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Petrophysical evaluation of the Gassum and Frederikshavn formations in the Gassum-1, Voldum-1, Rønde-1, Horsens-1 and Hobro-1 wells

Results of log interpretation, evaluation of reservoir parameters and a description of the interpretation procedure

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G E U S

The present evaluation forms part of an integrated study on the geothermal potential of APMH area of interest at Århus. The present sub-study deals with an analysis of well logs acquired in Gassum-1, Voldum-1, Rønde-1, Horsens-1 and Hobro-1. The objective is characterising the Gassum and Frederikshavn formations with respect to lithology, porosity, permeability, shale volume and thickness of net reservoir sandstone. The intention of the petrophysical study is to provide a basis for deciding on an appropriate exploration strategy within the Århus area. The current sequence stratigraphic subdivision of the Gassum Formation is applied on the well log figures; the subdivision may be slightly adjusted during the progress of sequence stratigraphic part of the study, but a revision will not influence the estimated reservoir parameters.

Log data are available from the five wells, but the log quality varies considerably due to rather old wells and occasionally, also poor borehole conditions. The existing log interpretation has been revised, based on a thorough log quality assessment and supplementary geological information from nearby wells. Cores are cut in the Gassum-1 and Horsens-1 wells, but no drill cores are available from Voldum-1, Rønde-1 and Hobro-1. In addition, the Well Completion Reports provide information about the reservoir rocks including geological and stratigraphic data.

The present log analysis includes a detailed lithological interpretation of the drilled sections, and the lithological interpretation is based on either the GR log or the SP log combined with information from cores and cuttings descriptions. The cores provide valuable information about quality of the reservoir sandstones and the geothermal potential of the sandstones. The logs may be used to induce information from the cored sections into the un-cored intervals and hence, the available cores and measurements of porosity and permeability (CCAL) provide support to the log interpretations.

In the Gassum-1 and Horsens-1 wells, only incomplete log suites are available for porosity evaluation, and a standard petro-physical evaluation cannot be carried out. However, cores are cut in these two wells, and a number of core porosity-permeability data exist, so information about e.g. porosity may be extrapolated to un-cored intervals using the sparse log data. The permeability is estimated from porosity-permeability relations (see below). The GR and SP logs provide information about the shale volume.

Horsens-1 (drilled 1958)

The raw and interpreted logs are plotted in Figures 6 and 11.

The shale volume is calculated from the SP log; a gamma-ray (GR) log was not acquired. The SP baselines for sandstone is approximately 74 mV, for claystone *c.* 166 mV. These numbers correspond to SP_min and SP_max, and the shale volume (Vshale) is then calculated as follows:

- Vshale = (SP – SP_min)/(SP_max – SP_min)

A distinct porosity log was not acquired in Horsens-1 and consequently, the porosity evaluation has been based on the Archie Equation: $(Sw)^n = \frac{a \cdot Rw}{Resistivity \cdot (porosity)^m}$

<u>When assuming</u>:
Water saturation (Sw): 100% (Sw = 1)
Saturation exponent (n): 2
Cementation exponent (m): 2 and
Resistivity: 64 inch resistivity log -

- The porosity (*PHIT*) may be estimated from re-arranging the Archie Equation, i.e.:

PHIT = $\sqrt[2]{a \cdot Rw/Resistivity}$, where a is the Archie Constant and Rw is the formation water resistivity. The ($a \cdot Rw$) term is not known, but calibration to core porosity data indicate that the $a \cdot Rw$ term is in the order of 0.040 ohm-m. Core analysis data are available from the Gassum Formation in the interval 1583–1587 m MD.
Finally, the effective porosity (PHIE) was calculated as follows: *PHIE* = *PHIT–PHIT·*Vshale.

Gassum-1 (drilled 1951)

The raw and interpreted logs are plotted in Figures 4 and 9

The shale volume is calculated from the GR log:

- Vshale = (GR – GR_min)/(GR_max – GR_min), using GR_min = 35 and GR_max = 235.

Neither a distinct porosity log nor a resisitivity log is available from the two target formations (i.e. the Gassum and Frederikshavn formations in the depth interval 1000–1800 m MD). A large number of core porosity data, representative of the two formations, exists in the database, however. Accordingly, GEUS established a correlation between gamma response and porosity, suggesting that a log-derived porosity may be estimated as follows:

- **Frederikshavn Formation**: PHIE = (75 – GR)/100 (fraction)
- **Gassum Formation**: PHIE = (75 – GR)/100 + 0.10 (fraction)

Such an unconventional method for porosity determination is uncertain, but with respect to the Gassum-1 well data, a good agreement between core and log-derived porosity is obtained, and hence the present Gassum-1 porosity evaluation is considered reliable. Core analysis data are available from both the Gassum and Frederikshavn formations, and the core data were used for calibrating the log-derived porosity.

Rønde-1 (drilled 1966)

The raw and interpreted logs are plotted in Figures 5 and 10

The shale volume is calculated from the GR log:

- Vshale = (GR – GR_min)/(GR_max – GR_min)

using GR_min = 20 and GR_max = 90.
A full log suite suitable for a standard petrophysical evaluation was acquired in the Rønde-1 well, but the log quality is questionable in places. The effective porosity is calculated from a combination of the density log readings (RHOB), the shale volume calculated from the GR log (Vshale) and an assumed shale density of 2.3 g/cc. The porosity is, occasionally, difficult to interpret due hole problems as indicated by the caliper log and in places, the density log readings are somewhat questionable.
Notice: No cores were cut in the Rønde-1 well.

Voldum-1 (drilled 1974)

The raw and interpreted logs are plotted in Figures 3 and 8

The shale volume is calculated from the GR log:

- Vshale = (GR – GR_min)/(GR_max – GR_min)

using GR_min = 30 and GR_max = 111.
A full log suite suitable for a standard petrophysical evaluation was acquired in the Voldum-1 well, but the log quality is generally poor. The density log readings are generally unreliable and even erratic within certain intervals, meaning that the raw density log cannot be used for porosity determination without prior correction and processing. In order to correct the density log, the density log responses from the Voldum-1 and Rønde-1 wells were compared and correlated. In both wells, a well-defined clayey interval occurs in the upper part of the Oddesund Formation, i.e. the interval in between the base of the Vinding Formation and salt deposits belonging to the Oddesund Formation. It is assumed that the density log response should be almost equal in both wells, meaning that the density log response of the Voldum-1 well should be corrected 0.2 g/cc (RHOBC = RHOB – 0.2 g/cc). This shift (-0.2 g/cc) is supported by the questionable log readings that are observed in Oddesund Formation rock salt deposits.

Even if the density log is corrected as listed above, the log readings are still unreliable in places. However, in a pronounced sandstone interval in the lower part of the Gassum Formation (1870–1885 m MD), both the corrected density log and the sonic log are suitable for analysis, and the density and sonic log porosities should therefore be equal in this interval. Nevertheless, the porosity calculated from the corrected density log (RHOBC) and the raw sonic log (DT) differs slightly, suggesting that the sonic log should be corrected as well. It is suggested to adjust the sonic log: DTC = DT + 17 µsec/ft. The DTC log forms the basis of interpreting the porosity in Voldum-1 using the Wyllie algorithm, and the applied sonic log response parameters are: Sandstone: 55.5 µsec/ft, Fluid: 189 µsec/ft, and Shale: 130 µsec/ft.

Notice: No cores were cut in the Voldum-1 well.

Hobro-1 (drilled 1974)

The raw and interpreted logs are plotted in Figures 7 and 12

The shale volume is calculated from the GR log:

- Vshale = (GR – GR_min)/(GR_max – GR_min) using:

Gassum Fm: GR_min = 30 and GR_max = 200 and
Frederikshavn Fm.: GR_min = 35 and GR_max = 100.

With respect to the Frederikshavn Formation, a density log (RHOB) is available for porosity determination despite the log quality is somewhat questionable. However, a standard petrophysical evaluation of the Frederikshavn Formation can be performed using GR and RHOB.

The Gassum Formation is only partly logged with a density log, but instead the sonic log is used for assessing the porosity using the Wyllie algorithm. The applied sonic log response parameters are: Sandstone: 55.5 µsec/ft, Fluid: 189 µsec/ft, and Shale: 60 µsec/ft. The quality of the sonic log is, however, somewhat questionable, introducing uncertainty on the porosity and net sand thickness estimates.
Notice: No cores were cut in the Hobro-1 well.

Porosity-Permeability relationships

The permeability is not logged and alternatively, the permeability is estimated from porosity-permeability relations that have been established based on conventional core analysis data (CCAL) from various wells located in Jylland. The CCAL data are measured at laboratory conditions.

With respect to the **Gassum Formation**, core data are available from the wells: Gassum-1, Horsens-1, Børglum-1, Farsø-1, Flyvbjerg-1, Frederikshavn-2, Skagen-2 Thisted-3 and Vedsted-1 (**Figure 1**). The core analysis data represent a variety of depositional environments and grain size distributions, leading to a rather scattered poro-perm plot. On average, a log-based permeability may be estimated as follows:

PERM_log = 196449·(Porosity)$^{4.3762}$ where the permeability is in mD and the porosity is in fraction.

The black line plotted in **Figure 1** illustrates this *general trend*, which indicates the expected relationship between porosity and permeability. With respect to the lower part of the Gassum Formation, a separate poro-perm relation is suggested; red line in **Figure 1**. Note that the data from lower interval is a subset of the total dataset.

With respect to the **Frederikshavn Formation**, core analysis data are available from the Gassum-1 and Haldager-1 wells **(Figure 2**). The Frederikshavn Formation sandstones are very fine to fine-grained and generally, the sandstones are characterised by a slightly higher clay content than the Gassum Formation sandstones. Both aspects lead to a poro-perm relation that is somewhat pessimistic compared the Gassum Formation. On average, a log-based permeability may be estimated as follows:

PERM_log = 78580·(Porosity)$^{4.3762}$ where the permeability is in mD and the porosity is in fraction. A short summary of these three porosity-permeability relationships is presented in **Figure 16**.

The CCAL data were measured in the core laboratory and these measurements must therefore be converted to reservoir conditions in order to reflect the flow rates in the reservoir sandstones. It is GEUS' experience that the reservoir permeability is about 1.25–1.50 times higher than the permeability measured on plug samples in the laboratory. This permeability enhancement factor is based on a limited dataset, but in a few Danish onshore wells both core and well test permeabilities exist for the same interval, e.g. the Stenlille-19 well (described in Kristensen et al., 2016). Stenlille-19 was cored in the lower part of the Gassum Formation (1630–1665 mMD), and the core analysis data signify an average *gas permeability* of approx. 4300 mD. This interval was also flow tested, leading to a *liquid permeability* in the order of 6300 mD (DONG, 2001), indicating that the two permeability assessments are somewhat dissimilar. Hence, the average permeability of net sand is herein estimated both at laboratory conditions (lab.) and at reservoir conditions (res.) using an up-scaling factor of 1.25. With regard to the Danish Basin in Jylland, no wells have both been cored and reliably flow tested in the Gassum Formation, so it is not possible to verify this factor using local well data from this region. However, herein it is assumed that the up-scaling factor listed above is valid for the 5 study wells.

