}$).

Table 4. Statistical parameters (means and standard deviations—SD) of the $K = 6$ and $K = 7$ clustering solutions/electrofacies obtained for the Cernavodă boreholes.

Cluster #	Data Points	GR (cps)		SHN (Ω m)		LONG (Ω m)		NPHI (V/V)		DT (μs/ft)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
K = 6											
1	3977	7.959	3.694	707.457	1.622	1793.081	1.701	0.096	0.041	63.758	21.840
2	3239	17.792	6.026	151.015	1.632	361.160	1.924	0.460	0.061	66.733	9.427
3	3021	25.454	6.815	45.678	1.545	82.016	1.642	0.314	0.078	96.805	23.330
4	4725	25.910	5.302	104.988	1.360	223.512	1.454	0.231	0.063	67.865	8.368
5	2737	37.711	6.969	62.463	1.463	133.321	1.620	0.324	0.072	81.458	13.720
6	923	42.434	7.981	25.601	1.573	38.300	1.716	0.439	0.095	165.867	27.420
K = 7											
1	520	5.785	1.765	394.912	1.746	835.853	1.748	0.169	0.060	128.789	31.360
2	3556	8.143	3.733	741.669	1.595	1921.366	1.643	0.090	0.038	57.645	10.220
3	3310	17.938	6.352	149.324	1.644	356.312	1.947	0.460	0.061	67.225	9.995
4	3978	25.958	5.770	113.177	1.326	244.974	1.412	0.220	0.061	66.978	7.980
5	4706	29.838	7.133	57.328	1.387	112.954	1.501	0.302	0.059	77.936	10.090
6	1954	35.846	9.696	41.824	1.621	76.507	1.821	0.355	0.086	113.833	16.050
7	598	43.351	7.583	22.046	1.443	31.501	1.622	0.473	0.085	181.870	18.640

Within these tight sections of the boreholes, electrofacies #1 from the seven-cluster solution (lowest I_γ , moderate ρ_A and ϕ_N , and highest Δt mean values) can be related to zones with a significant secondary porosity development and water-producing potential. Based on the extent of electrofacies #1 (red color in Figure 10b), these zones appear in the intervals 651–693 m in BH-1, 652–675 m in BH-2, and 639–696 m in BH-3.

Considering the 8.5 in. final sections of the boreholes, the highest occurrence of electrofacies #1 was observed in BH-3 (320 data levels), compared to BH-1 (108 data levels) and BH-2 (92 data levels). Such zones were not detected by the caliper tool run in the BH-2 borehole (CAL curve from Figure 5), possibly because isolated karst cavities were not intersected by the tool's arms.

Figure 11 shows multiborehole crossplots of the wireline logs jointly used in the cluster analysis, together with histograms of these logs, with data included from all the boreholes. The crossplots help visualize the particular log response combinations that defined the obtained seven-cluster solution. The correspondence between the main geological complexes/lithofacies and the principal cluster/electrofacies combinations is as follows: *Quaternary* and *Early Cretaceous Continental Deposits*—#7 (predominant) and #6 (subordinate); *Carbonate Complex I*—#6 (predominant) and #7 (subordinate); *Polychrome Marlstones and Shales Complex*—#7 (predominant) and #6 (subordinate); *Carbonate Complex II*—#4 (predominant)

and #5 (subordinate); *Evaporite Complex*—#3 (predominant) and #5 (subordinate); *Dolomite Complex (upper section)*—#4 (predominant) and #5 (subordinate); and *Dolomite Complex (lower section)*—#2 (predominant) and #1 (subordinate).

