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THE ARCTIC UNIVERSITY OF NORWAY

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Petroleum systems of the Barents shelf: a regional well - based study of the Mesozoic

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Abstract

The entire Barents Sea area has been experienced a complex geological evolution.
From orogenic processes connected to Caledonian mountain building in Palaeozoic to basin formation related to the opening of the Atlantic Ocean in Paleogene. Uplift and erosion processes (Exhumation) that fined place in Ceinozoic contribute to erosion and redepositing of thick sedimentary sequences over Barents Sea area.

Exhumation relates to one of the biggest problems due to petroleum exploration on Barents shelf. It has significant implication on source rock maturation, hydrocarbon potential and reservoir rock properties. Uplift and erosion processes affects basin geometry and burial sedimentary rock properties as well in that way that source rock uplifted to shallow level is not enough mature to produce hydrocarbons. Other consequences connected to exhumation are hydrocarbon redistribution and leakage from traps, decreasing in reservoir quality properties due to compaction processes and porosity reduction.

Unfortunately, implication of exhumation processes on petroleum system in the Barents Sea is not fully understood and need more research.

Uplift and erosion affects sedimentary rock properties. Log data from wells, especially velocity log, is very sensitive to lithological variation and compaction trends of the rocks.

Velocity log data from wells are cruel in executing of analysis of sedimentary basins. It can provide information about burial evolution of the area and changing in temperature gradient. Velocity log data is also important due to recognition of lithological units, overpressure and fluid content in the formations.

Log data from 19 wells in SW Barents Sea, including gamma ray, caliper, density, resistivity, neutron and velocity logs have been displayed and analysed with more accent on main vertical trend in density, resistivity and velocity log. Velocity – depth cross plot for study wells have been constructed, based on velocity log data from study wells to examine velocity variations due to lithology, porosity and quarts cementation in sediments. Velocity trend line has been established to follow variations in velocity with depth.

All observations have been analysed and discussed.

Acknowledgement

Jeg vil takke mine veiledere Professor Kim Senger og Iver Martens for god veiledning under arbeidsperiode med masteroppgaven. Takk til Schlumberger for tilgang til Petrel software og the Barents Sea well data set.

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Contents

1 Introduction

1.1 Objectives

Numerous authors (Henriksen et al., 2011; Dimakis et al., 1998) have discussed uplift and erosion processes and their implication on sedimentary basins evolution and petroleum system. The log data from 19 wells used in this study contains gamma ray, caliper, resistivity, density and velocity logs that provide data from Mesozoic – Cenozoic succession from SW Barents Sea.

The objectives for this thesis are to analyze main vertical trends in 19 wells with location in SW area in the Barents Sea with purpose to follow velocity trend due to variations in lithology. Furthermore, velocity and depth data obtained from log data of study wells can be plotted in scattered plot. First with data based on present depth and then with data that have been corrected for exhumation. This will indicate how velocity changes in shales, sandstones and source rock with depth in exhumated basins compare to present buried sedimentary basins.

1.2 Study area

The study area is located in SW part of the Barents Sea (*Fig.1*). The area, as an entire Barents Sea has been affected by two main continental collisions (Caledonian and Uralian orogeny) and following continental separation (Dore et al., 1995) what resulted in complex structural elements consist of numerous basins and platforms.

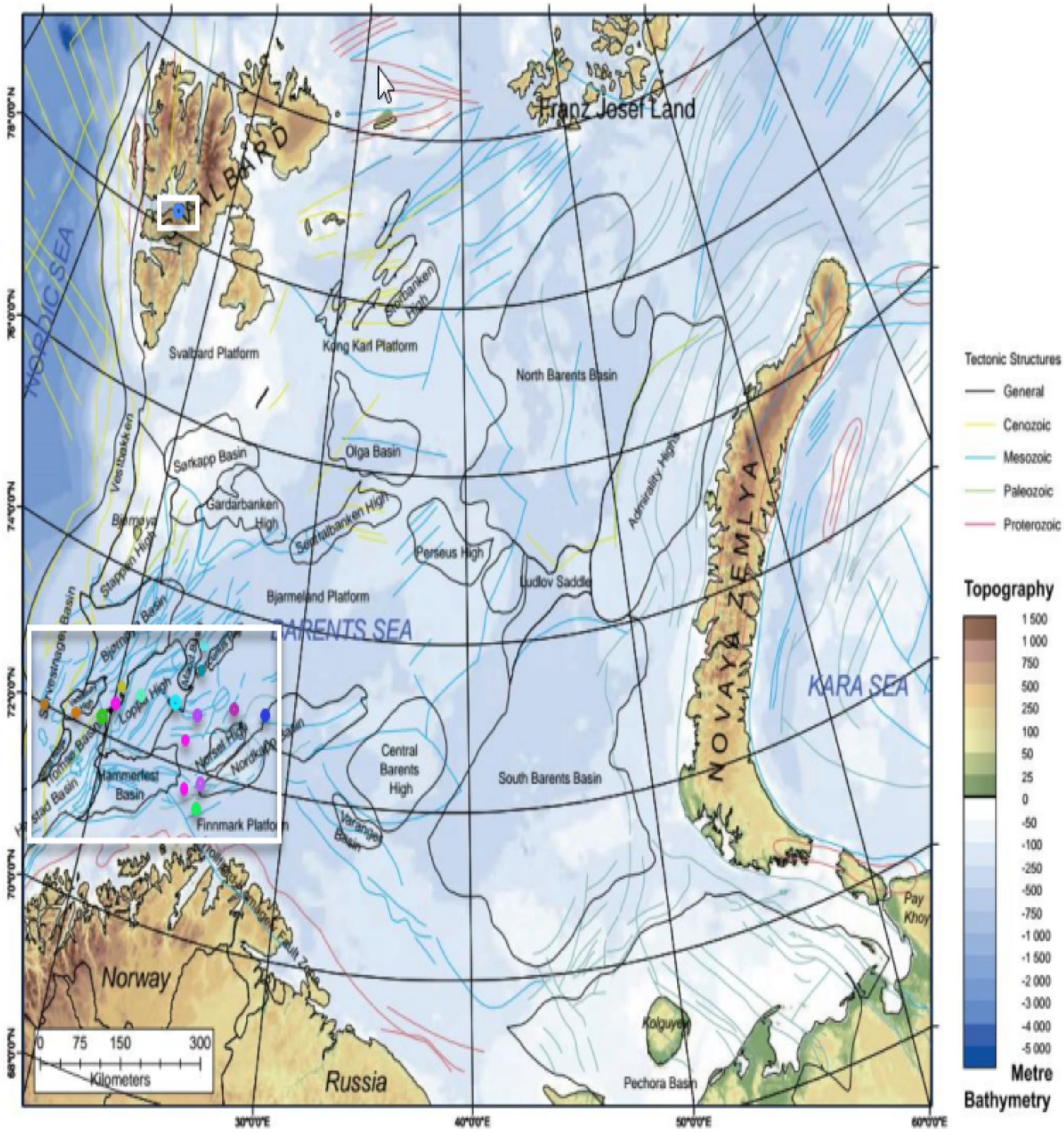


Figure 1: *Barents Sea map with location of studied wells (white rectangle). The main structural futures of the Barents Sea are included. Figure is modified after Smelror et al (2009).*

2 Geological Background

2.1 Introduction

The geological development of the Barents Sea and Svalbard has been carefully discussed by many authors (Dore et al., 1995, Faleide et al., Worsley et al., 2008) therefore geological evolution from Mesozoic to Cenozoic Era of the Barents Sea and Svalbard will be discussed briefly.

2.2 Geological evolution of the Barents Sea

The Barents Sea is an epi-continental basin that comprise numerous numbers of platforms and basins structures as showed in figure 1 (Dore et al., 1995). It covers an area of approximately 1.3 million km^2, with average water depth 300 m and defined by the north Norwegian and Russian coasts in the south, the Novaya Zemlja in the east, Franz Josef Land and Svalbard archipelagos in the north and the eastern margin of the Atlantic Ocean in the west (Dore et al., 1995).

The two main tectonic events that formed the Barents Sea basin are Caledonian orogeny (400 Ma) and additional collision (Uralian orogeny) between the Laurasian continental plate and Western Siberia (240 Ma) what contributed in creation of the eastern margin of the Barents Sea. Break –up phase of the Pangea continent is an important event that formed most of the basins, platforms and structural highs in the Barents Sea. (Dore et al., 1995).

Caledonian orogeny (400 Ma) is a mountain – building stage that represented closure phase of Iapetus Ocean and collision between Laurentian plate with Greenland and North America and the Baltic plate with Scandinavia and western part of Russia what results in Laurasian continent (Dore et al., 1995). The trace of Caledonian orogeny is dominating in N-S direction in the western area of the Barents Sea and Svalbard (Dore et al., 1995). The south – western part of the Barents Sea, where the study wells are located, influenced by opening of the Atlantic Ocean (Dore et al., 1995). The significant amount of sediments have been deposited in Ceinozoic due to uplift and erosion processes, however they have been eroded and redeposited during the glaciations processes in Pleistocene (Dore et al.,1995). Figure 2 shows the evolution of south – western margin of the Barents Sea.

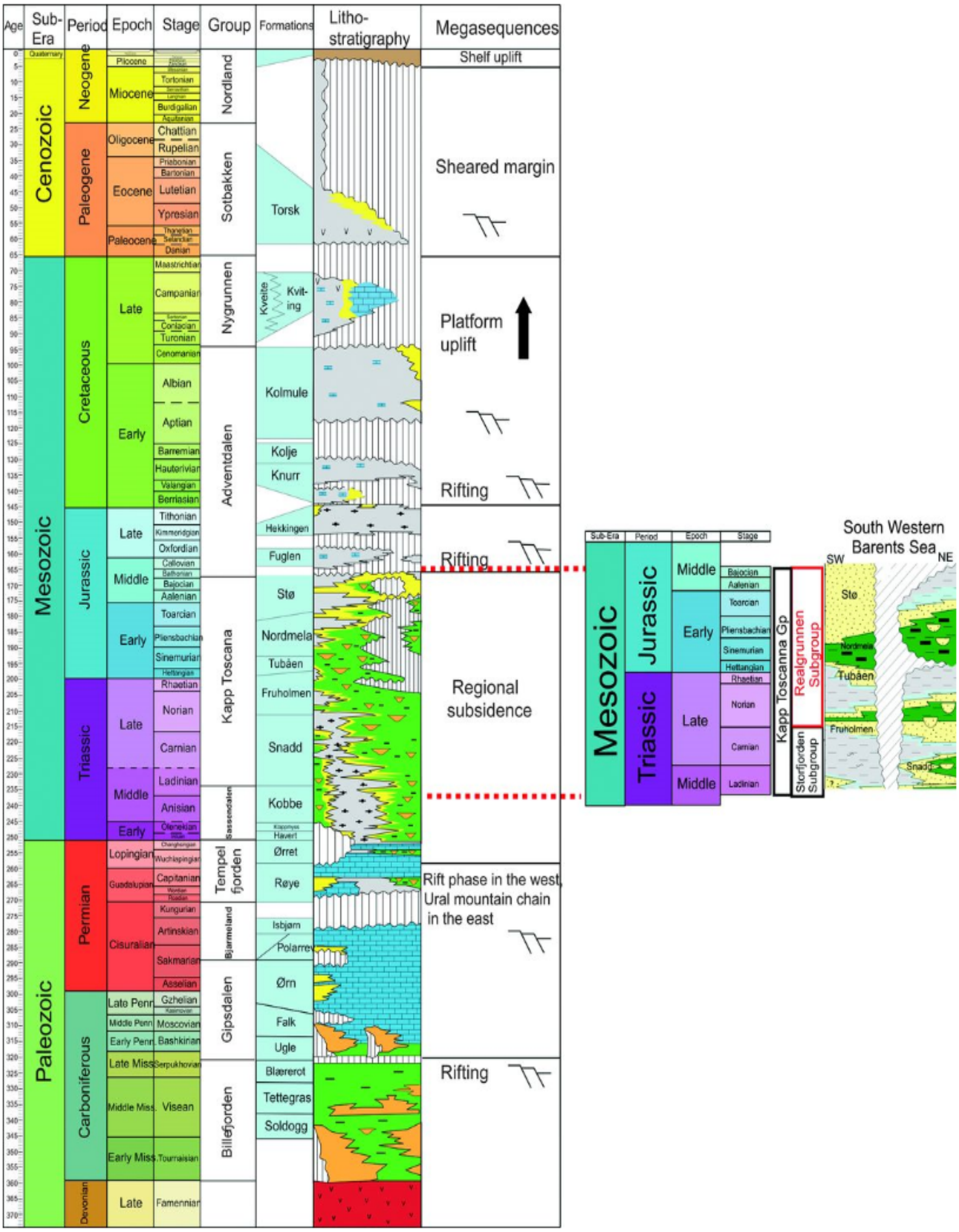


Figure 2: *Evolution and lithostratigraphy of South – Western Barents Sea in Mesozoic and Cenozoic. From Nøttvedt at al. (1993).*

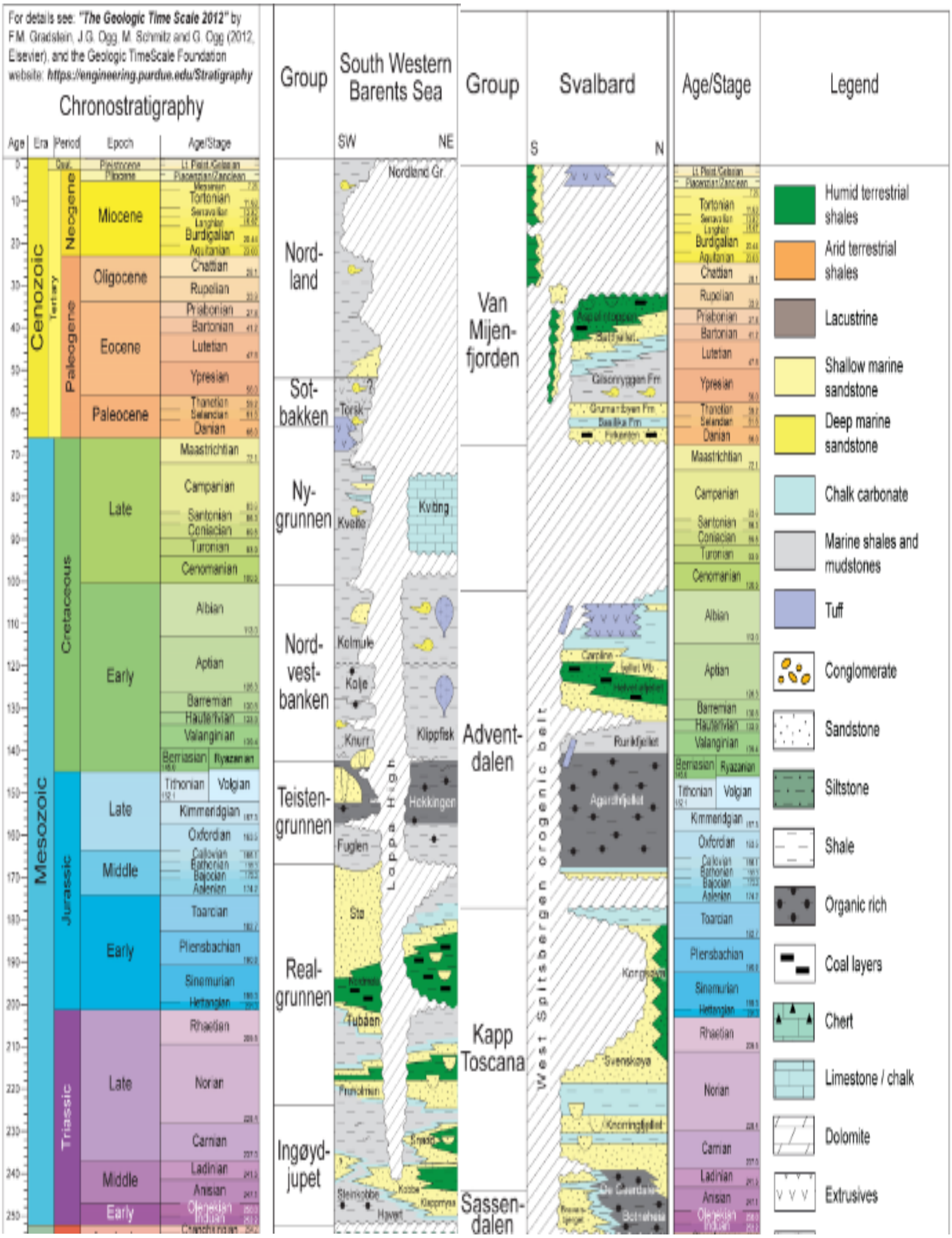


***Figure 3:** A chronostratigraphic chart of the South Western Barents Sea and Svalbard. Figure is modified after Gradstein at al. (2012).*

2.3 Stratigraphy of the Barents Sea and Svalbard

Mesozoic and younger lithological succession in the Barents Sea and Svalbard consists predominantly of clastic sediments (*Fig. 3*). This refers to drifting of the entire Barents shelf from low, 20^0N latitude in Carboniferous to higher, 75^0N latitude at present days. Changed geological position and tectonically processes have influenced Barents Sea lithology.

The Triassic was relatively quiet on Svalbard and in the western part of the Barents Sea, while northern and southern areas experienced subsidence (Riis et al., 2008). Triassic sediments represent a thick stratigraphically sequence that laterally spread over entire Barents Sea. Coarsening upward sequence in sediments related to transgressive-regressive depositional environment (Ohm et al., 2008).

The Lower – Middle Jurassic lithology in the SW Barents Sea dominates by sandstones.

The most part of the Paleogene –Neogene sediments has been removed by Pliocene – Pleistocene glaciations processes.

Mesozoic/Cenozoic succession on Svalbard is divided in following lithostratigraphic groups: Tempelfjorden, Sassendalen, Kapp Toscana, Adventdalen and Van Mijen-fjorden Groups.

In the Barents Sea, the Mesozoic/Cenozoic succession consists of the Tempelfjoreden, Ingøydjupet, Realgrunnen, TeistengrunnenNordvestbanken, Nygrunnen, Sotbakken and Nordland Groups.

The Tempelfjorden Group. Sedimentary successions of Tempelfjorden Group (Permian) on Svalbard are related to transgressional depositional environment. Svalbard`s migration northward contributed to changes in depositional environment. The main lithology from that time includes cool-water carbonates, sandstones with glauconite, cherts and siliciclastic sediments (Mørk et.al., 1989).

The Sassendalen group in central Spitsbergen, includes clastic sediments of Early and Middle Triassic age. Thickness of this stratigraphic succession is about 700m in Svalbard. The main lithology is dominated by shales and siltstones in this group but sandstones and carbonates are also present (Mørk et al., 1989).

The Sassendalen Group on Svalbard includes fore formations: Kobbe Fm, Steinkobbe Fm, Klappmyss Fm, Havert Fm. Depositional environment of Sassendalen group is characterizes by transgressive – regressive regime (Mørk et al., 1989).

The Sassendalen Group on the Barents Sea shelf includes Ingøydjupet Subgroup what comprise: Havert, Klappmyss and Kobbe formations.

Lithology in Ingøydjupet characterize by black shale and claystone with thin grey silt - and sandstones, related to marine depositional environment (Npd 2017).

The Kapp Toscana group in Central eastern Spitsbergen dominates by shales, siltstones and sandstones (*Fig. 3*). This group is of Late Triassic to Middle Jurassic (Bathonian) age (*Fig. 6*). Thickness is up to 475 m in Svalbard and about 2000 m on the Barents Sea shelf (Mørk et al., 1982). Depositional environment is nearshore, deltaic environment characterised as shallow marine (Mørk et al. 1982). The Kapp Toscana Group subdivided in two subgroups:

1. The Storfjorden Subgroup of Ladinian to Norian ages, which includes Snadd Formation (*Fig. 4*).
2. Realgrunnen Subgroup of Early Norian to Bathonian ages (*Fig. 3*).

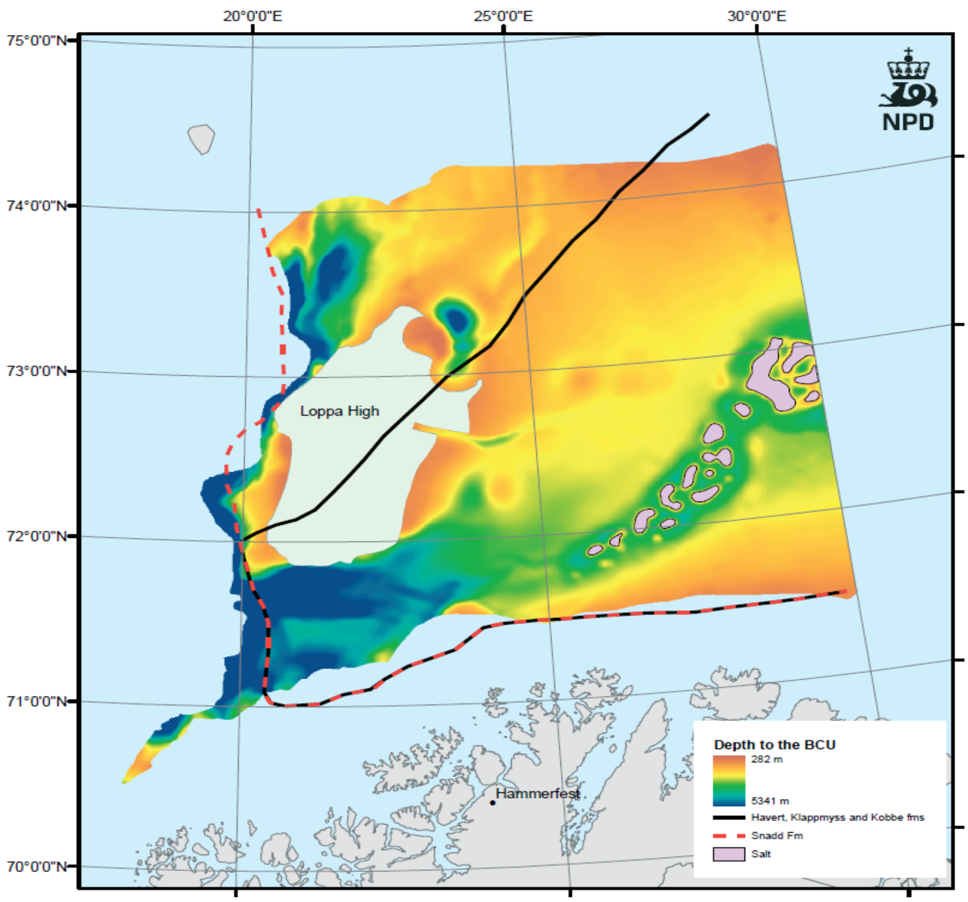


Figure 4. *Snadd Formation depositional area (red stipple line) in the Barents Sea. From Npd.no (2017).*

The Adventdalen Group.

The Adventdalen group in Central Spitsbergen represents shales, siltstones and sandstones. Ages of this group dated to Middle Jurassic – Lower Cretaceous.

Thickness of this succession on Svalbard is 750- 1600 m and 1000 – 1750 m on the Barents Shelf.

Marine mudstones, deltaic and shelf sandstones, thin carbonate beds comprise this succession. The Adventdalen Group includes five formations (*Fig. 2*).

Fuglen formation represents pyritic mudstones with interbedded strings of limestones rock that deposited in marine environment under ongoing tectonic processes (Npd, 2017).

Hekkingen formation dominated by shale and claystone (*Fig. 2*). Some thin beds of limestone, dolomite, siltstone and sandstone are also present in this formation. Depositional environment (*Fig. 5*) relates to marine, deep water with anoxic conditions (Npd, 2017).

Knurr formation (*Fig. 2, 5****)*** deposited in open distal marine environments where local restricted bottom conditions occurred and comprise predominantly claystone with strings of limestone and dolomite. Some thin beds of sandstone are present in the lower parts of the formation (Npd, 2017).

Kolje formation consists predominantly of shale and claystone that deposited in distal marine environment, with good water circulation conditions.

Kolmule formation deposited in open marine environment. Formation dominated by claystone and shale, but some strings of siltstone, limestone and dolomite are present.

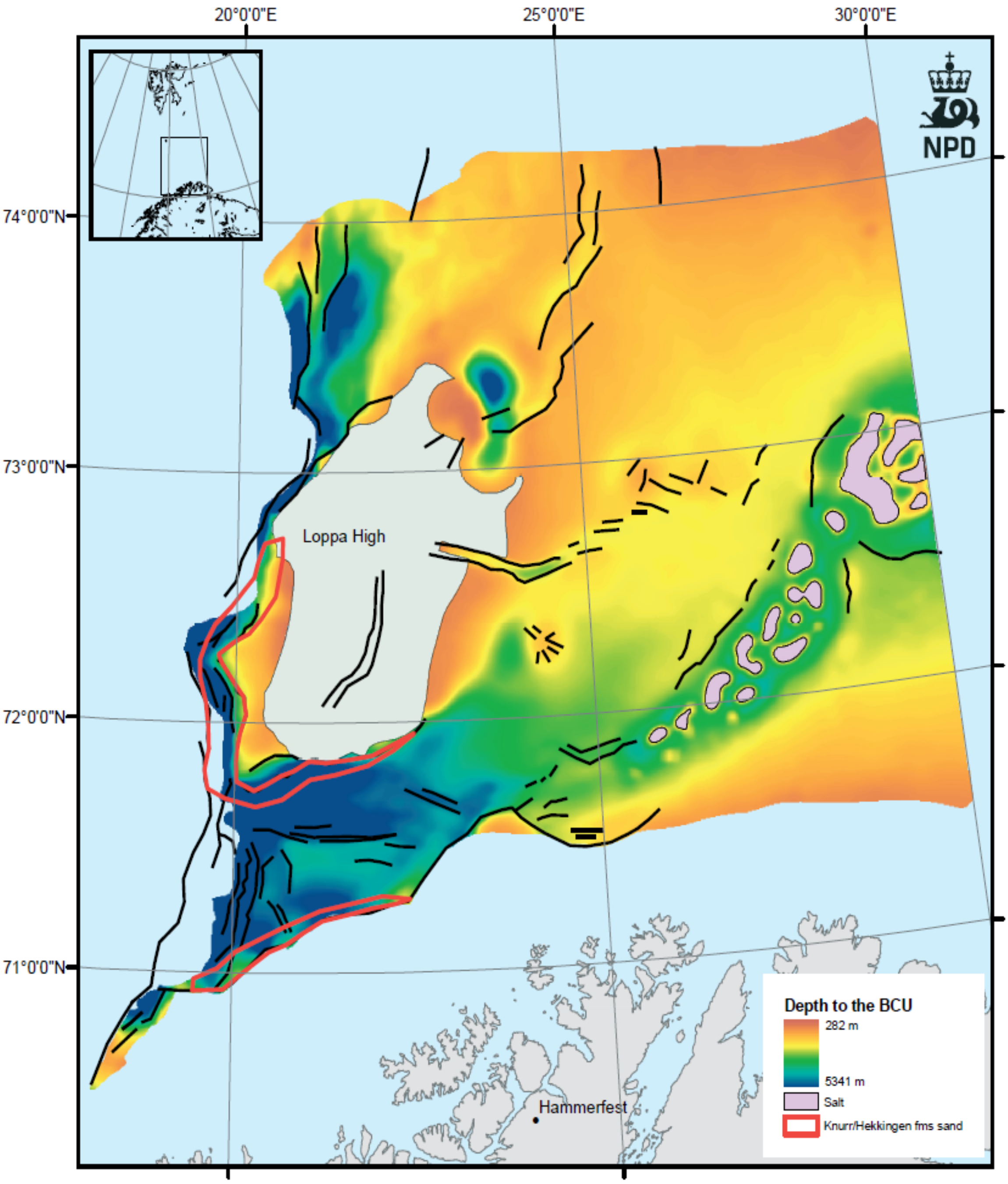


Figure 5. *Knurr and Hekkingen formations sand deposition (red color line). From Npd.no(2017).*

2.1.1 Main structural elements of South – West area of the Barents Sea

The South – West area of the Barents Sea is characterized by sedimentary basins of Cretaceous and Cenozoic origin, which includes the Harstad, Tromsø, Bjørnøya and Sørvestnaget basins. Figure 1 shows main structural elements in the Barents Sea.

Harstad Basin stretches between 69°20'/71°N and 16°30'/17°45'E (North of Andøya) with a NNE-SSW striking trend. Eastern boundary of Harstad basin defines by the southern part of the Troms – Finnmark Fault Complex while the western part represents transition to oceanic crust (Npd., 6).

Tromsø Basin is located in the north direction from Tromsø between 71°/72°15'N and 17°30' – 19°50E' and is defined by the Senja Ridge to the west and the Ringvassøy – Loppa Fault complex to the east. Tromsø Basin characterize by NNE – SSW trending that enhanced by a series of salt structures (Npd., 2017).

Bjørnøya Basin location defined by 72°30'-74N and 18° – 22^0 E geographical coordinates. It is limited by the Bjørnøyrenna fault complex in the SE and NW part represents a faulted slope which is dipping down towards the basin. Leirdjupet Fault Complex separates Bjørnøya Basin in shallow part in the east (the Fingerdjupet Subbasin) and deeper part in the west (Npd, 6).

Sørvestnaget Basin located between 71°- 73°N and 18°E and is a structural continuation of the Bjørnøya Basin. The Sørvestnaget Basin comprises a thick sedimentary succession of Cretaceous and Tertiary sediments and limited by the Senja Ridge and Veslemøy High in the south - east (Npd., 2017).

2.3 Petroleum system of the Barents Sea

The Barents Sea presents a petroleum province with more gas and minor oil discoveries. Figure 6 highlighted three major petroleum system in the Barents Sea. Paleozoic system with location in the eastern Barents Sea. Early – Middle Triassic petroleum system presents in South -West and South province of the Barents Sea and Late Jurassic petroleum system located in western area.

The Barents Sea has a high success rate (one of three wells shows hydrocarbons discovery) in hydrocarbon exploration (Ohm et al., 2008). Despite of that fact the most of the discoveries are gas prone and just a few discoveries contain oil (Ohm et al., 2008). Petroleum system in the Barents Sea controlled by Cenozoic uplift and erosion processes that removed significant package with sediments and allowed oil leakage.

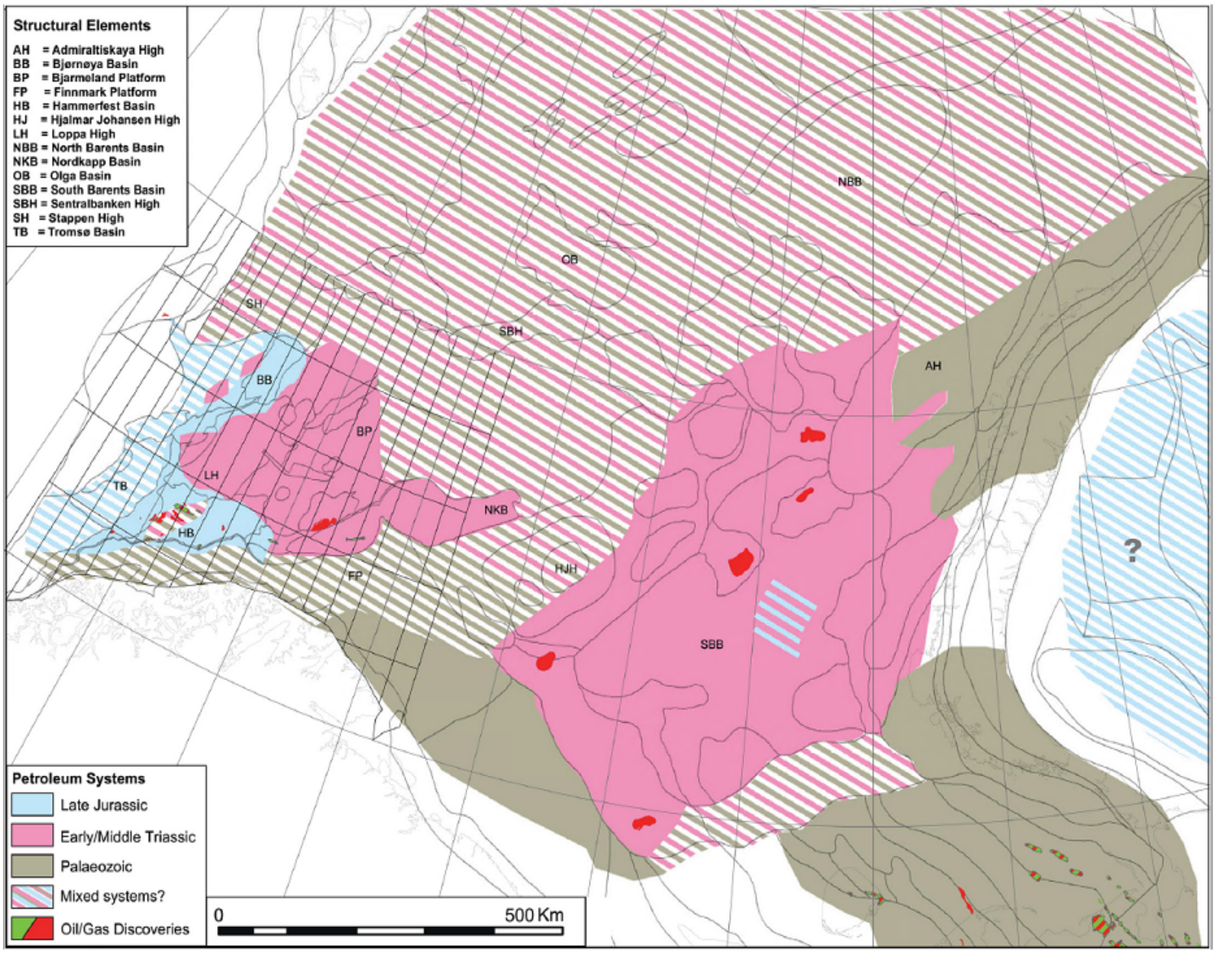


Figure 6. *Petroleum system of the Barents Sea with presence of source rock. From Henriksen et al., 2011.*

2.3.1 Source rock

Source rock defines sedimentary unit from that hydrocarbons can be generated with following migration to reservoir rock (Dore et al., 1995).
Source - rock formations from different stratigraphic levels is present in the SW part of the Barents Sea. Late Jurassic organic rich shales from Hekkingen formations count as the most important source rock (Dalland et al., 1988). With lateral extension over southern Barents Sea the Hekkingen formation has not improved hydrocarbon potential. This is due to varying depth level and hence maturity (Vadakkepuliyambatta et al., 2013). According to Dore (1995), source rock from Hekkingen formation in western margin of the Hammerfest Basin and western part of the Loppa High is mature for hydrocarbon generation. This unit is also describes as source rock with high TOC, high hydrogen index and has a good potential for oil and gas generating (Ohm et al., 2008)
The shales from Snadd and Havert formations (*Figure 7*) according to Bjorøy (2009) are also classified as important source rock in the Barents Sea of kerogen type II and TOC from1-12% (Bjorøy et al., 2009). Figure 9 gives overview over proving and potential source rock in the Barents Sea.

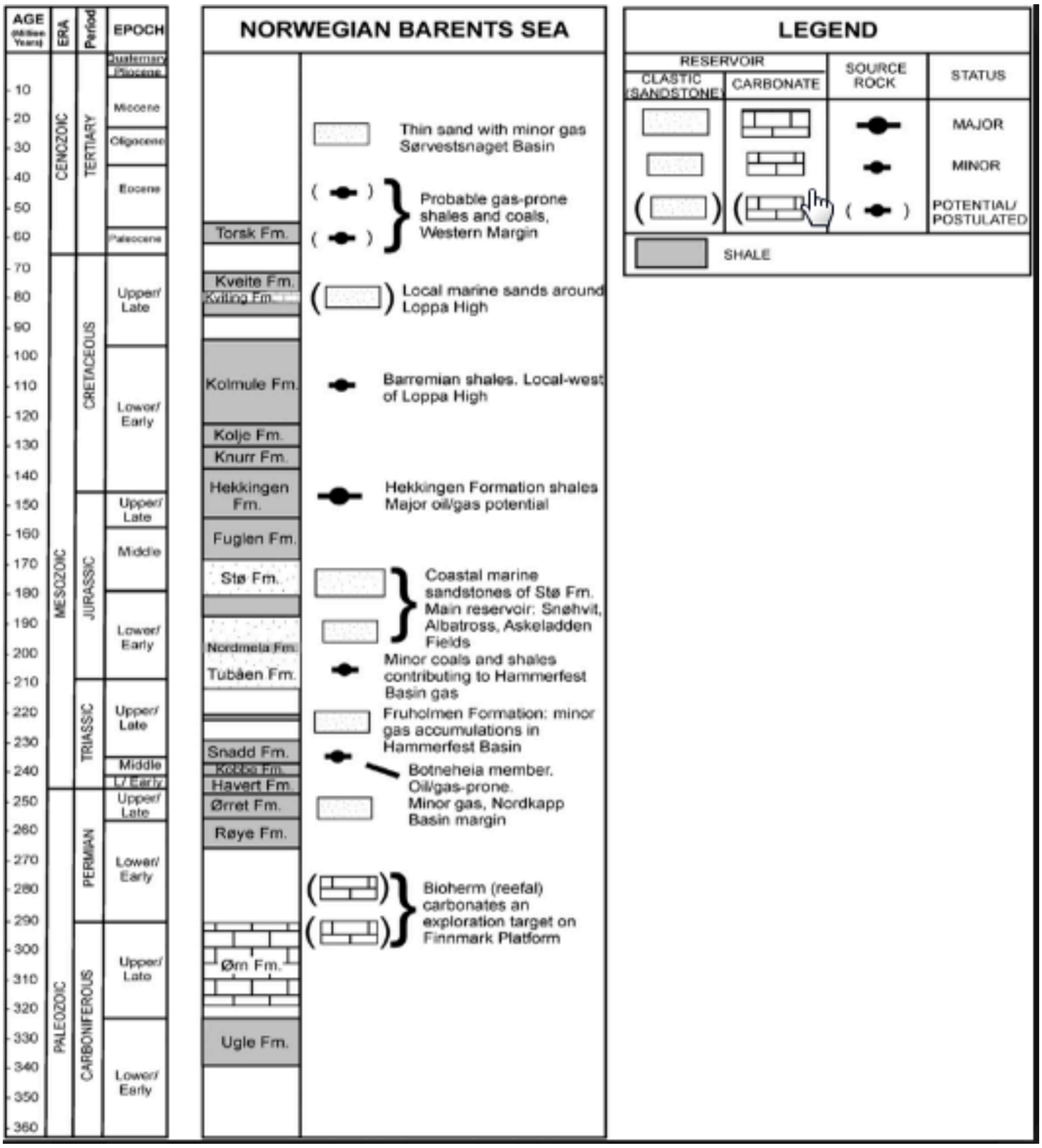


Figure 7.*Geological age and stratigraphic level of reservoir rocks (sandstones, carbonates), proven and potential source rock in the Barents Sea. Figure is modified after (Dore, 1995; Ohm et al., 2008).*

2.3.2 Reservoir rock

Reservoir rock comprises porous and permeable rock that can hold hydrocarbons. Porous limestone, sandstones and dolomites count as a good reservoir rocks.

Figure 7 gives an overview of geological age of proven and potential reservoir rocks in the Barents Sea.

Stø formation sandstones of Lower – Middle Jurassic age (*Fig. 7*) in the Barents Sea refer to reservoir where the most HC has been discovered (Dalland et al., 1988). This reservoir characterises by high porosity and permeability and refers to coastal marine depositional environment (Dore et al., 1995).

2.3.3 Cap rock

Triassic shales and Upper Jurassic shales from Hekkingen and Fuglen formations serve as a seal for petroleum system in the Barents Sea. Due to several phases with uplift and erosion in the Barents Sea the cap rock has been eroded or has thin sequence. However, it doesn't mean that it affected the petroleum system in a negative way. Thin cracked cap rock can serve as a migration pathway for gas, which due to low density will escape from the reservoir and let the oil remain in the reservoir (Karlsen, 2014).

2.4 **Uplift and erosion of the greater Barents Sea**

Both F. Nansen (1904) and Harland in 1969 were the first who approached the theory of the uplift and erosion of the Barents Sea floor. However, they gave a different origin to that process. F. Nansen based his theory on bathymetric observations (Dore et al., 1996) while Harland enhanced his theory by plate tectonics and observations from Svalbard (Dore et al., 1996). In present time, it assumed that initial stage of uplift in Cenozoic related to tectonic origin (Dore et al., 1996). The latest phase with uplift refers to the Plio – Pleistocene time and connects with glaciations of Barents shelf margin (Dore et al., 1996).

Petrographic studies confirmed that the Barents Sea have been subjected to several uplift and erosion processes (Henriksen et. al., 2012). From reservoir properties in the Hammerfest and Nordkapp basins, uplift was calculated and the results show that it varies from about 500 m in the west to about 1500 m to the east (Henriksen et. al., 2012). Net uplift is defined as difference between maximum and present burial (Henriksen et al., 2012) and it is highest in the north - western part in the Barents Sea (*Fig. 8*). According Henriksen (2012) net erosion in the Barents Sea estimated to be from 0-3000 m.