Results of the petrophysical evaluation

The results of the log interpretation, including estimated reservoir parameters, are presented in **Tables 1–3** below. The key parameters listed are: formation tops, formation thickness, sand thickness, average porosity, average permeability (both at laboratory and reservoir conditions), and estimated reservoir transmissivity. Furthermore, the net-to-gross ratio is calculated (N/G). Both the Gassum and the Frederikshavn formations are considered, and cut-offs are applied: The calculation of the gross sand thicknesses is based on 30% Vshale cut-off, whereas the remaining parameters are based on 15% porosity and 30% Vshale cut-offs (**Tables 1–3**). Furthermore, an estimated sandstone percentage is listed, reflecting the total amount of sandstone within a particular interval (formation), corresponding to gross sand thickness divided by gross interval thickness. The results of the petro-physical evaluations are also illustrated in a number of log plots (**Figures 3–12**).

Gassum Formation – sedimentology and net sand thicknesses

In the **Rønde-1 well (Figure 5)**, cuttings descriptions indicate that the upper part of the Gassum Formation consists primarily of shale, whereas the lower part consists of shale interbedded with thin sandstone and siltstone layers. These sandstones are predominantly fine-grained. This composition leads to a rather low net-to-gross ratio (N/G) as indicated by the petrophysical evaluation (**Table 1**). The interpreted net and gross sand thickness is about 20 and 30 metres, respectively, when dealing with the Gassum Formation. The assessed sandstone percentage, i.e. the amount of gross sand within the Gassum Formation, is around 23% in Rønde-1.

In the **Gassum-1 well (Figure 4)**, the petrophysical evaluation points out a number of sandstone intervals, and the presence of these sandstones are confirmed by information from the Gassum-1 Well Completion Report including core descriptions. Presence of fine-grained to coarse-grained sandstones are reported, occasionally the sandstones are micaceous. Details on the composition of the Gassum Formation sandstones is outlined in the Well Completion Report and Nielsen (2003). The net and gross sand thicknesses are considerably larger than observed in the Rønde-1 well. The accumulated thickness of the sandstone layers is in the range 40–45 metres, and the majority of the gross sandstone volume is considered to be net sand.

In **Voldum-1 (Figure 3)**, three pronounced sandstone layers in the Gassum Formation are interpreted from the logs within the interval 1815–1885 m MD. The sandstones are clear, coarse-grained and sub-angular as reported in the Well Completion Report. The accumulated thickness of the sandstone layers is in the range 35–40 metres, and majority of the gross sandstone volume is considered to be net sand.

According to the cuttings and core descriptions available from the **Horsens-1** Well Completion Report, the sandstone layers of the Gassum Formation consist of fine to medium-grained sandstone. The accumulated thickness of the sandstone layers is approximately 28 metres, and the entire gross sandstone volume is considered to be net sand. The Gassum Formation of the Horsens-1 well is illustrated in **Figure 6**.

The Gassum Formation in the **Hobro-1 well (Figure 7)** is characterized by a considerable sandstone content, and the interpreted net and gross sand thickness is round 52 and 86 metres, respectively. Accordingly, the net sand corresponds to about two thirds of the gross sandstone volume in Hobro-1. The Well Completion Report states the presence of fine to medium-grained sandstones in the Gassum Formation. The sandstones are occasionally are coarse-grained, and generally sub-rounded to rounded, well sorted and slightly calcareous.

A simplified net sand distribution map focussing on the Gassum Formation is illustrated in **Figure 15**. The net sand thicknesses as interpreted from the log data acquired in the Hobro-1, Gassum-1, Voldum-1, Rønde-1 and Horsens-1 wells are plotted, using the Top Gassum Formation depth structure map as base map (the map is available from the GEUS WebGIS Portal). The five data points signifies that the net sand thickness decreases towards the south.

Lower part of the Gassum Formation – high permeability

A layer with good–excellent reservoir properties seems to be presents at the base or in the lowermost part of the Gassum Formation in several wells in the basin, including the five wells studied here. It is cored in Gassum-1, Thisted-3 and Stenlille-19 – in these wells the layer thickness is minimum 20 metres. Core data from the Gassum-1 well indicate that the permeability in this lower part is significantly higher than indicated by the general trend (**Figure 1**). On this basis it is assumed that the lower part of the Gassum Formation forms a prominent flow unit in all five study wells, and **estimated** reservoir parameters for this particular interval are listed in **Table 2**. The definition and delineation of this lower interval is based on interpreted log data. As the permeability estimates listed in **Table 2** rely on an assumption (see above), the permeabilities listed in this table are particularly relevant to high case computations.

Upper part of the Gassum Formation

A separate table including estimated reservoir parameters for the upper part of the Gassum has not been generated. Average permeabilities of net sand are, however, expected to be somewhat lower than indicted by the general trend line (*cf.* black line in **Figure 1**) due to the presence of low permeability sections.

Frederikshavn Formation – secondary target

In **Rønde-1**, the Frederikshavn Formation consist of approximately 50% sandstone and 50% shale/clay. The sandstones are mostly very fine to fine-grained, as indicated by the cuttings descriptions from this well.

In **Voldum-1**, the sandstone content of the Frederikshavn Formation is significantly higher than in Voldum-1, as evidenced by information from the Composite log and the log-derived N/G ratio (*c.* 0.95). These sandstones are mostly clean, sorted, rounded and very fine-grained.

Fine-grained sandstones dominate the cored part of the Frederikshavn Formation in **Gassum-1,** whereas the Frederikshavn Formation sandstones are mostly medium to coarse-grained in **Horsens-1**.

Log plots and result displays

Ten log plots illustrate the results of the petrophysical evaluation (**Figures 3–12**). The plots present interpreted sequence stratigraphic surfaces (SB, MFS, TS), a lithological interpretation along with log-derived porosity and log-based permeability curves. The gamma-ray log (or SP) and the sonic log (if available) delineates the lithology column. Moreover, a number of raw log curves are plotted, and black bars illustrate cored intervals. Depth-shifted core porosity data (Shifted_CPOR) and core permeability data (Shifted_CPERM) are also plotted. Red bars indicate the position of potential reservoir sandstones.

The raw log logs include Caliper, GR, SP, Sonic, Resistivity (LL7, 16FT, 10IN, 38IN, 18F8, 64IN, IL, LL), and Density – if available.

Porosity-depth relationship

The re-interpreted log data form the basis of generating a local porosity-depth relationship for the Gassum Formation using present-day depths and averaged porosity data from Gassum-1, Voldum-1, Rønde-1, Horsens-1 and Hobro-1 (**Figure 13**). The local model does not deviate significantly from the general GEUS porosity-depth model set up for the Gassum Formation. A good correlation between porosity and present-day depth is observed, when dealing with the log-derived porosity values from Gassum-1, Voldum-1, Rønde-1, Horsens-1 and Hobro-1 (blue dots plotted in **Figure 13**, observe that 15% porosity and 30% Vshale cut-offs were applied prior to calculating averaged values). The local porosity-depth model (blue line) points to:
Porosity (in %) = 34.297 – 0.0056·Present-day Depth (in metres).

In addition, a regional porosity-depth model for the Gassum Formation based on estimated maximum burial depth is presented along with estimated maximum burial depths in the study wells (**Figure 14**). The regional porosity-depth model is described in Kristensen et al. (2016), and maximum burial depth estimates are based on works by Japsen et al. (1999, 2007). At Århus, the difference between present-day depth and estimated max. burial depth is in the order of 600 metres (*cf.* Japsen et al., 2007).

The latter two figures may be used for porosity prediction, leading to an average porosity of approx. 22% for the Gassum Formation within the Århus area. This porosity estimate is based on an assumed a present-day depth of 2200 m and an estimated maximum burial depth of 2800 m.

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T**able 1**: Estimated reservoir parameters for the ***entire*** **Gassum Formation** in the 5 study wells.
Cut-offs: Vshale < 30% and Porosity > 15%. (res.: reservoir, lab.: laboratory):

Gassum Formation	Voldum-1	Gassum-1	Rønde-1	Horsens-1	Hobro-1
Top Gassum, mTVDss	1722	1460	2571	1476	2343
Base Gassum, mTVDss	1850	1583	2711	1543	2488
Interval thickness/ formation thickness (m)	128	123	140	67	145
Net sand thickness, (m) *Gross sand thickness, m*	**35.5** *39.3*	**42.7** *45.4*	**20.1** *31.5*	**27.9** *28.0*	**52.5** *86.2*
N/G, (sandstone %)**^**	0.90, (31%)	0.94, (37%)	0.64, (23%)	0.99, (42%)	0.61, (59%)
Avg. Net porosity (%)	24.6	25.5	19.7	26.1	20.7
Avg. Permeability of net sand (mD)	500 (lab.) 625 (res.)	750 (lab.) 940 (res.)	200 (lab.) 250 (res.)	625 (lab.) 780 (res.)	220 (lab.) 275 (res.)
Reservoir transmissivity (Dm)	22	40	5	22	14

Table 2: **Estimated reservoir parameters for the distinct sandstone unit in the lower Gassum Formation.**
Cut-offs: Vshale < 30% and Porosity > 15%. (res.: reservoir, lab.: laboratory):

Gassum Formation	Voldum-1	Gassum-1	Rønde-1	Horsens-1	Hobro-1
Top flow unit, mTVDss	1828	1563	2685	1515	2434
Base Gassum, mTVDss	1850	1583	2711	1543	2488
Interval thickness/ unit thickness (m)	23	21	26	27	54
Net sand thickness (m) *Gross sand thickness, m*	**19.8** *20.6*	**18.2** *18.3*	**13.3** *17.2*	**22.1** *22.3*	**43.2** *49.0*
N/G, (sandstone %)**^**	0.96, (90%)	0.99, (87%)	0.77, (66%)	0.99, (83%)	0.88 (91%)
Avg. Net porosity (%)	24.6	28.4	19.7	27.3	20.7
Avg. Permeability of net sand (mD)	600 (lab.) 750 (res.)	1120 (lab.) 1400 (res.)	240 (lab.) 300 (res.)	680 (lab.) 850 (res.)	240 (lab.) 300 (res.)
Reservoir transmissivity (Dm)	15	25	4	19	13

Table 3: Estimated reservoir parameters for the **Frederikshavn Formation** in selected well
Cut-offs: Vshale < 30% and Porosity > 15%. (res.: reservoir, lab.: laboratory):

Frederikshavn Fm.	Voldum-1	Gassum-1	Rønde-1	Horsens-1	Hobro-1
Top Fr.Havn, mTVDss	1278	1020	2014	1168	1741
Base Fr.Havn, mTVDss	1344	1121	2059	1230	1805
Interval thickness/ formation thickness (m)	66	101	45	62	64
Net sand thickness (m) *Gross sand thickness, m*	**60.1** *63.3*	**64.6** *66.2*	**18.0** *25.3*	**50.6** *57.3*	**15.2** *40.3*
N/G, (sandstone %)^	0.95, (96%)	0.98, (66%)	0.71, (56%)	0.88, (92%)	0.38 (63%)
Avg. Net porosity (%)	28.4	29.9	19.9	21.1	19.3
Avg. Permeability of net sand (mD)	380 (lab.) 475 (res.)	500 (lab.) 625 (res.)	80 (lab.) 100 (res.)	140 (lab.) 175 (res.)	95 (lab.) 120 (res.)
Reservoir transmissivity (Dm)	29	40	2	9	2

Legend to Tables 1–3:

- N/G = Net sand thickness / Gross sand thickness,
- (^) The sandstone percentage (sandstone %) expresses the gross sand thickness relative to the interval thickness.