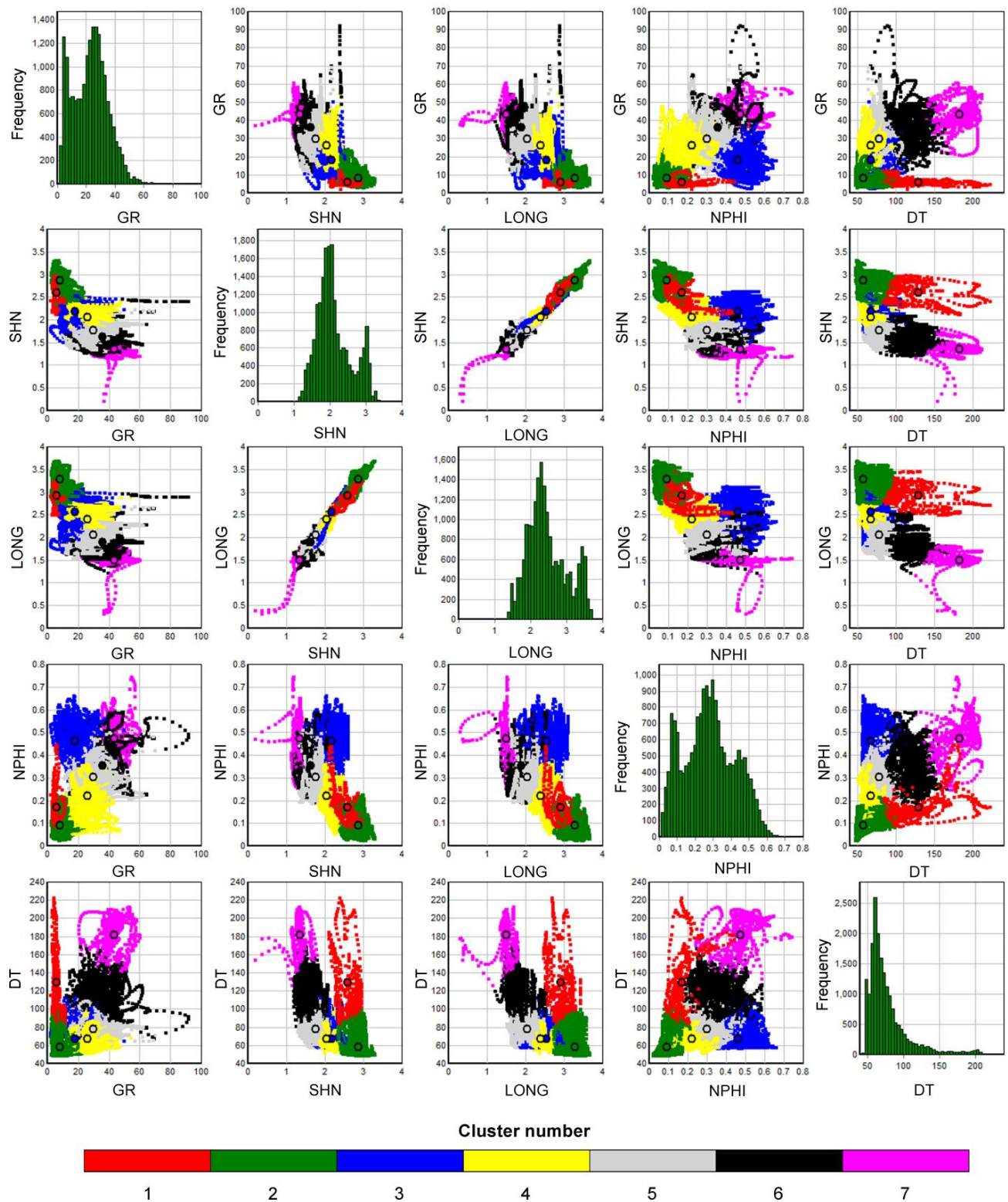


Figure 11. Illustration of the clustering solution obtained for $K = 7$, by means of multiborehole crossplots of the wireline logs used in the cluster analysis (ρ_A input data in logarithmic form). The circles mark the location of the final centroid for each data cluster.

The Δt vs. ϕ_N (DT vs. NPHI) dependencies had a good resolution for overall formation delineation and lithological classification, whereas the Δt vs. ρ_A (DT vs. LONG and DT vs. SHN) and the Δt vs. I_γ (DT vs. GR) dependencies provided a better separation of electrofacies #1, which likely associated with the fractured or karstified water-bearing zones.