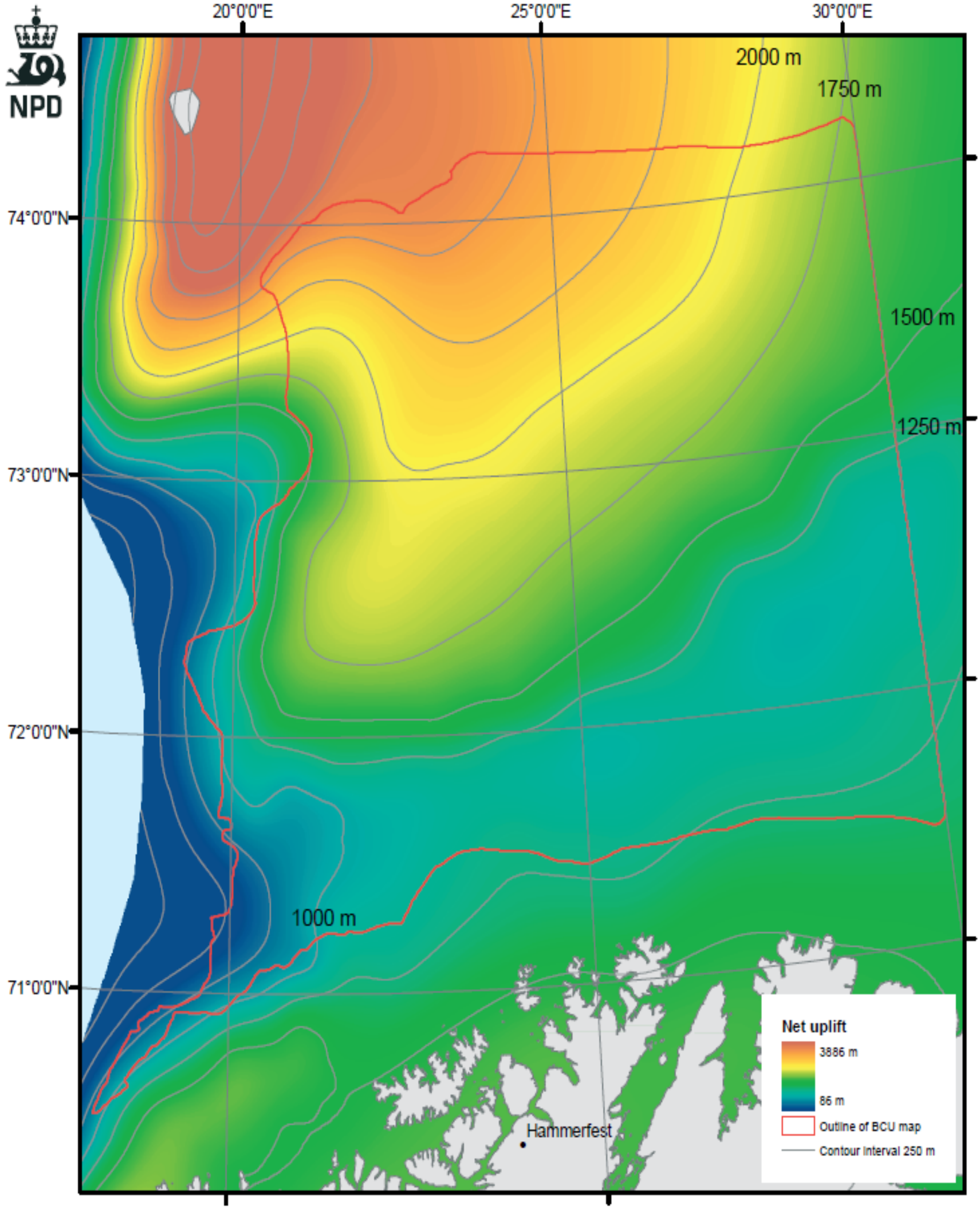


Figure 8*. Regional map with highlighted Cenozoic and Quaternary erosion and uplift of the Barents Sea. Net uplift is highest in the north - western part towards Bjørnøya (3000m) and it decrease towards the east and south areas. From Henriksen (2011).*

2.4.1 Exhumation and its implication for petroleum system

The fact that gas discoveries are prevalent over oil discoveries in the Barents Sea have been a reason to slow development of the area (Edvards et al., 2013). The low rate oil discoveries have been related to Cenozoic exhumation and erosion processes that removed about 2500 m of sediments. This may contribute to fracturing of cap rock and escaping oil. Other negative aspects related to exhumation connected to expansion of gas that will push oil out of trap, high risk for cap rock failure, cooling of source rock due to uplift and decreasing of reservoir quality (Dore et al., 1995). At the same time, it exists positive aspects such as mature source rock uplifted to the shallow depth, tight reservoir fracturing, and oil and gas remigration to shallow depth (Dore et al., 1995).

The Barents Sea has experienced at least three phases with Palaeocene, Oligocene and Pliocene - Pleistocene uplift (*Fig. 9*) and Paleogene, Neogene erosion that has had significant consequences for Petroleum system due to the risk of hydrocarbon leakage.

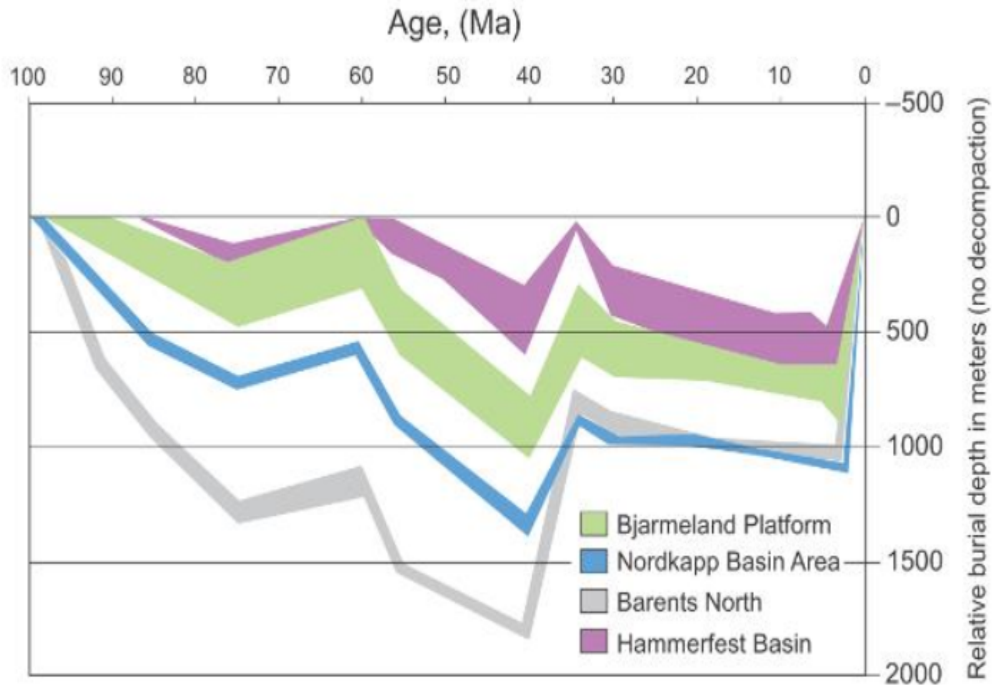


Figure 9. *Subsidence curves of the different areas of the Norwegian Barents Sea and illustrate three episodes of uplift what occurred in Paleocene (approx.60Myr), Oligocene (approx.33Myr) and Pliocene-Pleistocene (approx.5Myr) From Ohm et al., 2008.*

The main elements of petroleum system and processes connected to source rock maturation, hydrocarbon migration, reservoir quality and seal capacity affected by uplift and erosion (*Fig.10*).

Uplift and erosion caused changing in PVT (pressure, volume and temperature) condition in a hydrocarbon – filled structures. The pressure gradient decrease due to uplift and erosion that leads to expansion of the gas cap and risk of hydrocarbon leakage (Henriksen et al., 2012).

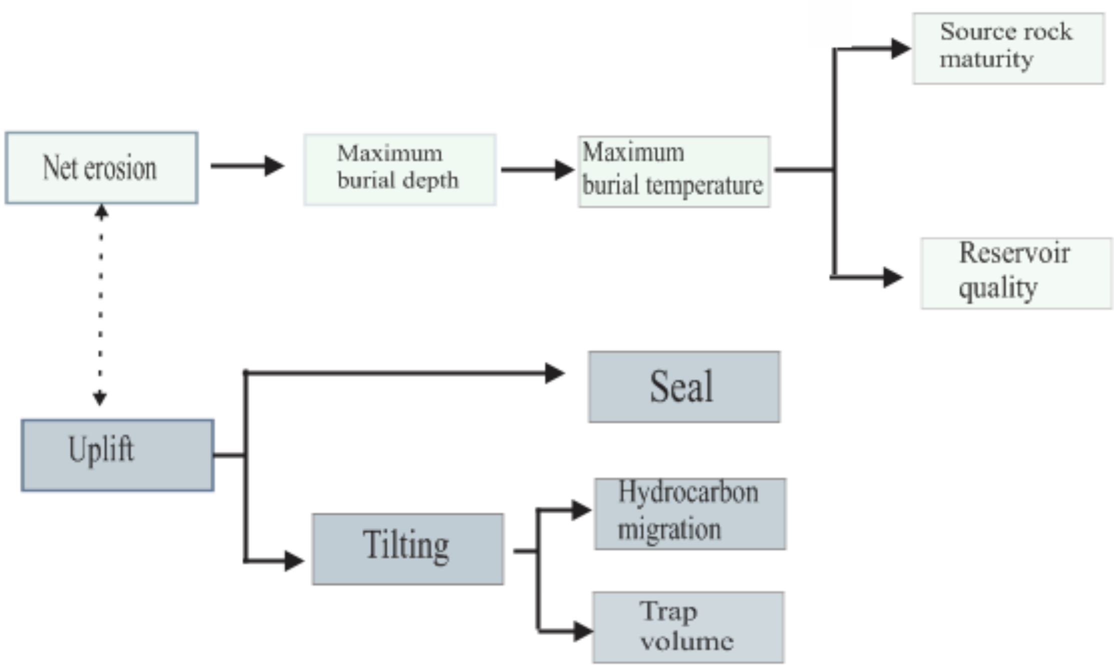


Figure 10. *Relationship between uplift, net erosion and how it affects the petroleum prospectivity. From Henriksen (2012).*

2.4.2 Compaction of sediments.

The one of the main reservoir properties – porosity (defined as a measure of reservoir rock to contain or store fluids) changes with increasing of depth and temperature of reservoir. Porosity reduces with depth due to compaction and thereby affects quality of reservoir rock.

Mechanical and chemical compaction of sediments (*Fig. 11*) represents in most cases irreversible diagenetic alteration of rocks, which relates to low porosity and high velocity in sediments.

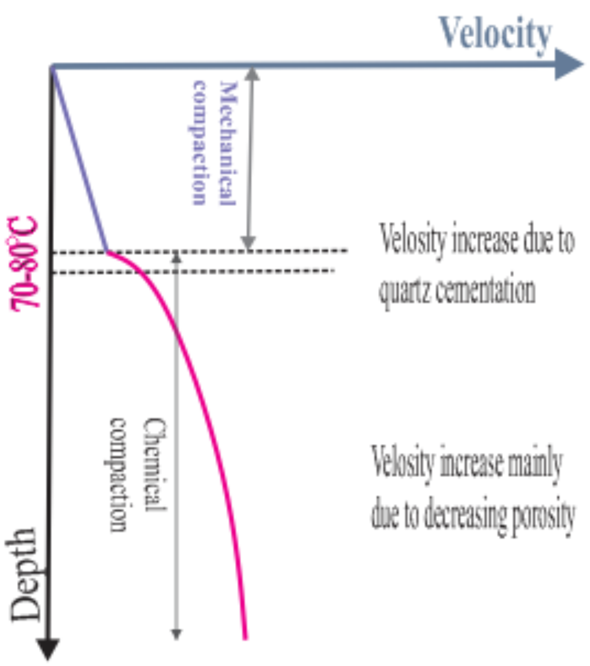


Figure 11. *Compaction curve trend as a function of velocity and depth. Modified from Storvoll (2004).*

Mechanical compaction controlled by the effective stress and chemical compaction controlled by dissolution and precipitation of solids, mineralogical and textural composition of sediments (Bjørnlykke et al., 2008). Compaction of sediments has a significant role for analyses of exhumation. It is known that compaction processes influence the physical properties of rocks. They change velocity, density and porosity characteristics in rocks.

2.5 Well logs.

Vertical trends based on log data from 19 wells in the investigated area will be analysed later in the Result chapter. Each well contain six logs: gamma ray, caliper, density, neutron, resistivity and Pvelosity. In this chapter a short overview over these logs will be given.

2.5.1 Gamma ray log (HGR)

The gamma ray log indicates gamma radioactivity of a formation and the unit used for GR log is API (American petroleum Institute). Gamma radioactivity derives from naturally - occurring chemical elements as uranium, thorium, and potassium. Most rocks include particle of gamma – emitting elements what is radioactive to some degree.

Igneous and metamorphic rocks are more radioactive than sedimentary. Shales, which is a type of sedimentary rocks, are more radioactive then other type of sediments. It explains why simple gamma ray log is sometimes named for ‘‘shale log’’. GR log is very useful to identify lithology.

High GR (about 100 API) indicates shale, but one should be aware that radioactivity from other formations can also give a high GR value. That is why indication of shale by GR should be compared to other logs. Sandstone formation usually gives a low GR reading due to low contain of non - radioactive quarts in sandstones. The gamma ray log response to different sedimentary lithology is illustrated in figure 12.

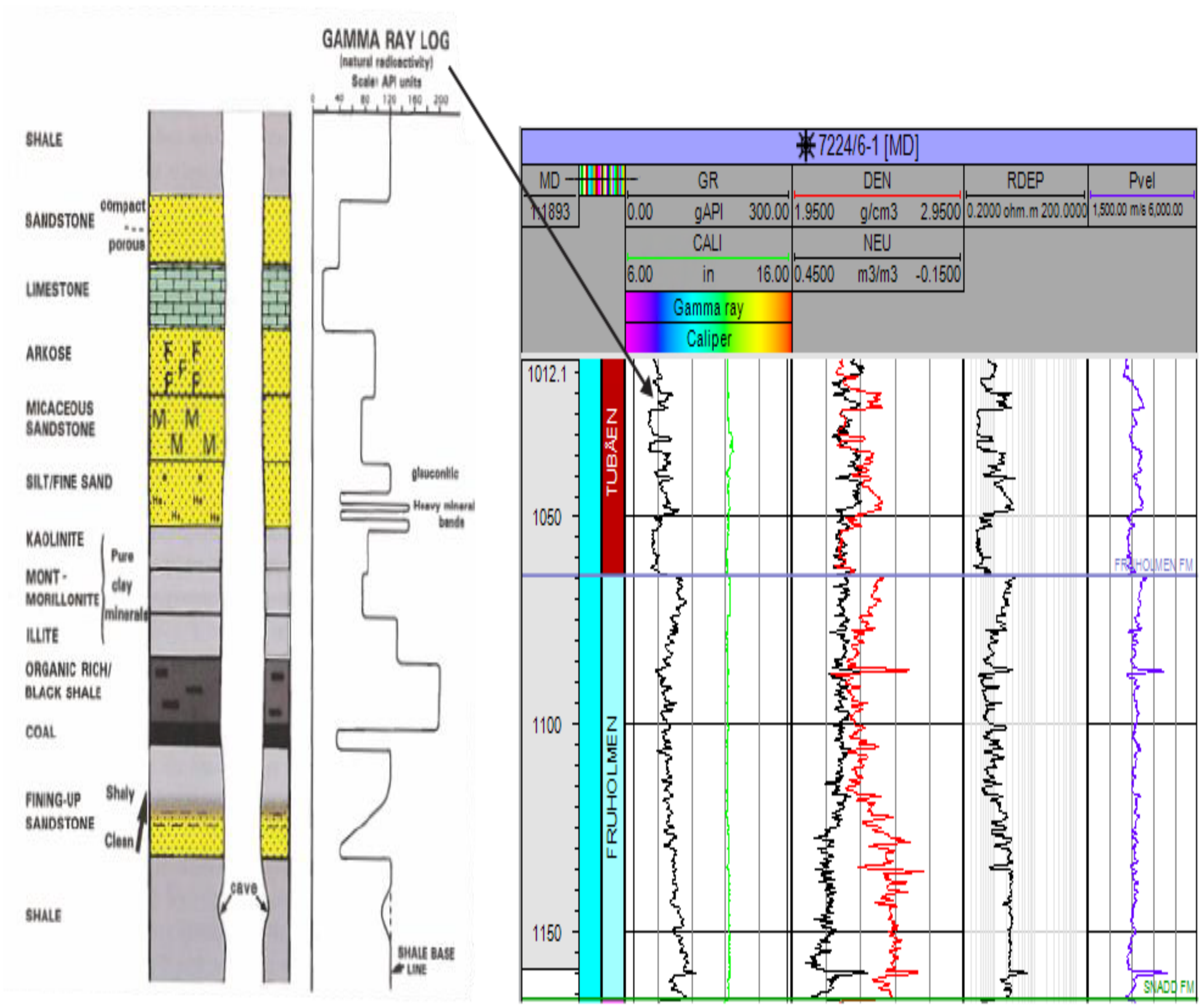


Figure 12. *Some typical response of gamma ray logs in sedimentary succession. Modified from Rider & Kennedy (2011).*

2.5.2 Caliper log

Caliper log gives dimension of the size and shape of borehole with depth as it usually has irregular form. The horizontal scale measured in inches of diameter. Caliper log is common in hydrocarbon exploration. Some typical responses of caliper logs are showed in figure 13.

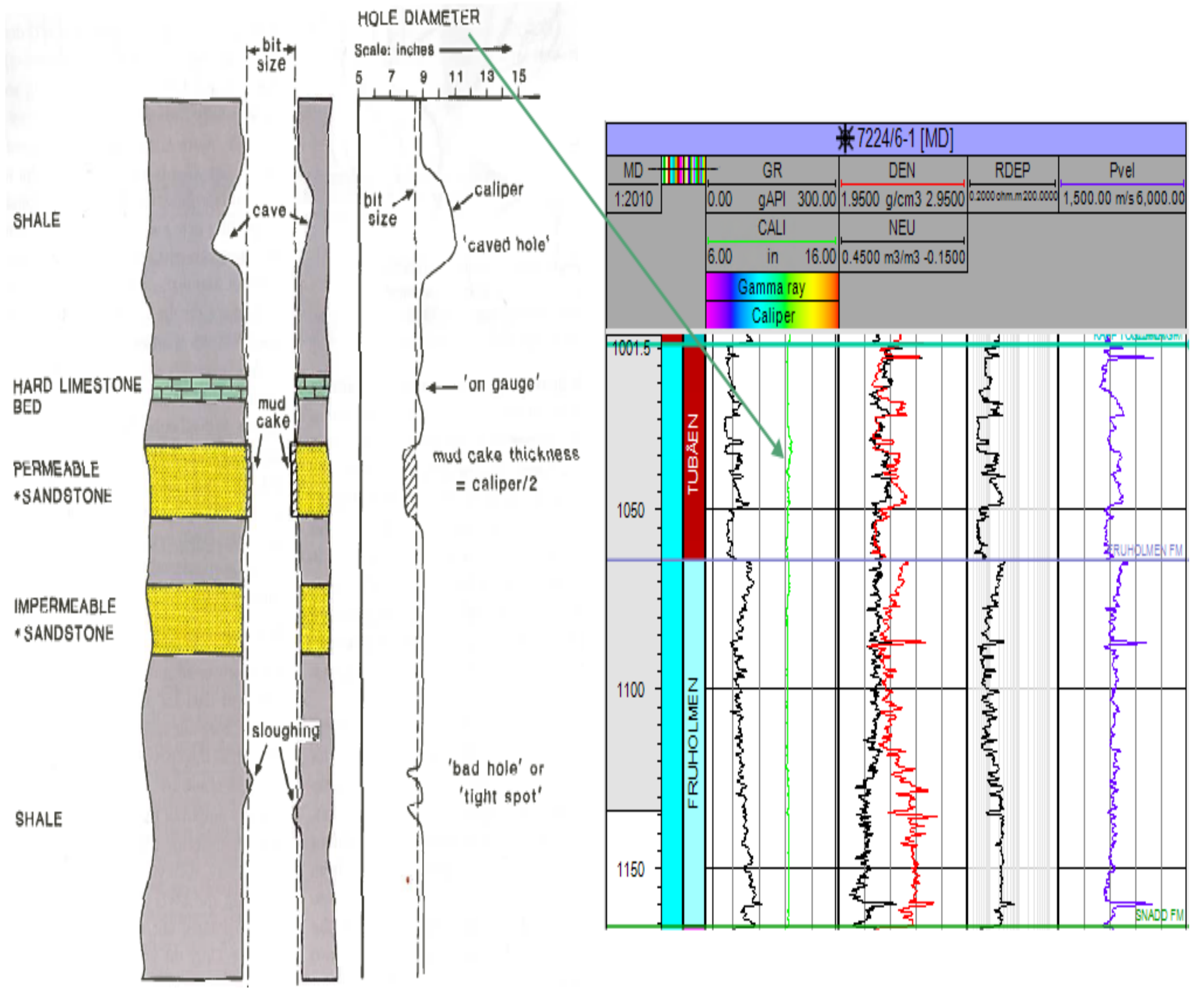


Figure 13. *Caliper log showing hole diameter and some typical response. Modified from Rider & Kennedy (2011).*

2.5.3 Density log (HRHOB)

The density log (*Fig.14*) represents a continuous record of a formation's bulk density (Rider & Kennedy, 2011). Bulk density is the total density of a rock what comprises solid matrix and the fluid enclosed in the pores.

In geological meaning, bulk density is a ''function of the density of the minerals forming a rock (i.e. matrix) and the volume of free fluids (and gases) which it encloses (i.e. porosity)'' (Rider & Kennedy, 2011). One example describing the bulk density can be a sandstone, which have no porosity, has a bulk density of 2.65 g/cm3. This is the density of pure quartz.

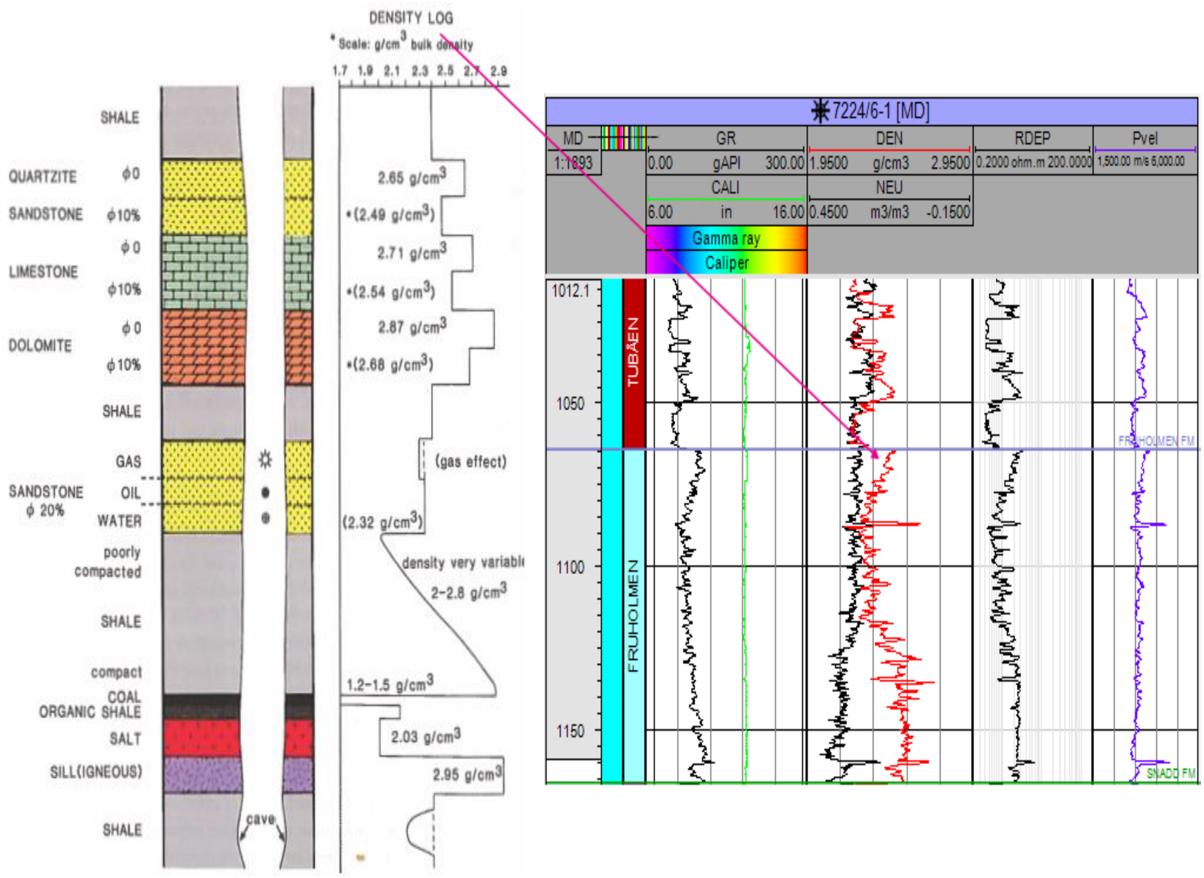


Figure 14. *Some typical responses of density log, which shows bulk density. Modified from Rider & Kennedy (2011).*

2.5.4 Neutron log

Neutron log is a continuous record of how a formation reacts to neutron bombardment. The measurements units of the neutron log is neutron porosity. Neutron porosity corresponds to Hydrogen Index of the formation, which indicates how much hydrogen contains a formation. Therefore, neutron log is useful for estimating the amount of water in a sedimentary formation. Neutron log in combination with density log can be used to calculate shale volume.

Neutron log is sensitive to variation in mineral content, mainly in shales, which include mixture of quarts, carbonates minerals and organic material. This gives a high neutron log value. Clays characterize by high hydrogen index and will give low neutron log response, if amount of quarts in the formation increase. The neutron log with some exemplary lithological response is shown in figure 15.

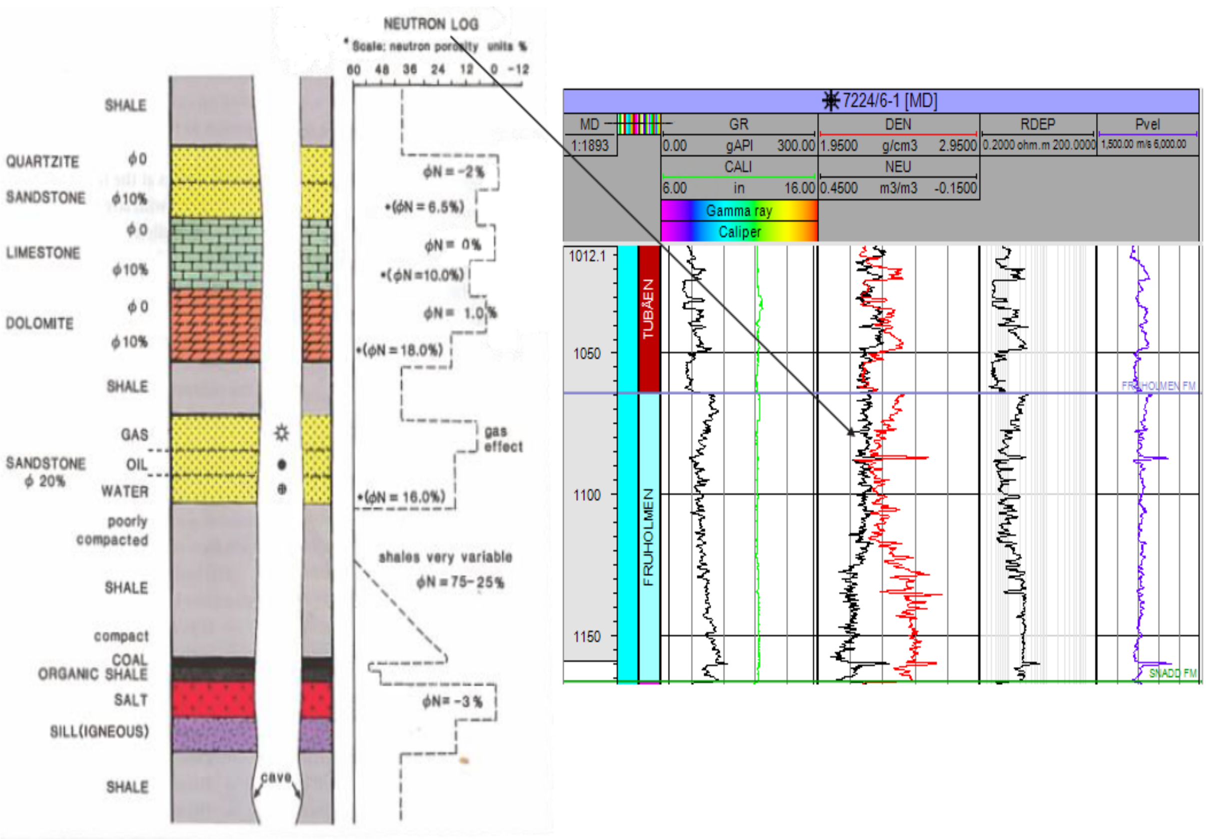


Figure 15. *Some typical responses of the neutron log. Modified from Rider & Kennedy (2011).*

2.5.5 Resistivity log.

Resistivity log measures the resistivity of the formation and important tool in HC evaluation. This is due to that hydrocarbons do not provide electricity but water in the formations does. The measurements unit of resistivity is ohm-m and in the most case it shows in logarithmic scale. A resistivity log with some typical lithological responses is shown in figure 16.

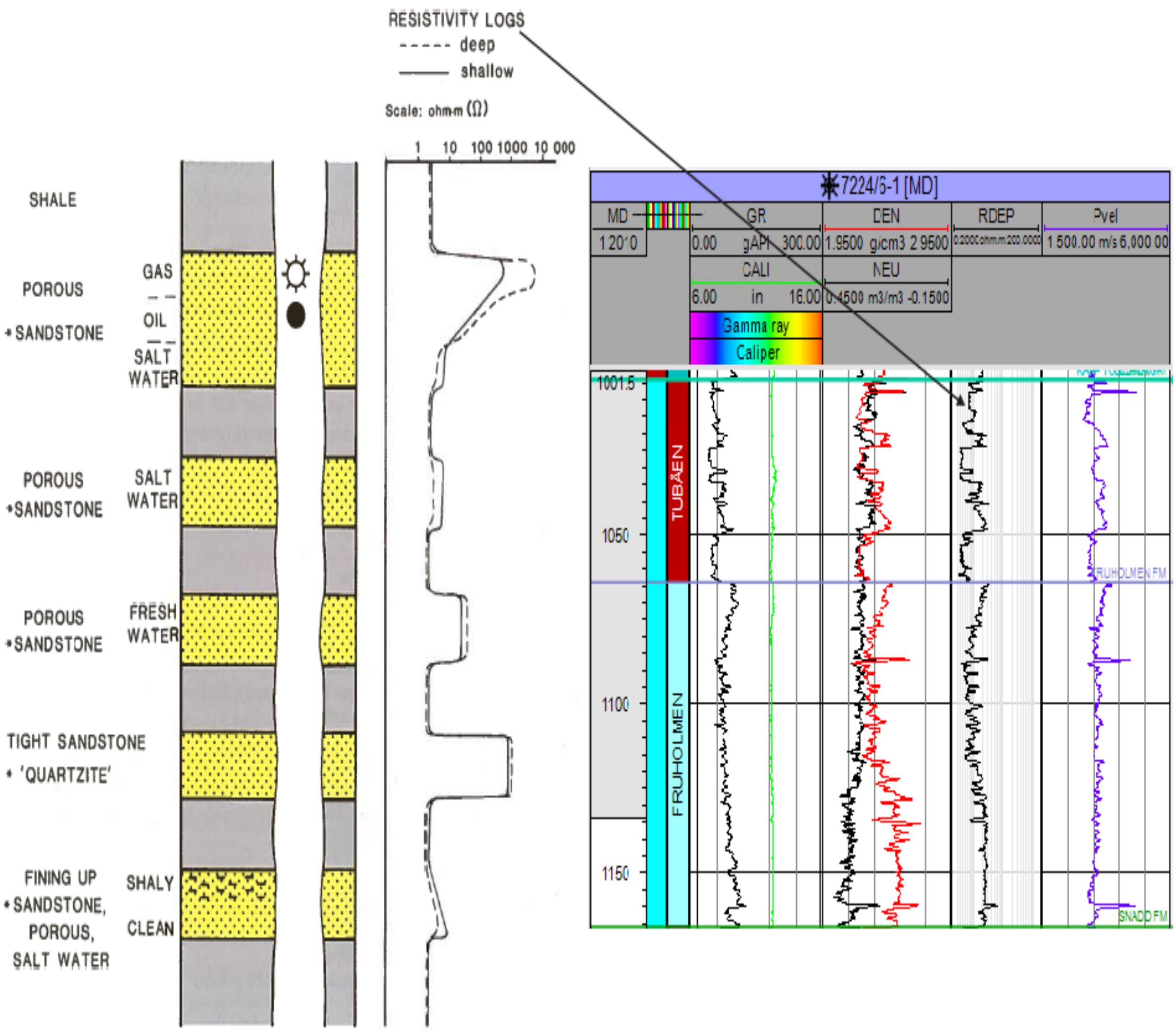


Figure 16. *Some typical response of resistivity log. Modified from Rider & Kennedy (2011).*

2.5.6 Sonic log (HDT)

Sonic (acoustic) log gives acoustic record of a formation and represents formation's slowness (interval transit time, Δt) In other words it reflects ''the time for a pulse of sound to travel a known distance through the formation''(Rider and Kenendy, 2011). The unit of measurement for sonic log is µs/ft or µs/m and it ranges in intervals from 50-150 µs/ft (150 – 450 µs/m) in subsurface formations. Some typical responses of Sonic log is shown in figure 17.

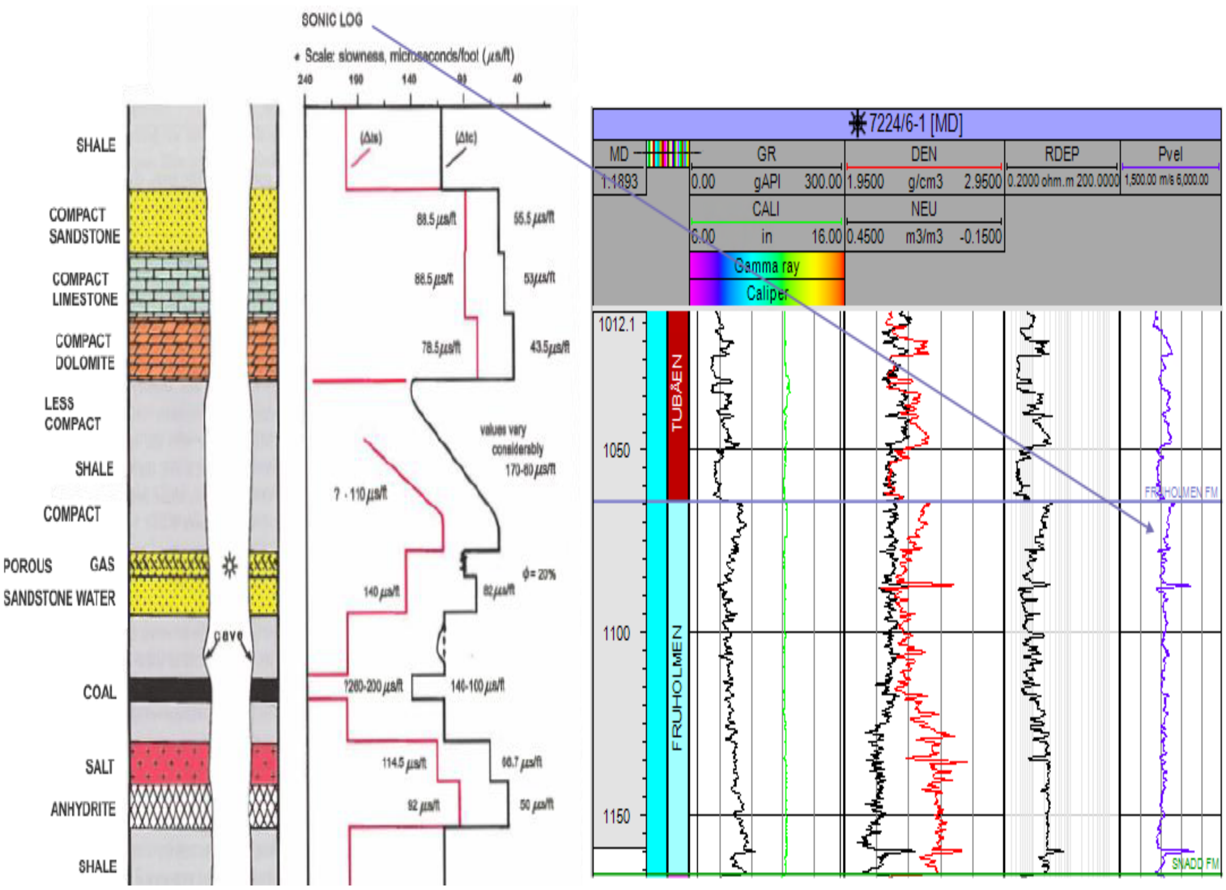


Figure 17. *Some characteristic responses of sonic log, which express a formations ability to transmit sound waves. The sonic log expressed as Slowness or Interval Transit Time, Δt.*(1 x 10*^{6}*)/ Δt = sonic velocity ft/sec.; Δtc = compressional slowness; Δts = shear slowness. Modified from Rider and kennedy, 2011.*

3 Data and methods

3.1 Well position

20 exploration wells have been analyse in this study.

13 wells are located along East – West cross-section and 7 wells are located along North - South cross - section in SW Barents Sea as shows in figure 18.

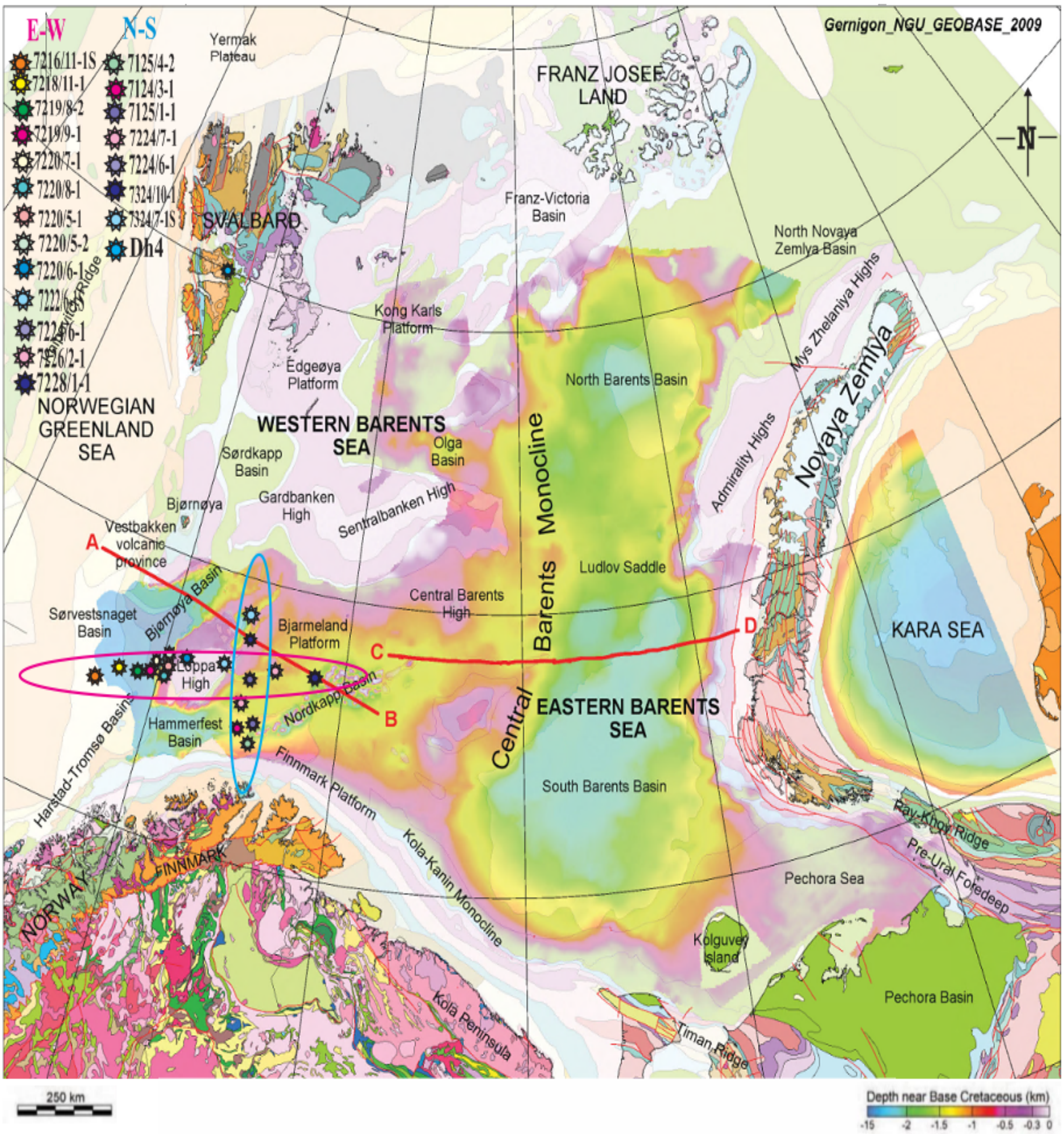


Figure 18. 1). Map over main structural futures in the Barents Sea. 2). Location of the study wells in E-W cross-section highlighted by pink circle and in N-S cross-section highlighted by blue circle in the SW part of the Barents Sea. The figure is modified from Smelrorr at al (2009).