Legend to petrophysical evaluation plots (result displays, Figures 3–12):

- Interpreted **porosity**: Black curve with blue colour fill (track five to the right). Scale 0–40%. Depth-shifted core porosity data (Shifted_CPOR) are also plotted.
- Interpreted **permeability**: Red curve left of the porosity curve. Scale 10000–1 mD. Depth-shifted core permeability data (Shifted_CPERM) are also plotted.
- Interpreted **shale volume**: Brow curve plotted in the same track as the porosity. Scale 0–100%.
- A **lithologica**l interpretation illustrating the distribution of sandstone (yellow) and shale (brown) is shown in track one. Also siltstone (orange) and coal (black). The gamma-ray log (or SP) and the sonic log (if available) delineates the lithology column. Sequence stratigraphic surfaces (SB, MFS, TS) in red, blue, green colours.
- Black bars illustrate **cored intervals**. Red bars indicate the position of potential reservoir sandstones.
- Apart from the GR, SP and sonic logs, a number of **raw logs** are also plotted (if acquired): Caliper, Density and Resistivity (LL7, 16FT, 10IN, 38IN, 18F8, 64IN, IL, LL).

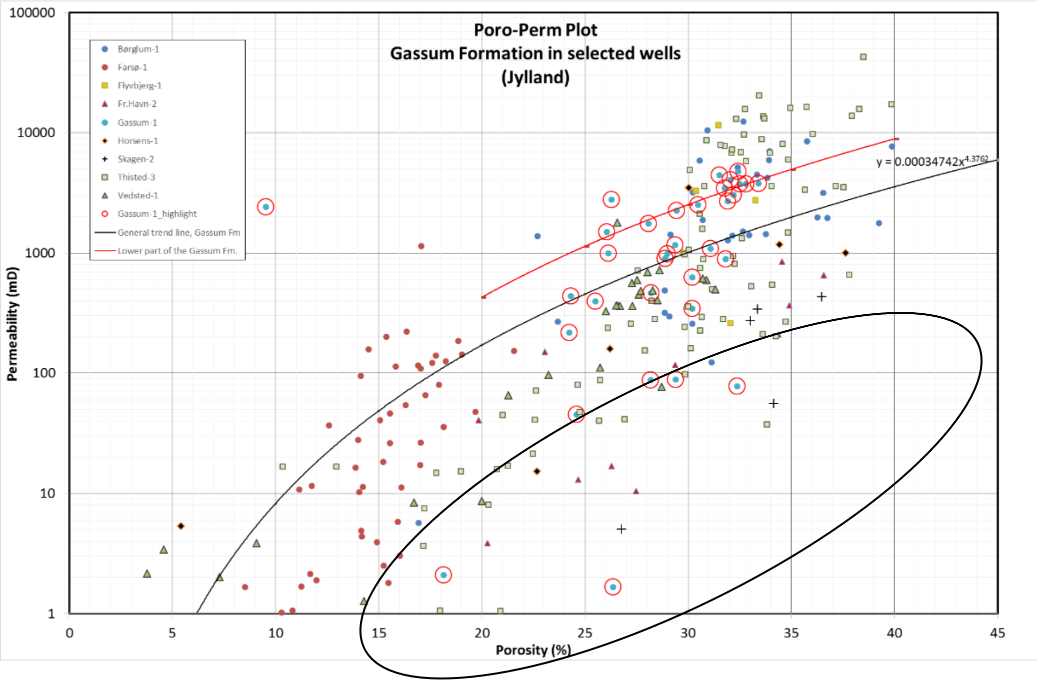

Figure 1: Poro-Perm plot for the **Gassum Formation** in selected wells (see legend). Based on CCAL. The black line represents the general trend; the red line is based on data points from the lower part of the Gassum Formation and thus characterises the lower part of the Gassum Fm. Distinct clay and siderite points marked by an ellipsis, the clay/siderite points are left out of calculations.

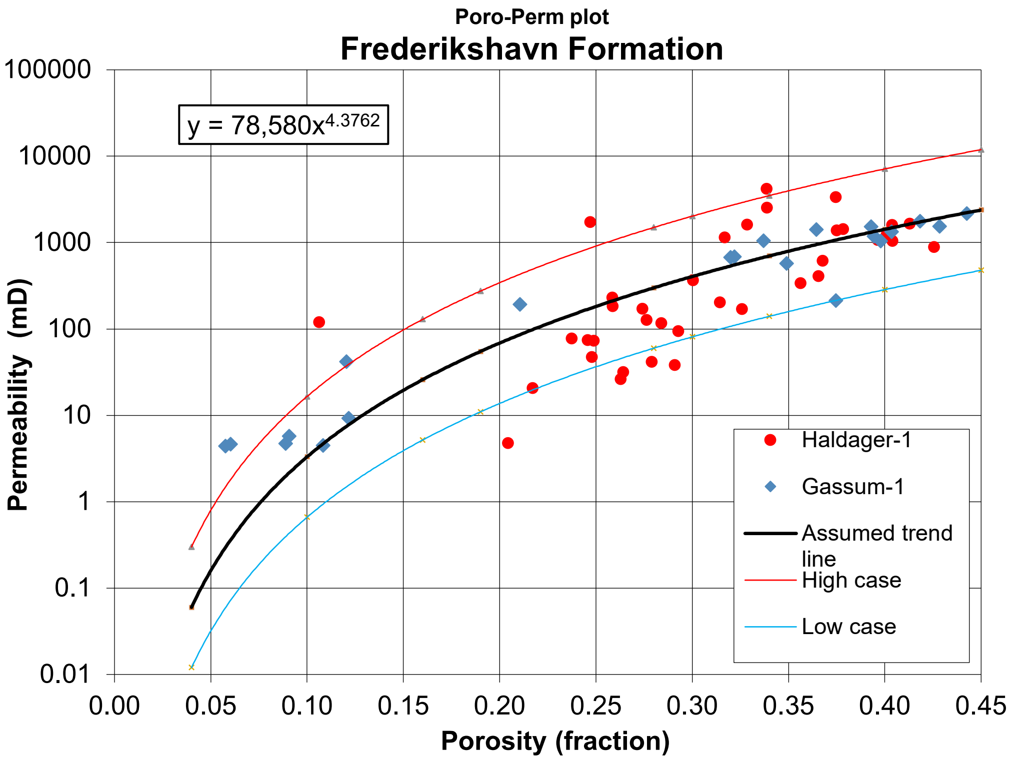

Figure 2: Poro-Perm plot for the **Frederikshavn Formation** in the Gassum-1 and Haldager-1 wells.

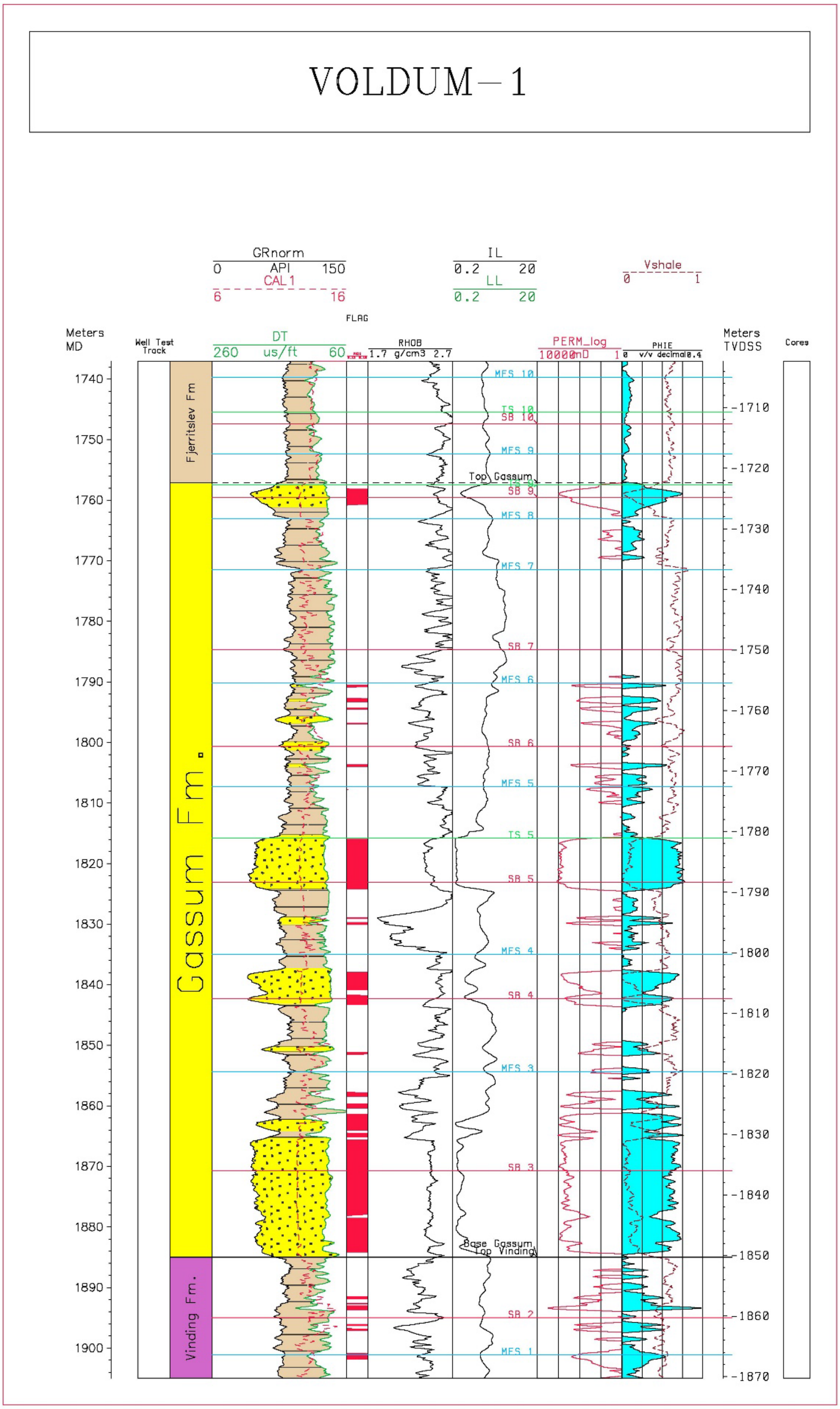

Figure 3: Petrophysical evaluation of the ***Gassum Formation*** in the Voldum-1 well. See legend.