5.3. Quantitative Log Interpretation Results

The approach and results of the wireline logging data inversion are exemplified in Figure 12 for the BH-1 borehole, which had the largest log coverage depthwise, encompassing the entire J₃–K₁ carbonate suite from the Cernavodă area. The investigated interval was divided into six interpretation zones, according to the formation boundary depths identified from the drilling data and cluster analysis (track 2). The depth-constrained inversion was carried out separately for each zone, using distinct multimineral models with varying mixtures of quartz, calcite, dolomite, gypsum, anhydrite, clay, and water (effective porosity ϕ), in relation to the dominant lithology of the geological complexes. An additional advantage of the zonal inversion approach employed in this study is the possibility of using interpretation models with more volumetric components than the number of available input logs would allow. Track 3 from Figure 12 shows the final (optimal) interpretation model resulting from the combination of the zonal models and providing a comprehensive litho-porosity characterization of the interval. The quality of the inversion results can be evaluated through the normalized total fitting error (track 4—TotErr curve; fitting error values greater than 1.0 are highlighted in red) and also through the degree of fitting for the main input logs by the theoretical response of the models, i.e., by the corresponding reconstructed/synthetic logs (tracks 5–7; curves GR_r, NPHI_r, and DT_r are the reconstructed I_γ , ϕ_N , and Δt logs, representing the theoretical response of the optimal interpretation model). The uncertainties assigned to the main input logs are visualized via the error/confidence bands (yellow shading) delimited by the curves GR_{pe}, NPHI_{pe}, DT_{pe} (+ σ) and GR_{me}, NPHI_{me}, DT_{me} (− σ).

To avoid a strong overestimation of ϕ from the sonic log on depth intervals with ϕ_S much larger than ϕ_N , we used a variable sonic uncertainty by setting a Δt threshold of 120 $\mu\text{s}/\text{ft}$. Thus, for measured $\Delta t \leq 120 \mu\text{s}/\text{ft}$, we used $\sigma_{DT} = 3 \mu\text{s}/\text{ft}$ as the default uncertainty, and for $\Delta t > 120 \mu\text{s}/\text{ft}$, we imposed a very large σ_{DT} , i.e., a very low (negligible) weighting factor for the sonic log contribution to the inversion solution. In Figure 12—track 7, this is reflected by the wide input confidence bands of the sonic log on the intervals with abnormally high Δt readings. The final interpretation models obtained for all the Cernavodă boreholes provided the best overall reconstruction of input logs. The larger data fitting errors are explainable by unfavorable measurement conditions, simplifications adopted for the model, or the local variability in the formation parameters (e.g., small-scale lithological/mineral heterogeneity or changes in the Archie parameters).

A correlation of the log interpretation models obtained for the analyzed boreholes is presented in Figure 13, together with a reconstruction of the measured $\rho_{A,64}$ logs (LONG curves) by means of theoretical ρ_o logs (Ro curves) corresponding to $S_w = 1$. As observed, the *Evaporite Complex*, which overlies the *Dolomite Complex* exploration target, thins out in the SE–NW direction, from BH-1 towards BH-3. Within the *Dolomite Complex*, the dolomitization of pre-existing limestones (evaluated through the computed V_{dolomite} fractions) appears vertically uneven, occurring mostly in the upper part and, to some extent, the middle part of the complex and suggesting a downward circulation of the magnesium-rich fluids.