3.2 Well data.

- Well data: Gamma ray, Caliper, Dencity, neutron, Resistivity and P - velocity log data from 13 wells in North-South cross-section, 7 wells in East – West cross section in SW area of the Barents Sea and one well in Adventdalen: Dh-4 have been considered in this study.
- All the well logs have been quality checked for formation tops based on data from NPD (2017) and add to base of wells.
- All the well logs have been quality checked for total depth based on data from NPD (2017) and corrected where it was necessary.
- All the well logs have been cropped to Triassic and younger stratigraphy due to the thesis is dealing with Mesozoic and Cenozoic Era.
- P-velocity log has been calculated from sonic log and applied to all of the study wells by using this calculation in Petrel database(Calculator for „Global well logs„)

Pvel = 1000000/AC*0.3048

- Despike (noise) from logs have not been removing due to that can delete the true data and whole data will be affected by inaccuracy. Analysing of log data from well has been proceeded with respect to presence of despike.
- The entire log data sets have been used in this study instead averaged parameters. This is contribute to more accuracy result of how velocity correspond to depth.
- The sample interval that has been used in study is 0.15 m.

3.3 Well logs

Well - section window with six logs for every well is showing in result chapter.
Table 1 present abbreviation value range and unit for logs used in this study, table 2 give a short information about the logs.

Log type	Abbreviation	Value range and unit
Gamma ray	GR	0-300 gAPI
Caliper	CALI	6-16 in
Density	DEN	1-3 g/cm3
Neutron	NEU	0.4500 -(-0.150) m3/m3
Resistivity	RDEP	0.2000 ohm.m 200.0000
Pvel	Pvel	1,500.00 - 6,000.00 m/s

Table 1. *Overview over logs what have been used in well-section window, their abbreviation and units range.*

.

Well	Total depth (m)	Water depth (m)	Discovery	Entered date	Completed date	Purpose
7216/11-1S	4239	361	Dry	24.07.2000	14.09.2000	WILDCAT
7218/11-1	2542	327.6	Dry	05.03.2013	10.04.2013	WILDCAT
7219/8-2	3425	344	Gas	16.07.2013	30.09.2013	WILDCAT
7219/9-1	4300	356	Shows	17.11.1987	25.02.1988	WILDCAT
7220/7-1	2230	365	Oil/Gas	05.12.2011	24.01.2012	WILDCAT
7220/8-1	2220	374	Oil/Gas	27.02.2011	02.05.2011	WILDCAT
7220/5-1	1740	388	Oil/Gas	27.01.2012	24.03.2012	APPRAISAL
7220/5-2	1780	398	Gas	19.05.2013	08.07.2013	WILDCAT
7220/6-1	1540	368	Dry	20.01.2005	29.03.2005	WILDCAT
7222/6-1S	2895	364	Oil/Gas	07.01.2008	10.03.2008	WILDCAT
7224/6-1	2338	266	Gas	22.07.2008	21.08.2008	WILDCAT
7226/2-1	2992	347	Gas	18.05.2008	19.07.2008	WILDCAT
7228/1-1	1714	351	Dry	29.03.2012	26.04.2012	WILDCAT
7125/4-2	1750	294	Oil	07.11.2008	01.12.2008	APPRAISAL
7124/3-1	4730	273	Oil/Gas	29.05.1987	20.10.1987	WILDCAT
7125/1-1	2200	252.2	Oil/Gas	30.11.1988	30.12.1990	WILDCAT
7224/7-1	3067	269	Shows	13.04.1988	19.06.1988	WILDCAT
7324/10-1	2919	408	Dry	03.06.1989	19.08.1989	WILDCAT
7324/7-1S	2535	413	Dry	20.09.2013	03.11.2013	WILDCAT
Dh 4	970		Dry	10.10.2009	27.11.2009	WILDCAT

Table 2. *General information about study wells.*

3.4 Estimating of exhumation value for studying wells.

Present depth for all 20 wells in the Barents Sea has been corrected for exhumation value and results have been notated in table 3, based on estimated net erosion map from Henriksen et al., 2011 (Figure 19).

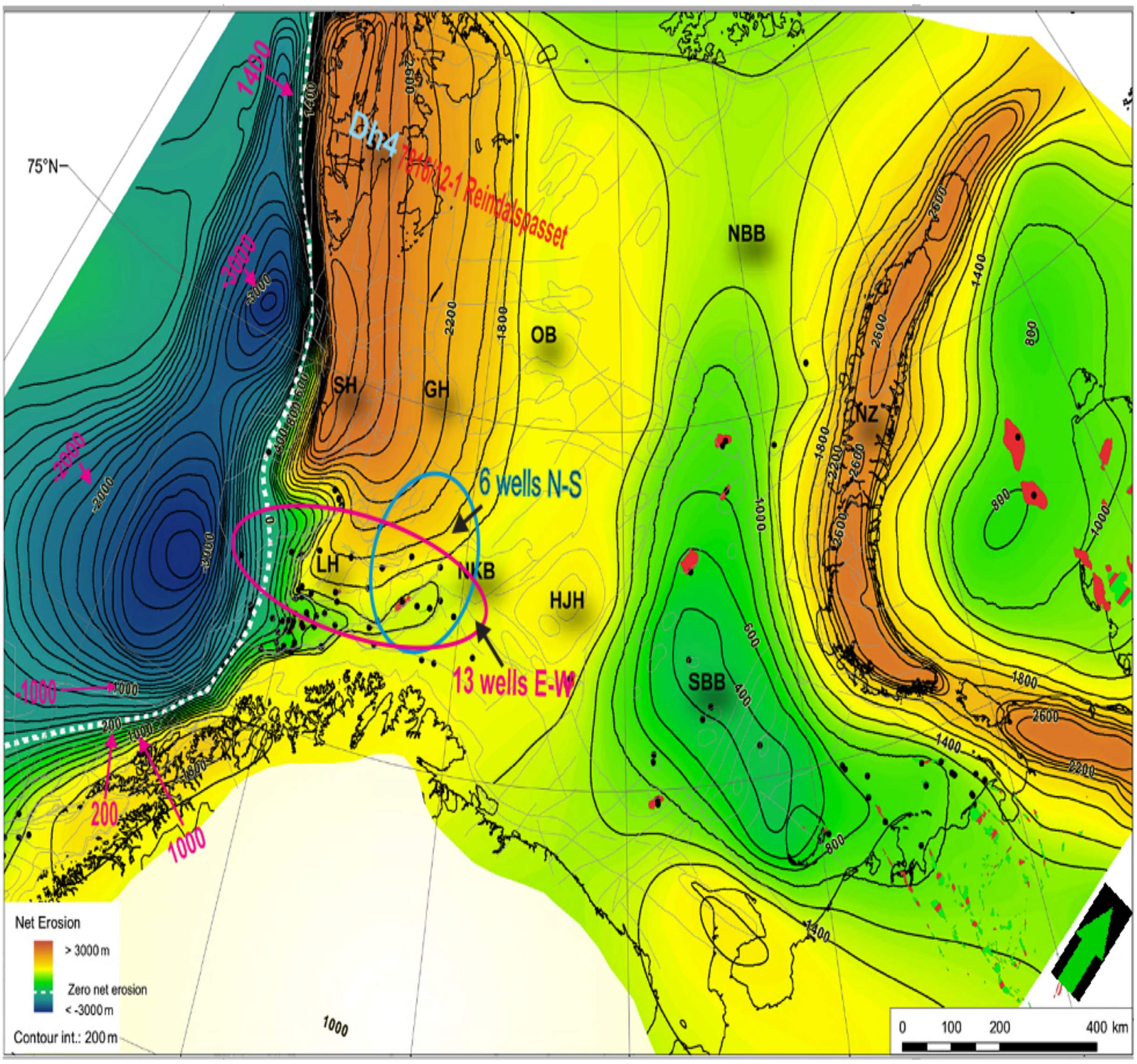


Figure 19. *Estimated net erosion map for the Greater Barents Sea. Pink color circle highlighted area with location of 13 wells along EW cross-section and blue color circle indicate location of other 8 wells along NS cross-section. Figure is modified after Henriksen et al. (2011).*

Exhumation value for every well has been founded in estimated erosion map for the great Barents Sea (*Fig.19*), added to present depth and results have been noted in table 3.

Well	Present depth (m)	Exhumation (m)	Depth corrected for exhumation (m)
7216/11-1S	4239	-1150	3089
7218/11-1	2542	100	2642
7219/8-2	3425	800	4225
7219/9-1	4300	1100	5400
7220/7-1	2230	1200	3430
7220/8-1	2220	1200	3420
7220/5-1	1740	1200	2940
7220/5-2	1780	1200	2980
7220/6-1	1540	1600	3140
7222/6-1S	2895	1800	4695
7224/6-1	2338	1700	4038
7226/2-1	2992	1700	4692
7228/1-1	1714	1200	2914
7125/4-2	1750	1500	3250
7124/3-1	4730	1300	6030
7125/1-1	2200	1400	3600
7224/7-1	3067	1600	4667
7324/10-1	2919	2000	4919
7324/7-1S	2535	2200	4735
Dh 4	970	3300	4270

Table 3. *Present depth, exhumation value and depth corrected for exhumation for studying 20 wells in the SW Barents Sea and Dh-4 well in Adventdalen (Spitsbergen).*

3.5 Published sonic velocities.

To compare and analyze velocity trends in study wells I have choose to use the trend line estimated by Storvoll (2005) from different velocity publications (Storvoll et al., 2005).

Velocity data that have been used by Storvoll (2005) for estimating trend line derives from different lithological units that closure to sedimentary rocks in Barents Sea. For instance, velocity data from Lower Triassic Bunter Shale Formation (southern United Kingdom sector of the North Sea) that comprises predominantly shales, sandstones, silt and shows high velocity response was included in estimating of trend line (Storvoll et al., 2005). Figure 20 shows estimated trend line that represents average velocity values from published velocity data and defines by high slope gradient (Storvoll et al., 2005).

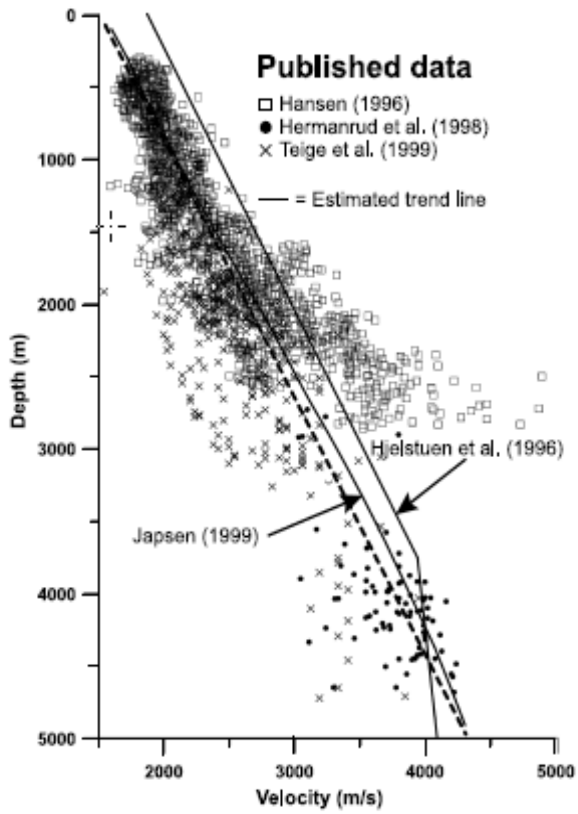


Figure 20. *Dash line represents an estimated first-order trend line Z=1.76Vp-2600, Z – depth (m), Vp-velocity(m/s). From Storvoll (2005).*

4 Results

The results chapter represents analyzing of log data from study wells with focus on variations density, resistivity and P-velocity log data in vertical trend scale. The cross – plot based on study well data have been constructed and presented. The major velocity – depth trend will be described and discussed.

4.1 Analysing of wireline data from 20 wells

The wireline log data have been analysed in 20 wells with location in NW Barents Sea area and Spitsbergen (*Fig.19*). Vertical trends in log data (Density, resistivity and Pvelocity) from Mesozoic and Cenozoic strata have been described and indicate by pink colour narrow in every well section window. Analysing of study wells is mainly based on fact data from Npd (2017). The main trend in DEN, RDEP, Pvel highlighted by pink colour line.

East – West cross-section

4.1.1. Well 7216/11-1S

The well 7216/11-1S with location in the Barents Sea has been drilled by Norsk Hydro Produksjon AS with main target to prove the hydrocarbons potential in the A-structure in PL221. The well confirmed a total 30 m gross reservoir sandstone that deposited as turbidite and penetrated in in the Late Palaeocene A1 structure. No hydrocarbons have been proved in this well. Figure 21 showing GR/CALI, Den/NEU, RDEP, Pvel logs respons in well 7216/11-1S and 3 lithostratigraphical units the well penetrated.

Vertical trends.

The main vertical trend refers to depth interval 1416 – 3215 m. Gamma Ray increase from 2 – 2.5 g/cm3, resistivity slightly decreasing from 1.9 – 0.8 ohm.m and Pvelosity increase from 2200 to 4000 m/s. High GR reading at interval 1397- 2734 m suggests a shale interval. Low GR reading below shale interval (2734-4238m) in Torsk Fm can be related to clay stones, which was deposited as deep shelf clay stones under transgressive conditions in the mid-Paleocene. Low GR value above 1397m in Nordland group detect claystone which is related to bathyal/glacial marine deposited clay stones.

High - density value in Torsk formation can be associated with carbonate horizons and in Nordland group can be associated with boulders of quartzite, granite and other metamorphic rocks. Cross over trend between density and neutron log can be a good indicator for reservoir rock.
Velocity value is high (4200-5100m/s) at depth interval 3204- 2917m. Decreasing in velocity value between Sotbakken (3500m/s) and Nordland Groups (2200m/s) can be explain by changes in lithology from claystone in Sotbakken Group to sandstones in Nordland Group. (Oligocene and Miocene unconformity, Npd(2017)).

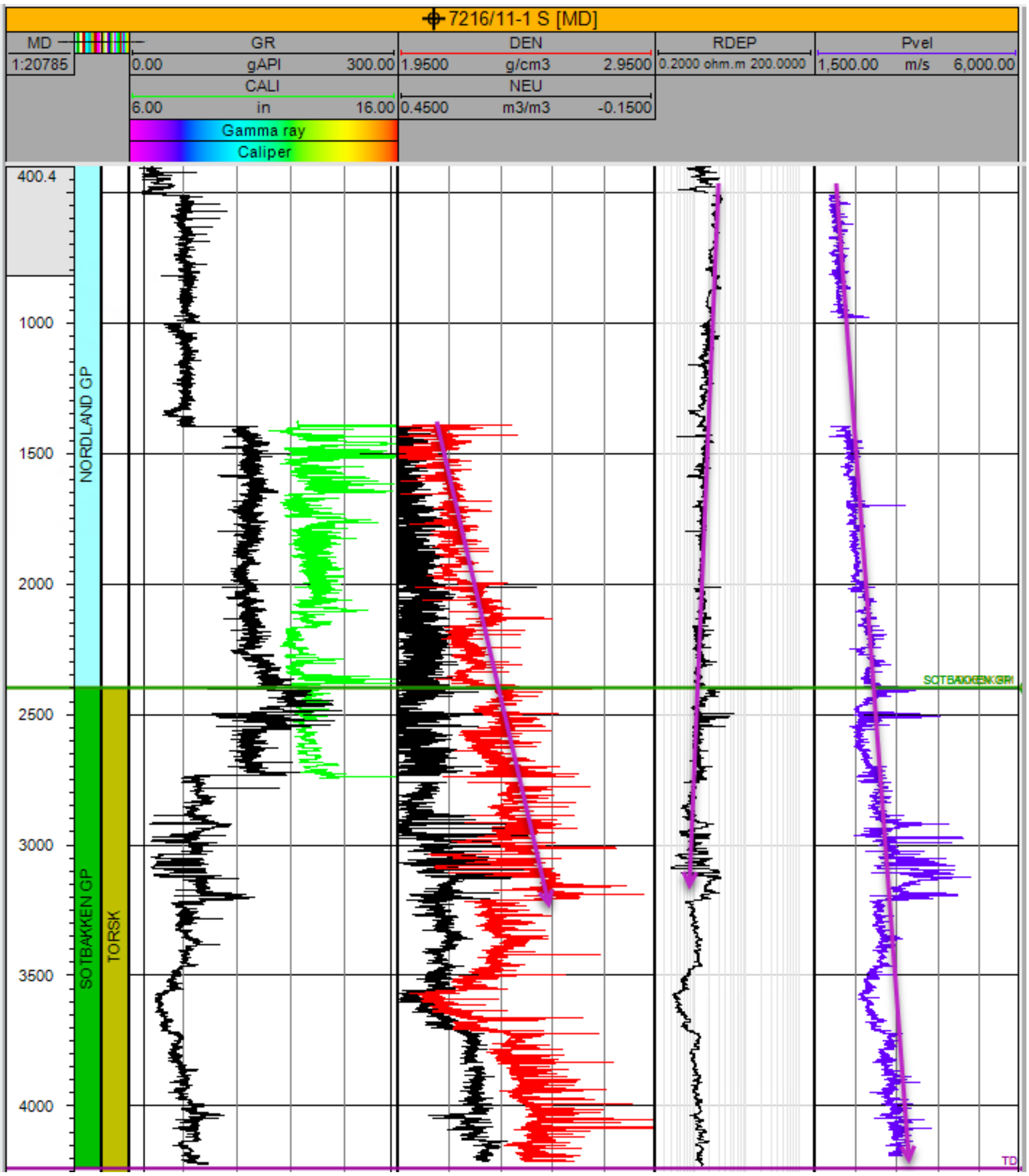


Figure 21*.GR/CALI, Den/NEU, RDEP, Pvel logs respons in well 7216/11-1S.*

Source rock zone.

The claystone in the lower part of Nordland Group according to TOC values ranging between 2.40% - 3.60% are good potential source rock. (Npd, 2017) Vitrinite reflectance analyses of claystone shows 0.29 %. It too low rate that means that Nordland Gr claystones are not able to generate significant amounts of HC at the present maturity level, but it can have potential for gas (Npd, 2017). Interval at 2734m (Upper Torsk Fm) – 1397 m (Midle Nordland Gr) characterize with high GR value and has been interpreted as organic rich shale interval as they can be high radioactive and shows high GR reading. HC bearing shale can be identified from log data due to high value on GR, low velocity and low density reading.

Gas bearing sand was indicated by cross-over trend between Density and Neutron log at 2012m depth. (*Fig.22*)

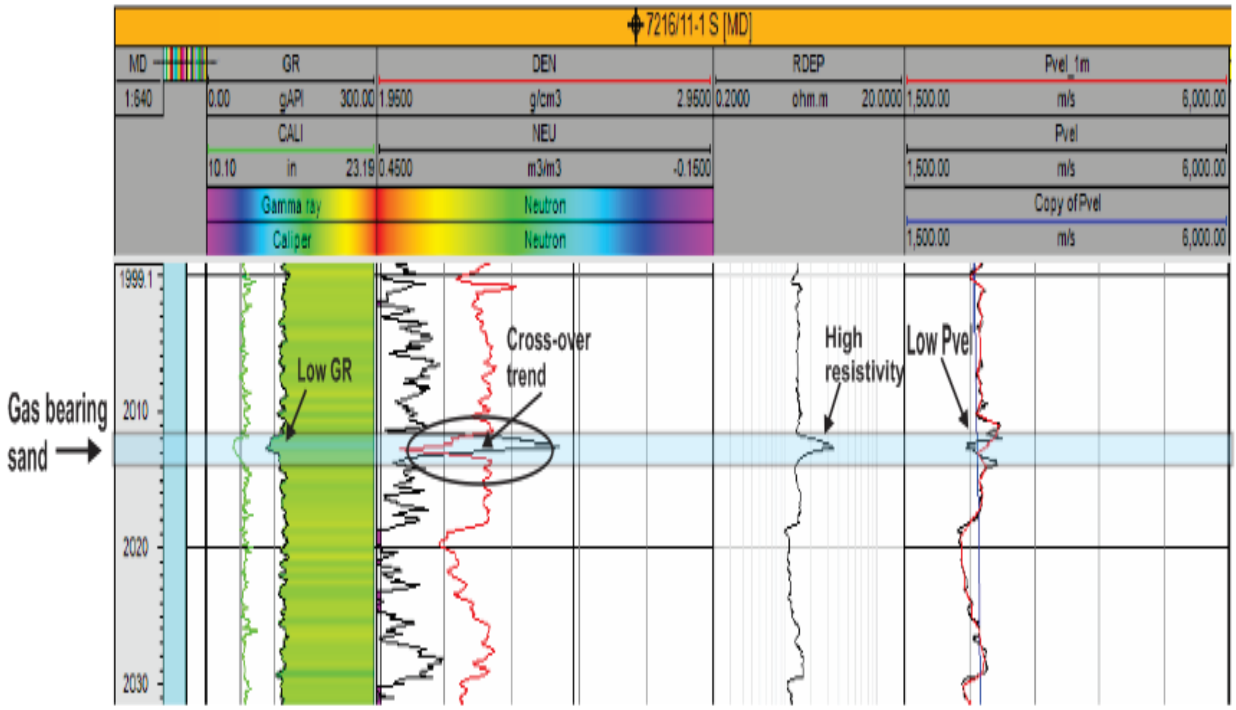


Figure 22. *Den/NEU log in gas-bearing sand interval in Nordland Group in well-7216/11-1S.*

Reservoir rock zone.

Low GR, cross-over neutron- density trend and low resistivity values (*Fig. 23*) have been detected in Sotbakken Group in upper Torsk Formation (Late Palaeocene) at depth 3118-3111m (7m), 3091-3083 (8m), 3046-3036(10m), 2991-2982 (9m). Those sandstone sequences characterize as reservoir sandstone which was deposited as turbidites.

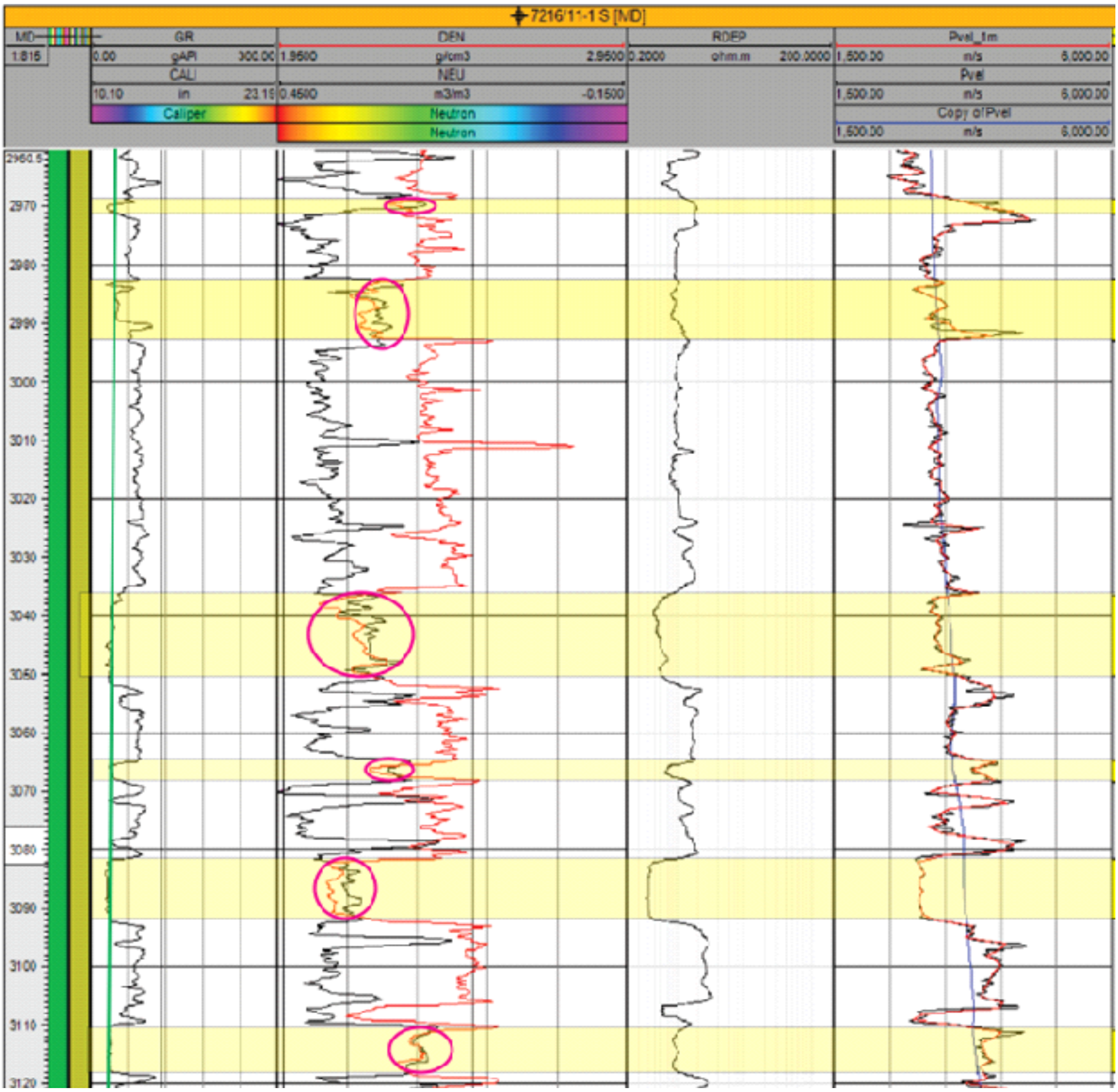


***Figure 23**. Well section panels showing low value of gamma Ray log and cross over trend between density log and neutron log that is a good indicator on reservoar rock.*

4.2.2 Well 7218/11-1

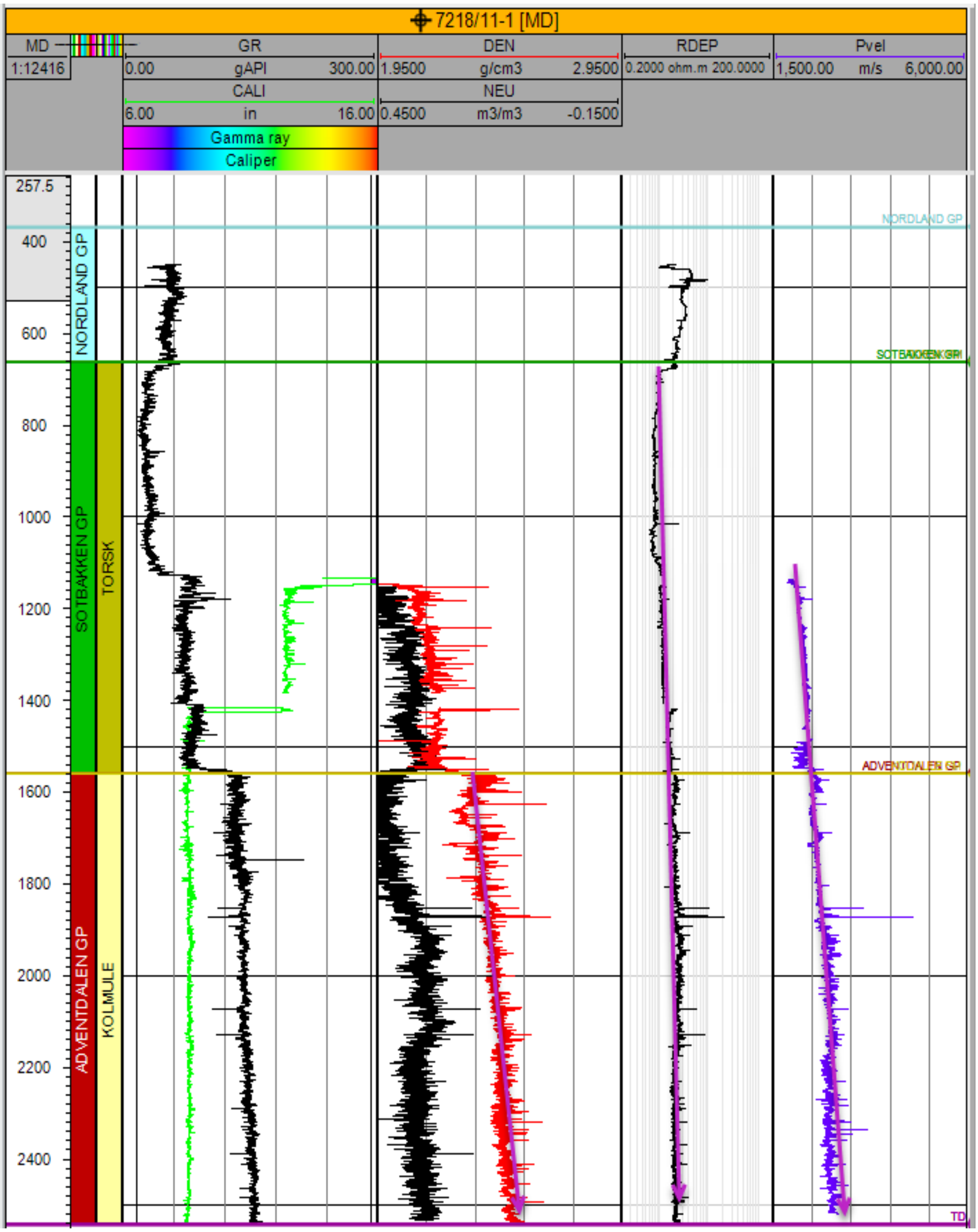


Figure 24. *GR/CALI, Den/NEU, RDEP, Pvel logs respons in well 7218/11-1.*

Wellbore 7218/11-1 has been drilled by Repsol Exploration Norge AS in the western part of Barents Sea with main target to detect hydrocarbons potential in the Late Cretaceous (Kveite Formation).
Target number two was to indicate hydrocarbons in the Paleocene Torsk formation.
Wellbore location is 230 km NW direction of Hammerfest and 80 km SW of the 7220/8-1 (Skrugard) discovery in the western part of Barents Sea. (Darwin prospect)

The total depth is 2542m. The well was abandoned as a dry well. The well penetrates five main lithological units (*Fig. 24*).

Vertical trends in well.

Density values increase with depth interval 1560 – 2542m from 2.3 – 2.5 g/cm3, resistivity is approximately constant at 3 ohm.m at 690 – 2540 m, pvelocity increase from 1800 – 3000 m/s at depth 1160 – 2500 m.

The GR value is high in interval from about 1580m and down, shows approximately 150 gAPI. This is indicated by lithological change from Kolmule Formation shale (high GR reading) to Torsk Formation which comprise predominantly claystones (low GR reading). The lowest value of GR shows in interval from middle Torsk Formation from about 1126m to 667m, is about 25 gAPI, can be interpreted as sandstones interval. Density value is high about 2.5 g/cm3 in Kolmule Formation (from 1580m and down) corresponds with high GR reading in this interval. Density value decrease in transition zone between Kolmule Fm. and Torsk Fm. (1580m) indicating in lithology changing.

P-vel. value is about 2,500.00 m/s in Kolmule Fm and then it decrease in transition zone between Kolmule and Torsk Formations (1,590.00m/s from 1580m-1150m).

Source rock zone.

Potential source rock is detected in interval between 1610-1750 m in upper Kolmule Formation (*Fig.25*). TOC of the source rock is about 2-3.5% wt. Rock –Eval Hydrofen index shows 200-300 mg HC/g TOC. Inspite of kerogen presents in this section, it is immature for petroleum generation.

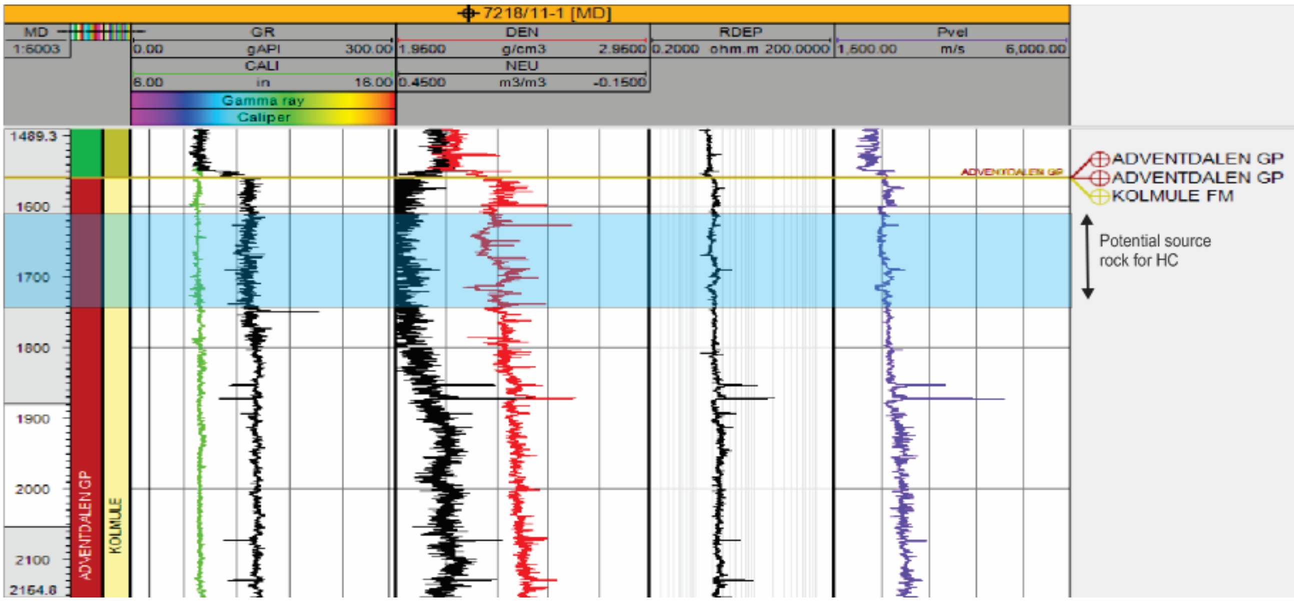


Figure 25. *Showing potential source-rock for HC at interval between 1610-1750m in the upper Kolmule Formation.*

Reservoir rock zone:

Low GR value (the value is about 25 gAPI) in well section at 667m – 1126 m depth (Upper Torsk formation) indicates sandstones, which can be consider as reservoir for HC. (*Fig.26*).

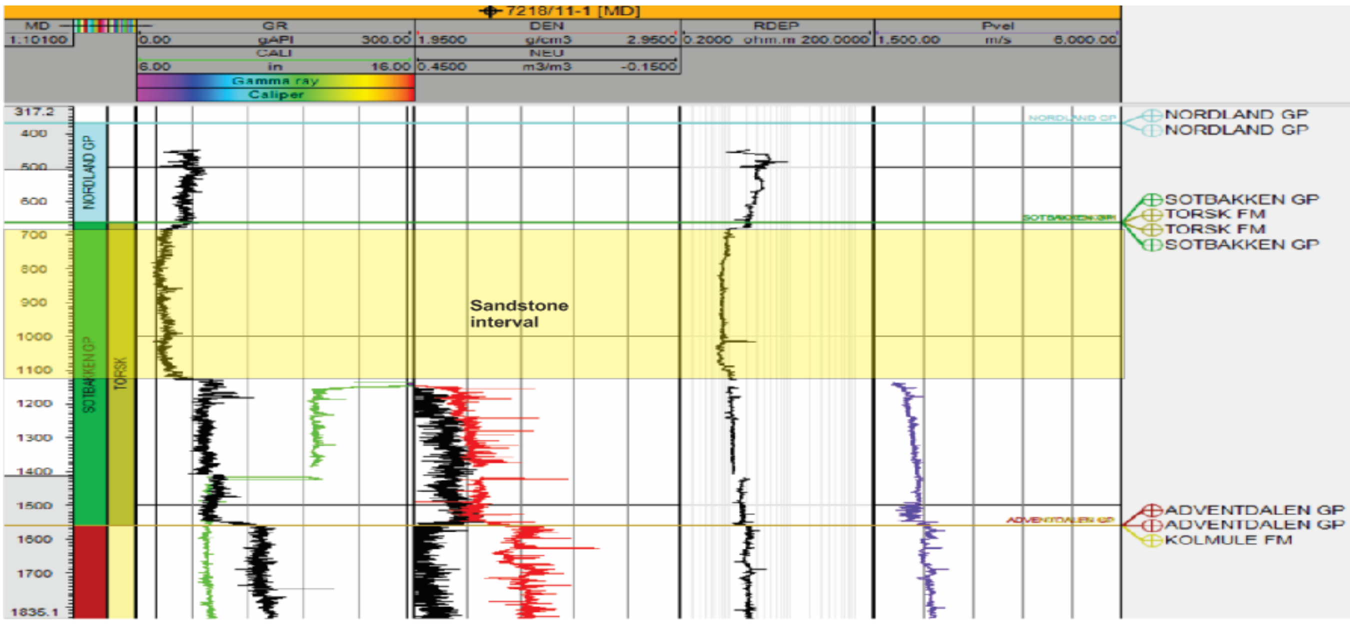


Figure 26. *Sandstone interval in well 7218/11-1 highlighted with yellow color.*

4.2.3. Well 7219/8-2

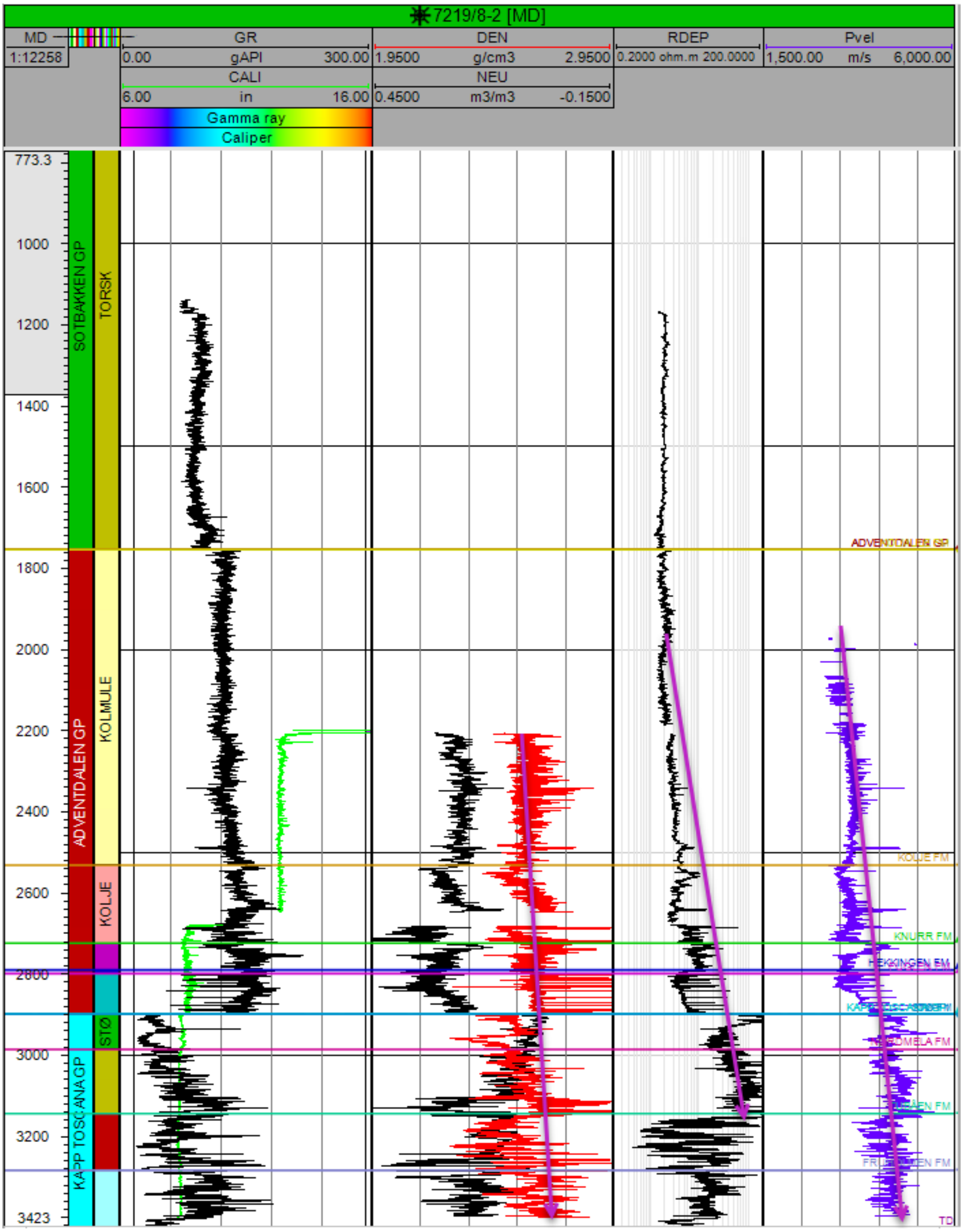


Figure 27. *GR/CALI, Den/NEU, RDEP, Pvel logs respons in well 7219/8-2*

Well 7219/8-2 has been drilled with main target to prove HC in the Stø, Nordmela and Tubåen Formations. Main operator is Statoil Petroleum As. Well has been drilled to depth of 3425m in the Bjørnøyrenna Fault Complex in southeast direction of the Johan Castberg Field in the Barents Sea. The well was abandoned as a gas discovery. The well penetrates 14 main lithological units (*Fig.27*).