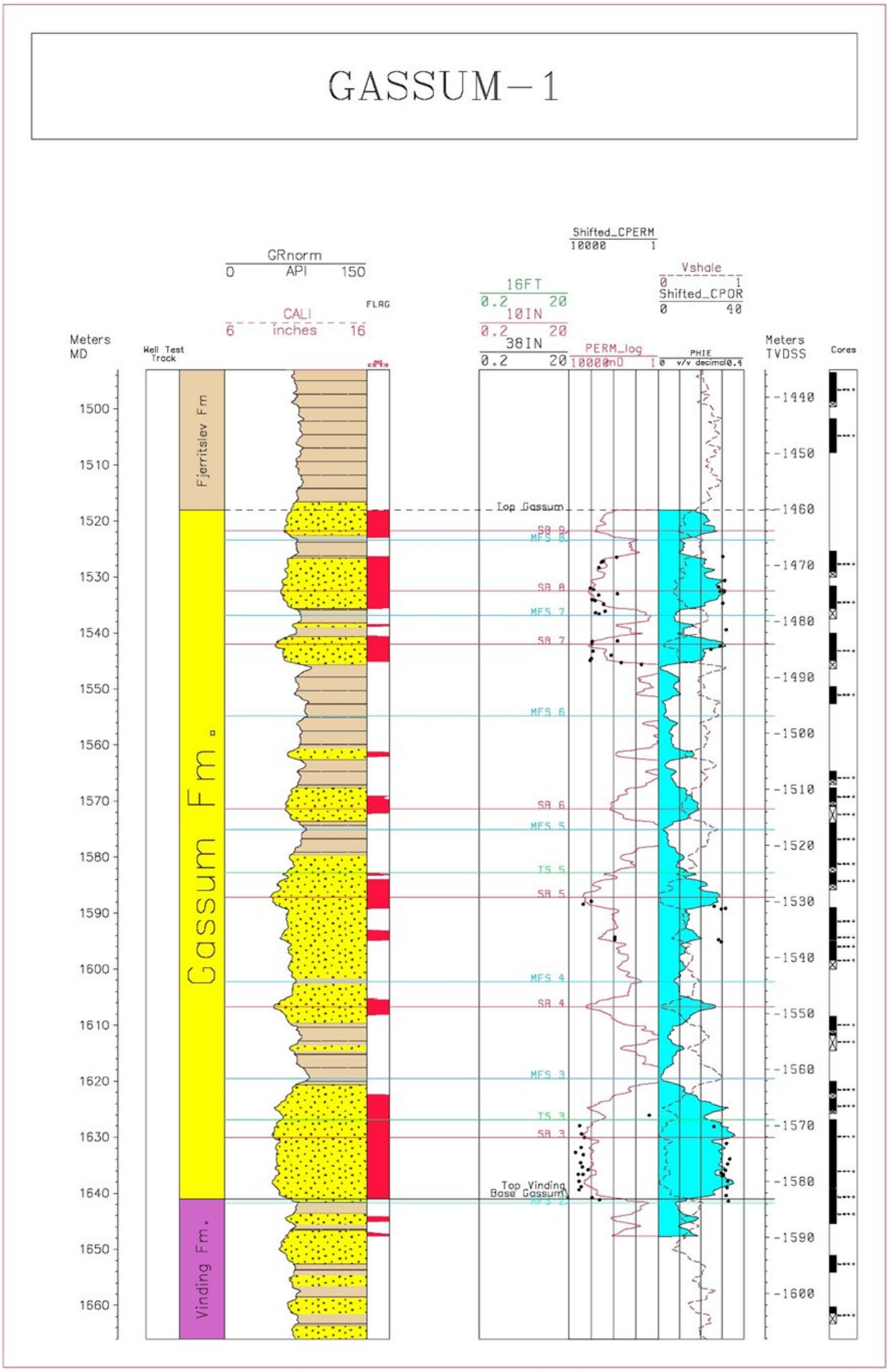

Figure 4: Petrophysical evaluation of the ***Gassum Formation*** in the Gassum-1 well. See legend. Core porosity and core permeability data are depth-shifted (1633–1647: 5.5 m up; 1598–1604: 9 m up; 1535–1647: 4.5 m up).

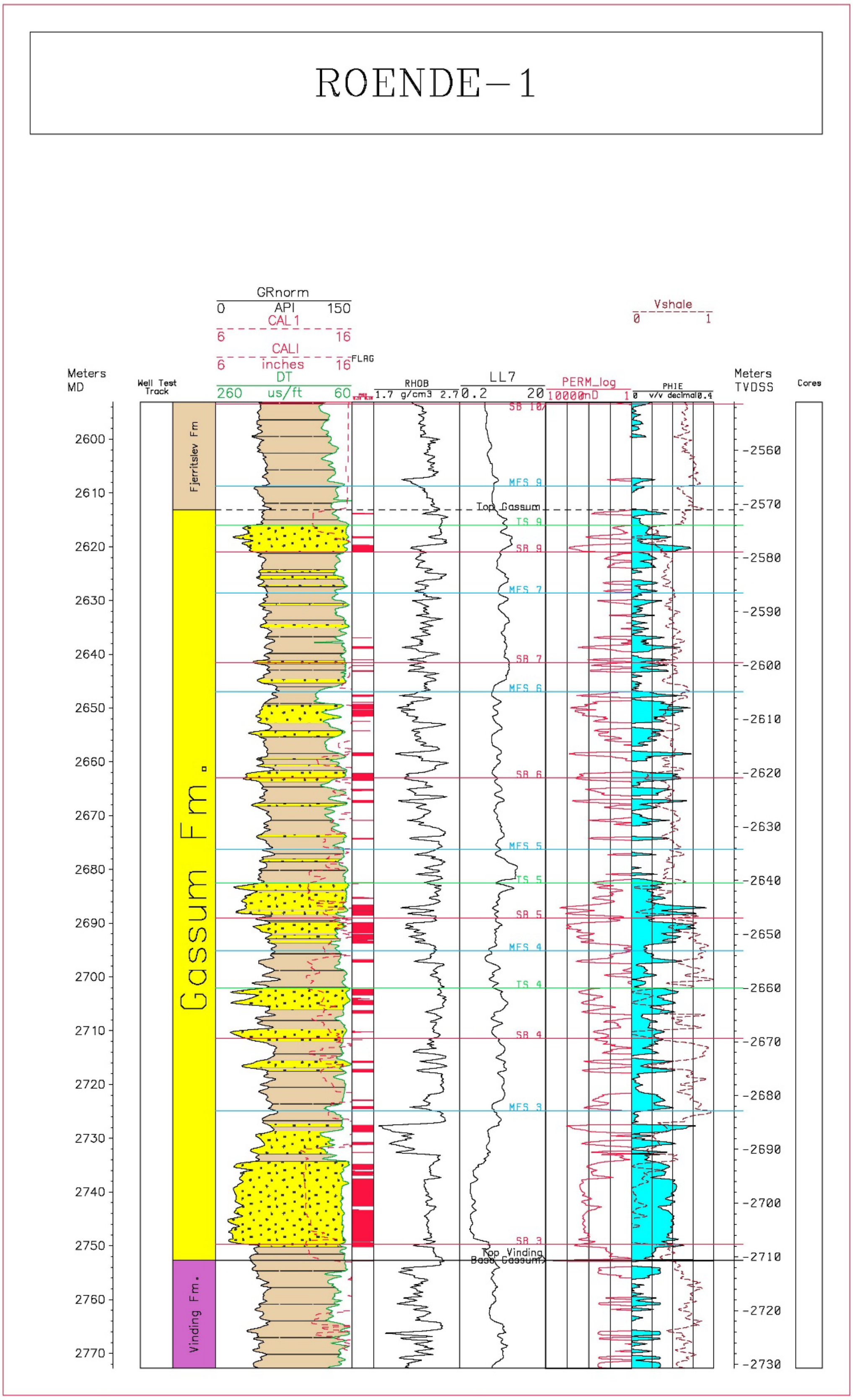

Figure 5: Petrophysical evaluation of the ***Gassum Formation*** in the Rønde-1 well. See legend.