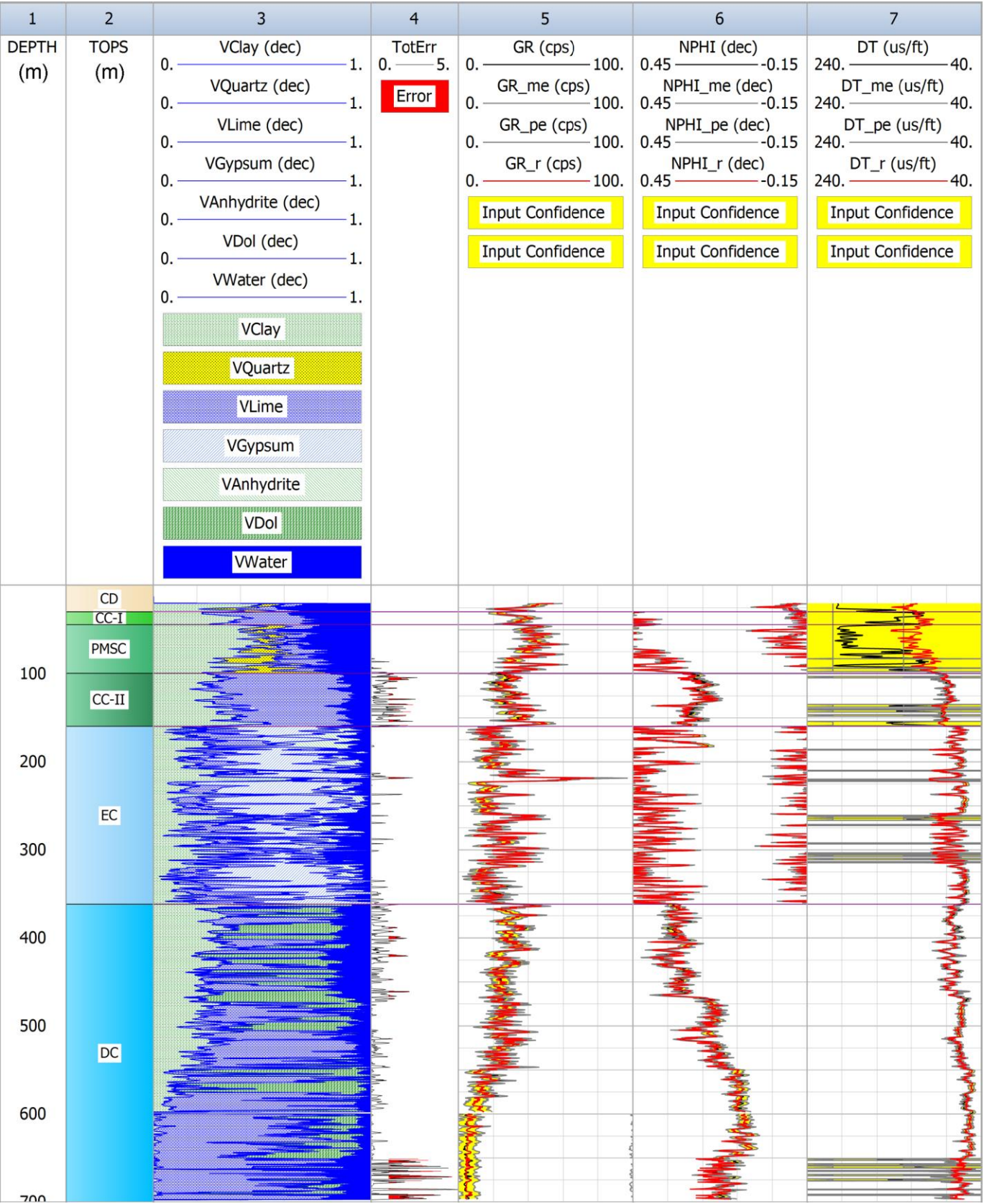


Figure 12. Example of petrophysical interpretation results based on depth-constrained (zonal) inversion of the wireline logs recorded in the BH-1 borehole. The formation boundaries obtained from cluster analysis (TOPS track) define the depth intervals for each distinct multiminerall model used.