Vertical trends in well.

Density slightly increase at depth interval 2200 – 3340 m from 2.5 – 2.7 g/cm3. Resistivity sharply increase from 1.6 – 120 ohm.m at depth interval 2000 – 3100 m. Velocity increase from 3100 - 4800 m/s at depth interval 2080 – 3390 m/s.

GR value in Kapp Toscana GP characterize by changing in trend from low value (30gAPI) to high value (130 gAPI) indicating transition zone between sand to shale lithology. Transition zone between Kapp Toscana and Adventdalen GP showing changing in GR value from 30gAPI to 150gAPI at 2900m depth. Increasing in GR value can be associated with changing from sandy to shale lithology sequence. Interval from 2500 – 1750m (Adventdalen GP) shows GR value at 129 gAPI. Low part of Torsk Fm has GR reading (81gAPI) at interval between 1750 – 1180 m.

Source rock zone. Source rock zone indicate in Nordmelle and Stø Fm, shows in figure 28.

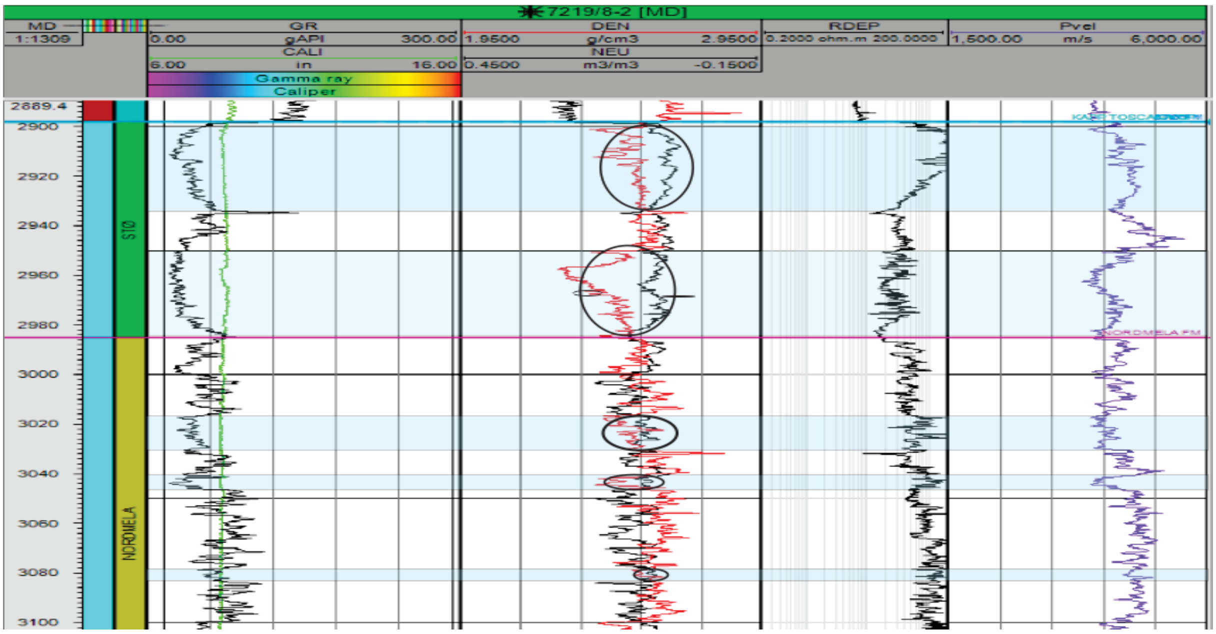


Figure 28*. Source rock zone in Stø and Nordmella Fm.*

Reservoir rock zone.

Sandstones reservoir has been indicated by low GR reading (40-49gAP I at depth intervals 2984 – 2945m, 2934 – 2898m) in Stø Fm and in Nordmela Fm (depth interval 3016 – 3030m, 3046 – 3041m, 3080 – 3078 m) and also cross-over trend between DEN and NEU as showing in fig. 25.

Cap rock zone.

High GR value (173 gAPI) in Fuglen formation related to interbedded mudstones and limestones (*Fig. 29*) deposited in marine environment under tectonic movements, constitute a cap rock zone.

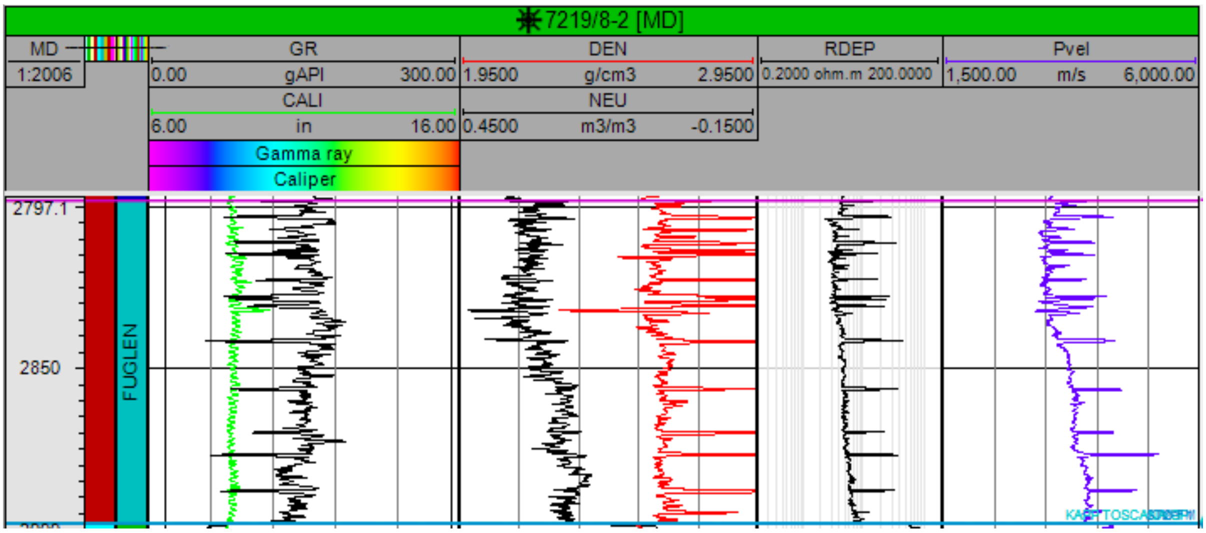


Figure 29. *Log data of Fuglen Formation in well section window.*

4.2.4. Well 7219/9-1

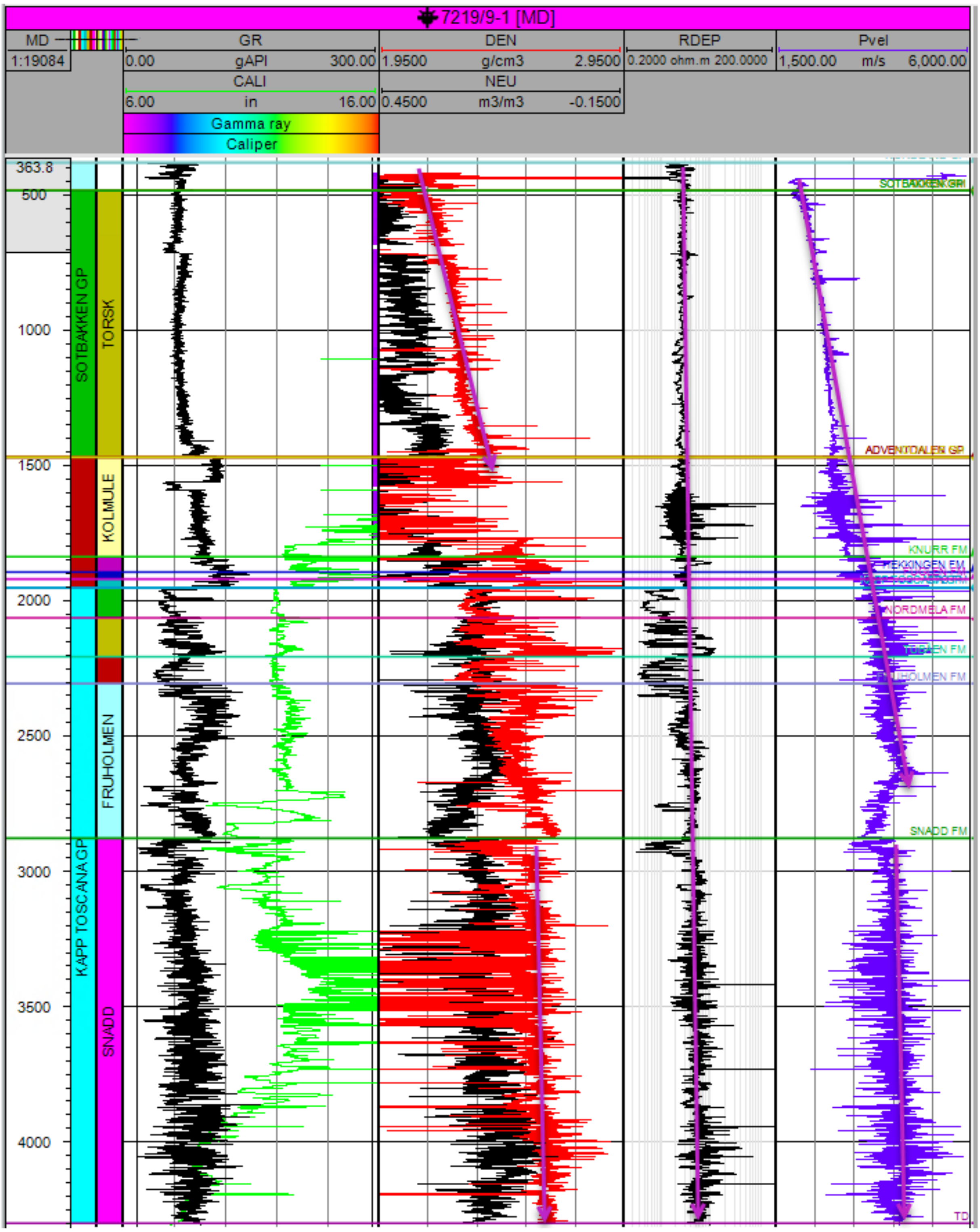


Figure 30. *GR/CALI, Den/NEU, RDEP, Pvel logs respons in well 7219/9-2.*

The well 7219/9-1 has been drilled with two main target. The main target was to prove reservoir and HC potential of sandstones of Early-middle Jurassic age. The secondary target was to identify Late Triassic sandstone of the Snadd formation. Total depth of the well is 4300 m in the Bjørnøya Sør area between the Veslemøy High and the Polheim Sub-platform. The well penetrated 14 main lithological units (*Fig.30*). The well counts as a dry well and was permanently abandoned.

Vertical trends in well.

Density increased from 2.2 - 2.56 g/cm3 at depth 430 – 1456 m. It slightly decreases and apparently constant 2.5 – 2.6 g/cm3 at depth 2880 – 4300 m. Resistivity slightly increases 3 – 8 ohm.m at depth 400 – 4300 m. Pvelocity increases at depth interval 430 – 2600 m from 2200 – 4400 m/s and at depth interval 2880 – 4300 m 3800 – 4500 m/s.

Variable GR (in range between 50-100 gAPI), and uniform response of DEN and Pvel logs in Snadd Fm (4300-2877m) can be explained by mixed lithology which is consists of limestone, sandstone, shale strings which was deposited in distal marine environment (Npd, 2017). Interval between 2518 – 2300m (upper part in Fruholmen Fm) showing increasing in GR value (up to 116gAPI) and separation between DEN and NEU logs. This logs response can be related to mixed lithology of sandstone and carbonates. Tubåen Fm (2300-2207m) showing variable GR reading (37 – 65 gAPI) that represents sand/shale/sand stratigraphic sequence related to stacked series of high-energy marine environment (Npd, 2017). Interval between 1844 – 1478m (Kolmule Fm) characterised by GR value at 86 gAPI, decreasing in DEN, Pvel value (3000m/s.) This is can be interpreted as clay stone/shale deposition in open marine environment (Npd 2017). Interval between 1458- 716 m (Torsk Fm) showing low GR (64 gAPI), decreasing in DEN and Pvel (2500m/s). This interval represents clay stone, deposited in open-deep marine environment (Npd, 2017).

4.2.5 Well 7220/7-1

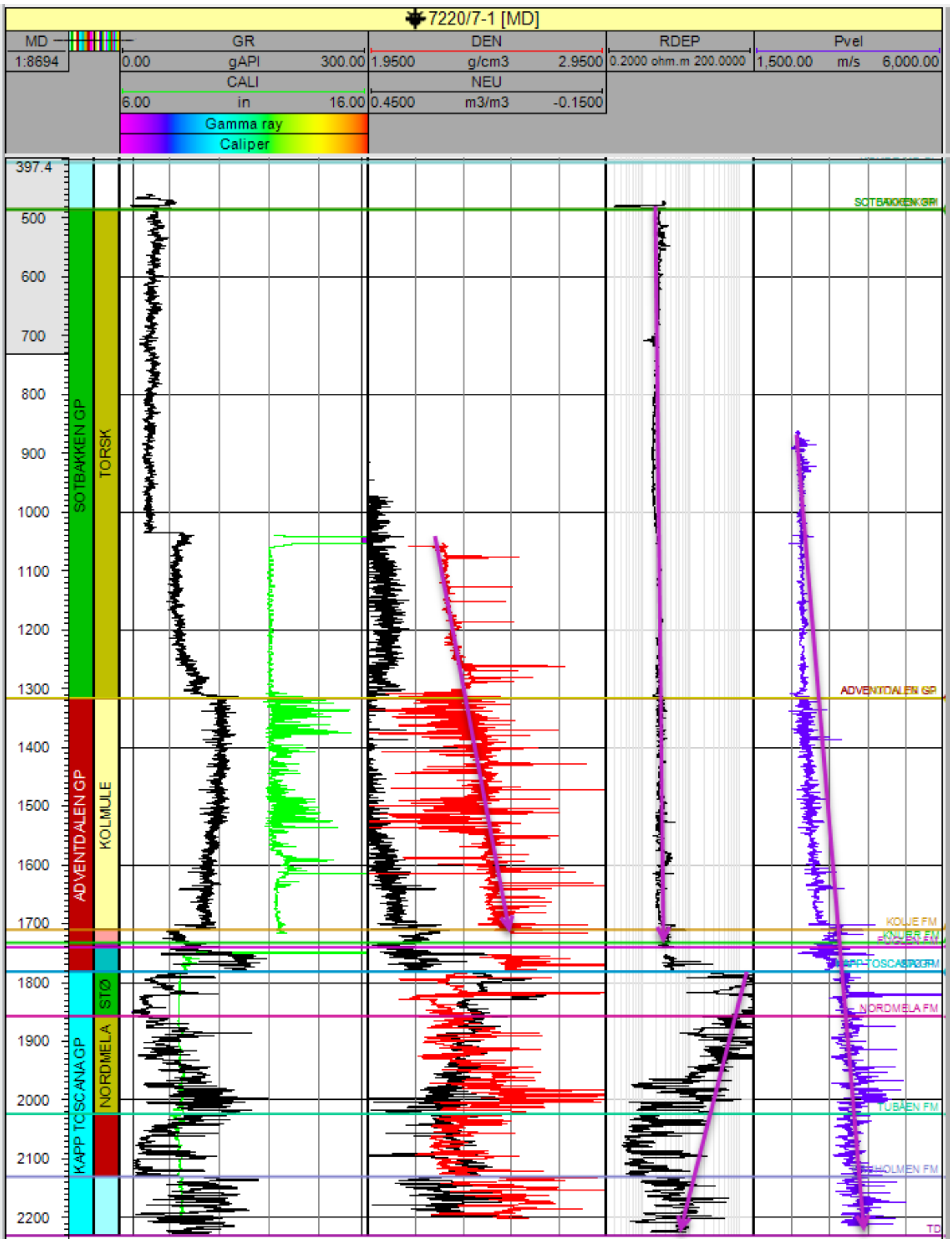


Figure 28. *GR/CALI, Den/NEU, RDEP, Pvel logs respons in well 7219/8-2.*

Well 7220/7- 1 (Johan Castberg) has been drilled by Statoil Petroleum AS to depth 2230m with main target to improve HC potential in the Stø, Nordmela and Tubåen formations. The second target was to test reservoir quality of sandstones of the lower Triassic ages in Fruholmen formation. The well is located in west direction of the Loppa High in the Barents Sea and it penetrated 13 lithostratigrafical units (*Fig. 28*). The well was abandoned as an oil and gas discovery.

Vertical trends in wells.

Density increase from 2.25 – 2.5 at depth 1060 – 1700 m. Resistivity is apparently constant 2.4 – 2.6 ohm.m at depth 500 -1700 m. Pvelosity increase from 2500 – 4000 m/s at depth 870 – 2200 m.

GR value is highest in Kolmule Fm is about 140 gAPI. Transfer zone from Kolmule Fm to Torsk Fm (1310m) characterise with decrease in GR from 140 gAPI to 75gAPI. GR value is lowest (30 gAPI) from 1010m (Middle Torsk Fm) and upwards, which indicate sandstone sequence.

P-vel is highest in Kapp Toscana GR (4000m/s) It decrease in Adventdalen GR and velocity value is about 2500 m/s. Velosity in Torsk Fm is 2100m/s. (interval 1310 – 870 m)

Source rock. Source rock zone defined in interval 2100-2118m and 2122-2130m in low part in Tubåen Fm.

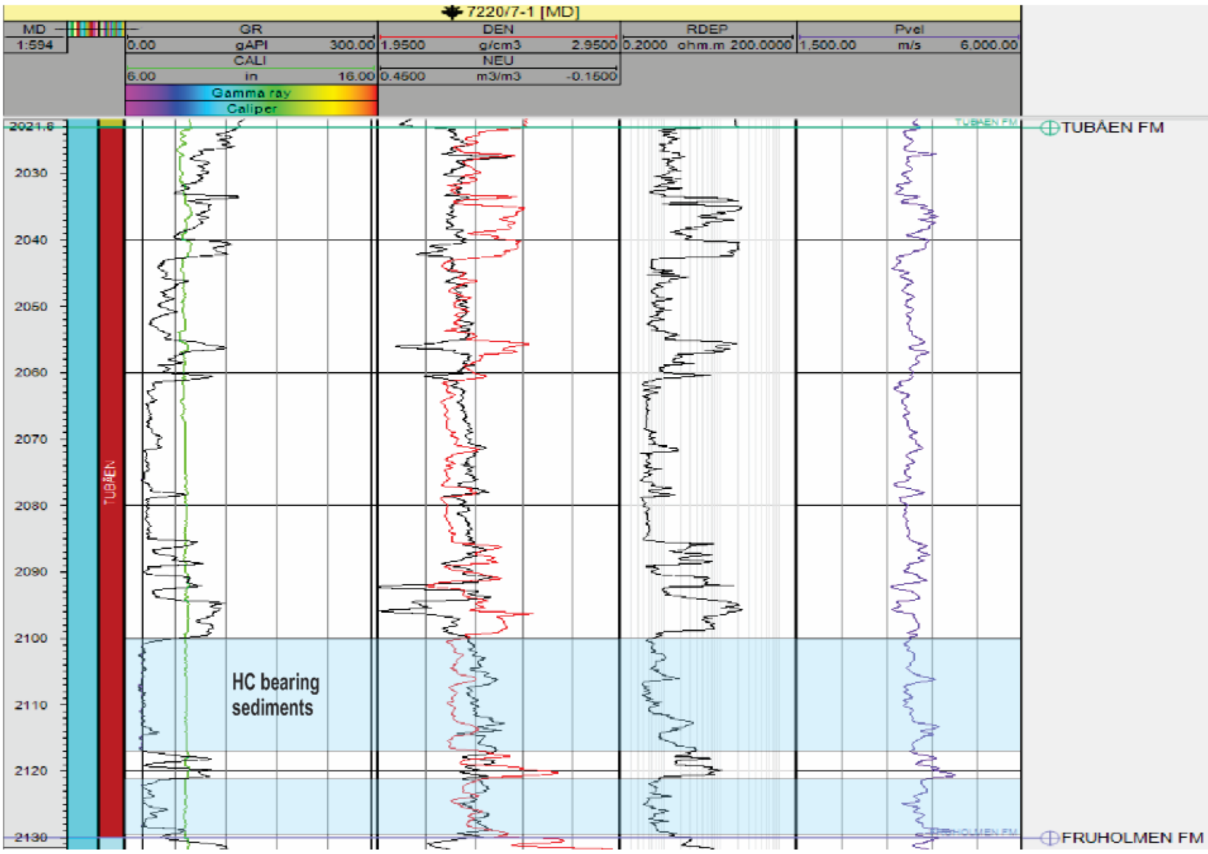


Figure 29. *Interval with HC bearing sediments in Tubåen formation in well 7220/7-1.*

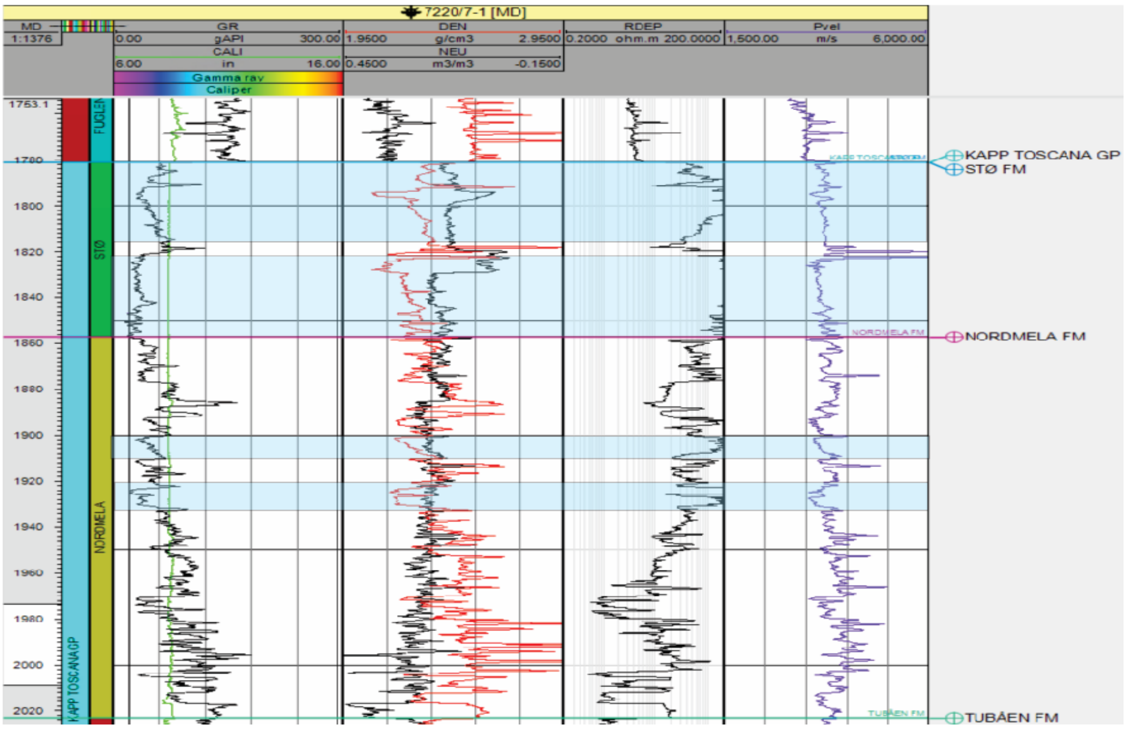


Figure 30. *Interval with HC bearing sediments in well 7220/7-1.*

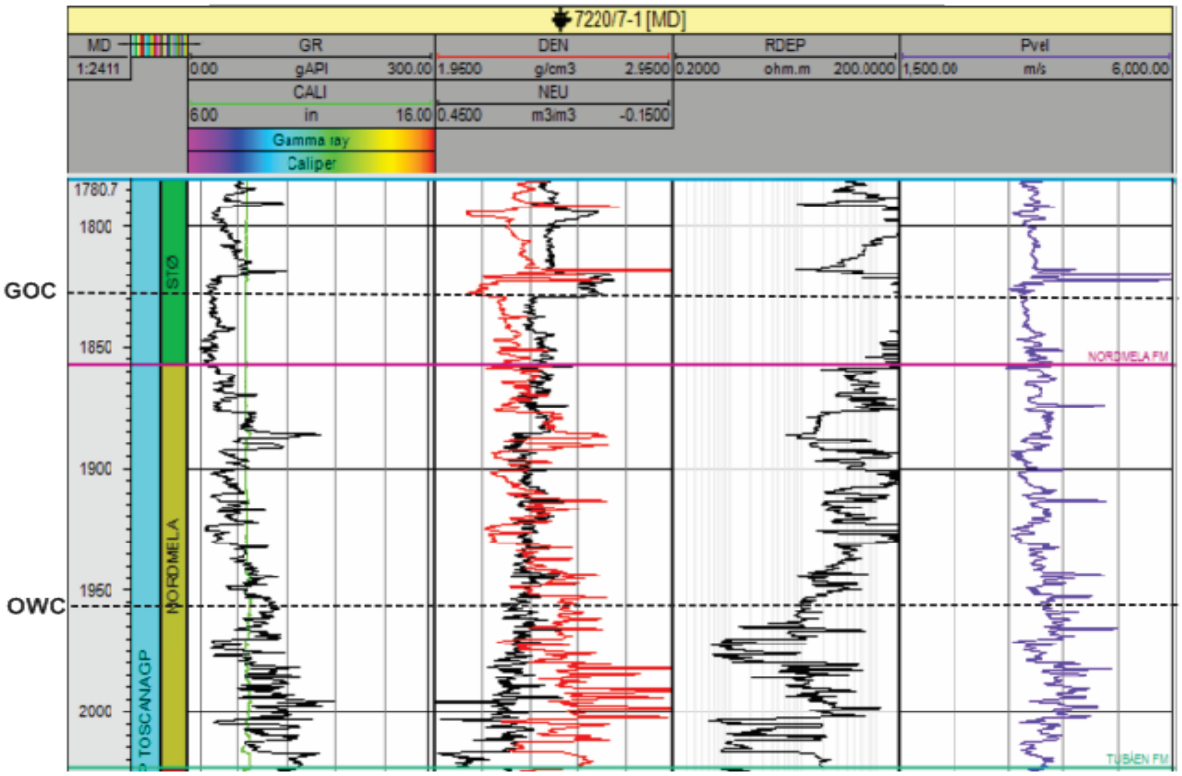


Figure 31. *Gas/oil contact at 1828 m and oil/water contact at 1956 m (black stippled line).*

Reservoir rock

Reservoir sandstone units in Stø and Tubåen Formations indicated by low GR value and cross-over trend between Density and Neutron logs (*Fig.32, 33*).

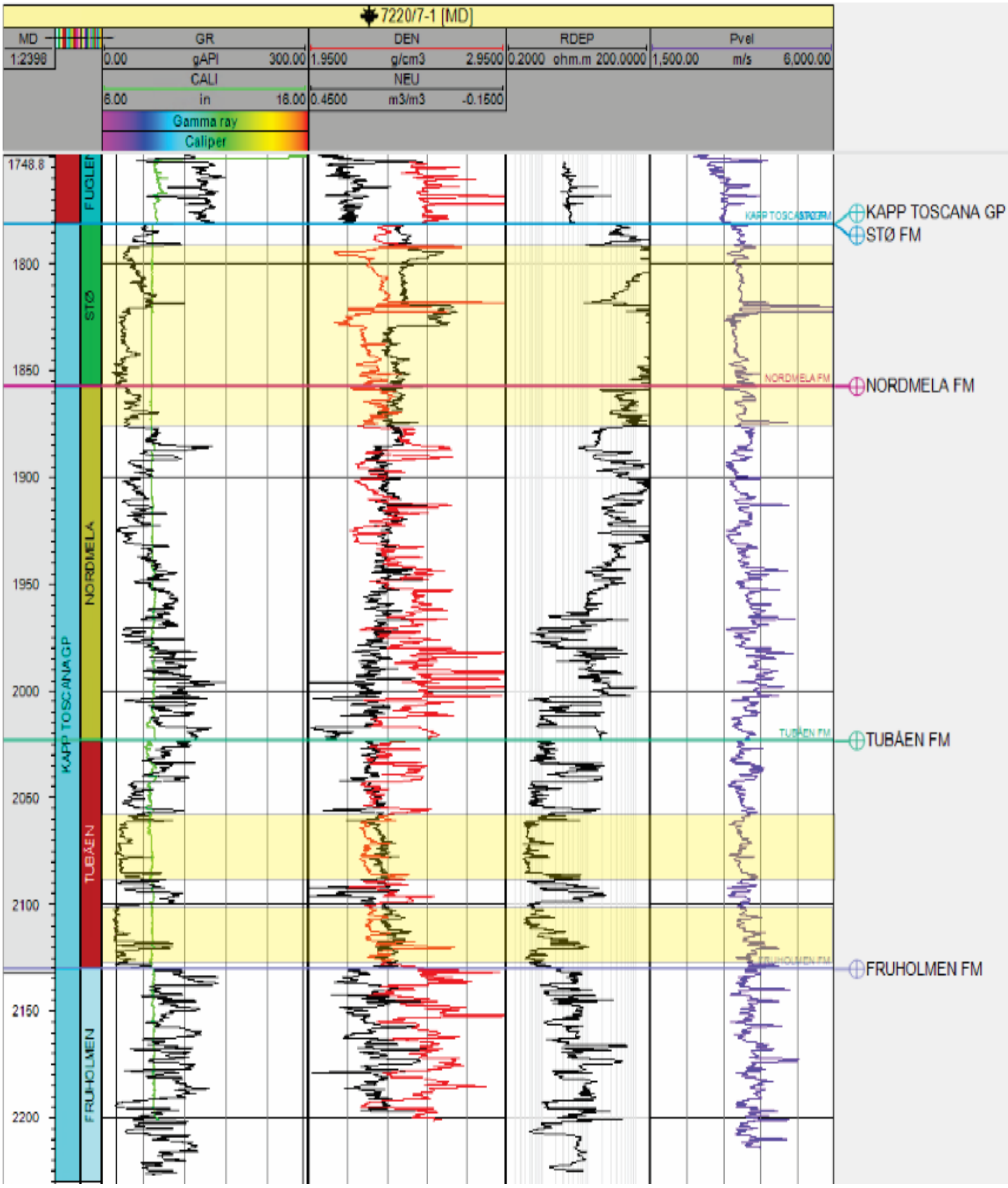


Figure 32. *The interval shows reservoir sandstones in well 7220/7-1.*

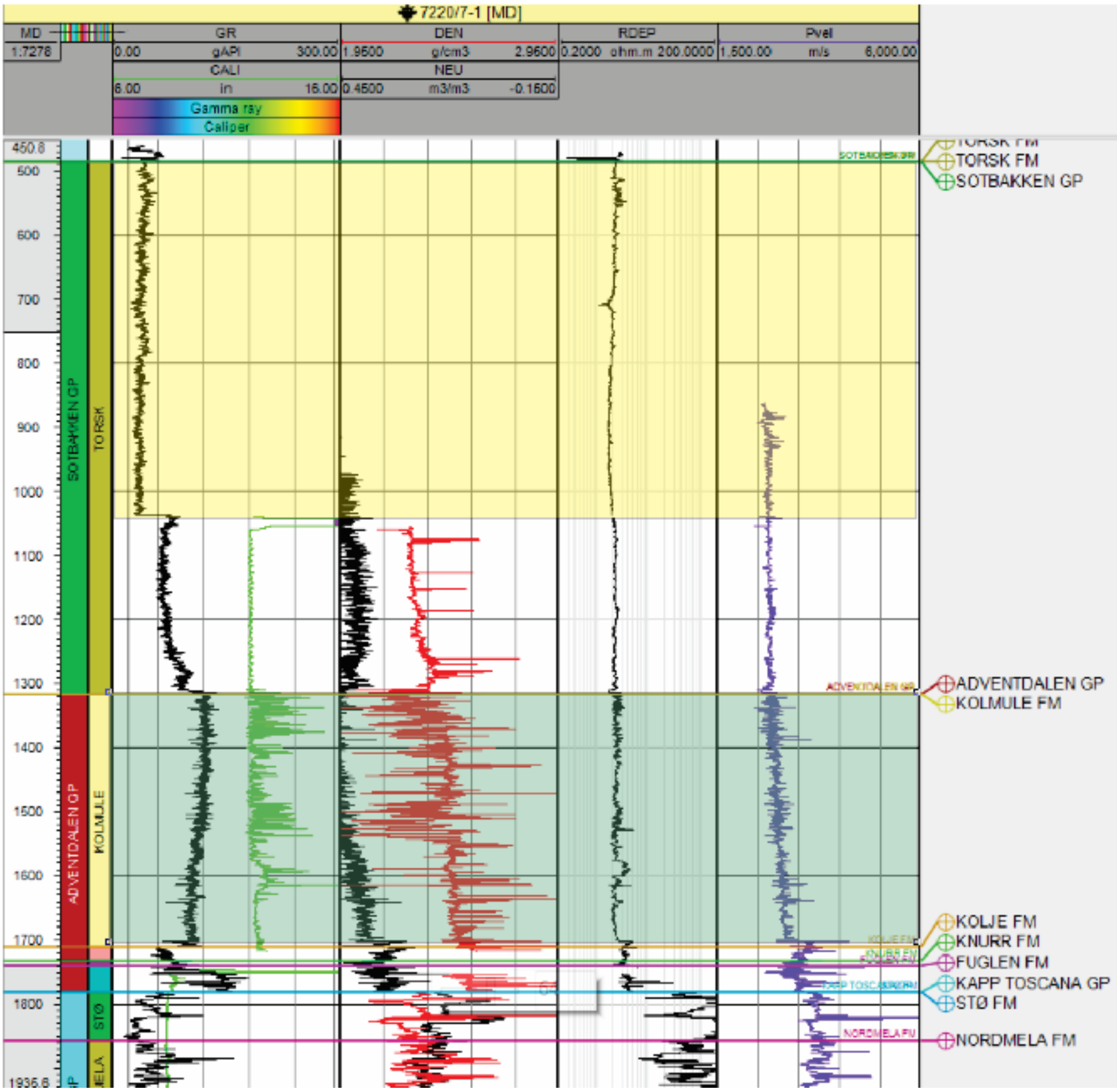


Figure 33. *The interval indicates reservoir sandstones and shale in well 7220/7-1.*

4.2.6 Well 7220/8-1

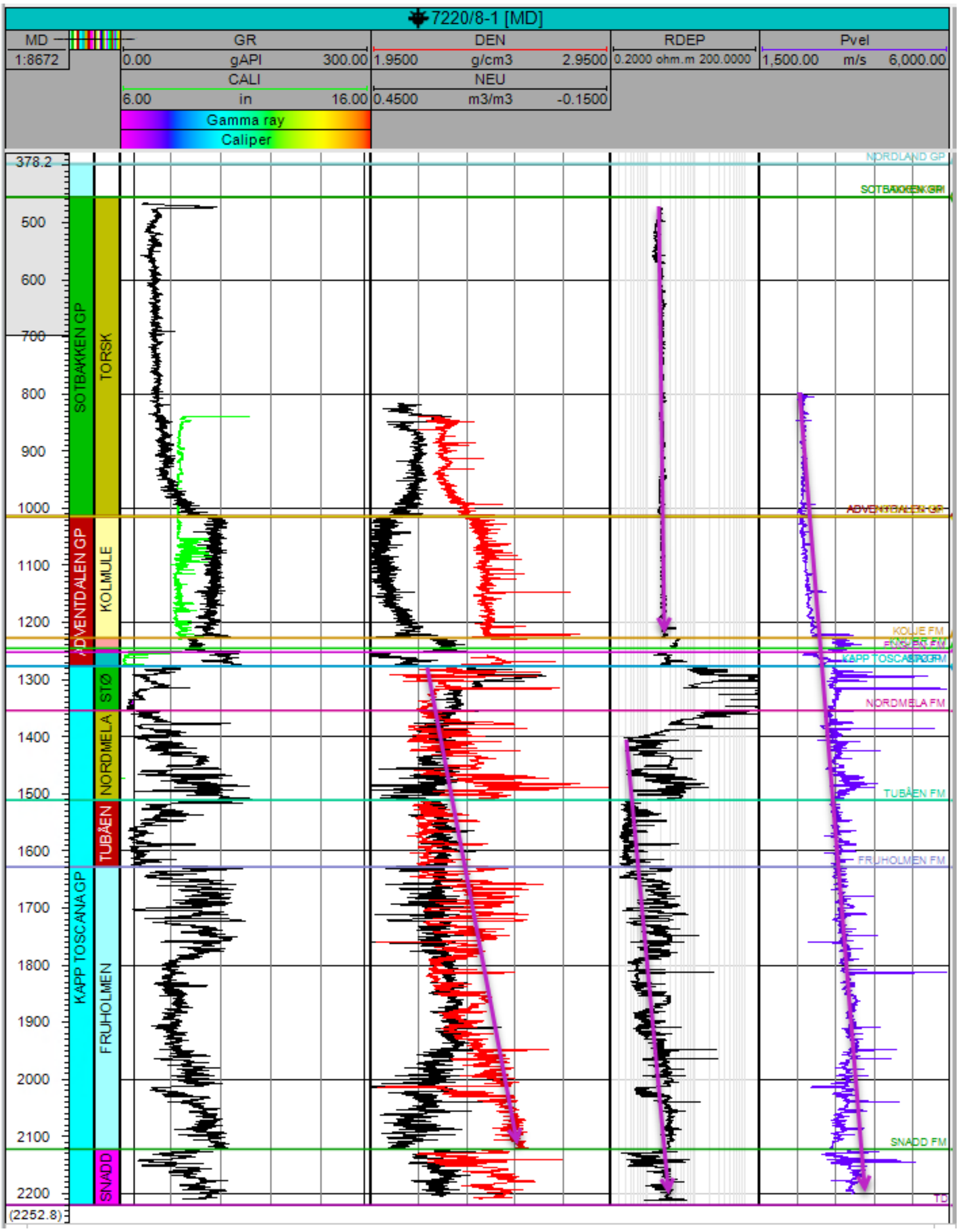


__Figure 34.__ GR/CALI, Den/NEU, RDEP, Pvel logs respons in well 7220/8-1.

The well 7220/8-1 has been drilled to 2222 m with location in the western part of Polheim Sub-platform and Loppa High. The main target was to improve HC potential in the Stø and Nordmela formations in the Skugard Prospect. The well penetrated 14 lithostratigraphic units (*Fig. 34*) and was permanently abonded as oil and gas discovery.

Vertical trends in well:

Transition zone between Snadd and Fruholmen Fm characterizes in increasing in GR value from 79gAPI to 122gAPI and decreasing in Pvelocity from 3600 – 3400 m/s. Reason to that can be explained by changing in lithology: from sand to shale.

GR in the middle part of the Fruholmen Fm (2000 – 1780m) is low, about 70gAPI. P-velocity is 3600m/s in this interval. Low GR and slightly increasing in velocity can be interpreted as sandstone deposited due to fluvial depositional processes (Npd, 2017). Interval 1799-1653 m characterizes by increasing in GR(139gAPI), Resistivity and slightly P-velocity decreasing (3450m/s) detects shale interval deposited in marine environment. Transition zone between Tubåen and Nordmela Fm (1510m) shows in sharp increasing in GR (134gAPI) and separation between NEU and DEN log. This transition zone can be interpreted as changing from sand to claystone deposited in tidal flat to flood plain environment (Npd, 2017).

Source rock zone. It has been detected GOC at 1312m and OWC at 1395m in Nordmela Fm and Stø Fm (*Fig. 35*). According NPD(2017) Nordmela Fm containes 83m thick oil column (OWC at 1395m) and Stø Fm contains 37m thick gas column (GOC at 1312m).