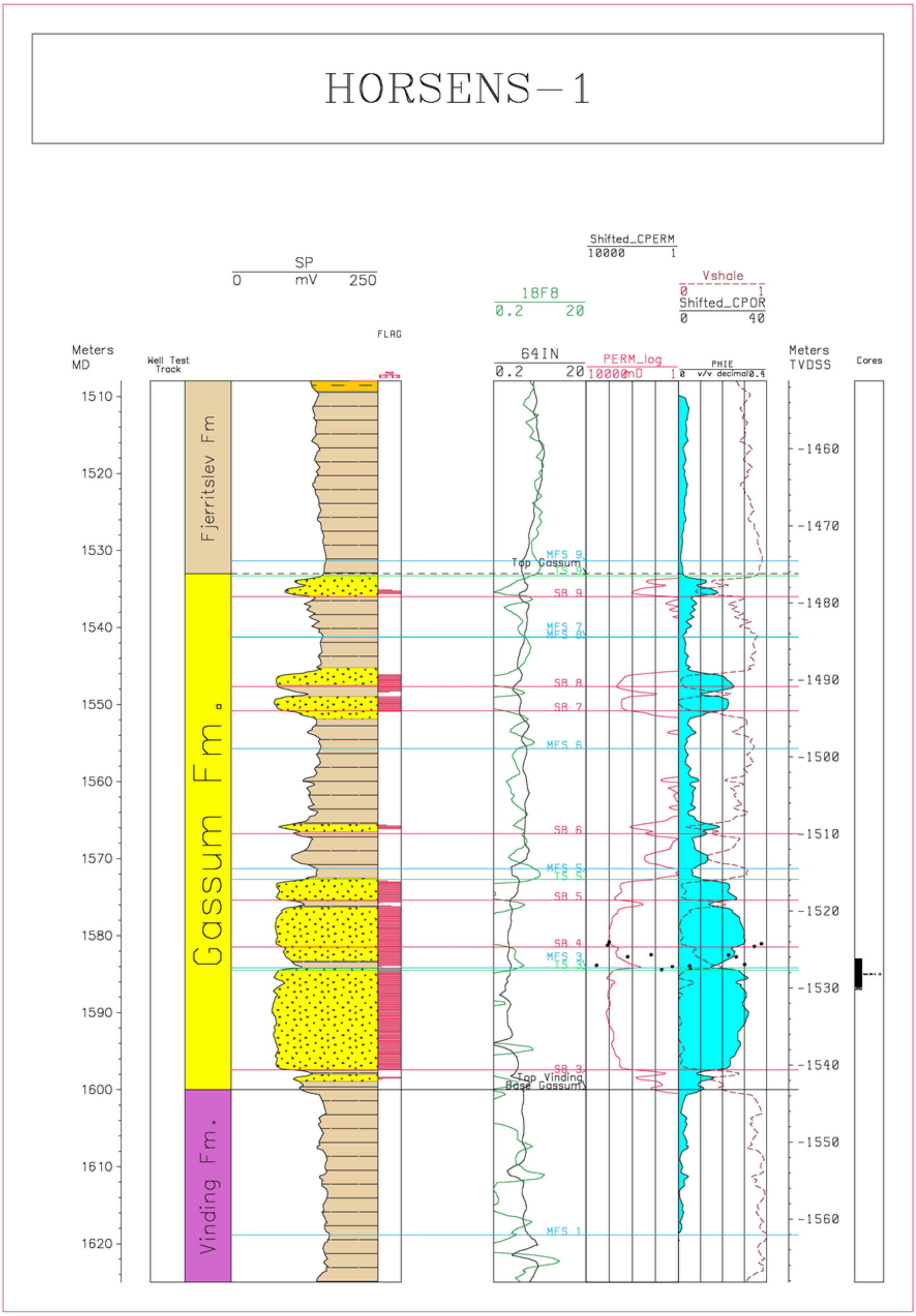

Figure 6: Petrophysical evaluation of the ***Gassum Formation*** in the Horsens-1 well. See legend. Core porosity and core permeability data are depth-shifted (2.5 metres up).

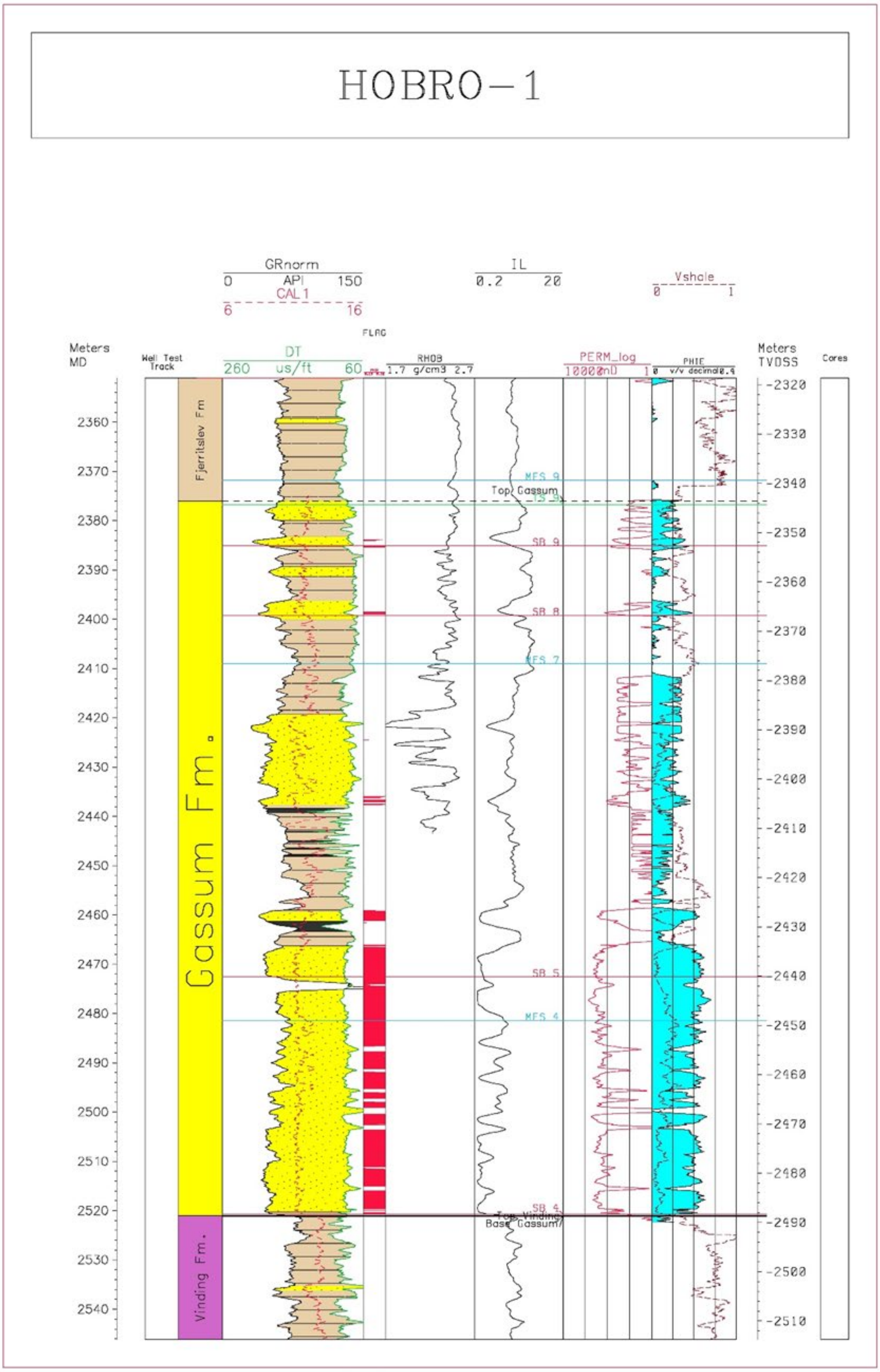

Figure 7: Petrophysical evaluation of the ***Gassum Formation*** in the Hobro-1 well. See legend

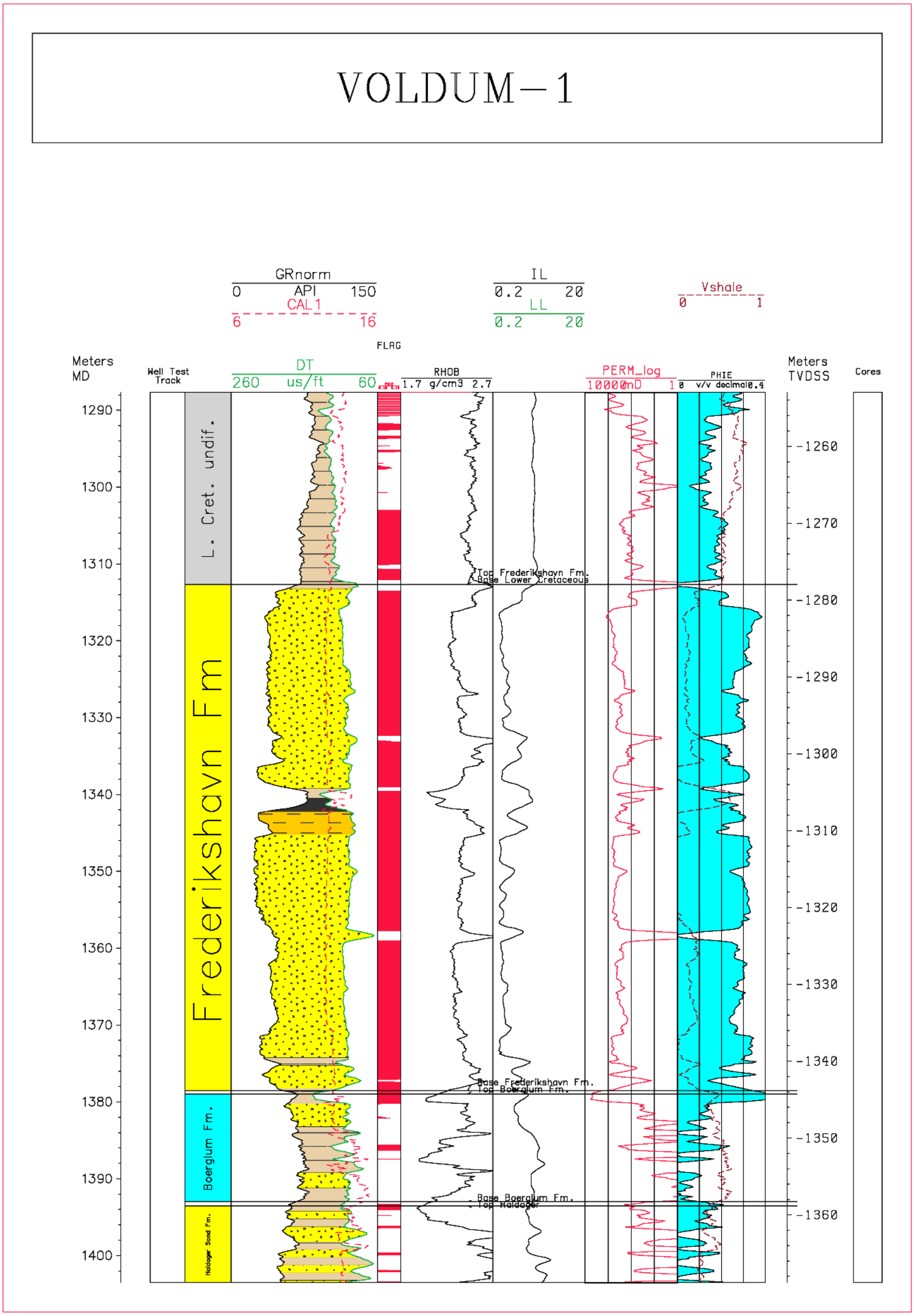

Figure 8: Petrophysical evaluation of the **Frederikshavn Formation** in the Voldum-1 well. See legend.