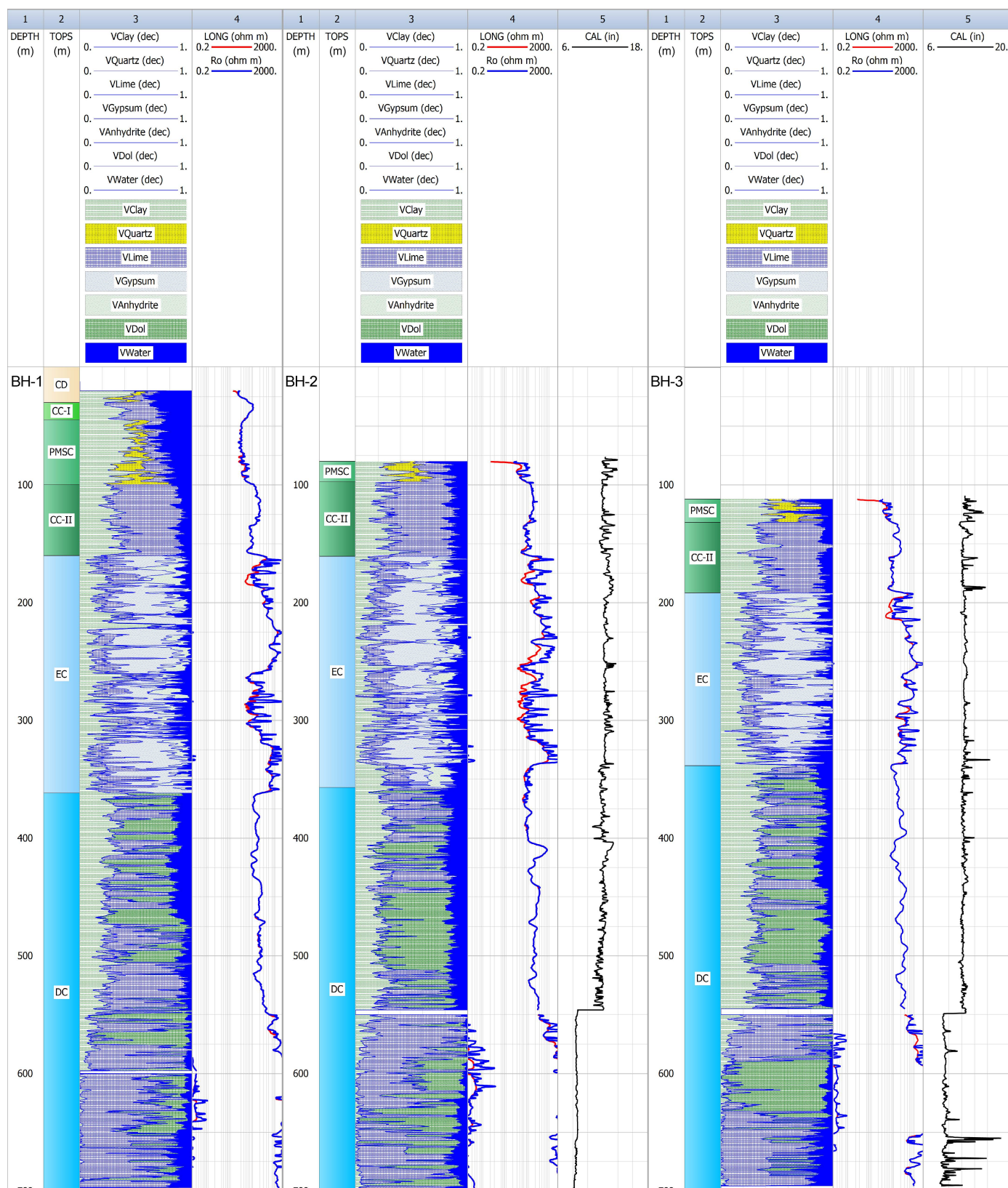


Figure 13. Optimal petrophysical interpretation models obtained from depth-constrained (zonal) inversion of the wireline logs recorded in the Cernavodă boreholes. The measured $\rho_{A,64}$ (LONG) and reconstructed ρ_o (Ro) resistivity logs are shown in tracks 4 (Ω m). For the BH-2 and BH-3 boreholes, the measured caliper (CAL) logs are presented in tracks 5 (in) to illustrate borehole size changes.