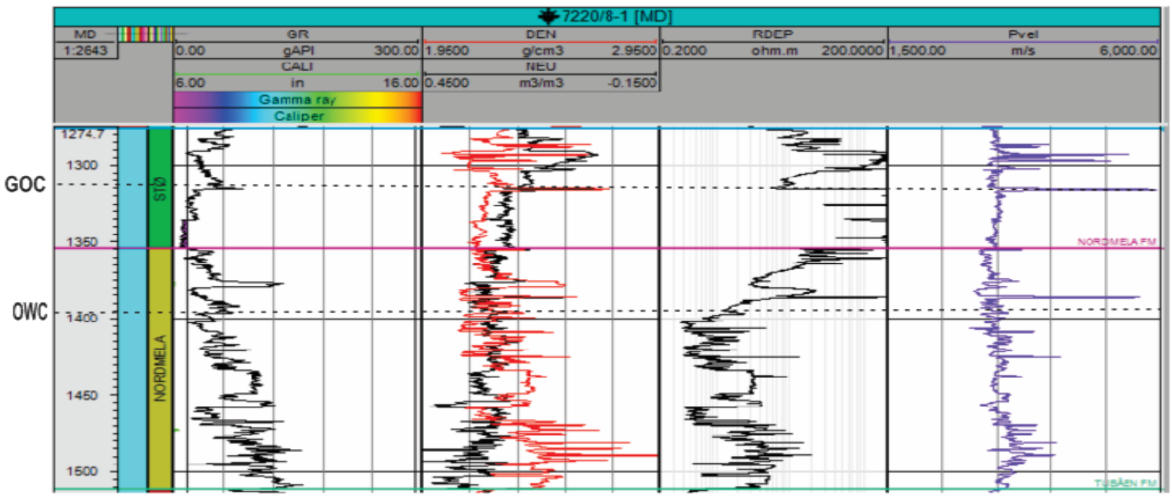


Figure 35*. Black dotted lines showing GOC at 1312m and OWC at 1395m in well 7220/8-1.*

Reservoir rock zone.

Reservoir rock zones detect in Tubåen, Nordmela and Stø Formations at depth interval 1628 – 1592m, 1585 – 1550m (Tubåen Fm), 1665 – 1457m, 1408 – 1402m, 1386 – 1379m (Nordmela Fm) and 1358 – 1315m (Stø Fm) Those intervals are characterize by low GR value (10-20 GAPI), cross-over trend between DEN and NEU logs (*Fig.36*).

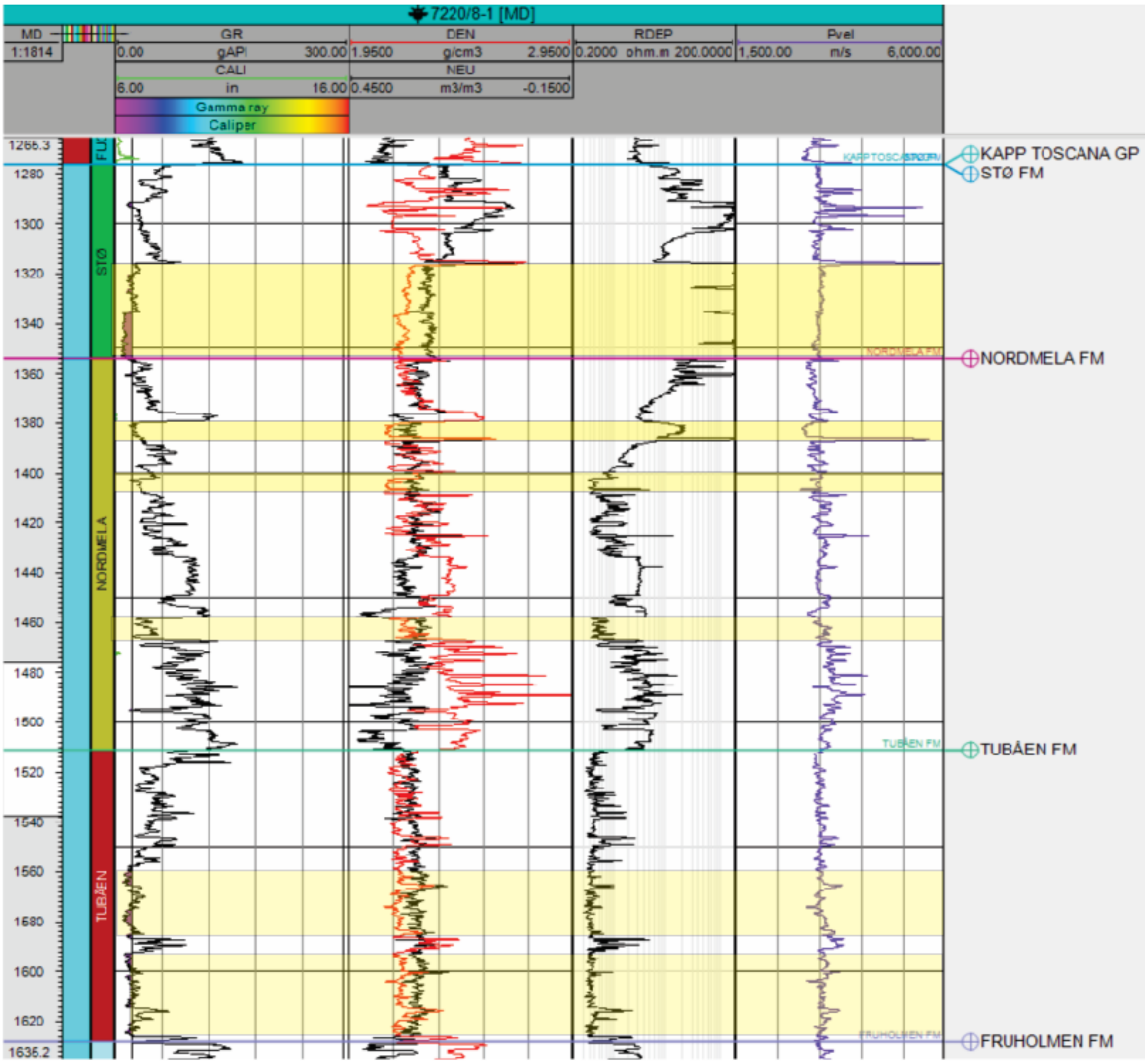


Figure 35. *Interval with reservoir rock sediments in well 7220/8-1.*

4.2.7 Well 7220/5-1

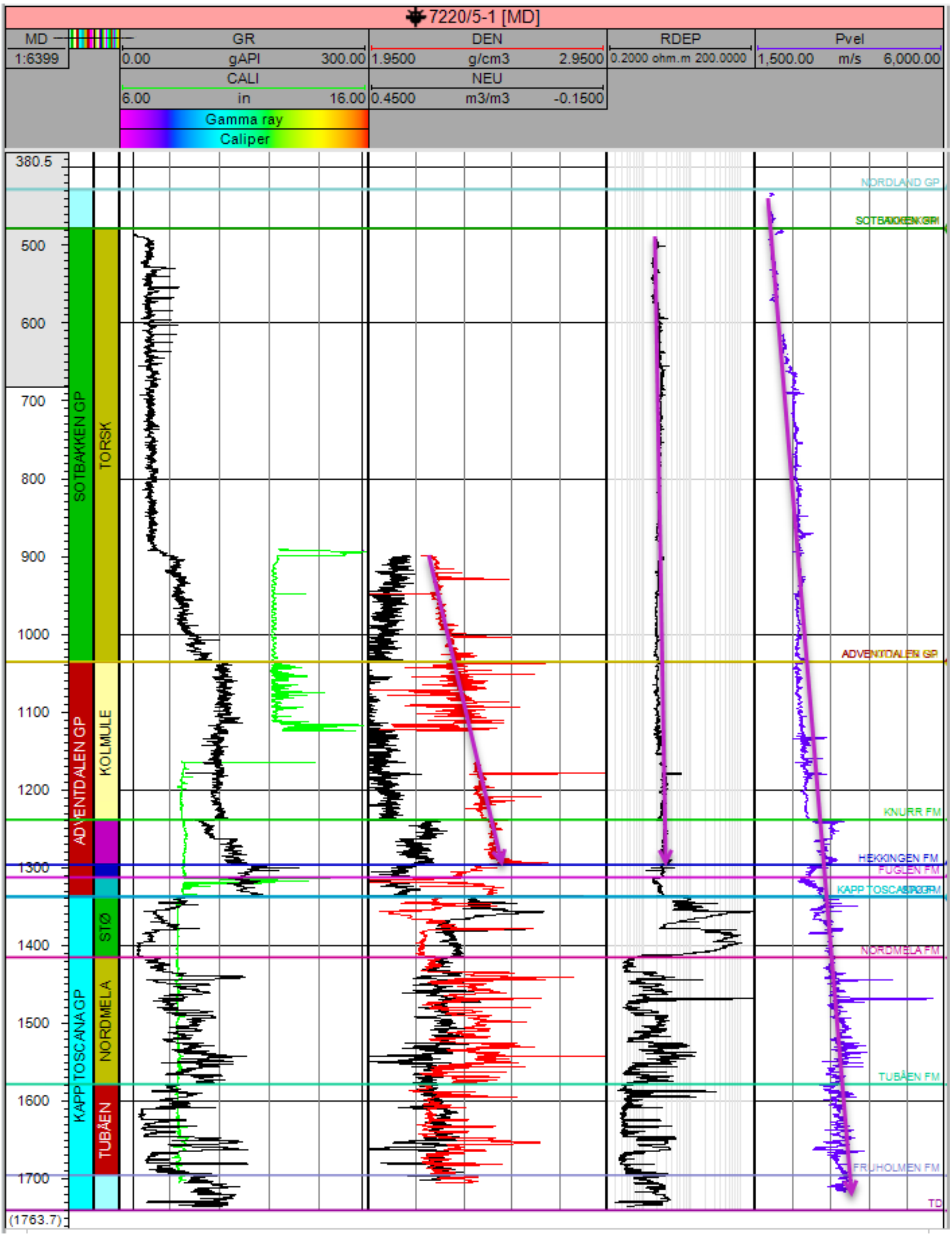


Figure 36. *GR/CALI, Den/NEU, RDEP, Pvel logs respons in well 7220/5-1*

The main objective of the well 7220/5-1 was to detect HC potential in the Skrugard middle segment. The well has been drilled to 1740 m in the Bjarmøyrenna Fault complex in west direction of the Loppa High. The well is permanently abandoned as an oil and gas appraisal well. It penetrates 13 lithological units (*Fig 36*).

Vertical trends in well. GR value at interval between 1740 – 1336m (Kapp Toscana Gr) characterized by uniform value. It has highest reading in Nordmela Fm (125gAPI). Density value is also relative high comparing with other depth intervals. In Knurr Fm (1297-1240m) density has the highest value (2.3gAPI).

Transition zone (1337m) between Stø and Fuglen Fm characterize by sharp increase in GR value (from 76gAPI – 165gAPI) and DEN value (2.2 to 2.5 g/cm3) This GR and Density responses can be explained by changing in lithology, from sandstones to pyritic mudstones with interbedded thin limestones, deposited in marine environments with ongoing tectonic movements (Npd.no). Interval between 1240 – 1035 m (Kolmule Fm) characterize by relative stable GR value (127gAPI) and Pvel (2600m/s) represents claystone/shale/siltstone interbeds. Transition zone (1035 m) between Kolmule and Torsk Fm defined by decreasing in GR from 127 to 105 gAPI.

Source rock zone.

Figure 37 highlighted gas-oil and oil-gas contact in Stø formation.

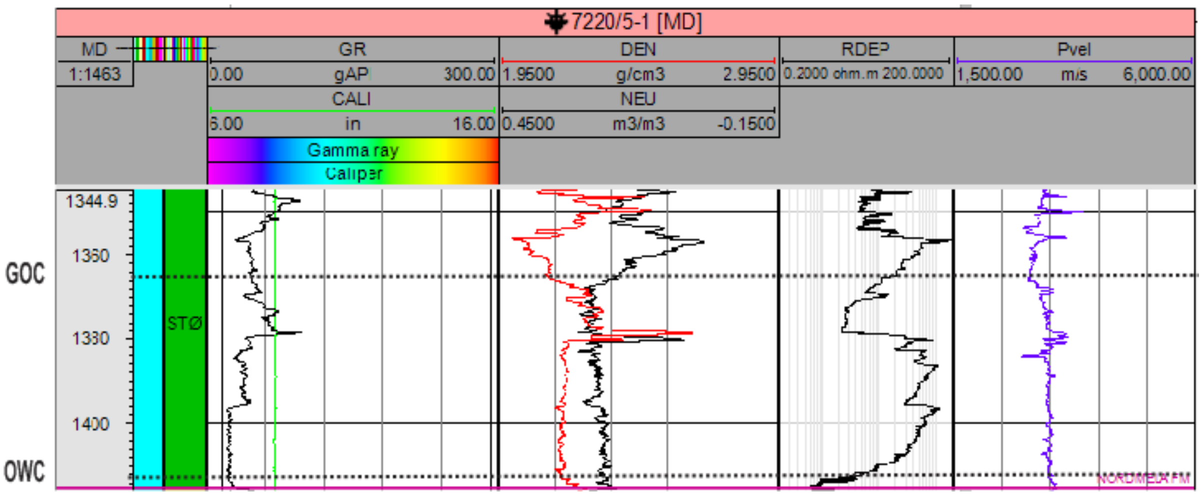


Figure 37. *Gas - oil and oil - water contact at 1365m and 1412m respectively in well 7220/5-1.*

Reservoir rock zone. Reservoir rock zone defined by low GR log reading in Tubåen, Nordmela and Stø Fm and highlighted by yellow colour in figure 38.

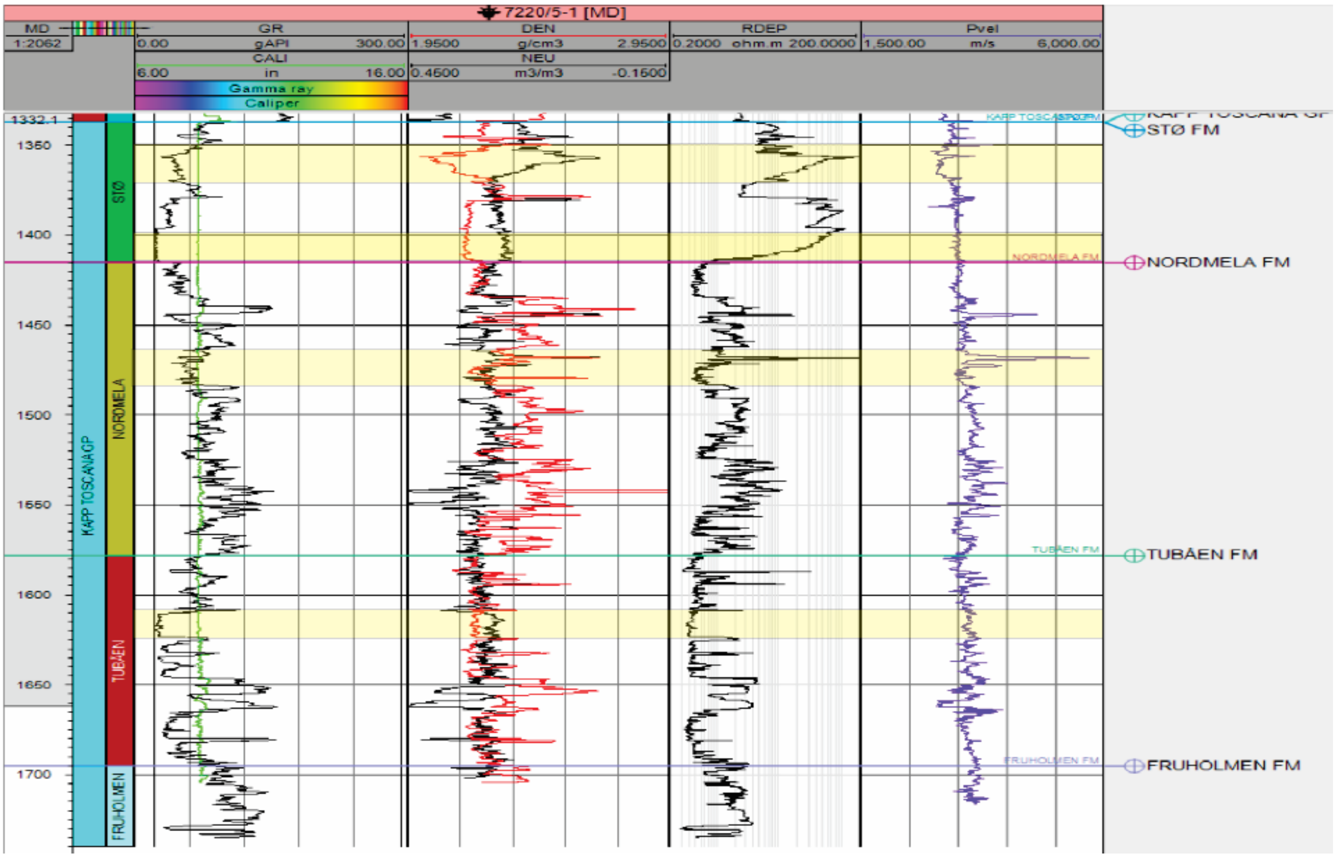


Figure 38. *Interval with reservoir rock in well 7220/5-1.*

Cap rock zone. Hekkingen Fm (1311 – 1295m) which comprises shale/claystone, consider as a good cap rock for HC (*Fig.39*).

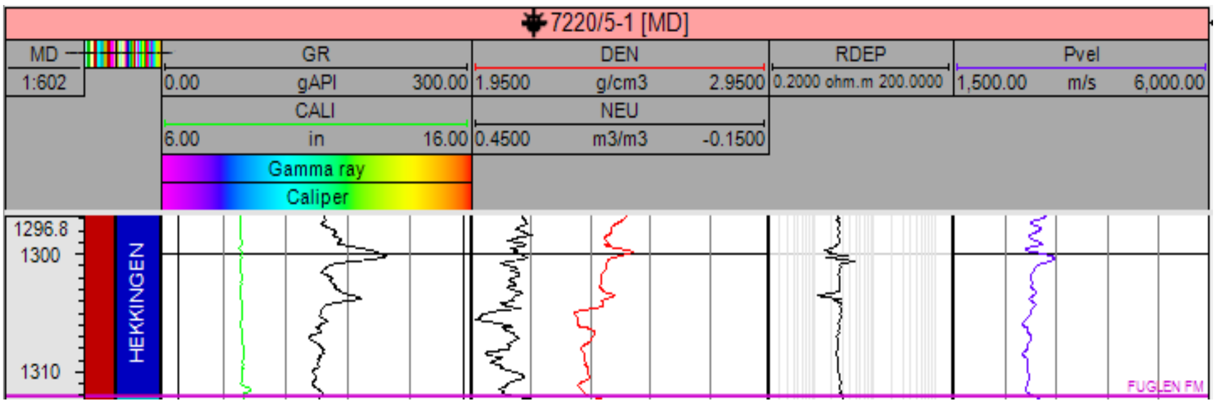


Figure 39. *Depth interval and logs with Hekking Fm.*

4.2.8 Well 7220/5-2

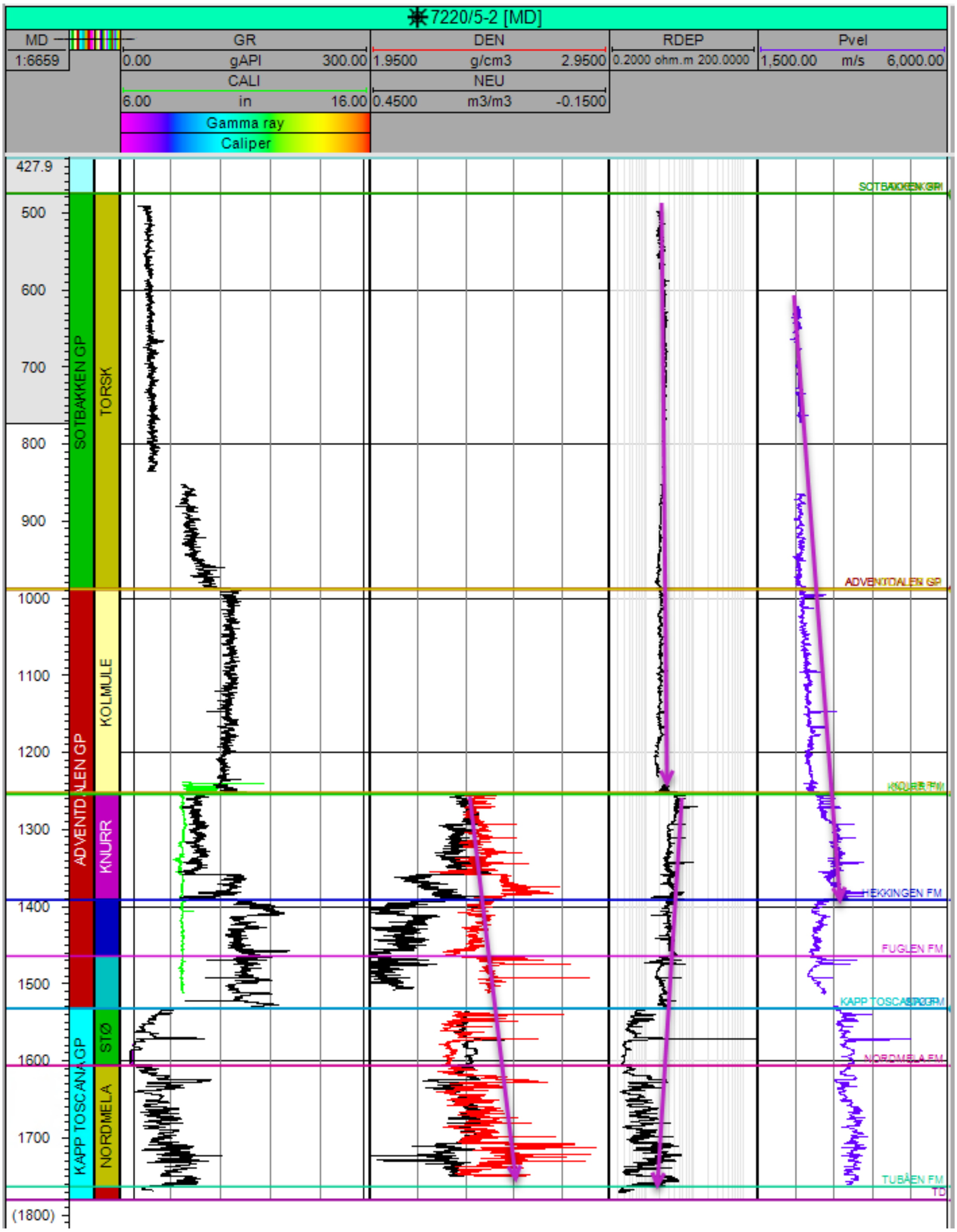


Figure 40. *GR/CALI, Den/NEU, RDEP, Pvel logs respons in well 7220/5-2.*

The main goal of well 7220/5-2 Nunatak was to detect HC in Knurr Formation (reservoir rocks of Cretaceous age). The second goal was to detect potential of sandstones (Intra Hekkingen Formation). The main depth of the well is 1780 m. Location of the well in the Polheim sub-basin what lies west of the Loppa High in the Barents Sea. The well was drilled by Statoil Petroleum As and was permanently abandoned as gas discovery. It penetrates 14 main lithostratigrafical units as showing in figure 40.

Vertical trends in well:

Interval between 1785 – 1606 m (Nordmela Fm) showing variable GR value from 49 – 80 gAPI. Pvel value is constant, approximately 3600m/s. Transition zone between Nordmela and Stø Fm characterize by decreasing in GR (13gAPI) and DEN(2.2g/cm3) at depth 1605m.

Transition zone between Stø and Fuglen Fm (1530m) marks by sharp increasing in GR (173gAPI) and decreasing in Pvel. Interval between 1530 – 1590 m showing high GR (147gAPI), variable DEN and apparent constant Pvel (2800m/s).

Transition zone between Hekkingen and Knurr Fm characterize by sharp decreasing in GR(from 152 to 84 gAPI), increasing in Pvel (from 2900 to 3600m/s). Interval between 1250 – 987m showing consant GR (130gAPI) and Pvel (2600m/s). Interval between 835 – 491 m (middle-upper Torsk Fm) showing very low GR (34gAPI)

Source rock zone. Source rock zone i Hekkingen Fm consists of shale (*Fig. 41*), which deposited in a deep shelf with partly anoxic condition (Npd, 2017).

Reservoir rock zone. Middle and Upper Knurr Fm represents a good reservoir rock, which consits of sandstones. GWC (*Fig. 41*) was indicate at 1372m in low Knurr Fm (Npd, 2017).

Cap rock zone. Kolmule Fm, which comprise claystone and shale serve as a cap rock zone for HC (*Fig.41*).

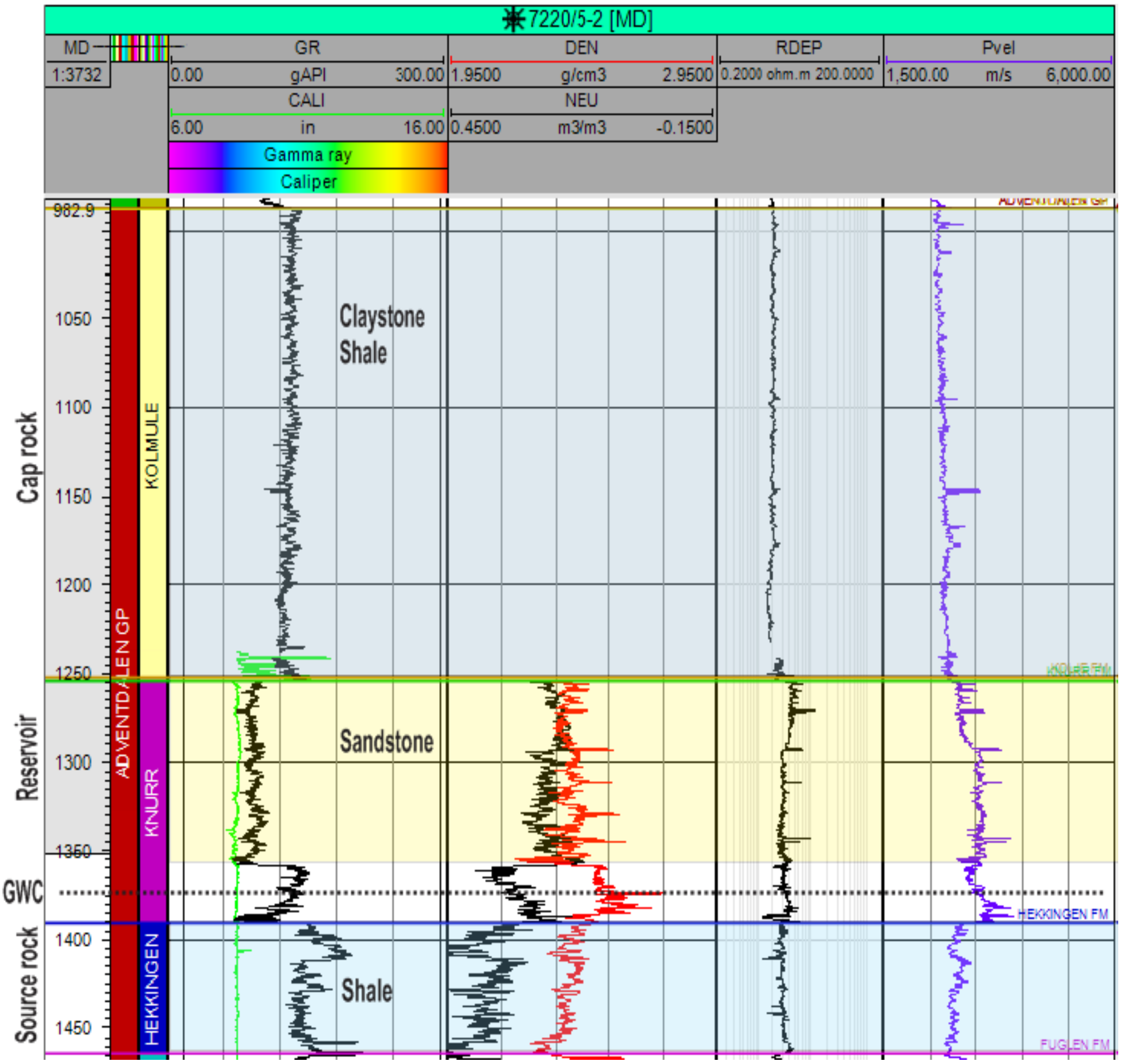


Figure 41. *Interval with source rock zone, reservoir and cap rock in well 7220/5-2. GWC detected by black stippled line at 1372m.*

4.2.10 Well 7222/6-1S

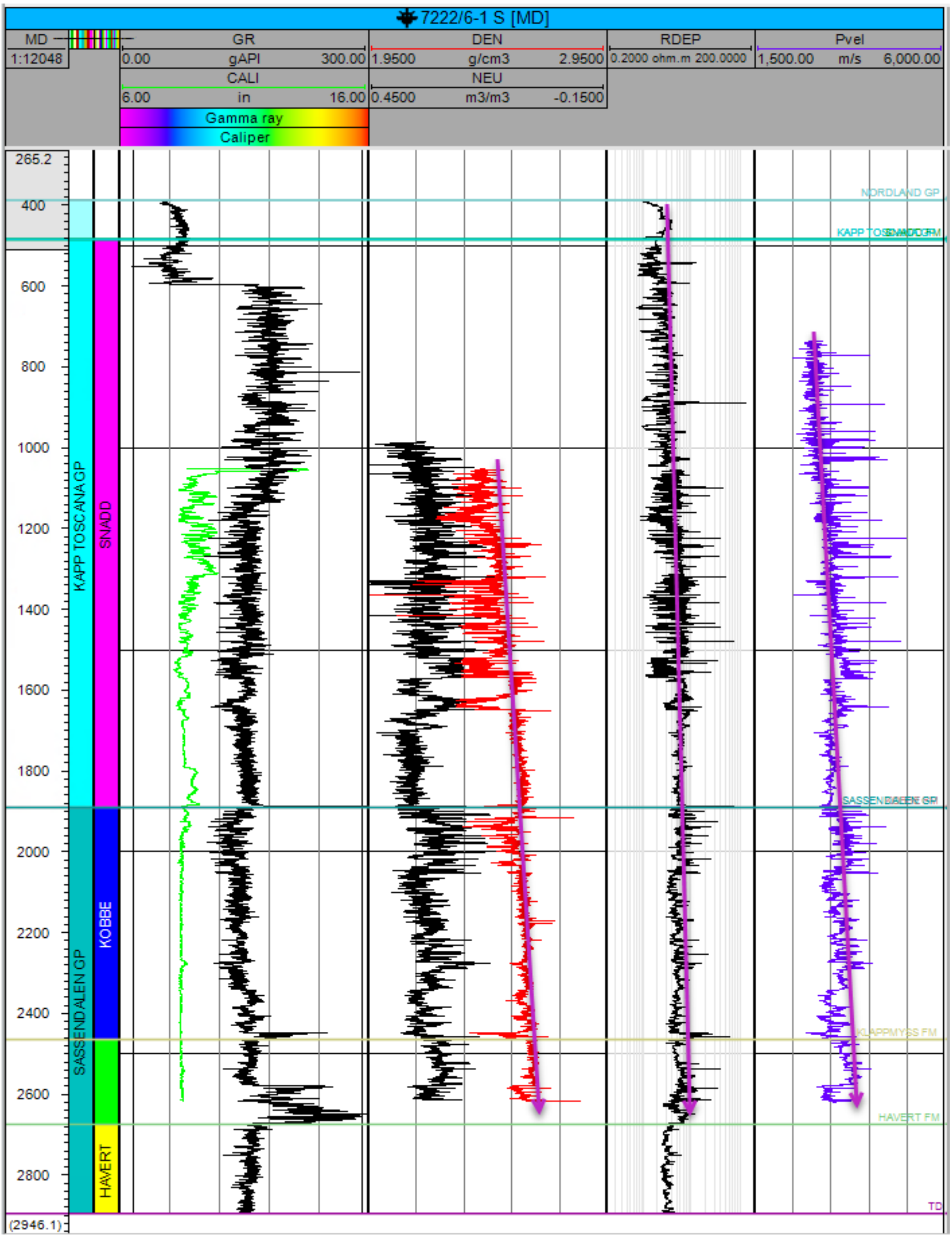


Figure 43. *GR/CALI, Den/NEU, RDEP, Pvel logs respons in well 7222/6-1S*

Wellbore 7222/6-1S Obesum was drilled by Statoil Hydro Petroleum AS with main target to detect HC in the Snadd Formation and in the Kobbe Formation. Geological location of well is Bjarmeland Platform, south of the Swaen Graben, east of the Loppa High in the Barents Sea. The well was permanently abandoned as an oil and gas discovery. It penetrates 7 lithostratigraphical units as shown on figure 43.

Vertical trends in well. Depth interval between 2900 – 2672m (Havert Fm) characterise by relative constant GR value (157 gAPI). Transition zone between Havert Fm and Klappmyss Fm showing sharp increasing in GR (from 157 to 235 gAPI) This is due to changing in lithology. Depth interval between 2575 – 1890 m showing GR value 135gAPI. DEN is relative constant and has value 2.5g/cm3. Transition zone between Kobbe and Snadd Fm (1890 m) indicates slightly increasing in GR from 150 to 165 gAPI. Depth interval between 1890 – 1140m shows GR 168gAPI. Pvel is relative constant (3400m/s)**.** GR decreases from 168gAPI to 175gAPI at depth interval 1140 – 600m.

Source rock zone. Chemical analysis indicate source rock (*Fig.44*) in Klappmyss Fm at depth interval 2579 – 2675 m and Kobbe Fm at depth 2447 - 2465 m (Npd, 2017). This interval characterizes by high GR value, low DEN (2.4gAPI) and low Pvel (2000m/s) at depth 1887 m. Source rock in Klappmyss Fm is gas prone, but source rock in Kobbe Fm is very rich oil prone source rock (Npd, 2017).

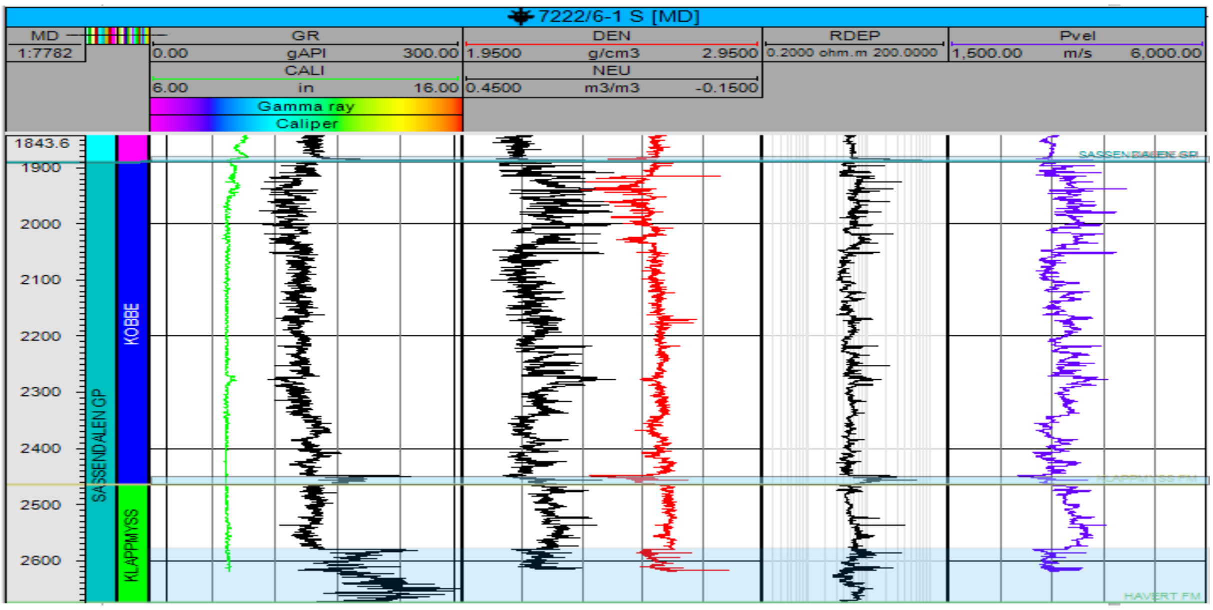


Figure 44. Source rock intervals in Klappmyss and Kobbe Fm, highlighted by light blue colour.

Reservoir rock zone. Channelized strings of sandstones in Snadd Fm and thin sandy beds in Kobbe Fm consider as sandstones with reservoir properties (Npd, 2017). Some larger intervals are highlighted by yellow colour as showing on (*Fig. 45*). HC has been proven in this sandstones strings (Npd, 2017).

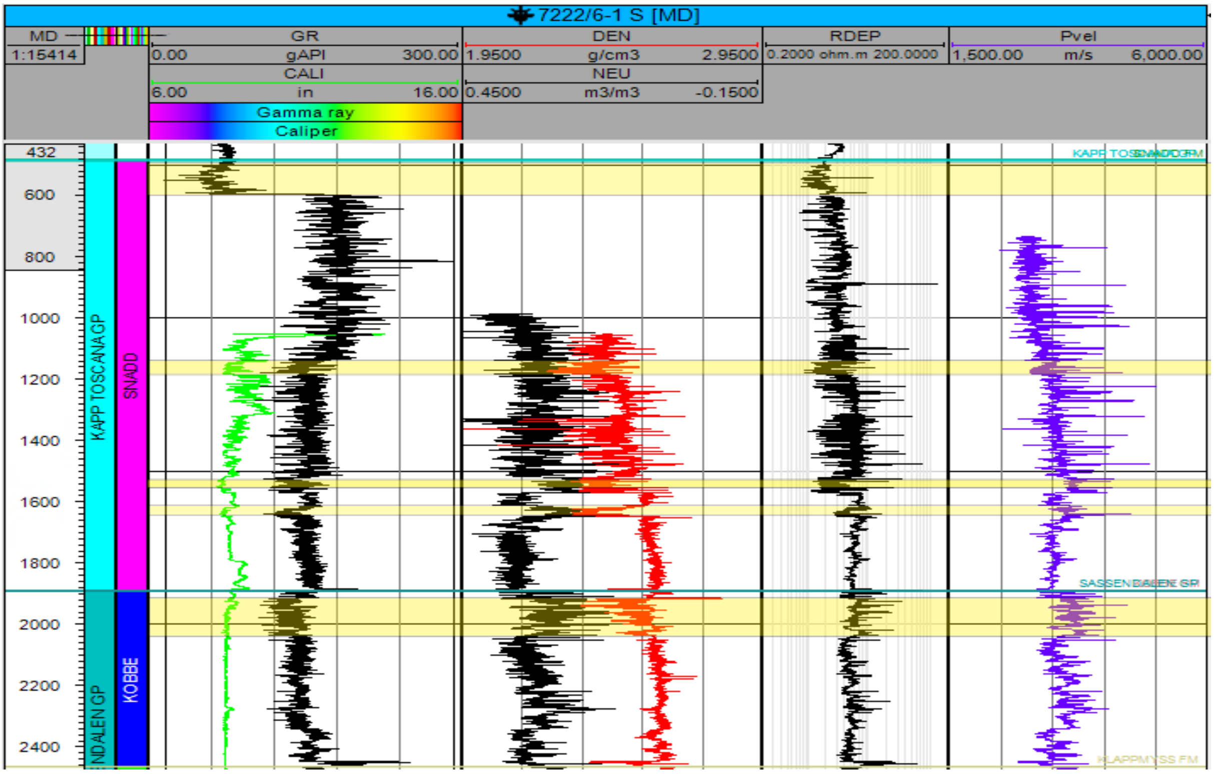


Figure 45. *Reservoir rock zone in well 7222/6-1S, higtlighted by yellow colour.*

Cap rock zone. Interval between 1120 – 591 m, with high GR reading at 185gAPI (upper Kapp Toscana Gr) and probably interval between 498 – 382 m, with GR at 90 gAPI (Nordland Gr) can be consider as a cap rock zone for this wellbore (*Fig. 46*).