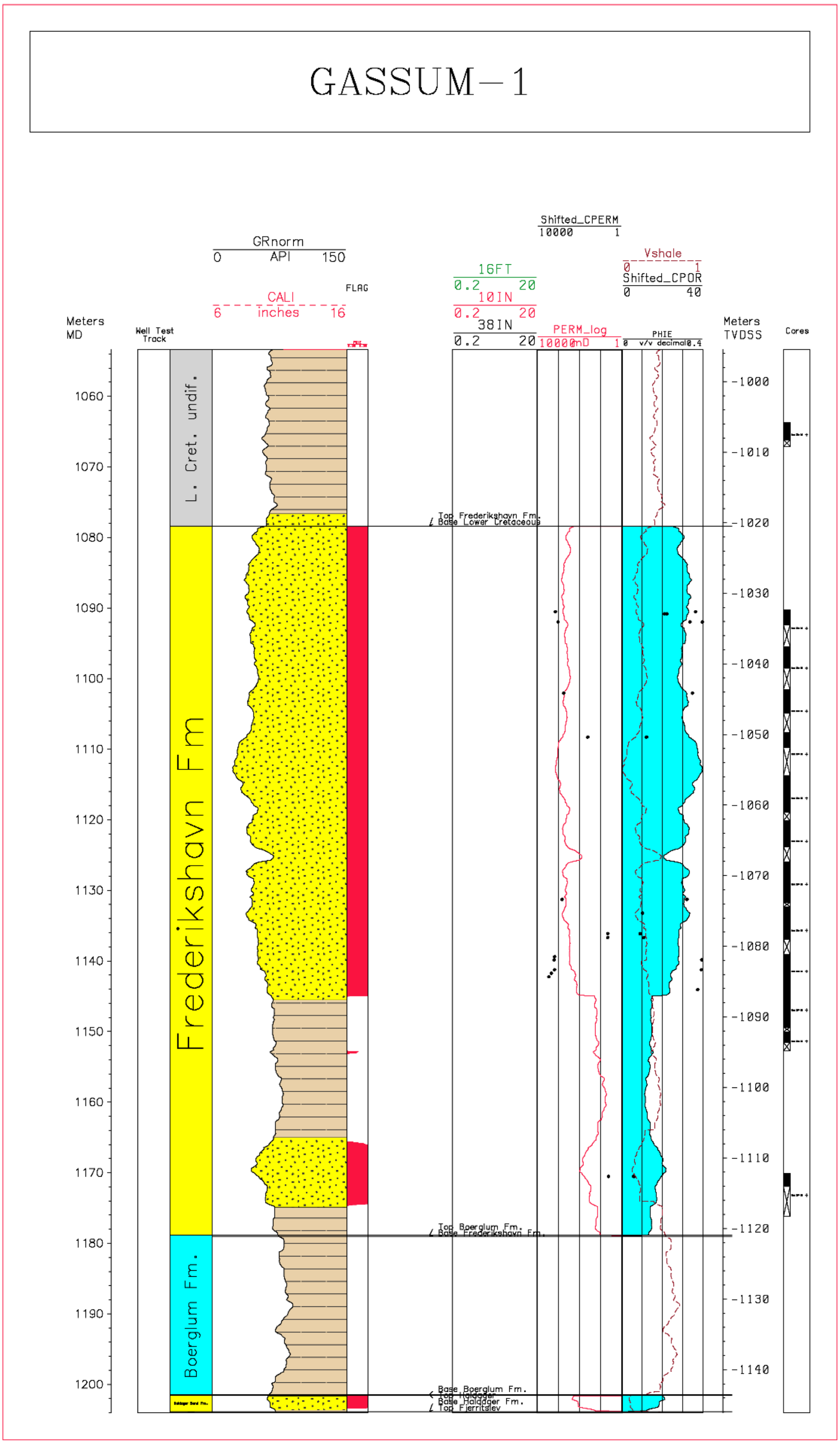

Figure 9: Petrophysical evaluation of the **Frederikshavn Formation** in the Gassum-1 well. See legend.

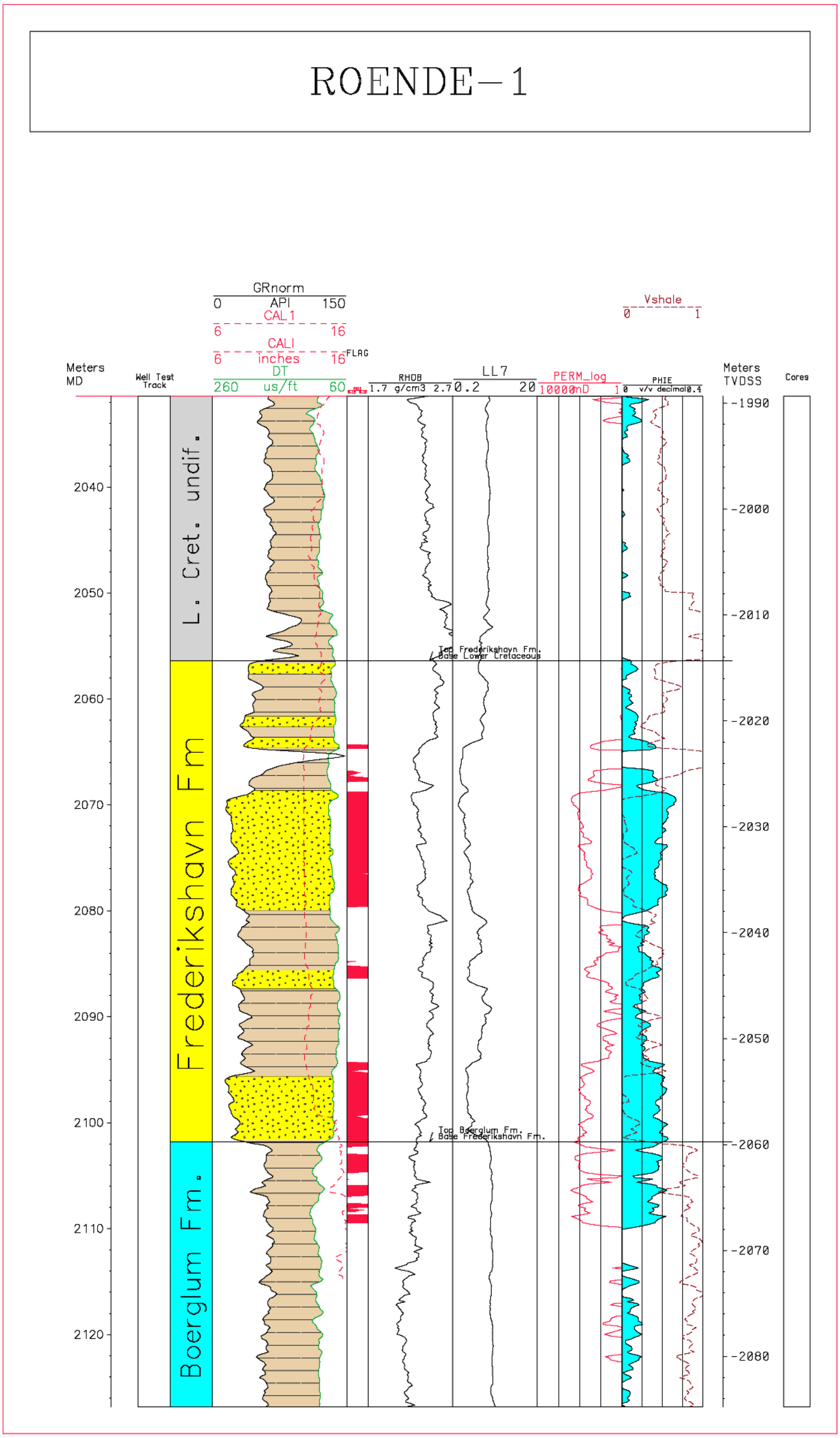

Figure 10: Petrophysical evaluation of the **Frederikshavn Formation** in the Rønde-1 well. See legend.

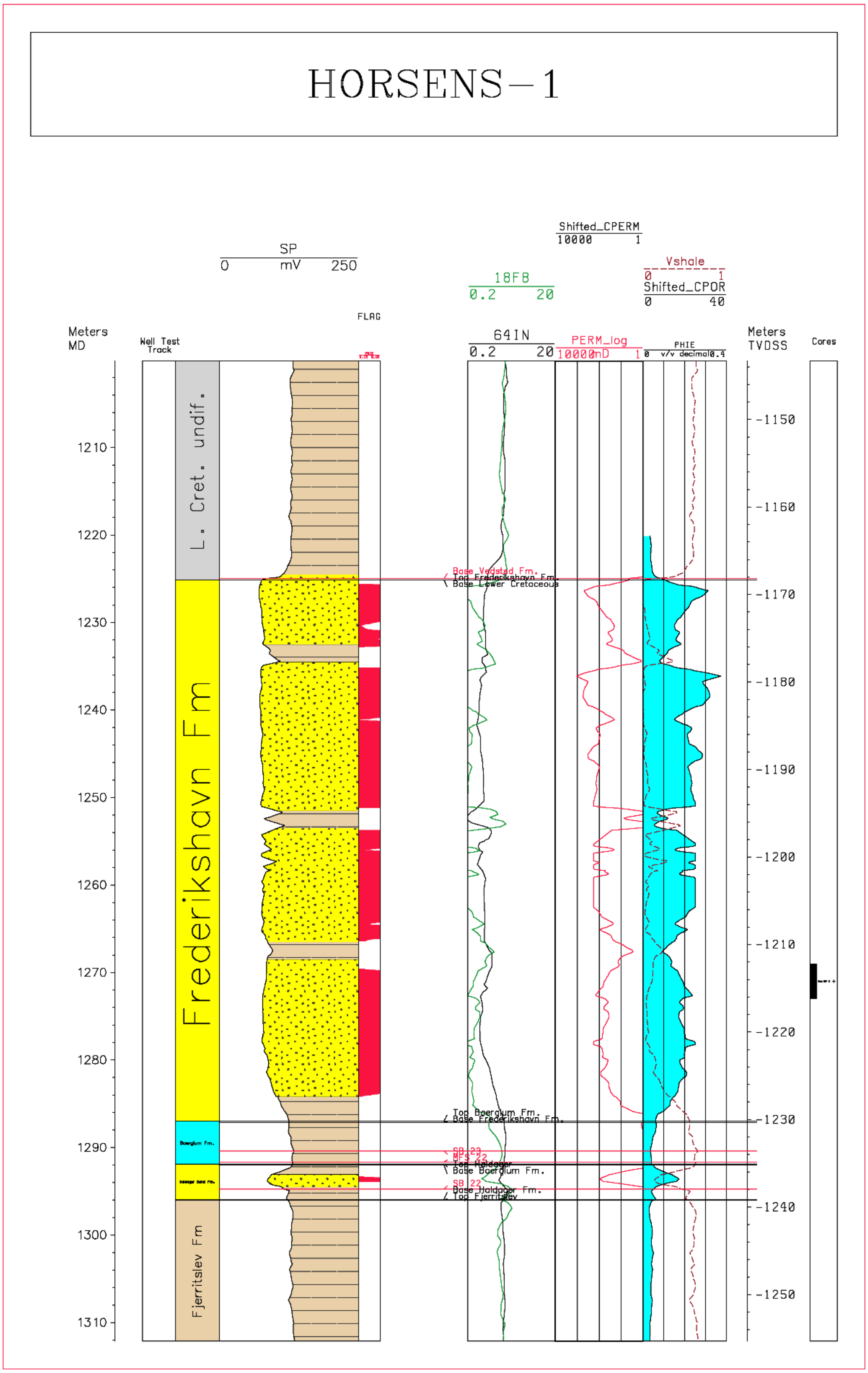

Figure 11: Petrophysical evaluation of the **Frederikshavn Formation** in the Horsens-1 well. See legend.