In agreement with the cluster analysis results (electrofacies #1 from the seven-cluster solution), the secondary porosity—indicated by significant and local increases in the computed effective porosity—appears to be preferentially developed in the lower part of the *Dolomite Complex*, within limestones less affected or not affected by dolomitization. In this regard, for the 8.5 in. sections of the analyzed boreholes (approximately 550–700 m depth) the computed maximum effective porosities are 0.277 for BH-1, 0.258 for BH-2, and 0.378 for BH-3, compared with computed mean effective porosities of 0.087 for BH-1, 0.071 for BH-2, and 0.088 for BH-3. The porosity due to fractures or fissures usually adds less than 0.01–0.02 and rarely adds up to 0.05 to the primary/matrix porosity [1], so it can be assumed that the higher ϕ values that resulted from the interpretation are related to vuggy porosity (e.g., karstic dissolution vugs or caverns). The association of the secondary porosity predominantly with nondolomitized limestones may result from the generally higher solubility of limestones compared to dolomites but also from an obliteration of pre-existing porosity via the dolomitization process [8,9] in the upper-middle parts of the *Dolomite Complex*.

Besides the vertical variability of the dolomitization, the log interpretation results also reveal a lateral (horizontal) heterogeneity in the *Dolomite Complex*. The dolomitization magnitude gradually increases from BH-1 to BH-3 (SE to NW). The mean $V_{dolomite}$ fractions computed for the entire *Dolomite Complex* intervals are 0.288 for BH-1, 0.357 for BH-2, and 0.363 for BH-3. For the 8.5 in. borehole sections within the complex, the mean $V_{dolomite}$ fractions are 0.275 for BH-1, 0.318 for BH-2, and 0.356 for BH-3. This progressive lateral increase may indicate a tectonic–structural control of the flow pathways for the dolomitizing fluids that is related to a variable degree of fracturing and, consequently, the pore space connectivity and permeability in the *Dolomite Complex*—highest for BH-3, lowest for BH-1 boreholes. Consequently, the SE to NW direction could correspond to a trend of increasing groundwater productivity, which represents an important practical outcome of this study for the drilling of future exploitation boreholes in the Cernavodă area and in neighboring sectors.

The best overall reconstruction of the recorded long normal $\rho_{A,64}$ logs through synthetic ρ_o logs was achieved for ρ_w values of 15–20 Ω m (Figure 13—tracks 4). Downhole temperature data were available for the 8.5 in. final sections of BH-2 and BH-3 boreholes, and the measured T ranged from 20.4 to 21.7 °C. Considering a mean T of 21 °C, the best-fit ρ_w range obtained corresponds to a groundwater mineralization (salinity) of 250–340 ppm NaCl equivalent [36], and the actual one depends on the specific ionic composition of the groundwater. The low mineralization obtained from log interpretation allowed for the characterization of the groundwater of Cernavodă carbonate reservoirs as fresh.

5.4. Groundwater Production Analysis (Borehole Testing)

After completion, the boreholes were tested for groundwater production from the 8.5 in. sections that penetrated the lower part of the Late Jurassic *Dolomite Complex*. The boreholes were equipped with submersible pumps installed at a 32 m depth, and constant rate discharge tests were performed through pumping (Figure 14). The results are presented in Table 5.

Table 5. Results of the groundwater pumping tests performed for the Cernavodă boreholes.

Borehole	SWL (m)	PWL (m)	Q (L/s)	SC (L/s/m)
BH-1	4.00	10.00	16.0	2.67
BH-2	3.10	5.00	28.5	15.00
BH-3	5.17	5.92	21.2	28.27

SWL—static water level, PWL—pumping (dynamic) water level, Q—discharge (pumping rate), SC—specific capacity.