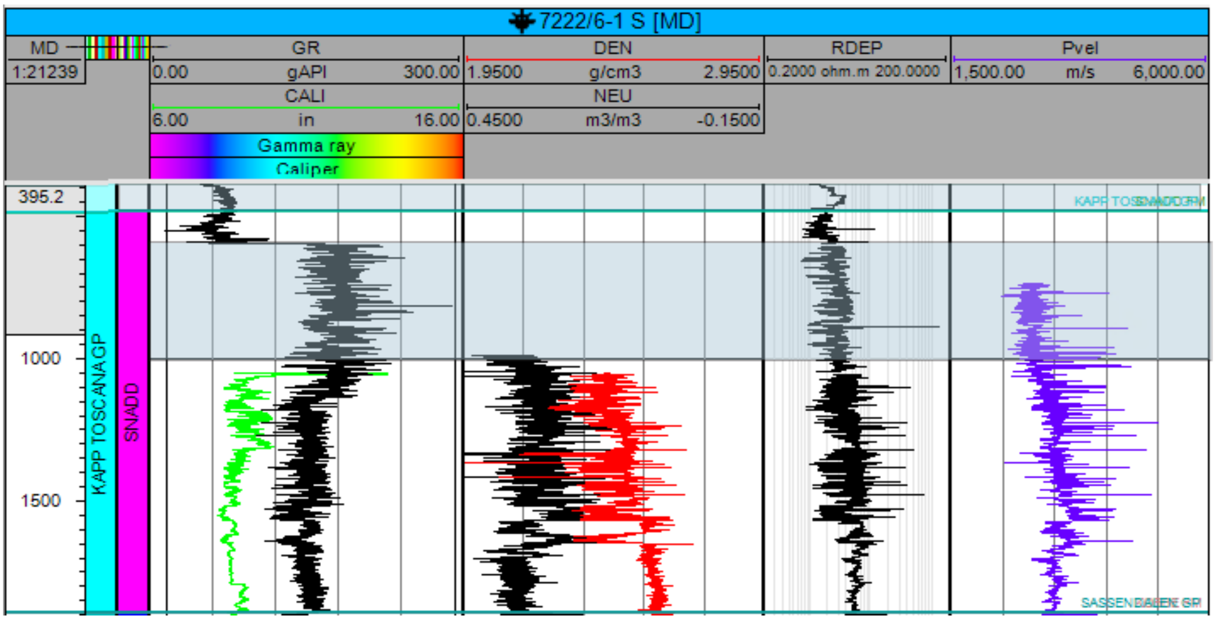


Figure 46. *Interval shows Cap rock zones (highlighted by light grey colour) in well 7222/6-S1.*

4.2.9 Well 7220/6-1

The well 7220/6-1 was drilled by Norsk Hydro Produksion AS in the Loppa High with main target to improve reservoir properties and HC potential in carbonates of Carbon and Permian age in Gipsdalen Group (Npd, 2017). Evaluation of Triassic formation was a secondary target. The well was drilled to 1540 m and penetrates 7 lithostratigraphical units. Gipsdalen Gr has been excepted from well section since it belongs to Paleozoic period, so just Kapp Toscana with Snadd Formation are showing in figure 42 since those groups belongs to Mesozoic. The well was abandoned as a dry well with shows.

Vertical trends in well.

GR in Snadd Fm is about 137gAPI at depth interval 1113 – 546 m indicates siltstone / shale lithology. GR value decreasing from 546 m to 400 m (137 - 45 gAPI) indicates transition from shales to sandy lithology in Lower Nordland Group.

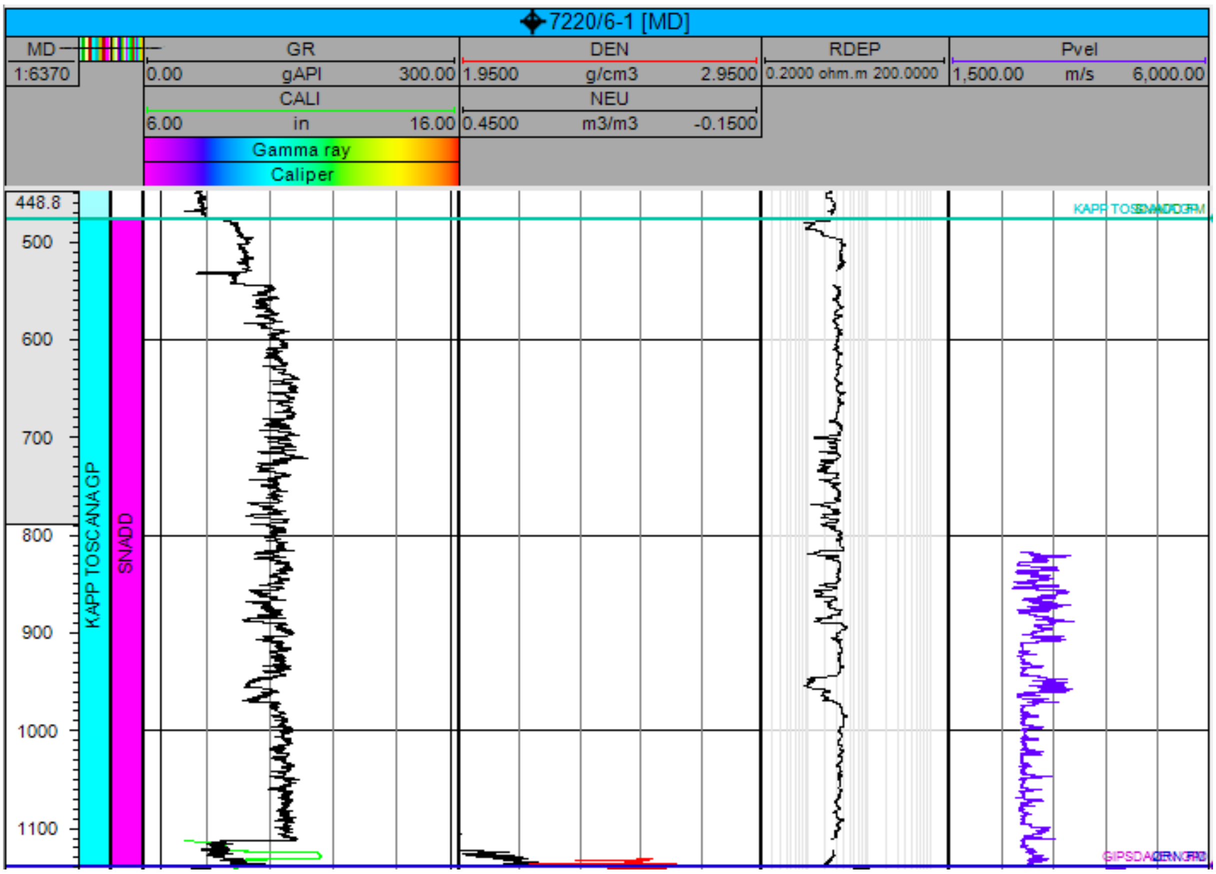


Figure 42. *GR/CALI, RDEP, Pvel logs respons in well 7220/6-1.*

4.2.11 Well 7224/6-1

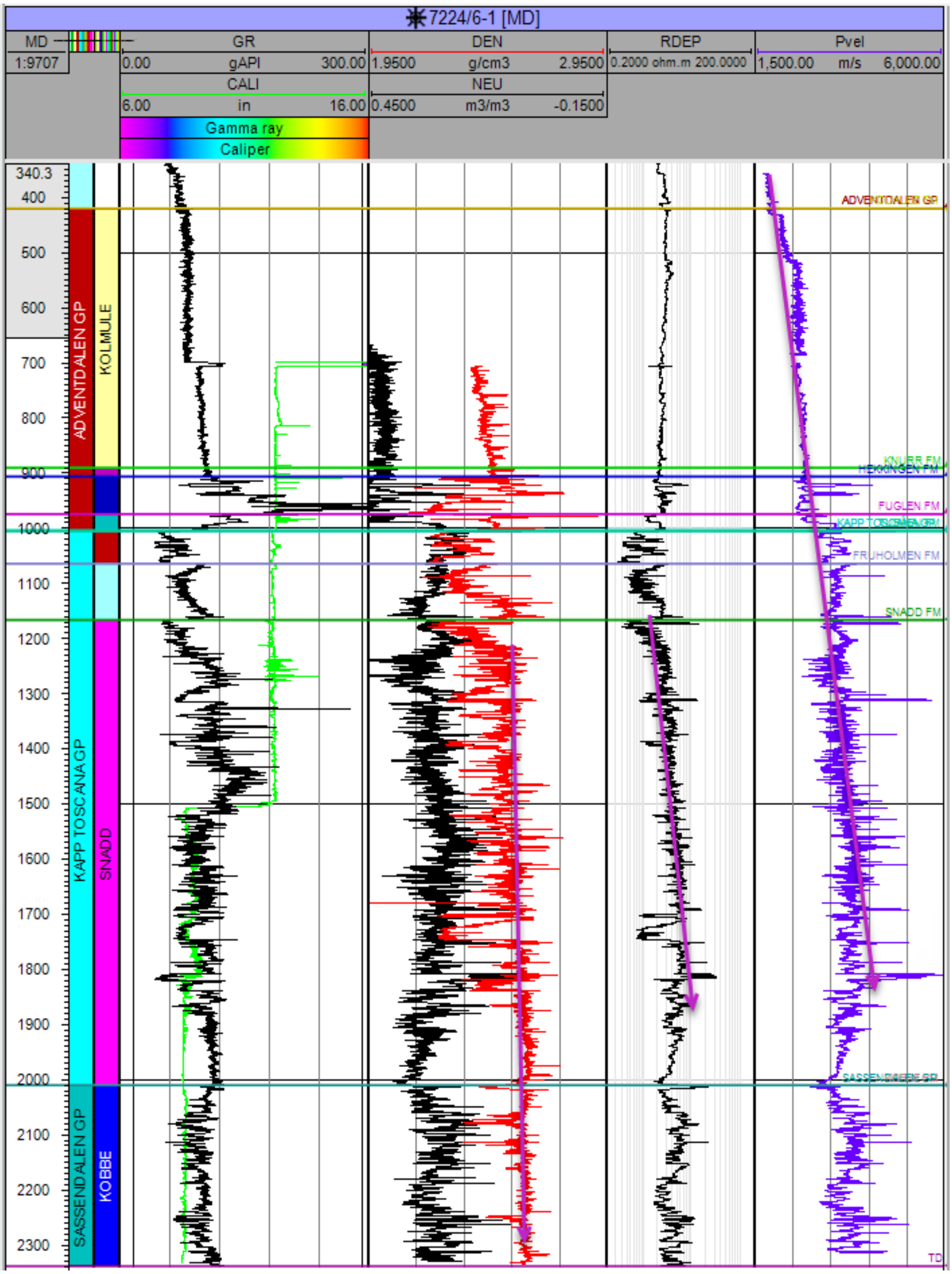


Figure 47. Showing GR/CALI, Den/NEU, RDEP, Pvel logs respons in well 7224/6-1.

The well 7224/6-1 Arenaria was drilled by StatoilHydro petroleum AS with target to detect HC in Stø, Nordmela, Tubåen Formations (Jurassic age) and Snadd Formation (Triassic age). Geological location of the well is Bjarmeland Platform, south of the Swaen Graben, north-east of the Loppa High and west of the Nordkapp Basin (Npd, 2017). Gas discovering in four levels in the Kobbe Fm at 2015 m, 2080 m, 2113 m, 2252 m highlighted in figure 52. The depth of the well is 2338 m. It penetrates 12 lithostratigrafical units, showing on figure 47. The well was permanently abandoned as a gas discovery (Npd, 2017).

Vertical trends. Interval between 2340 – 2009 m (Kobbe Fm) characterise by GR which varies between 70 – 100gAPI. Density is quite same, about 2.5g/cm3, Pvel value changes due to lithological composition of the group which comprise shale, siltstones and carbonate cemented sandstones deposited in transgressive environment. It low at depth interval 2239 – 2160m (3200m/s) and highest at depth interval 2159 – 2058 m (3800m/s). Transition zone between Kobbe and Snadd Fm at 2010m characterise by slightly decreasing in GR (107 to 101 gAPI), Pvel (3600 to 3300m/s) and some little increasing in DEN (2.4 – 2.5 gAPI).

Interval between 2004 – 1164 m (Snadd Fm) showing variable GR value. It stable at the base of Snadd Fm (2004 – 1885 m) and shows value at 110 gAPI. Interval between 1164 – 1201m showing variable GR values. It lowest at depth interval 1820 – 1807 m (72gAPI), at the same interval DEN value increase (2.6gAPI) and Pvel increase 5400m/s. This interval possibly can represent mixture of sandstone with siltstone. Highest GR reading at interval between 1500 – 1429 m (150 gAPI).

Reservoir rock zone. Well penetrated jurassic reservoir sandstones in Tubåen Fm, which were deposeted under shallow marine conditions. Alluvial and shallow marine sandstones in Fruholmen and Snadd Fm (*Fig. 48*) assosiates with prograding shelf system are indicate as reservoir too (Npd, 2017).

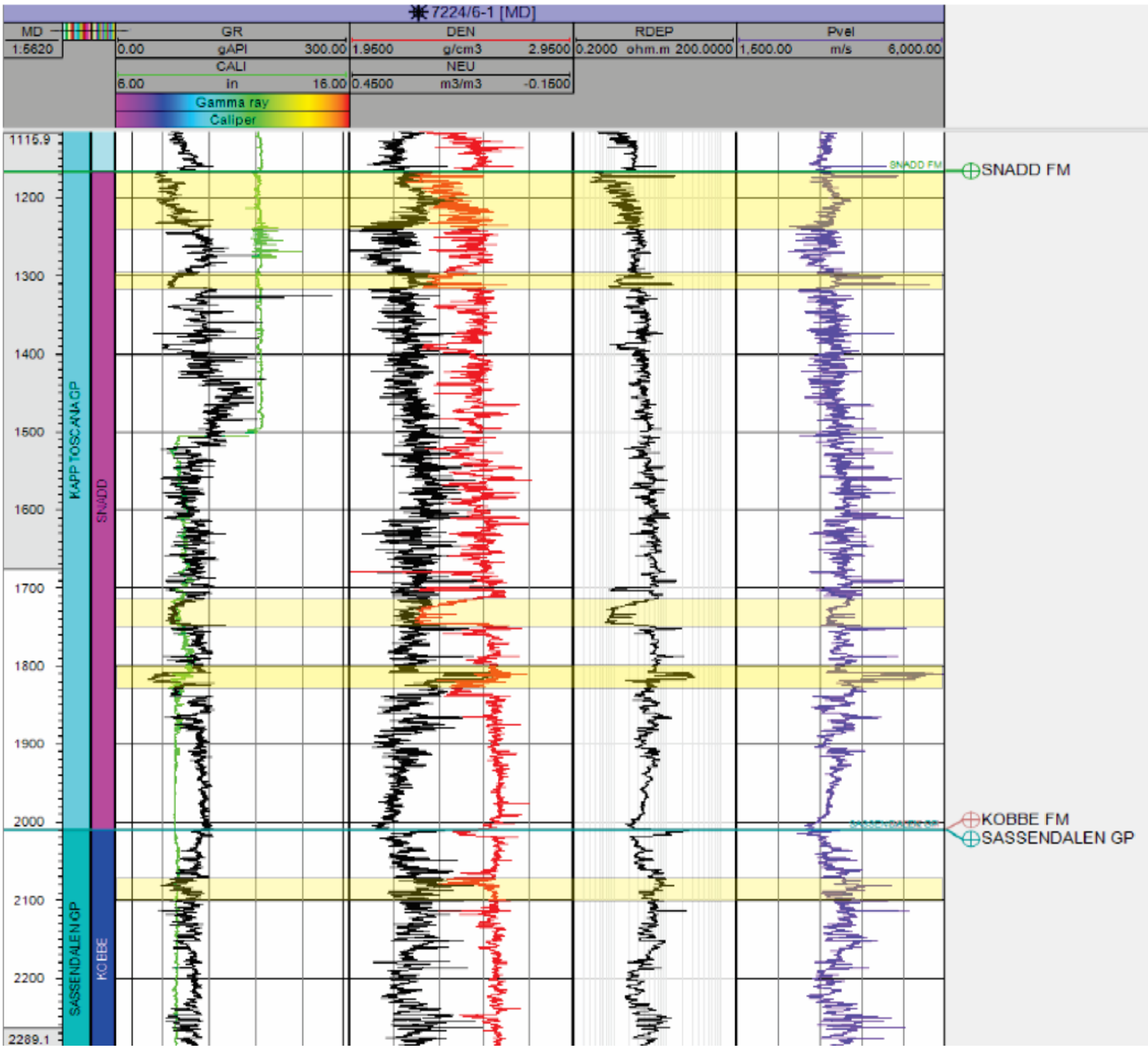


Figure 48. *Reservoir rock (highlighted with yellow colour) in well 7224/6-1.*

Cap rock. Shales from Hekkingen Fm serves as a cap rock for HC (*Fig.49*).

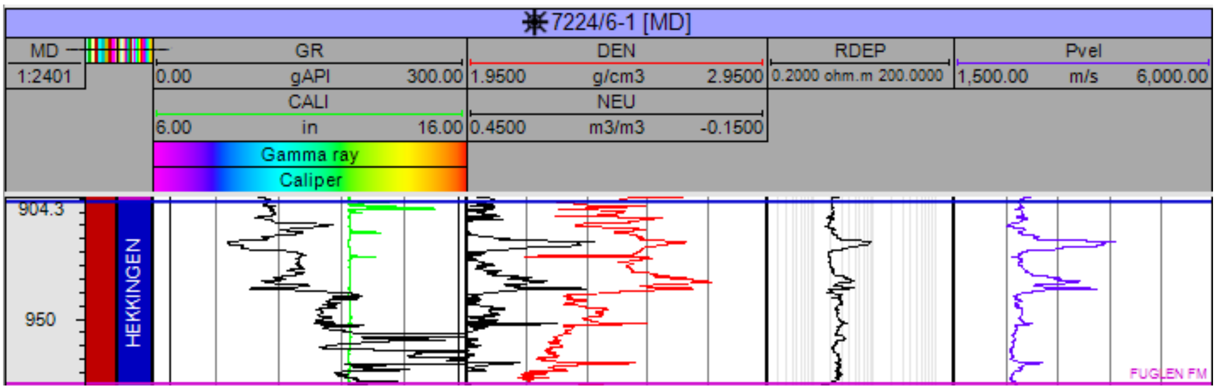


Figure 49. *Interval with Hekking formation in well 7224/6-1.*

HC zone. Low saturated gas (*Fig. 50, 51, 52*) have been indicated in the Tubåen Fm at depth interval 1020 – 1022 m and 1042 – 1034 m and in Kobbe Fm at depth 2015 m, 2080 m, 2113 m, 2252 m (Npd.no 2017).

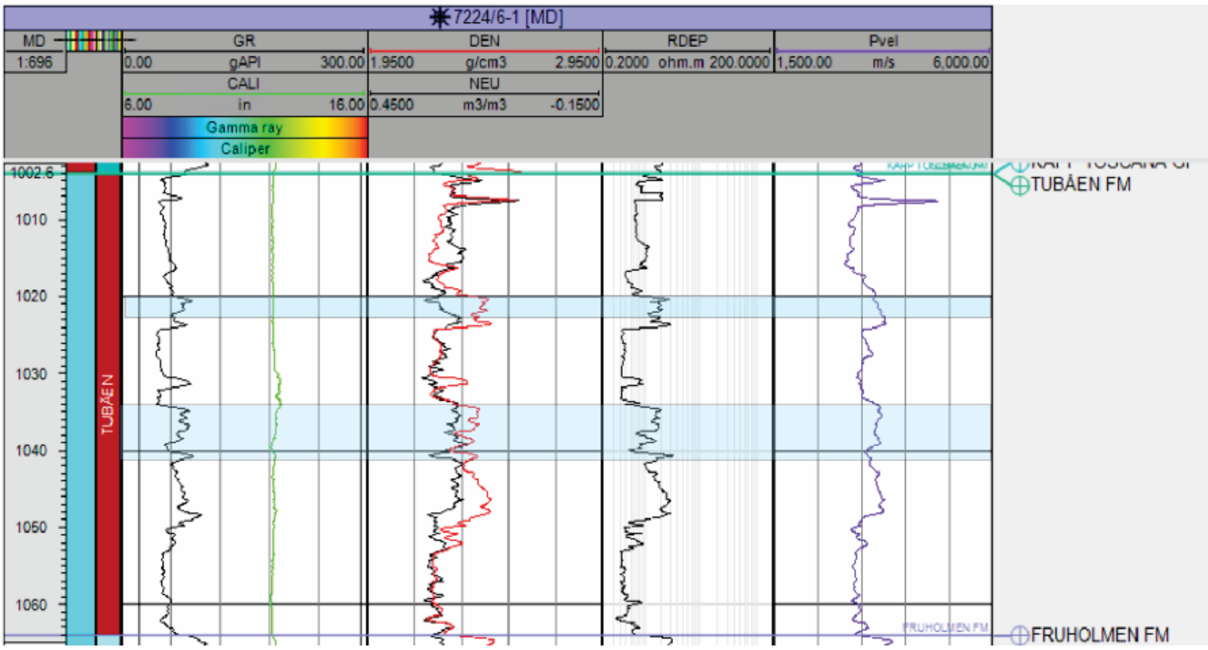


Figure 50. *HC bearing sediments (highlighted with light blue colour) in well 7224/6-1.*

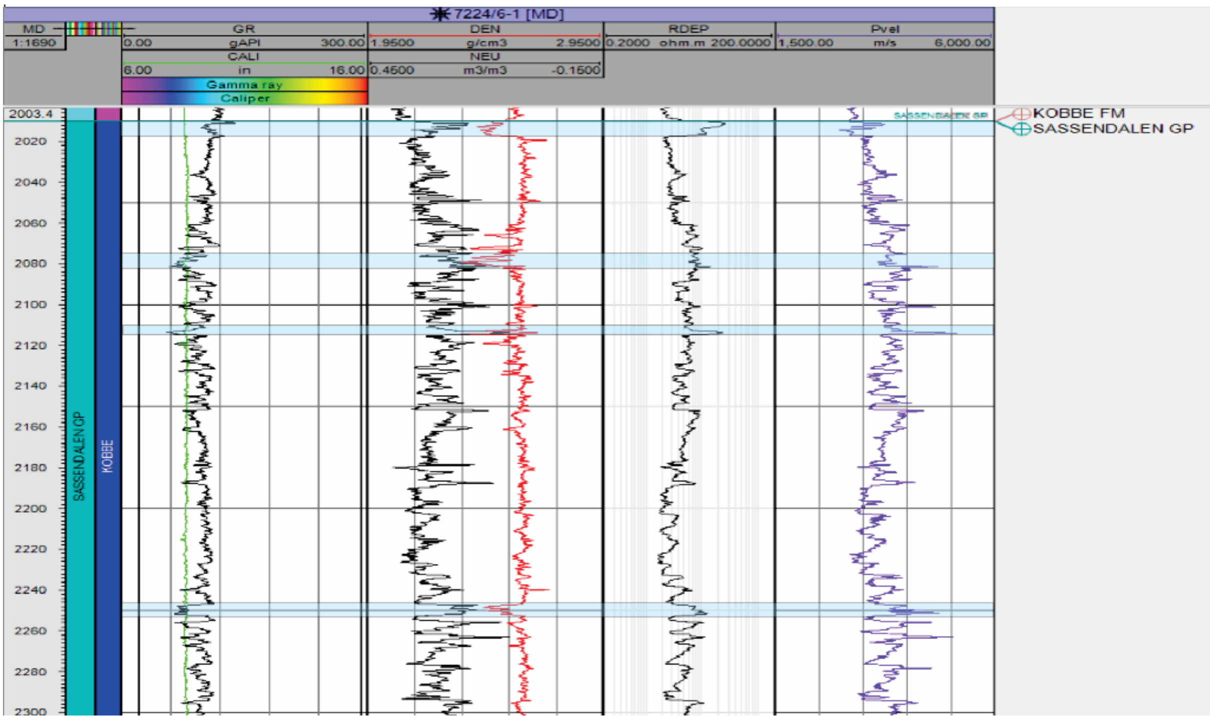


Figure 51. *HC bearing sediments (highlighted with light blue colour) in well 7224/6-1.*

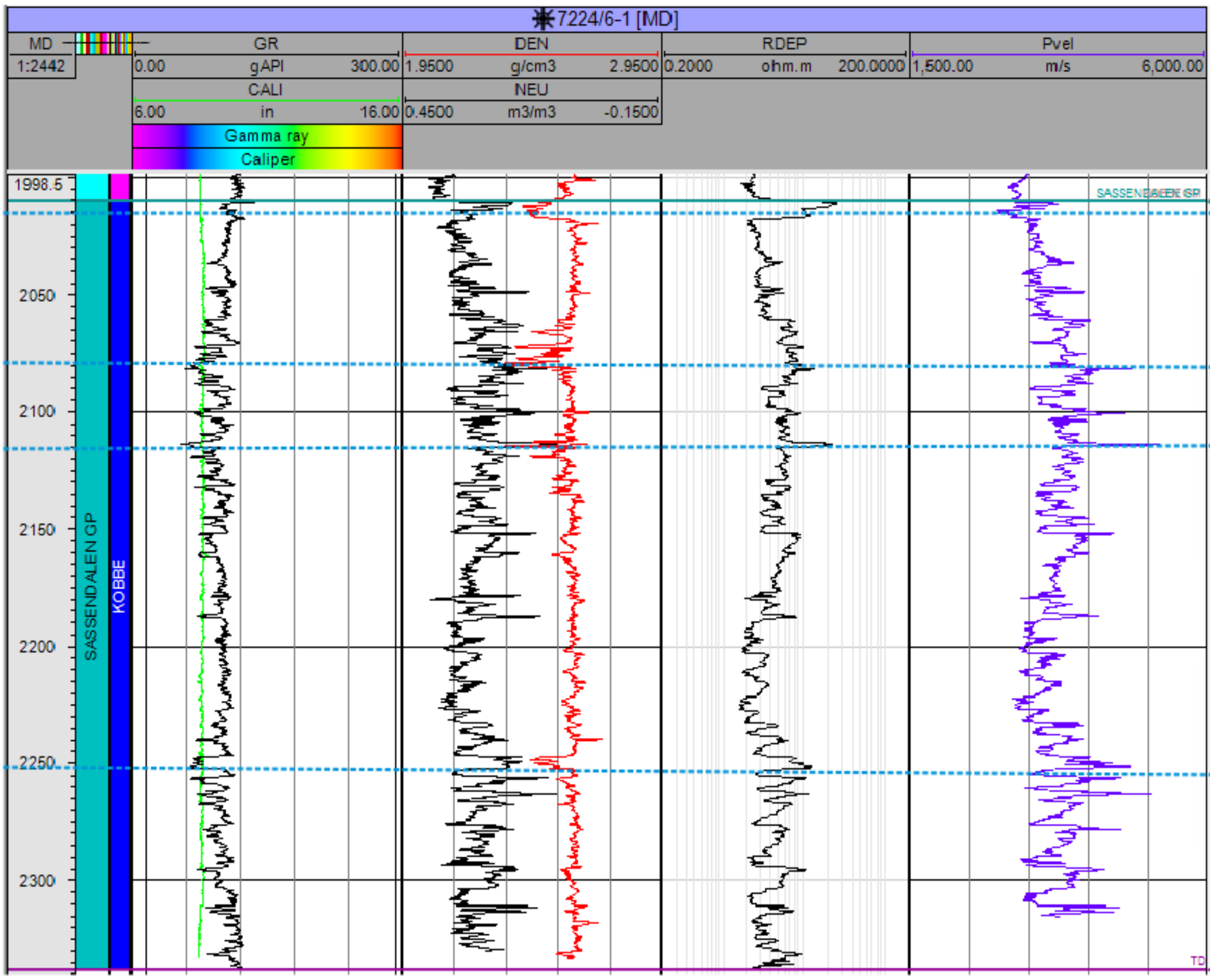


Figure 52. *Blue stippled lines showing gas discovering in four levels in the Kobbe Fm at 2015 m, 2080 m, 2113 m, 2252 m. Sand units in Kobbe formation associated with prograding shelf edge system of Anisian age. From Npd (2017).*

4.2.12 Well 7226/2-1

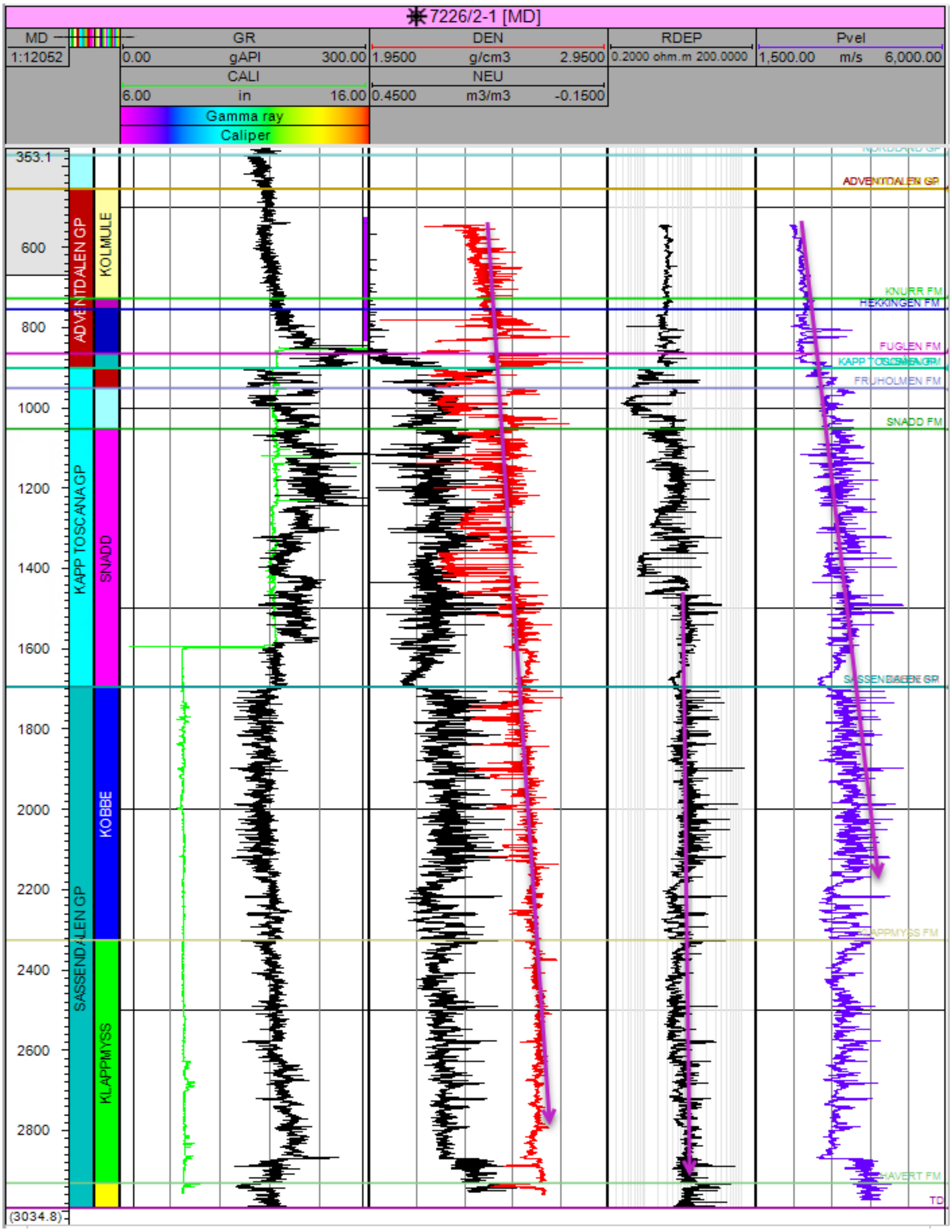


Figure 53. *GR/CALI, Den/NEU, RDEP, Pvel logs respons in well 7226/2-1.*

The well 7226/2-1 was drilled by StatoilHydro ASA with main target to identified HC in the Realgrunnen Group, Snadd Formation and Kobbe Formation. The location of the well is Bjarmeland platform and the depth of the well is 2992 m. It penetrates 14 lithostratigrafical units (*Fig. 53*). The well was permanently abandoned as a gas discovery.

Vertical trend. Interval between 2929 m – 1694 m characterise by GR at approximately 165gAPI, DEN at 2.7 and Pvel what varies in range between 3500 – 3900 m/s.

Transition zone between Kobbe and Snadd Fm defined by slightly increasing in GR from 169 – 189 gAPI, decreasing in RDEP and Pvel from 3200 – 2990 m/s. Interval between 2326 – 1696 (Kobbe Fm) characterize by GR range between 189 – 230 gAPI. DEN is approximately 2.6 g/cm3 and Pvel changes between 3400 – 3800 m/s.

Snadd Fm (1698 – 1051 m) characterize by variable GR value. It lowest (183 gAPI) at interval between 1698 – 1587 m, when it increases from 183 gAPI to 223 gAPI at 1580 - 1418 m depth. DEN is approximately 2.5 g/cm3 between 3100 – 3600 m.

Interval 1245 – 1098 m shows high GR (230 – 245 gAPI), DEN about 2.5 g/cm3 and Pvel 3200 – 3500m/s. This is related to shale lithological unit. Interval between 790 – 543 m shows stable GR value at 176gAPI, DEN is about 2.3 g/cm3 and Pvel at 2.5 m/s.

Source rock. Marine shales from Hekking and Fruholmen Fm represent source rock.

Cap rock. Fuglen and Hekkingen formations constitute a cap rock for HC.

Reservoir rock. Low GR reading at Upper Havert Fm (2928 - 2945 m) and almost cross – over trend between DEN and NEU logs detect reservoir sandstones (*Fig.54*). In addition, high RDEP reading indicates HC bearing sandstones (Npd, 2017).

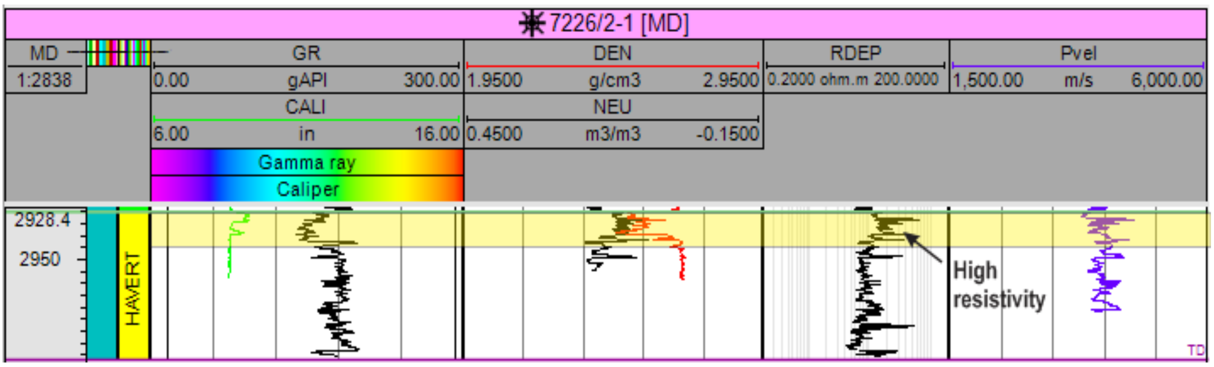


Figure 54. *Reservoir rock interval (highlighted with yellow colour) in well 7226/2-1.*

Weak oil shows (Npd, 2017) has been detected at interval depth 903 -952 m and 1746 -1747 m (*Figure 55*).

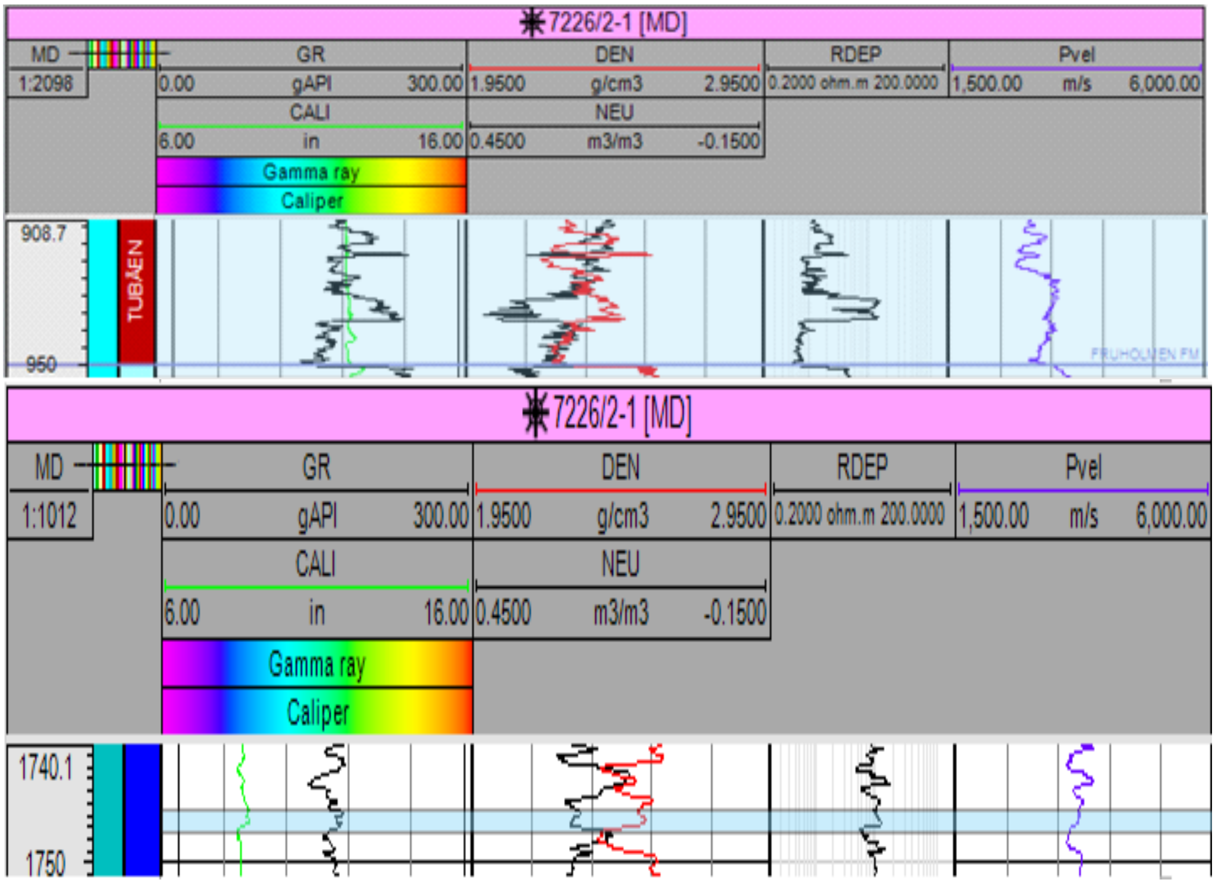


Figure 55. *Interval with weak oil shows in reservoir rock in Tubåen and Kobbe Formations.*

4.2.13 Well 7228/1-1

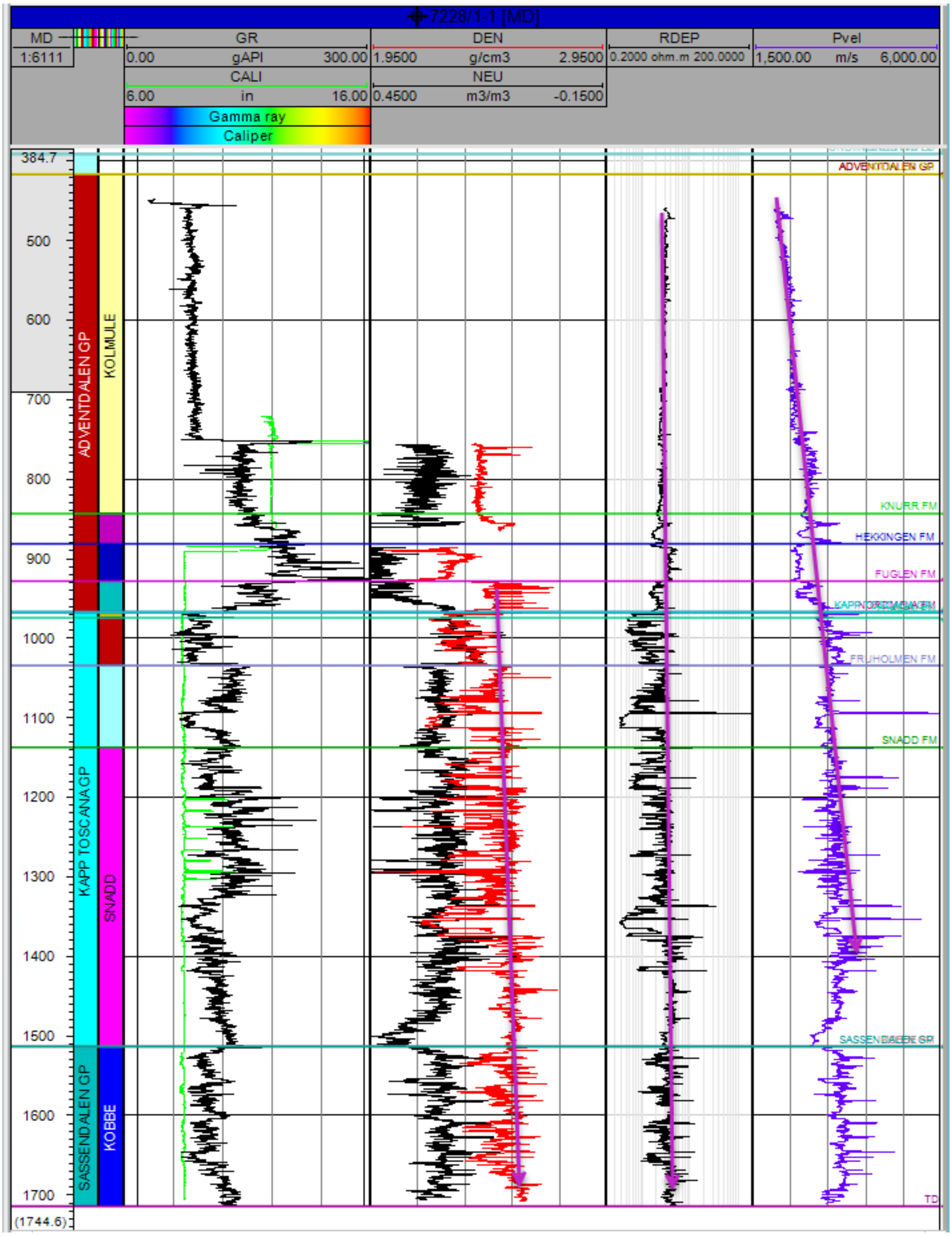


Figure 56. *GR/CALI, Den/NEU, RDEP, Pvel logs respons in well 7228/1-1.*

The main object of the well 7228/1-1 was sandstone sequence in Toscana Group of early Jurassic – Late Triassic ages and the secondary target were sandstone in Intra-Snadd formation and in Kobbe Formation. The well is located on the Eik prospect in the Barents Sea on the eastern border of the Bjarmeland Platform. The total depth is 1714m and it penetrates 14 lithostratigraphical units as showing in figure 56. The well was permanently abandoned as a dry well (Npd, 2017).