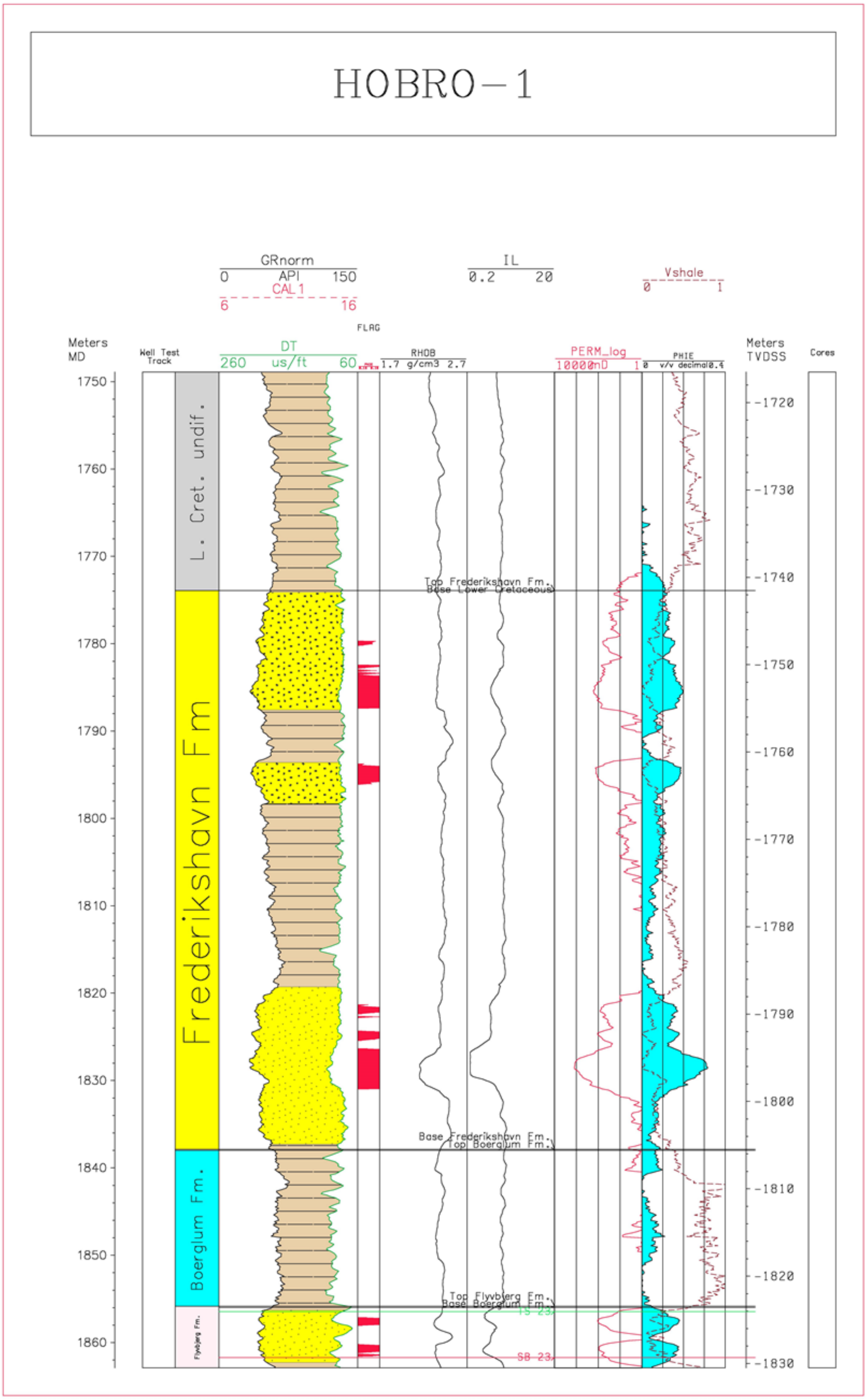

Figure 12: Petrophysical evaluation of the **Frederikshavn Formation** in the Hobro-1 well. See legend

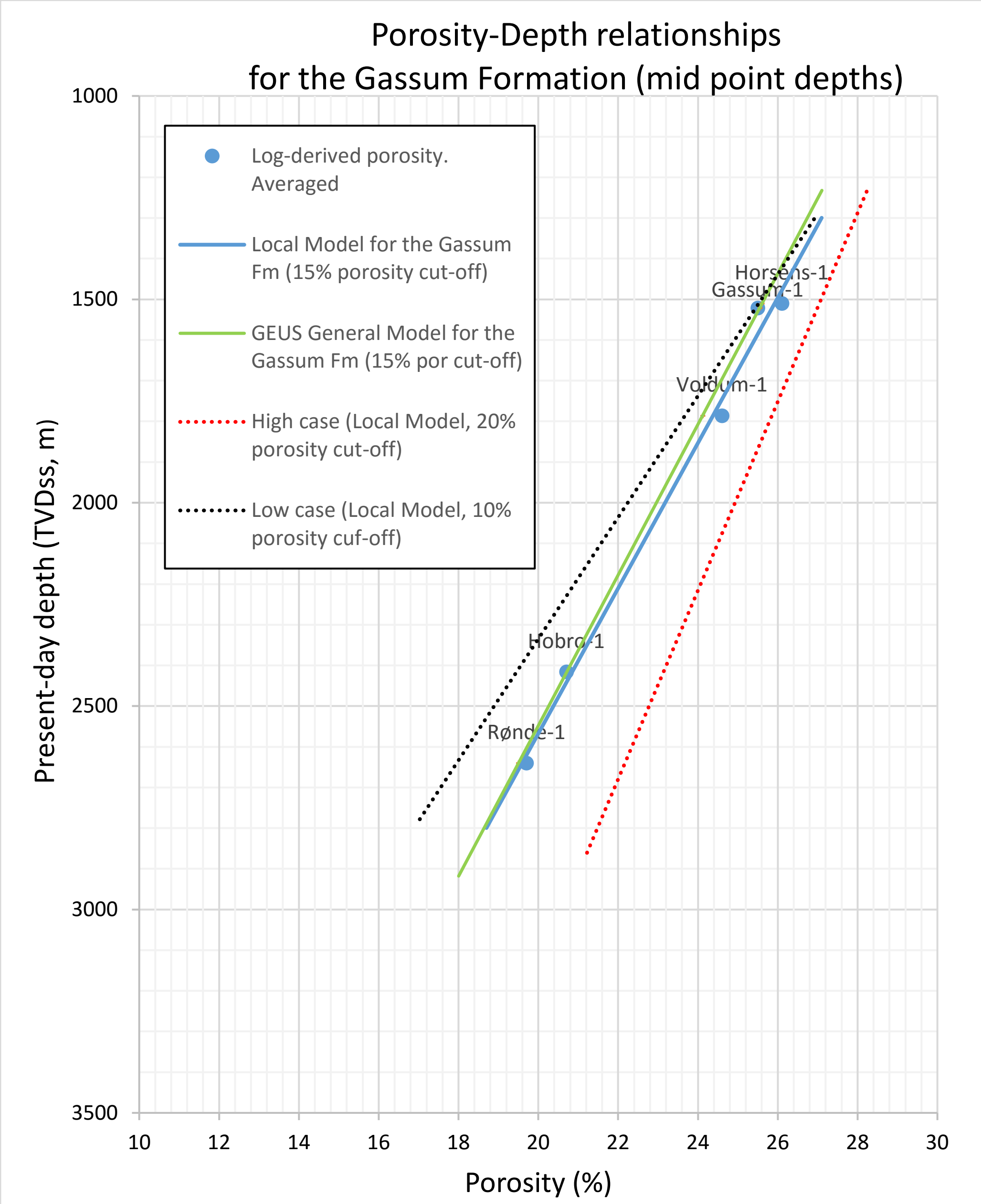

Figure 13: Porosity-depth plots for the Gassum Formation based on data from the five study wells (blue line), and the general GEUS porosity-depth model set up for the Gassum Formation (green line). Note that the local porosity-depth model (blue) does not deviate significantly from the general GEUS porosity-depth model. The porosity values (blue dots) represent averaged log-derived porosities from the Gassum-1, Voldum-1, Rønde-1 Horsens-1 and Hobro-1 wells. Prior to calculating averages, shale and porosity cut-offs were applied (Vshale <30% and porosity >15%). The depth reference is mid-point depth, i.e. the middle of the Gassum Formation. The effect of applying different cut-off values is addressed by introducing 'high case' and 'low case' lines (red: Vshale <30% and porosity >20%; black: Vshale <30% and porosity >10%). All lines may be used for porosity predictions. The local porosity-depth model (blue line) points toward the following relationship: Porosity (in %) = 34.297 – 0.0056·Present-day Depth (in metres).