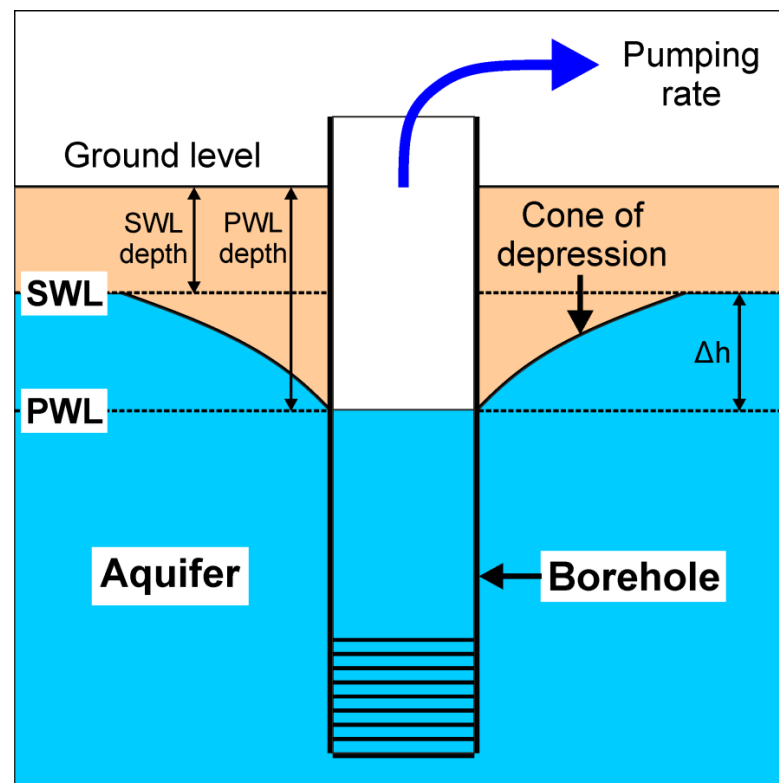


Figure 14. Illustration of a pumping test performed for a groundwater exploitation borehole. SWL—static water level (m), PWL—pumping water level (m), Δh —drawdown (m).

To evaluate the test results, we calculated the specific capacity in Table 5 as $SC = Q / \Delta h$, where $\Delta h = PWL - SWL$ is the drawdown (m) in a borehole resulting from the aquifer's response to pumping. Generally, the SC is an important indicator of borehole productivity and reflects, to a certain extent, the aquifer's quality (e.g., porosity, permeability). Higher SC values indicate more productive boreholes, yielding more groundwater for a given drawdown.

The SC comparison indicates important differences between the boreholes: BH-1 has the lowest productivity, BH-3 has the highest productivity, and BH-2 has an intermediate productivity. The pumping test results are partially supported by the petrophysical interpretation models, which showed a significantly higher maximum porosity at the base of the *Dolomite Complex* in the BH-3 borehole compared with BH-1 and BH-2. However, the large disparity in productivity between the BH-1 and BH-2 boreholes, which are in close proximity to each other, cannot be explained based on their comparable maximum and mean porosities computed for their final sections. In this case, the main controlling factors for the observed differences in groundwater productivity are likely the variable degree of pore space connectivity and fracture permeability of the carbonate-rock aquifer. This interpretation is in agreement with the increased extent of dolomitization indicated by the log interpretation from BH1 towards BH3, which suggests an increased fracture density and better flow characteristics in the SE to NW direction. Such an outcome of the present study could significantly improve the placement of additional boreholes for a more efficient exploitation of the aquifer.

The analyses conducted on groundwater samples collected from the BH-1 and BH-2 boreholes showed electrical conductivities in the 714–721 $\mu\text{S}/\text{cm}$ range (equivalent to $\rho_w \approx 14 \Omega \text{ m}$), total dissolved solids concentrations of 533–539 mg/L, and an average salinity of 0.3 g/L (300 ppm). The ρ_w and salinity measured on the samples match the values obtained from logging data inversion, validating the interpretation methodology and the parameter selection.