Vertical trends in well. Depth interval between 459 – 752 m characterize by GR at 88 gAPI and Pvel is about 2400 m/s. GR increases from 88 to 226 gAPI and Pvel shows slightly increasing from 2400 to 2600 m/s at 752 m depth. Intreval between 756 – 858 m shows variation in GR between 130 – 150 gAPI. DEN at the same interval is about 2.4 and Pvel is in range between 2500 – 2900 m/s. GR increases at 858 m to 928 (140 – 282 gAPI) and decreases from 928 to 970m (282 – 80 gAPI).

Transition zone between Tubåen and Fruholmen Fm characterize by sharp increasing in GR value from 87 to 160 gAPI, increasing in DEN from 2.3 – 2.5 g/cm3 and decreasing in Pvel from 3.8 – 3.1 m/s. Depth interval between 1135 – 1514 m (Snadd Fm) characterize by variation in GR value from 80 – 140 gAPI. DEN value is in interval between 2.3 – 2.5 g/cm3 and Pvel is about 2800 – 3600 m/s. Transition zone between Snadd and Kobbe Fm describes by slightly decreasing in GR (134 -120 gAPI), increasing in DEN (from 2.3 to 2.5 g/cm3) and Pvel 2900 to 3400 m/s.

Source rock zone interval shows in figure 57 (Fruholmen Formation).

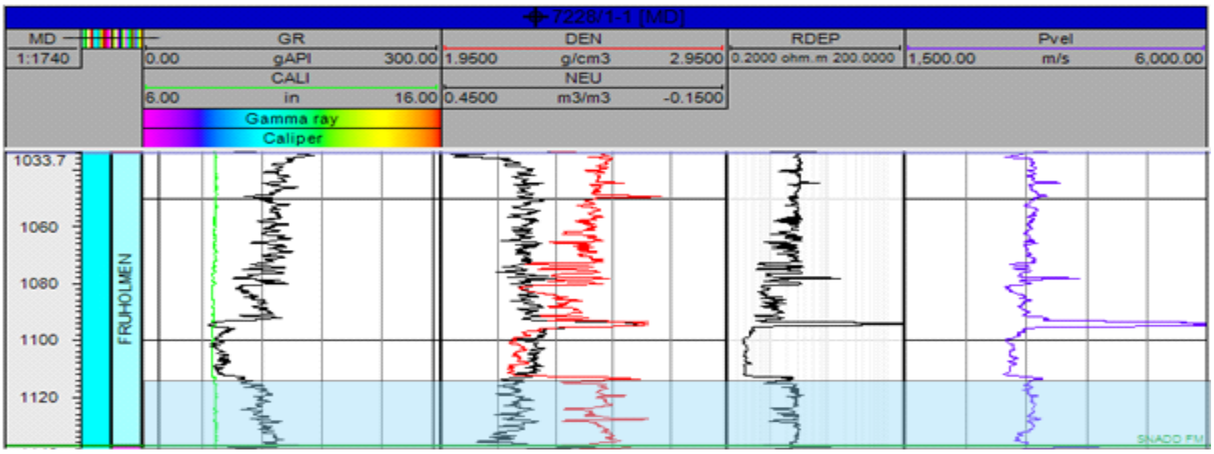


Figure 57. *Interval with source rock zone (highlighted with light blue colour) in well 7228/1-1.*

Reservoir rock. According Npd 2017, reservoir rock of good quality (*Fig.58*) has been identify in the Nordmela, Tubåen and Fruholmen Formations (Kapp Toscana Gr). It has also been indicate some sand sequences within Kobbe Fm with low porosity. Unfortunately, none of those sand sequenses was oil/gas bearing.

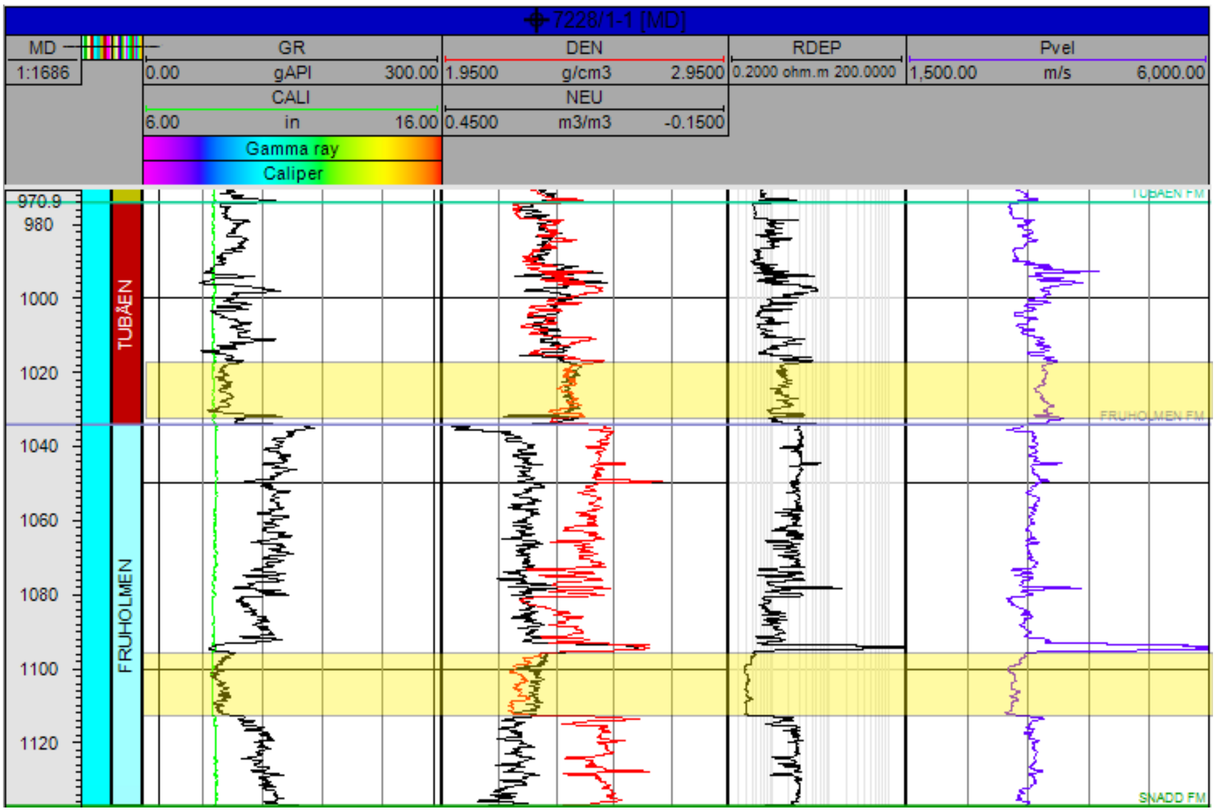


Figure 58. *Interval with reservoir rock zone (highlighted with yellow colour) in well 7228/1-1.*

North – South cross-section

4.2.14 Well 7125/4-2

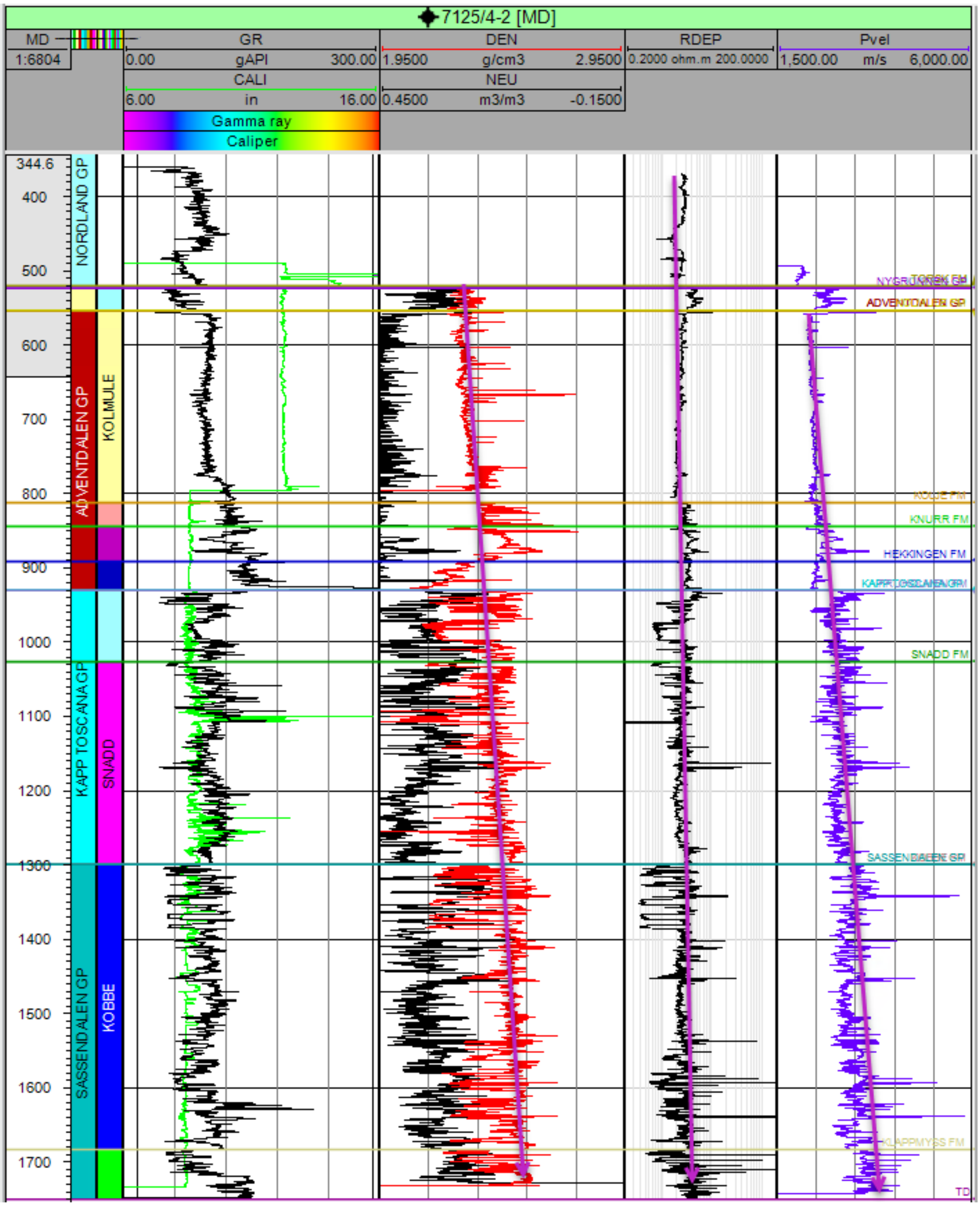


__Figure 59__. GR/CALI, Den/NEU, RDEP, Pvel logs respons in well 7125/4-2

The main object of the well 7125/4-2 (Nucula Appraisal well) was to identified hydrocarbons in the Nucula B segment with the Kapp Toscana Group sands and the lower Kobbe Formation sands. The well drilled by StatoilHydro Petroleum AS in the Måsøy fault Complex in the Barents Sea to 1750 m depth and it penetrates 15 lithostratigraphic units as showing in figure 59. The well was abandoned as an oil appraisal well.

Vertical trends in well. Log response from GR shows variation in range between 63 – 110 gAPI at depth interval 1718 – 1107 m (middle Klappmyss – upper Snadd Fm). The same variation trend for DEN (2.1 – 2.5 g/cm3) and for Pvel (3.1 - 3.7 m/s). Transition zone between Fruholmen and Hekkingen Fm (929 m) defines by increasing in GR from 136 to 188 gAPI. DEN decrease from 2.4 to 2.1 g/cm3 and Pvel decrease from 2900 to 2300 m/s. Depth interval between 776 – 558 m (Kolmule Fm) defined by approximately the same GR (95 gAPI), DEN (2.3 g/cm3) and Pvel (2500 m/s).

Source rock zone with low GR reading, cross-over trend between DEN and NEU log shows in figure 60.

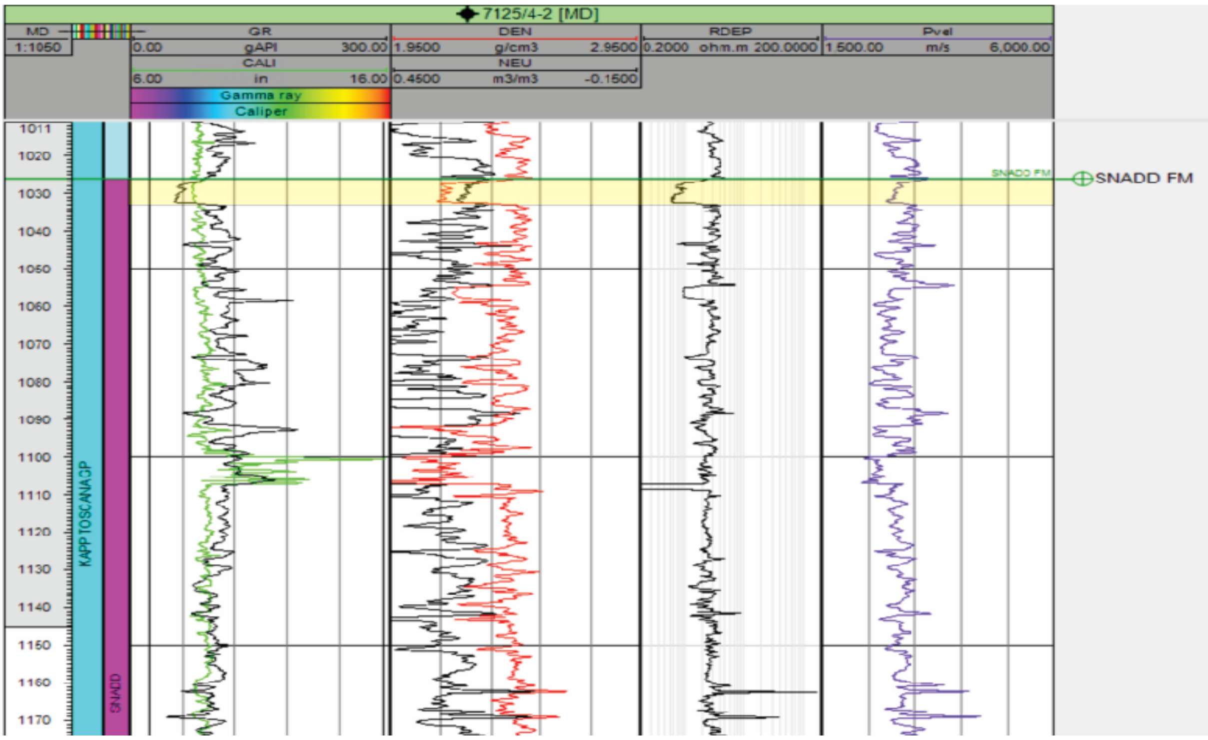


Figure 60. *Interval with reservoir rock (highlighted with yellow colour) in well 7125/4-2.*

Source rock zone shows in figure 61.

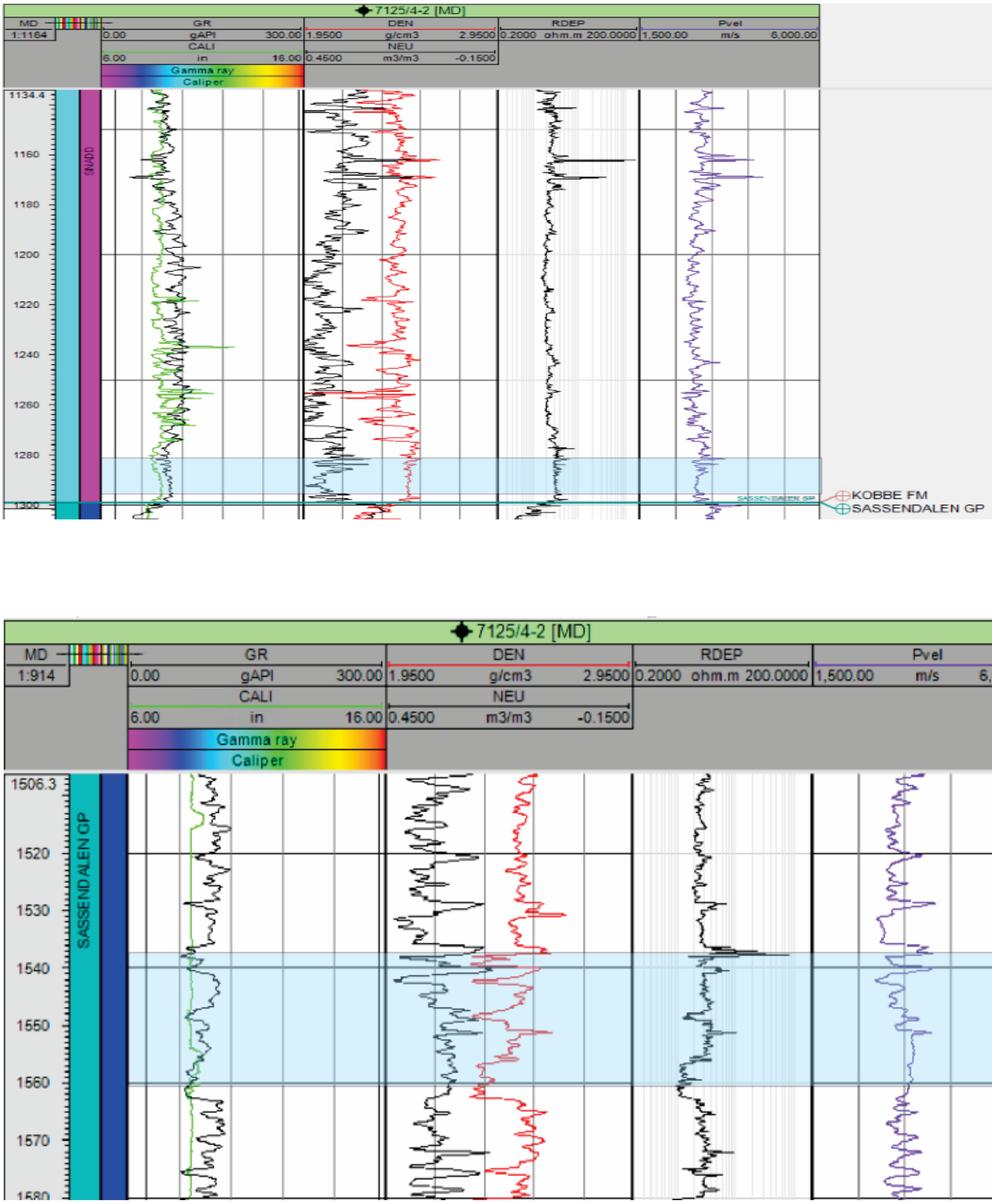


Figure 61. *Source rock zone (highlighted with light blue colour) in well 7125/4-2.*

4.2.15 Well 7124/3-1

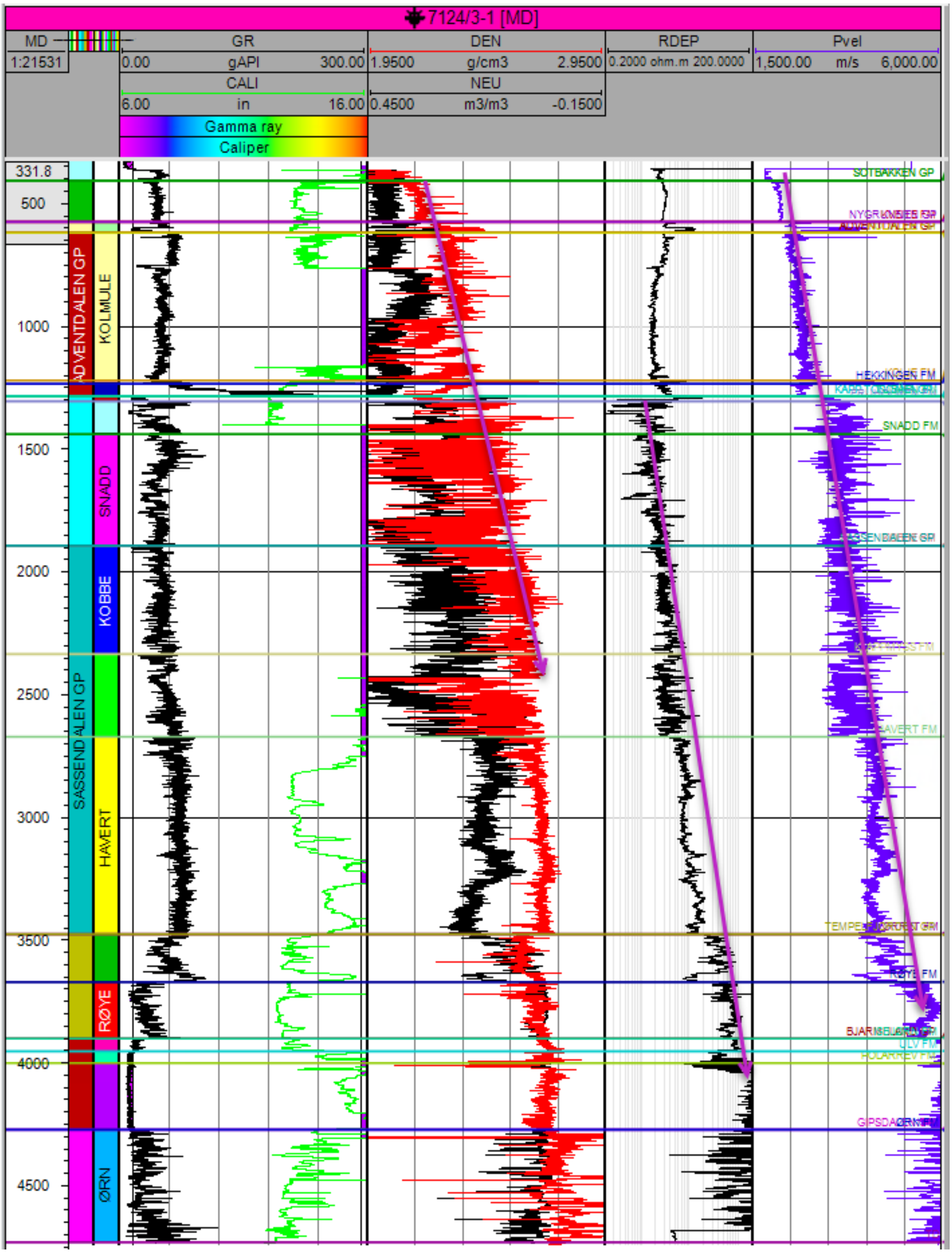


__Figure 62.__ GR/CALI, Den/NEU, RDEP, Pvel logs respons in well 7124/3-1.

The main object of the well 7124/3-1 was reservoir rocks of Middle Jurassic age and the secondary object was Late Carboniferous rocks. The well was drilled by Saga Petroleum ASA to 4730m with location to east of the Hammerfest Basin on the Nyslepp fault Complex. It penetrates 25 lithostratigraphic units as showing on figure 62. The well was permanently abandoned as a minor gas and oil discovery.

Vertical trends in well. Interval between 3900 – 3670 m (Røye Fm) shows low value of GR (15 - 35 gAPI), high DEN value (approximately 2600 m/s) and high Pvel (5300 – 5800 m/s)**.** Transition zone between Røye and Ørrett Fm (3669 m) detects sharp increasing in GR value (from 37 to 87gAPI).

Depth interval between 3670 – 3475 m (Ørret Fm) shows changing in GR reading from 101 to 39 gAPI. DEN is approximately the same through that depth interval (2.5 - 2.6 gAPI). Pvel is variable. It has lowest value 3900 m/s and highest value 5300 m/s. Depth interval between 3475 to 2667 m characterize by GR at 60 - 70 gAPI, DEN 2.6g/cm3 and Pvel is between 4200 – 4500 m/s. Transition zone between Havert and Klappnyss Fm describes by slightly increasing in GR (from 65 to 77gAPI), decreasing in DEN (from 2.7 to 2.5 g/cm3) and Pvel (from 4500 to 3400 m/s). Depth interval between 2332 – 1437 m (Kobbe, Snadd Fm) characterize by GR at approximately 50 gAPI, DEN response shows a variation from 2.2 to 2.5 g/cm3 and Pvel changes between 3100 – 4000 m/s. Rapid increasing in GR (from 15 – 240 gAPI) characterises transition zone between Tubåen and Hekkingen Fm at 1285 m depth. DEN decreases from 2.2 to 2.0 g/cm3 and Pvel decrease too from 3400 to 2500 m/s. **Source rock zone** at depth interval 1286 – 1306 m (Tubåen Formation) shows in figure 63.

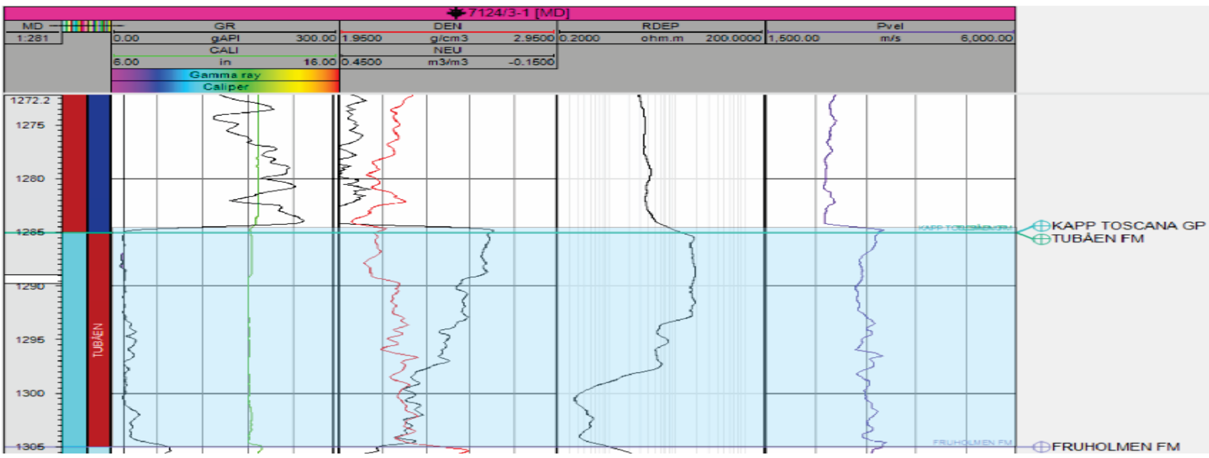


Figure 63. *Interval with source rock zone (highlighted with light blue colour) in well 7124/3-1.*

4.2.16 Well 7125/1-1

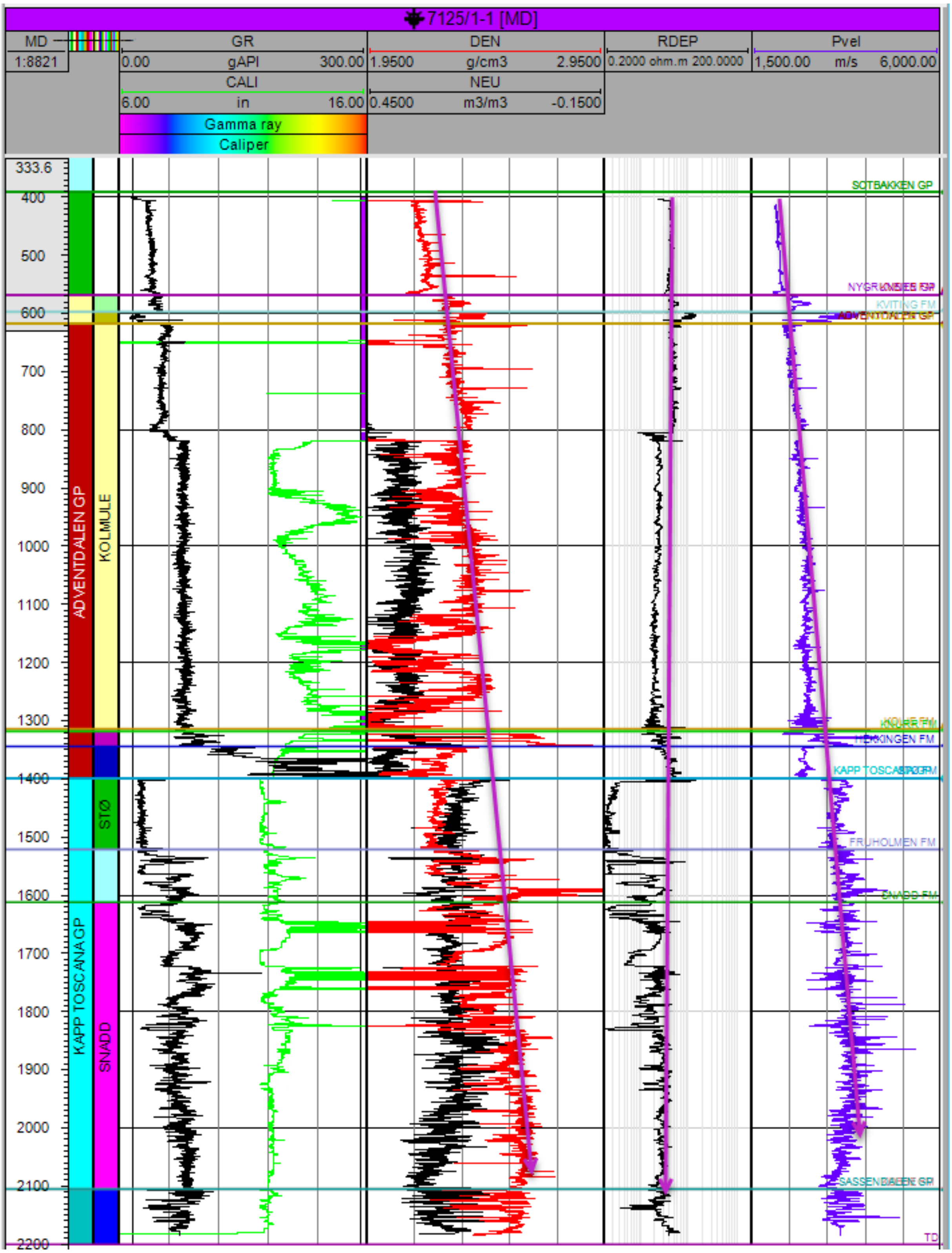


Figure 64. GR/CALI, Den/NEU, RDEP, Pvel logs respons in well 7125/1-1.

The well 7125/1-1 was drilled by Saga petroleum ASA to 2200m depth with main objective to improve HC presents in sandstones of the Kapp Toscana Group. The secondary target was to check HC potential in Kobbe Formation. Wells position in the Lopparyggen East area on the southern end of the Bjarmeland Platform towards the Nyslepp Fault Complex. It penetrates 16 lithostratidraphic units (*Fig.64*). The well was permanently abandoned as a minor oil and gas discovery

Vertical trends in well. Lowest GR value (26gAPI) shows at depth interval between 1520 – 1402 (Stø Fm). It accompanies by high Pvel (3600m/s) and DEN at 2.3 g/cm3. This interval represents sandstones with unit of shale and siltstones.

The highest GR belongs to Hekking Fm, where value of GR reaches 300gAPI at depth interval 1398 – 1387 and 1370 – 1364 m. Highest Pvel (3500 - 3700 m/s) detects at depth interval 2158 – 1407 m (Kapp Toscana Gr). Depth interval between 1390 – 628 m describes by Pvel value 2400 – 2800 m/s. DEN is highest at depth interval at 2188 – 1838 m (2.5 – 2.7g/cm3).

Reservoir rock zone. Reservoir development indicated in the Stø Fm (Kapp Toscana Group). According Npd 2017, it has been detected 130 m sandstone sequence with good reservoir properties. Low GR and cross-over between DEN and NEU in Stø formation shows in figure 65.

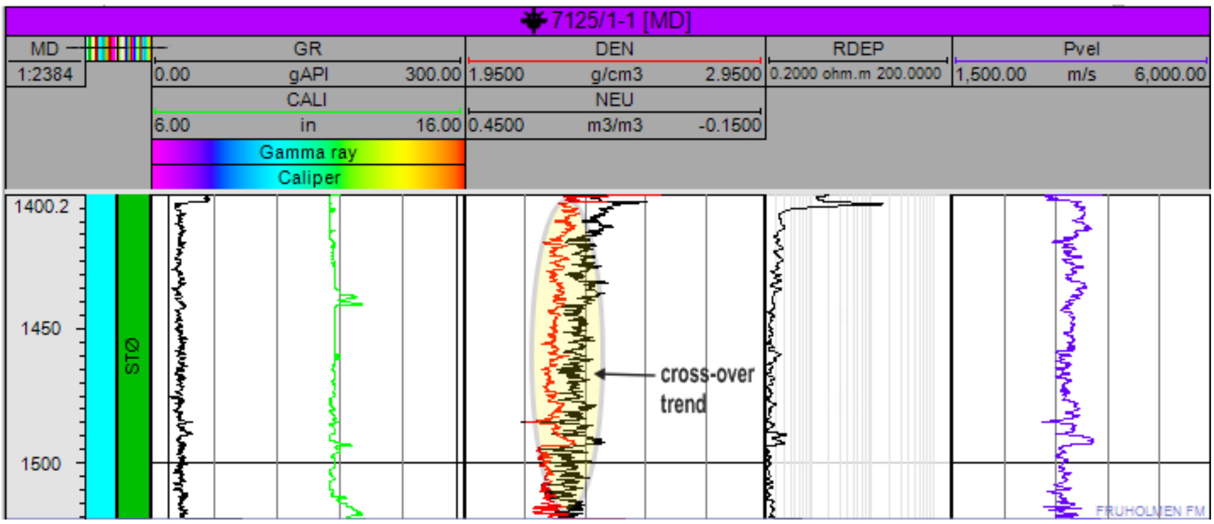


Figure 65. *Interval with reservoir rock (highlighted with yellow colour) zone in well 7125/1-1.*

Cap rock zone. Hekking Fm, at depth interval between 1399 – 1350 serves as a good cap rock. Special intervals with high GR value (at depth 1399 – 1388 m and at depth 1375 – 1364 m) detect tight shale sequence (*Fig. 66*).

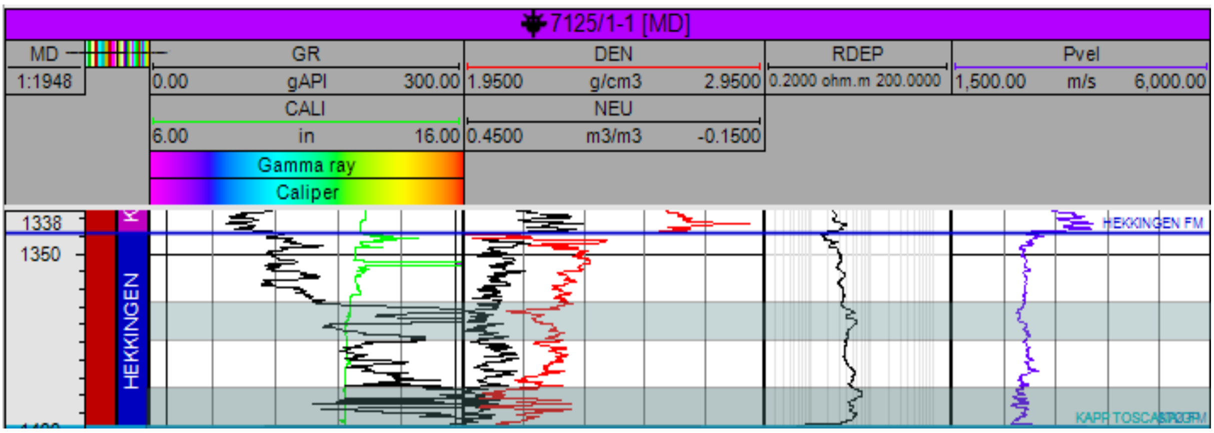


Figure 66. *Interval with Cap rock zone (highlighted with light grey colour) in well 7125/1-1.*

4.2.17 Well 7224/7-1

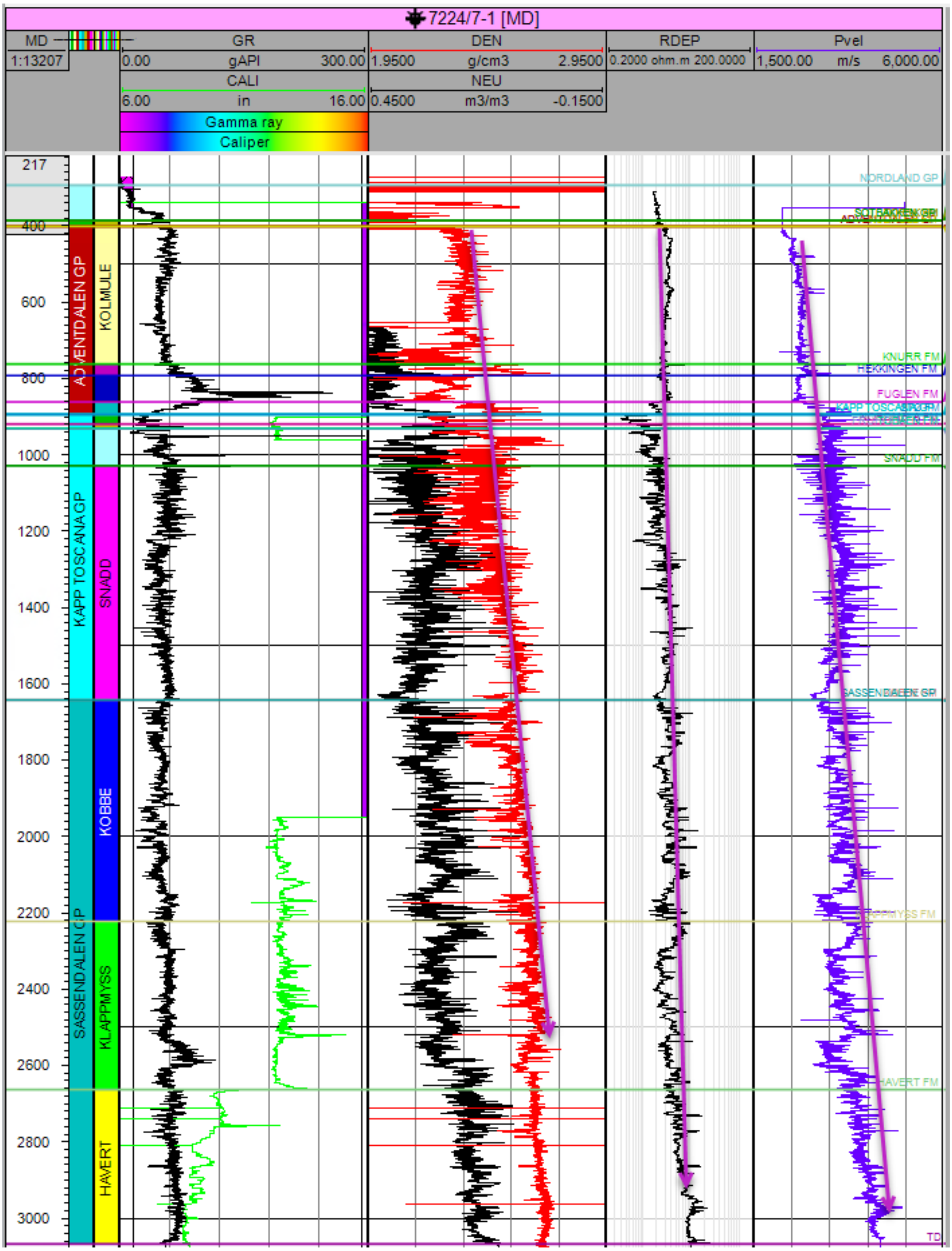


Figure 67.*GR/CALI, Den/NEU, RDEP, Pvel logs respons in well 7224/7-1.*

The well 7224/7-1 has been drilled 3067 m with main objects to check sandstone reservoir capacity of Early Jurassic /Late Triassic and Early Triassic ages and Permian carbonaceous rocks. Well is located in Lopparyggen in the East area of the Bjarmeland Platformen and penetrates 18 lithostratigraphic units (*Fig. 67*). The well was plugged and abandoned with shows.