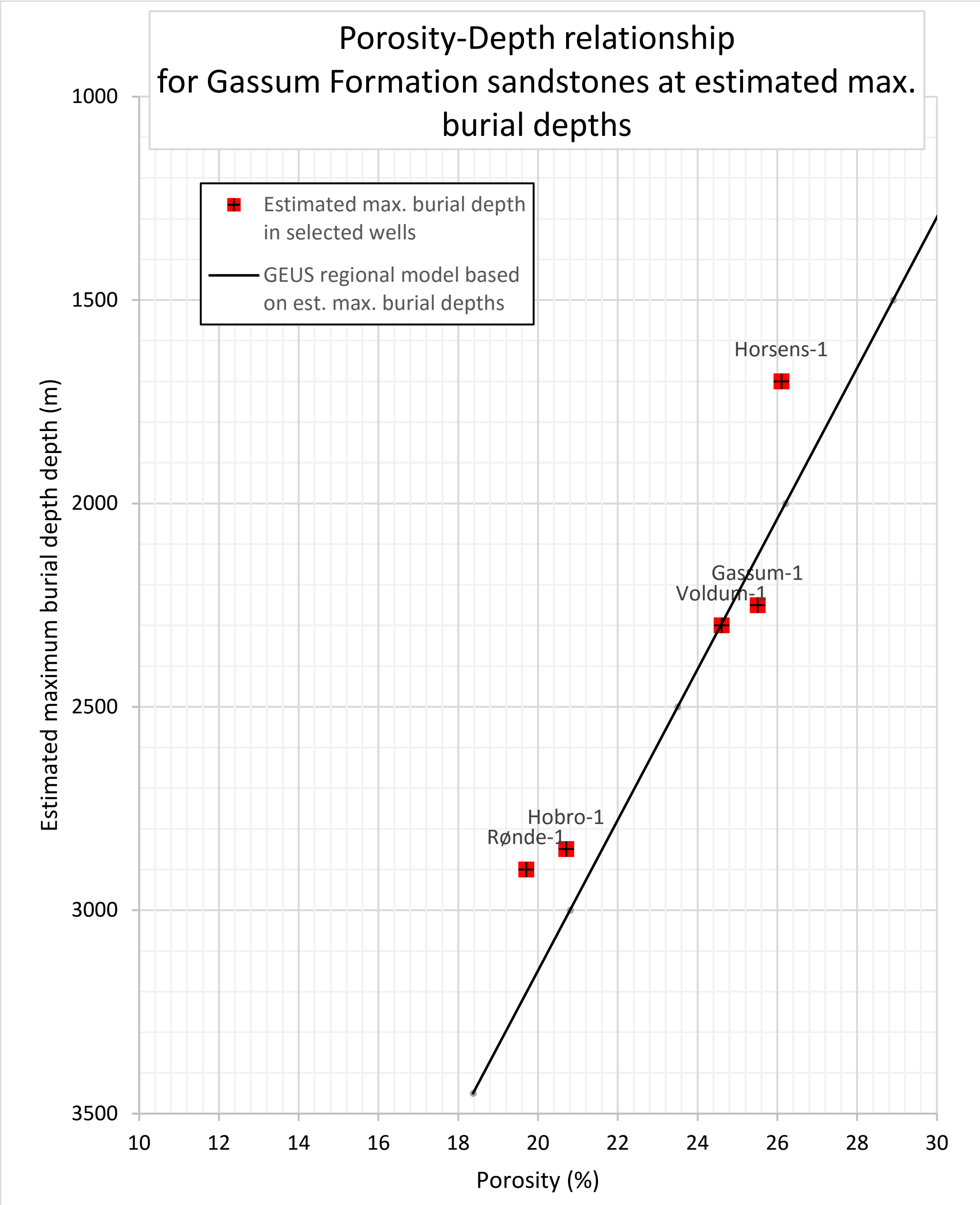

Figure 14: Regional porosity-depth model for the Gassum Formation based on estimated maximum burial depth. The depth estimates are based on works by Japsen et al. (1999, 2007). The maximum depth differs from present-day depth due to uplift in Neogene times. At Århus, the difference between present-day depth and estimated max. burial depth is in the order of 600 metres (cf. Japsen et al., 2007). The regional porosity-depth model (black line) is described in further detail in Kristensen et al. (2016).

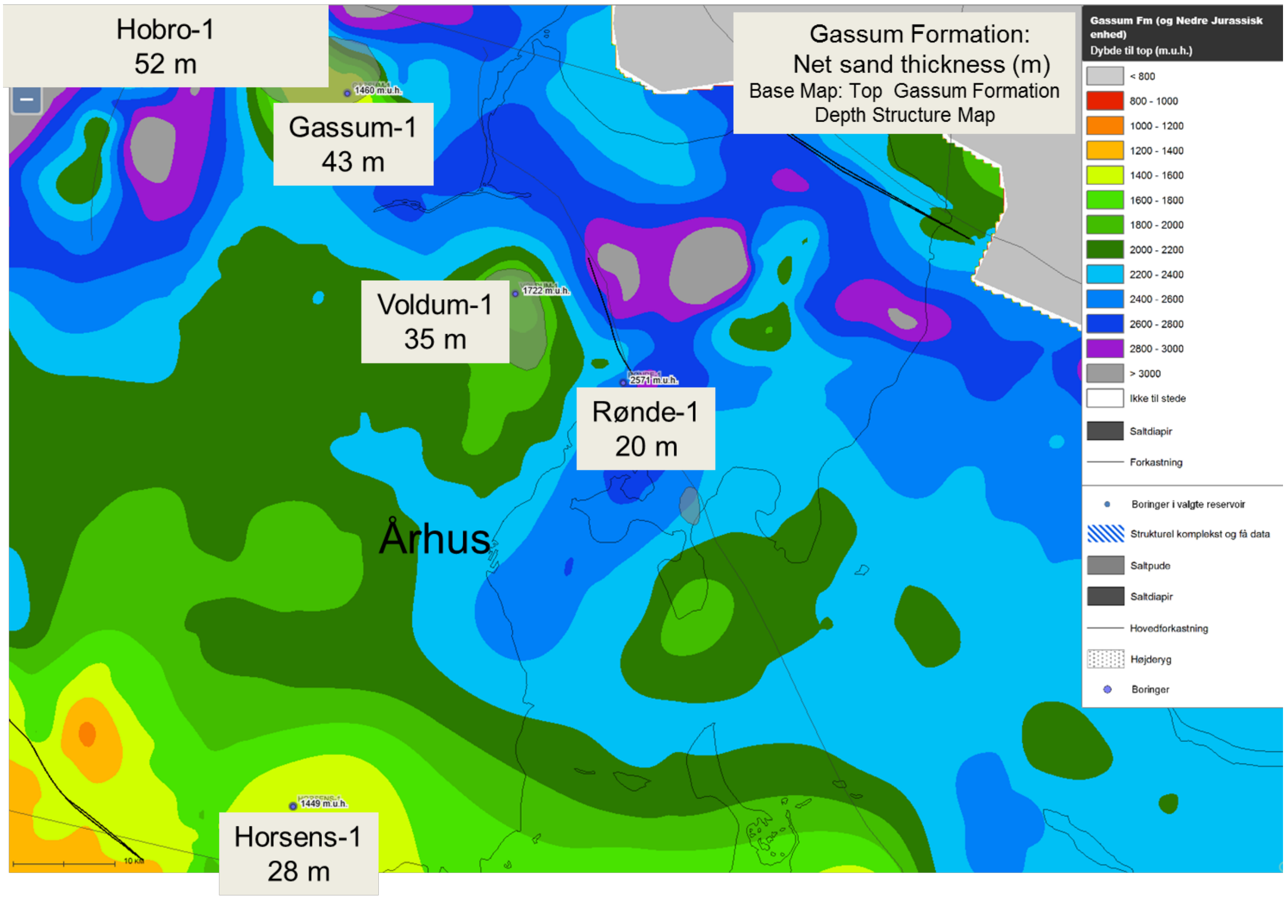

Figure 15: Net sand thicknesses of the Gassum Formation in selected wells (metres) located close to Århus. The base map is the Top Gassum Formation depth structure map (with respect to the base map, reference is made to the GEUS WebGIS Portal).

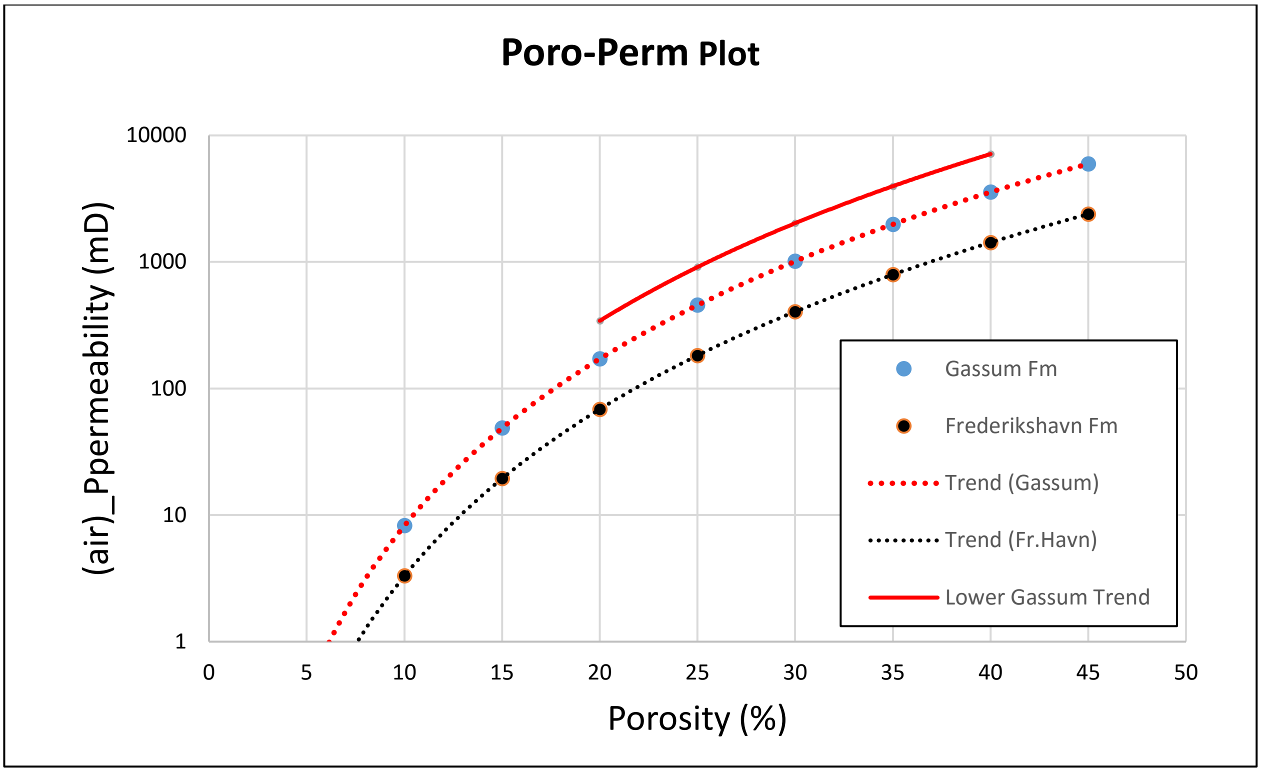

Figure 16: Summary of the Porosity-Permeability relationships described in the text. Estimated trend lines for the Frederikshavn Formation, the upper and lower part of the Gassum Formation are plotted. The permeability data represent laboratory measurements on plug samples (CCAL). The following relations have been derived, note that permeability is in **mD** and the porosity is in **fraction**:

- **General trend for the Frederikshavn Formation: PERM_log = 78580·(Porosity)$^{4.3762}$**
- **General trend for the Gassum Formation: PERM_log = 196449·(Porosity)$^{4.3762}$**
  - In addition, the Lower part of the Gassum Formation is considered as a special case: PERM_log = 400000·(Porosity)$^{4.3762}$. The data from the lower part of the Gassum Formation is thus a subset of the total dataset for the Gassum Formation.