6. Conclusions

This study aimed to evaluate the petrophysical and reservoir properties of the most important aquifer system in southern–southeastern Romania, the Late Jurassic–Early Cretaceous (J_3 – K_1) groundwater body shared with Bulgaria and developed in karstic–fractured carbonates. We analyzed three 700 m deep groundwater exploration–exploitation boreholes drilled in the Cernavodă town area, South Dobrogea region, Romania, which intercepted in their lower sections the J_3 -age *Rasova Formation* (the water-bearing “*Dolomite Complex*”), where significant secondary porosity is present in carbonate deposits ranging from limestones to dolomites. Our investigation utilized an approach combining geophysical wireline logging, drilling and geological data, multiborehole cluster analysis, and zonal inversion of the logging data with variable confidence assigned to the input logs, as well as groundwater pumping tests, sampling, and analysis. The following conclusions can be drawn from this research:

- In the studied area, and likely in the entire Cernavodă tectonic block, the main interval with secondary porosity development (karstic dissolution features, fractures) and the maximum water-producing potential is located in the lower part of the *Rasova Formation* (639–700 m depth), in the limestones least affected by dolomitization. This finding has an important practical implication for the planning and drilling program of subsequent groundwater exploitation boreholes;
- The pumping tests and log interpretation results demonstrate a strong heterogeneity of the aquifer, with highly variable borehole productivities even on short distances. This variability is not only due to differences in porosity but also to different degrees of hydraulic connectivity within the carbonate reservoir, which are likely related to tectonic factors (amount of fracturing) or unequal karst development;
- The SE to NW direction appears to correspond to a trend of increasing groundwater productivity in the Cernavodă area and, possibly, at a larger scale. This is also suggested by a direct correlation between productivity and the lateral (horizontal) intensity of the calcite-to-dolomite replacement, with the dolomitization extent reflecting pore space connectivity. If confirmed by further research, this novel outcome can help optimize the placement of future extraction boreholes.

The limitations of the present study are related to the relatively restricted geophysical investigation program conducted in the analyzed boreholes and the unfocused resistivity logging tool employed, which did not provide a minimization of the borehole conductive effect. However, within the main exploration target (the *Rasova Formation*), in the 8.5 in. final sections, the borehole effect upon the measured apparent resistivity data and the log interpretation results is minimal. A beneficial addition to the logging programs run in such carbonate reservoirs would be the inclusion of electrical, acoustic, and/or optical imaging tools for superior and highly detailed secondary porosity quantification and reservoir characterization.

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Data Availability Statement: The data are available on request from the authors.

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Appendix A

MATLAB code for limestone neutron porosity (ϕ_N) computation based on the long-spacing and short-spacing detectors count rates:

```
clear all; close all; clc
load Logs;
N = length(DEPTH);
for i = 1:N
    CAL(i) = CAL(i) * 25.4;
    if NEAR(i) > 1
        TMP1 = FAR(i)/NEAR(i);
    else
        TMP1 = 1;
    end
    TMP2 = TMP1 * TMP1;
    TMP3 = TMP2 * TMP1;
    P214 = 0.01080258/TMP3 - 0.2344151/TMP2 + 4.779079/TMP1 - 9.517288;
    P150 = 0.01149102/TMP3 - 0.2548200/TMP2 + 4.857260/TMP1 - 8.734154;
    if CAL(i) >= 214
        P(i,1) = P214;
    elseif CAL(i) <= 150
        P(i,1) = P150;
    else
        TMP4 = (P214 - P150)/64;
        TMP5 = P150 - TMP4 * 150;
        P(i,1) = TMP4 * CAL(i) + TMP5;
    end
end
dlmwrite('NPHI.txt', [DEPTH P], 'delimiter', '\t')
```

where: *Logs* is a MATLAB (.mat) data file containing the vectors *DEPTH* (m), *CAL*—caliper values (inch), *FAR*—long-spacing detector count rates (cps), and *NEAR*—short-spacing detector count rates (cps); *P* is a vector storing the computed ϕ_N values (%); and *N* is the number of logging data samples in each vector. For the BH-1 borehole, the *CAL* curve (not available) was replaced with the bit size values.

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