Vertical trends in well. GR is low (60 gAPI) in interval from 3067m to 1022m. When it decrease from 1000 – 894 m. Transition zone between Stø and Fruholmen Fm characterize with increasing in GR value from 33 -50gAPI.

GR value increases in interval from 894 – 836 m. (50- 200 gAPI) when it slightly decrease to 20gAPI from 836m – 292m. P- velocity increase with depth. From 2000m/s at 400 m (top Kolmule Fm) to 4500m/s at base of the well (Havert Fm). Density value is also increasing with depth from 2.2g/cm3 at 400m to 2.7g/cm3 at base of the well.

Reservoir rock zone with low GR, cross-over pattern in DEN and NEU logs indicate reservoir zone in Stø Formation (*Fig.68*).

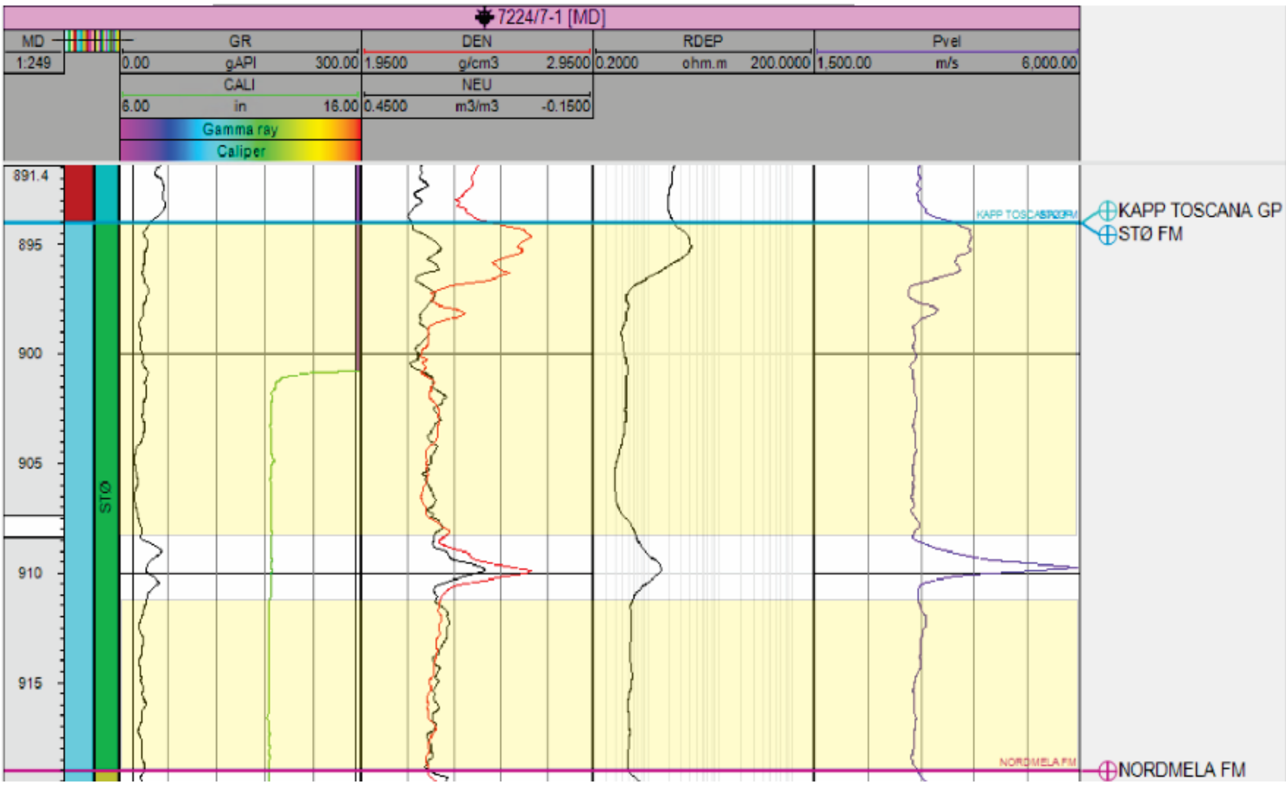


Figure 68. *Interval with reservoir rock (highlighted with yellow colour) in well 7224/7-1.*

Source rock zone in Kobbe formation shows in figure 69.

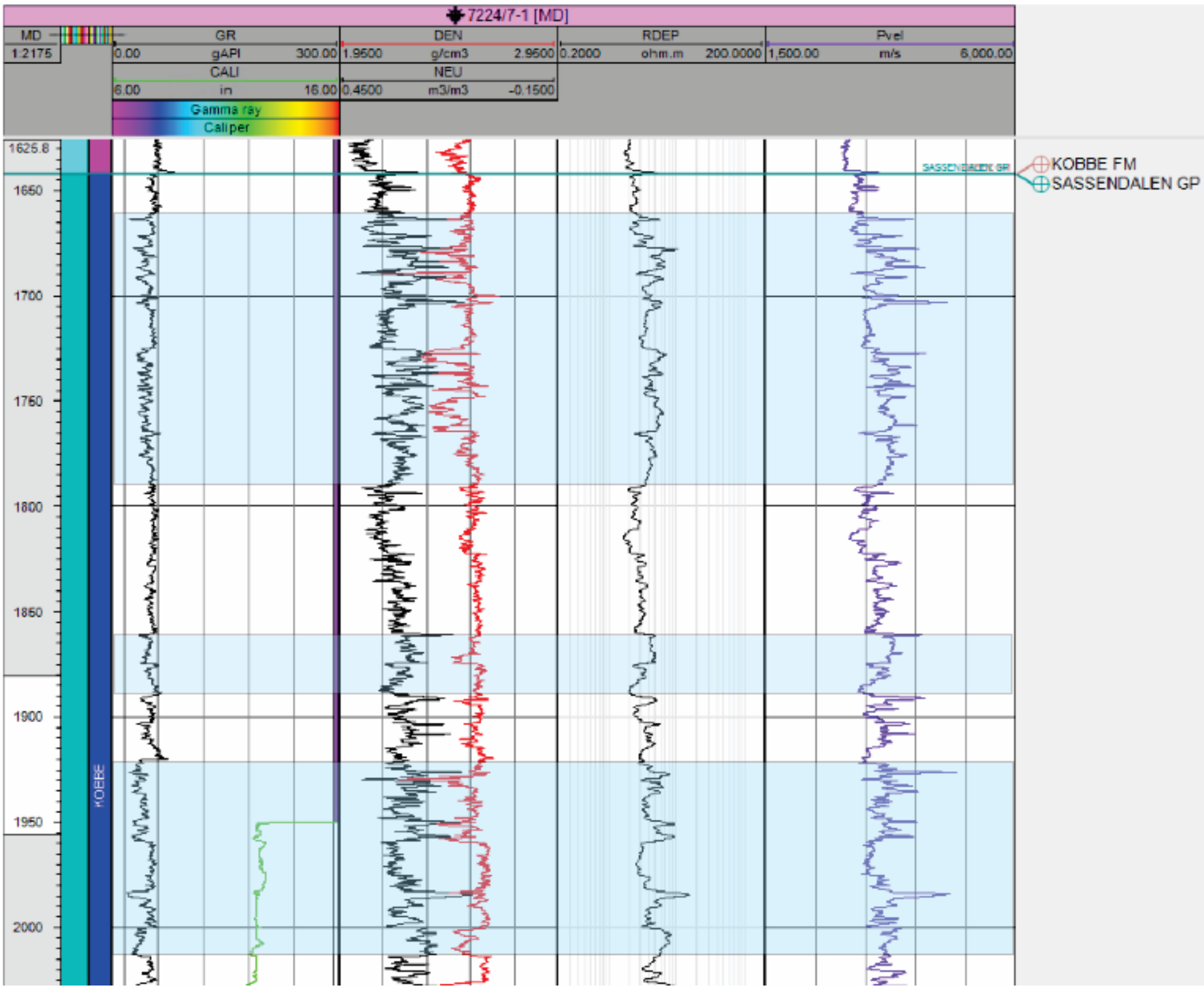


Figure 69. *Interval with source rock zone in Kobbe formation (highlighted with light blue colour) in well 7224/7-1.*

4.2.18 Well 7324/10-1

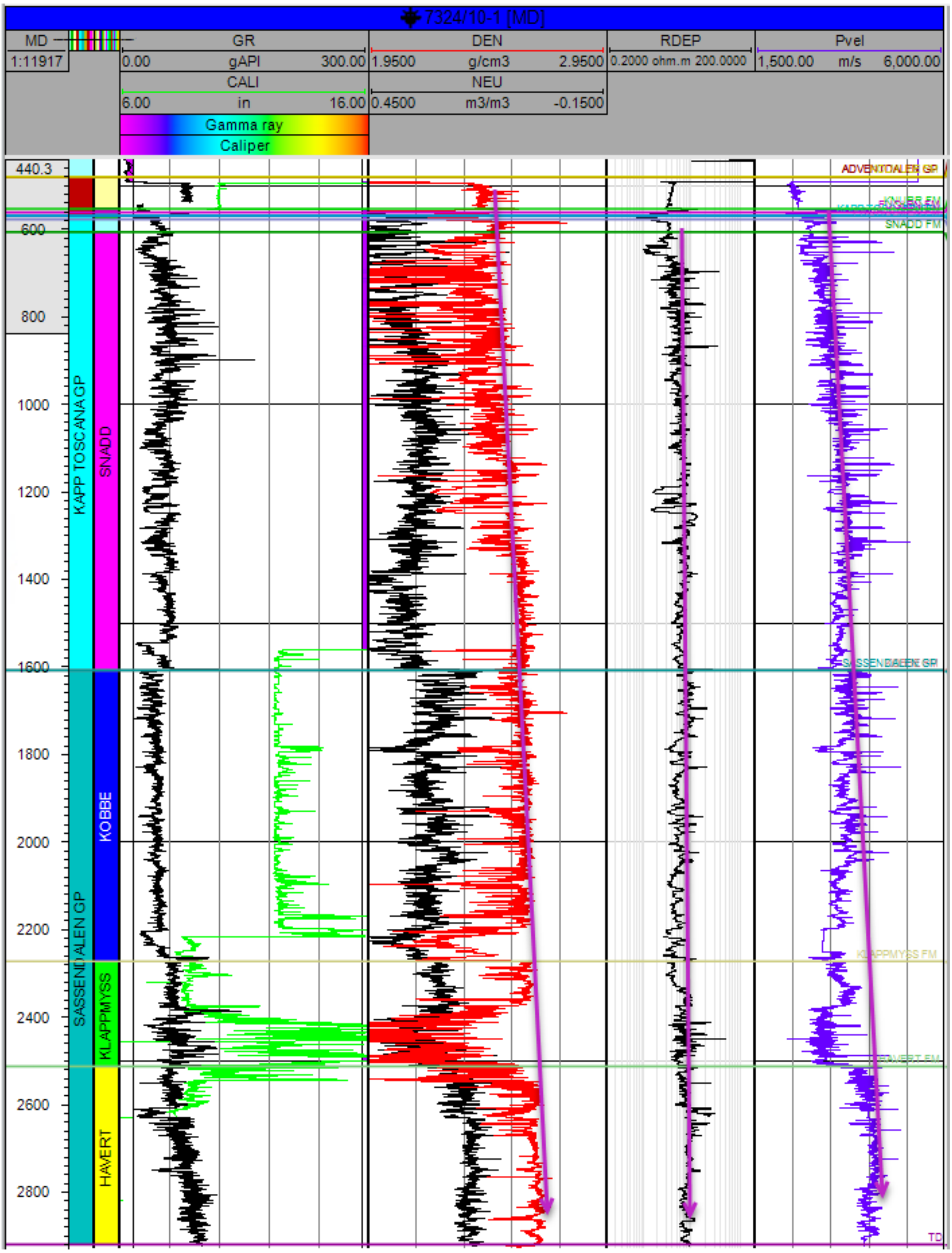
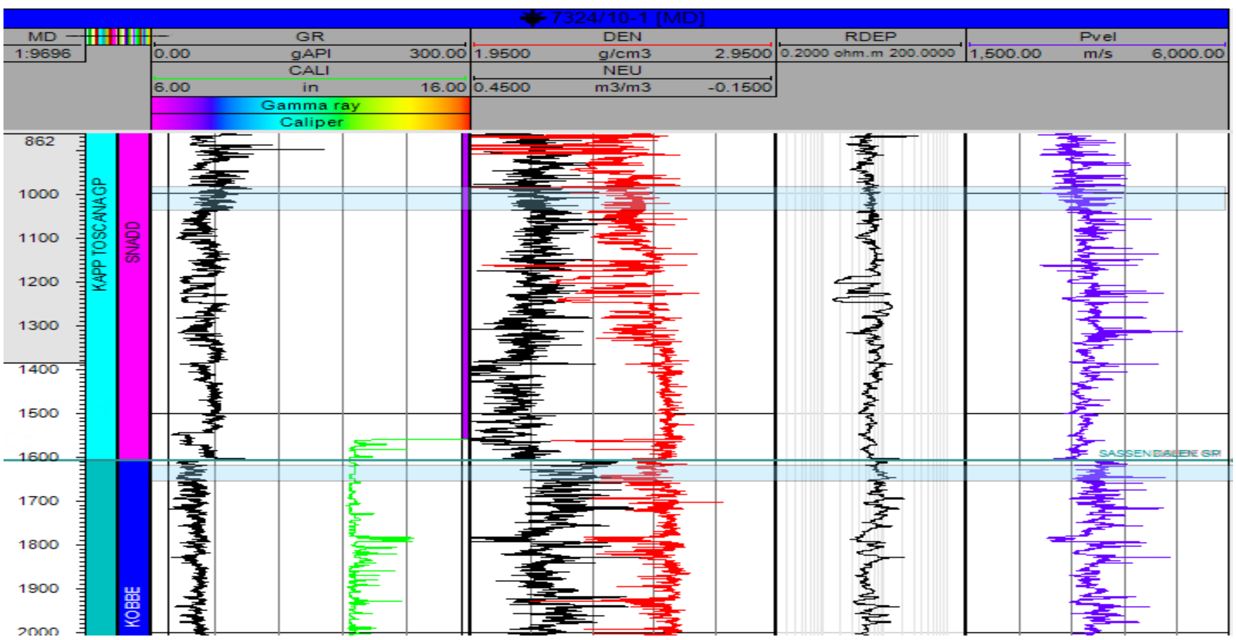


Figure 70. *GR/CALI, Den/NEU, RDEP, Pvel logs respons in well 7324/10-1.*

The well drilled to 2919 m in the Maud Basin (Alpha structure) on the Bjarmeland Platform. The main target of the well was to improve oil/gas potential in a Top Klappmyss Formation. The other one was to test sandstones in Top Havert Formation and check the source rock potential in the Base Snadd, and Base Kobbe Formations. The well was permanently abandoned as a dry well with shows. It penetrates 13 main lithological units (*Fig.70*).

Vertical trends in well. GR value decreases in interval 2919 – 2277m (from 130 – 100 gAPI) marking the transition zone between Klappmyss and Kobbe Fm. GR is about 70gAPI in interval between 2200 – 1608 m. Gr value increase from 1608m and in interval 1608 – 650 m it has value about 125 gAPI). P-velocity value is high in Havert Fm (2919 – 2512), is about 4000m/s. When it slightly decrease from 4000 m/s to 2,500 m/s in interval 2512- 510m.

Source rock zone. Source tock zone, which comprises organic rich shales have been detected in Snadd, Kobbe and Klappmyss Fm at 989 m, 1603 – 1607 m and at 2267 m respectively (*Fig. 71*). In Klappmyss Fm source rocks interval characterize by GR at 65gAPI, DEN 2.5g/cm3 and Pvel – 3400m/s. In Kobbe Fm, GR showing average value at 47gAPI, DEN at 2.4 – 2.5 m/cm3, Pvel -3700m/s, that represents clay stone sequence (Npd 2017)**.** Source rock in Snadd Fm characterize by GR at 65gAPI, DEN at 2.4g/cm3 and Pvel at 3300m/s and represents carbonaceous shale. From organic geochemistry analyzing, only source rock from Snadd Fm could be referred as good, oil-prone source rock (Npd, 2017).



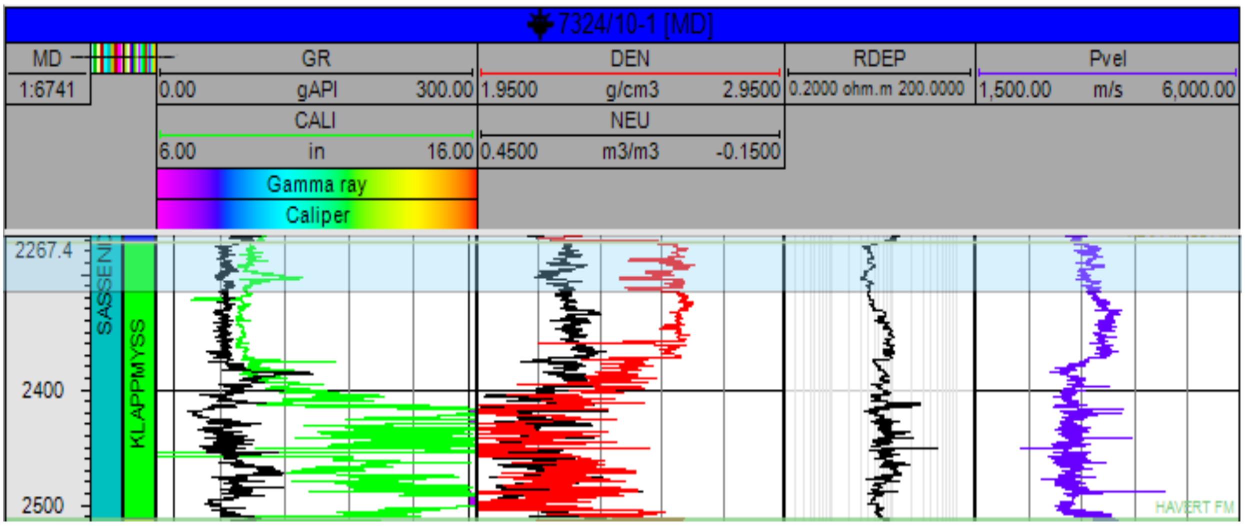


Figure 71. *Source rock interval in Snadd, Kobbe and Klappmyss Fm hightlighted by light blue colour, in wellbore 7324/10-1.*

Reservoir rock zone. Reservoir properties in Kobbe Fm unfortunately had a low permeability. Klappmyss Fm showing no reservoir development either. Upper part of Havert Fm had a restricted reservoir development (Npd, 2017).

Cap rock zone. Fuglen Fm with mudstones strings can be count as a cap rock for HC.

4.2.19 Well Dh-4

The borehole Dh-4 in Adventadalen has been drilled to identify sandstone location for CO2 store. It has been drilled to 970m and the well reached the main reservoir sandstone. The logging of the well starts with interval 440-970. The upper 440m was not fully logged (*Fig. 72*). The main vertical trend characterizes by increasing in velocity 3000 – 5000m/s (at depth 440 – 780 m) and decreasing in density 3.2-2.5 at depth interval 440 – 700 m.

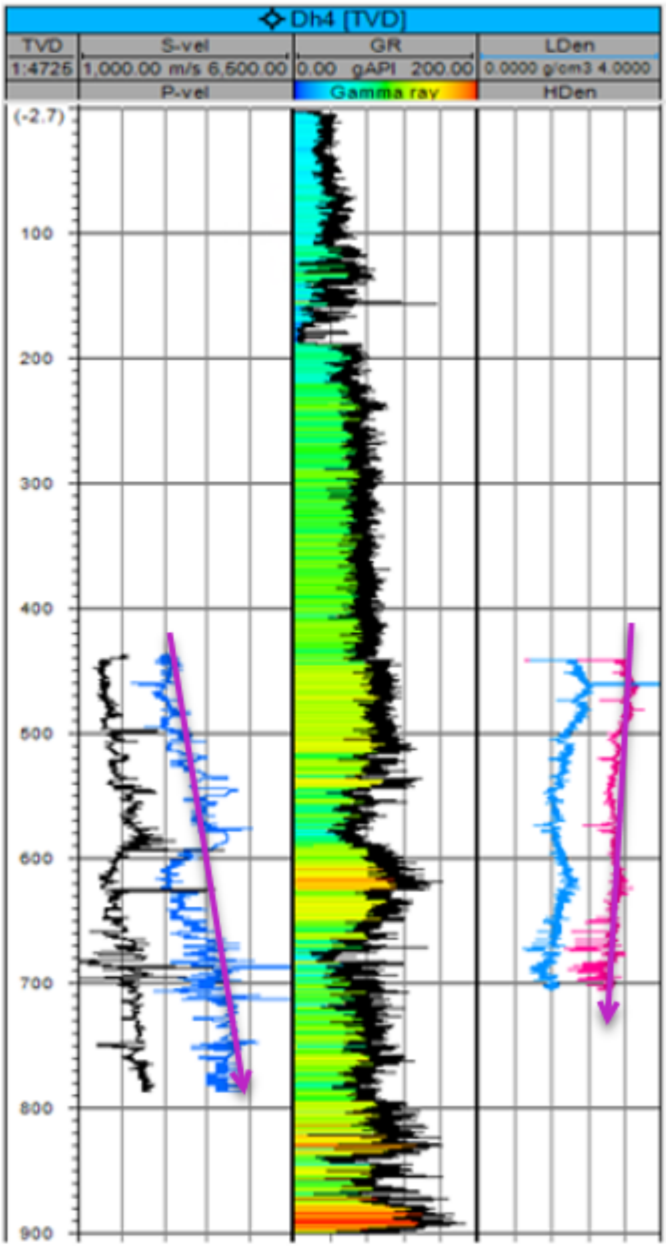


Figure 72. *GR, Den, Pvel logs respons in well Dh-4.*

4.2 Dynamic data.

In this chapter the exhumation value for depth for each well has been estimated and corrected (*table 3*) according estimated net erosion map for the Greater Barents Sea (Henriksen et. al 2011). Scattered plot depth vs velocity has been constructed. Observed trend has been described and compared with published estimated trend line (*Fig.20*).

Depth versus Velocity plot for studied 20 wells in the SW Barents Sea.

The South – Western area of The Barents Sea has been affected by uplift and erosion during Paleogene –Neogene. Uplift and erosion processes classified as exhumation due to avoid misleading (England and Molnar, 1990). The sedimentary succession in this area refers to Triassic – Paleogene age (Dalland at al., 1988).

The velocity values from Mesozoic - Cenozoic sedimentary succession from study wells in the SW Barents Sea has been plotted versus depth without correction for exhumation (*Fig. 73*(a)) and with correction for exhumation (*Fig. 73* (b)). Compare results with estimated trend line one can see that velocity increased with depth.

The data that highlighted in pink circle (*Fig.73* (*b*)) indicates that area that well 7216/11-1S penetrated has been uplifted before and now it buried.

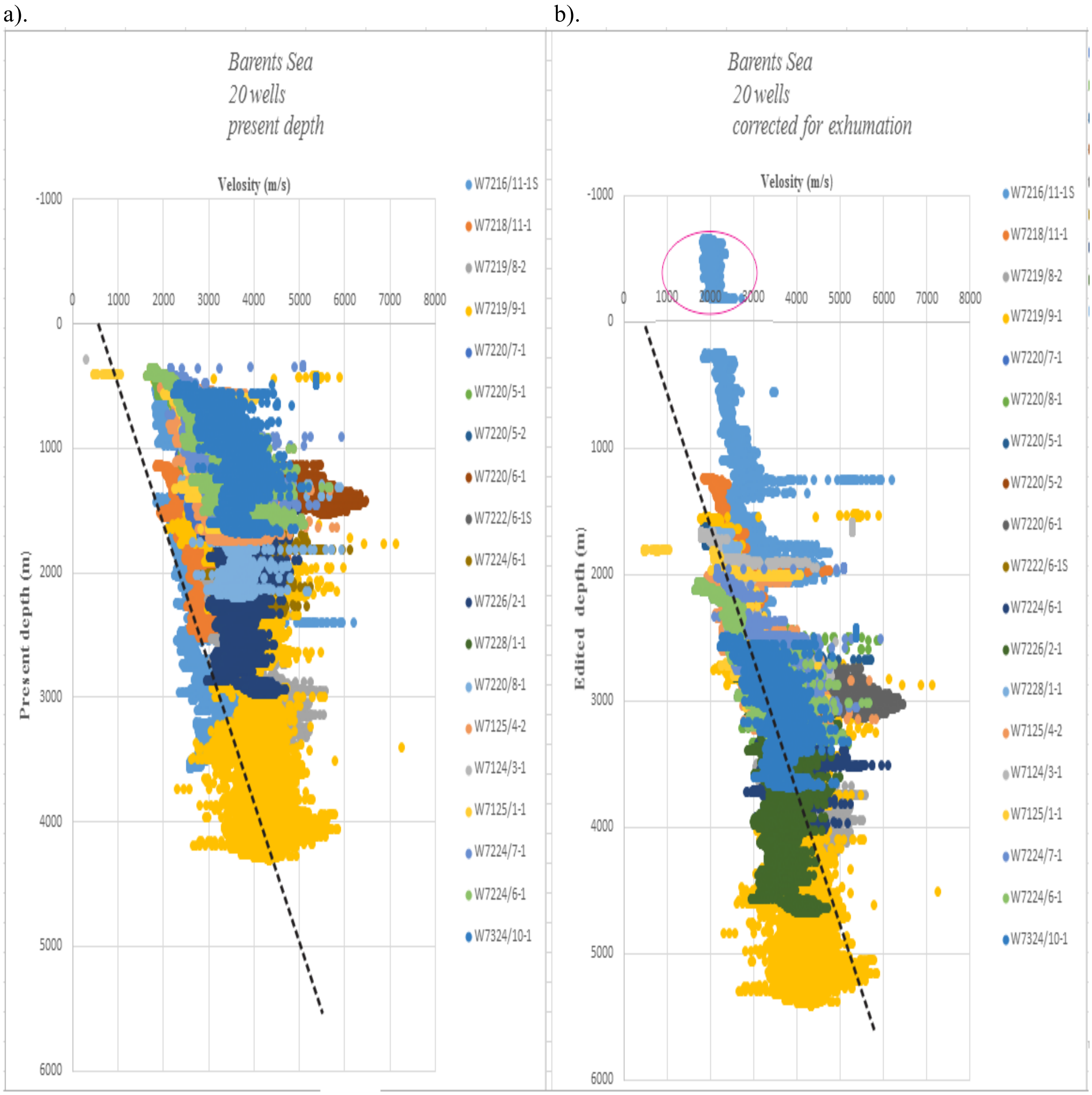


Figure 73. *Pvelosity measurements (every 15 cm with depth) from 20 wells studied in the Barents Sea represent present depth without correction for exhumation (a) and with correction for exhumation (b). Velocity – depth trend line has been estimated and shows porosity compaction trend. The data which is in pink circle shows that the area in well 7226/11-1 S was uplifted before present time.*

Depth versus Velocity plot for studied wells with NS and WE location in The Barents Sea.

Figure 74 shows the velocities of sediments in W-E (*Fig. 74* (*a*)) and N-S (*Fig. 74* (*b*)) cross section in SW Barents Sea at their present burial depth.

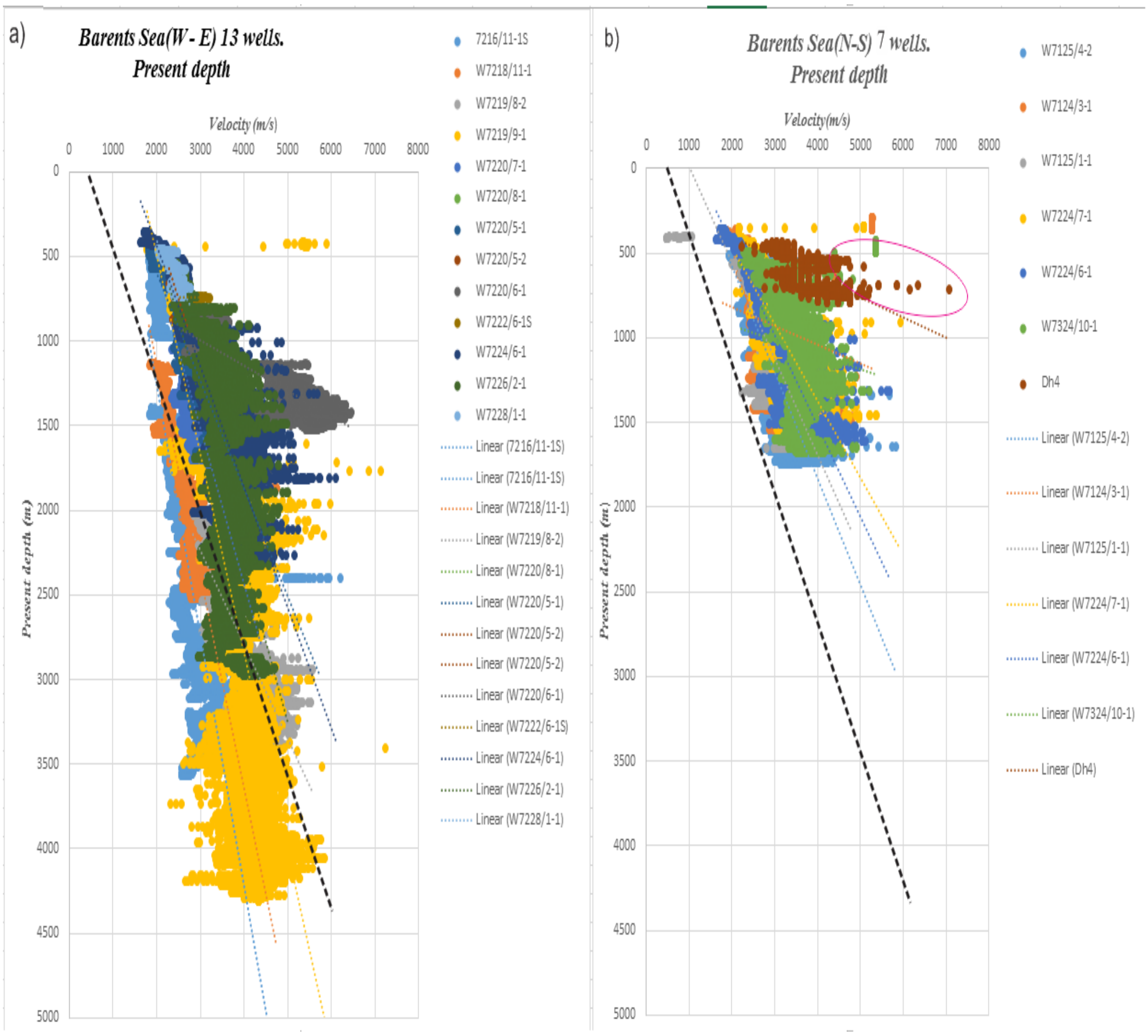


Figure 74. *Cross plot Depth vs Velocity from wells in W-E area (left) and N-S area (right) in the Barents Sea. Present depth.Stippled black line indicates compaction trend. Circle indicate data from well Dh-4 in Adventdalen (Spitsbergen.)*

Figure 75 shows the velocities after correcting for the exhumation. It seems that velocity increase with depth more rapidly in wells located along N-S cross-section than in W-E. Note that N – S is more uplifted area than W – E area (*Figure 8*).

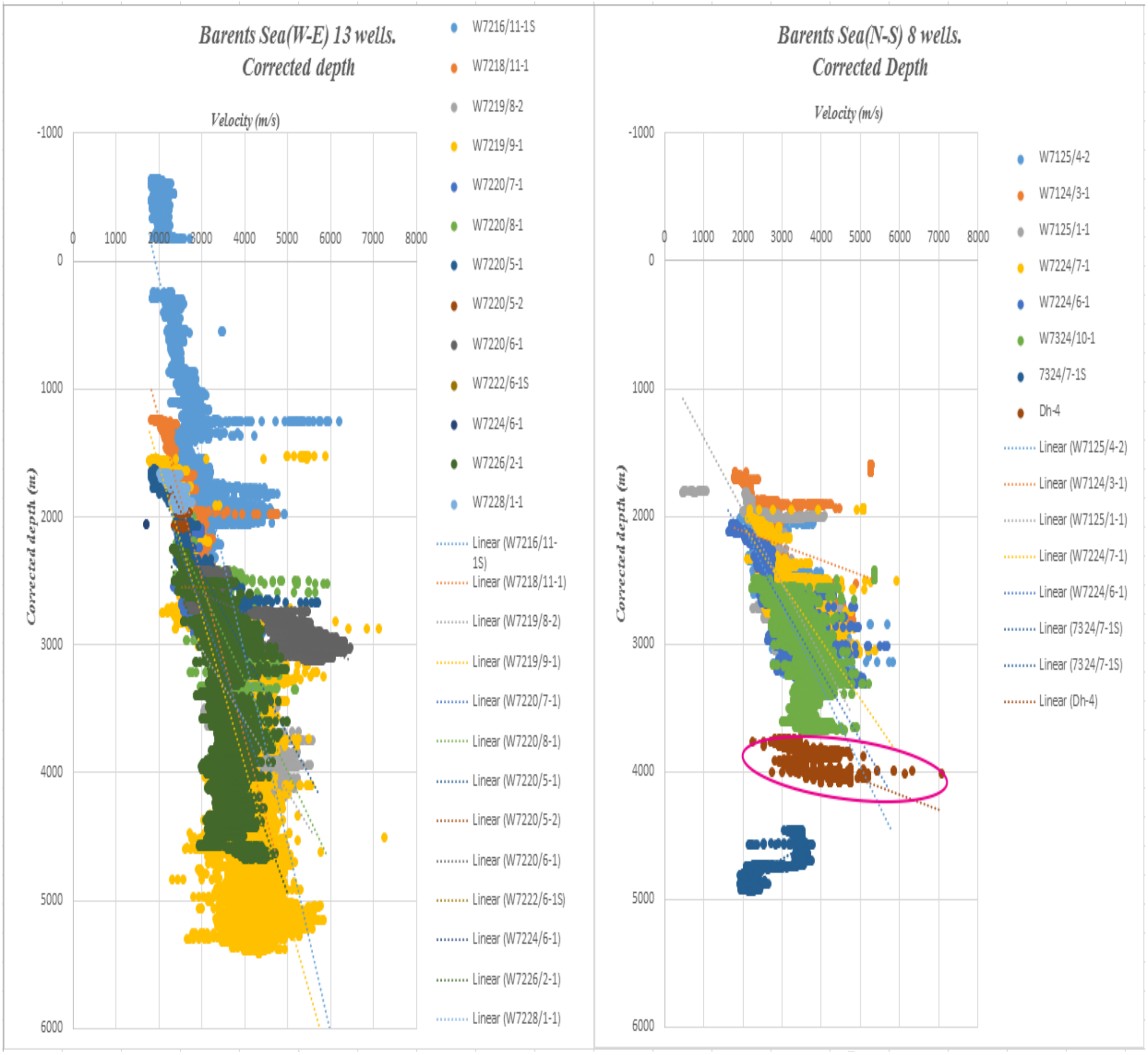


Figure 75. *Cross plot Depth vs Velocity from wells in W-E area (left) and N-S area (right) in the Barents Sea, corrected depth for exhumation. Circle indicate data from well Dh-4 in Adventdalen (Spitsbergen).*

Depth versus Velocity plot for sandstones, shale, source rocks in SW Barents Sea.

Velocity interval in study wells that penetrated sandstones within Stø, Nordmella, Tubåen Formations, shale within Kolje , Kolmule formations and shale within Hekking formations have been choose and plotted in cross – plot. Depth interval for every well has been corrected for exhumation (table 3). Whole velocity interval has been divided in smaller velocity trend interval by line to demonstrate how velocity changes. Noticed that figure 76 showing only study wells that contain preferred formations in SW Barents Sea with present depth and with depth corrected for exhumation (maximum burial depth).

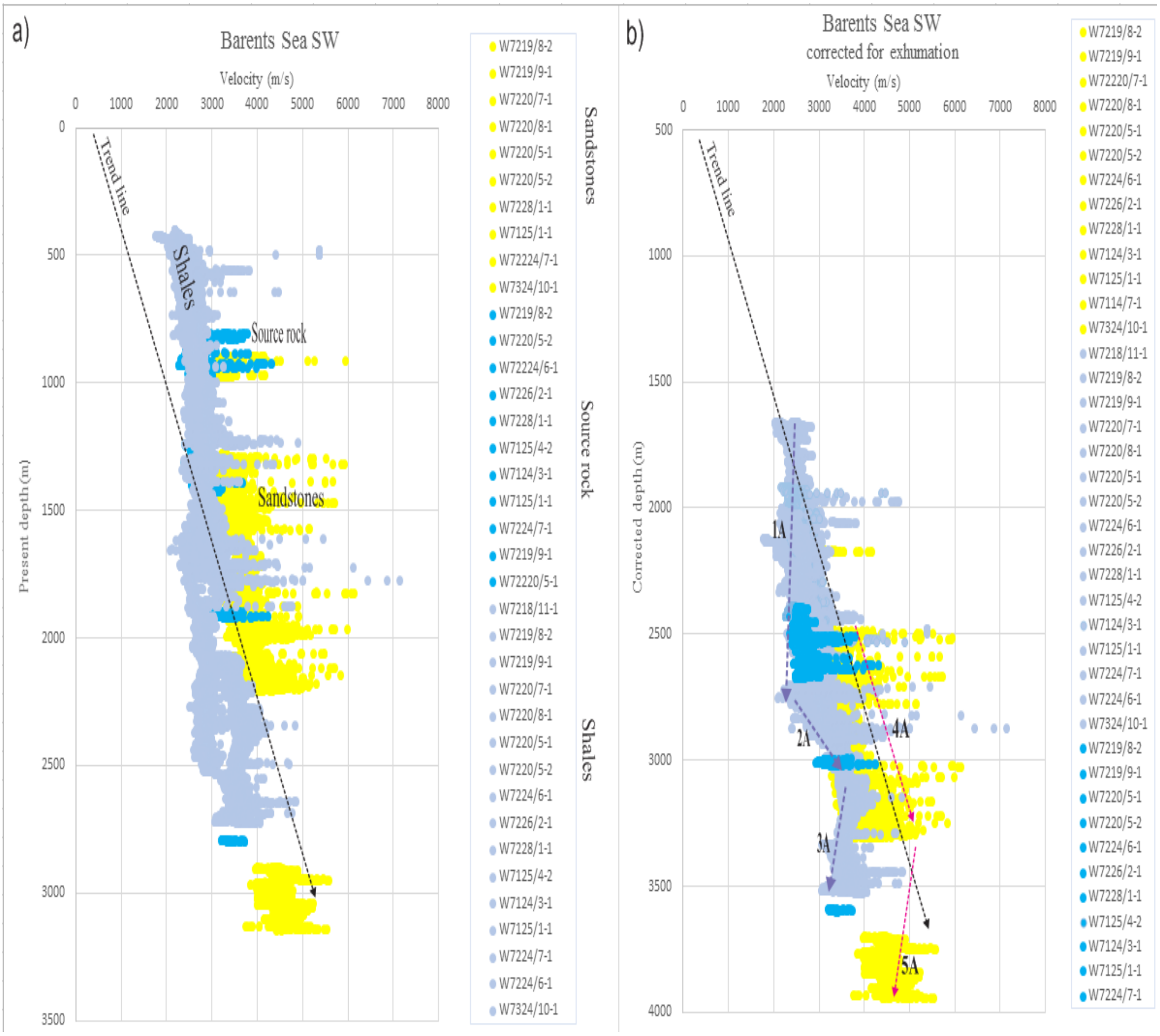


Figure 76*.Crossplot Velosity vs depth for wells in the Barents Sea based on well log data with sandstones from Stø, Nordmella formations(highlighted in yellow), shales from Kolje, Kolmule formations(highlighted light lilac) and source rock from Hekking formations (highlighted light blue) before correction and after correction for exhumation. Trend line from published data applied to compare the velocity trend. Sonic velocity measurements every 15cm from wells in the SW Barents Sea.*

Compare velocity trend one can see that velocity in sandstones increase rapidly in plot with depth corrected for exhumation (*Fig. 76(b)*) and then decrease at depth interval 3700 – 5000m. Interval 5A shows low velocity comparing with trend line.

Shale in interval 1A shows small decreasing in velocity then increasing in interval 2A and then decreasing again (interval 3A). Anomalous velocity (5000 – 6000 m/s) in sandstones and shale (6000 – 7000 m/s) occurred at depth interval 2500 – 3000 m and 2700 – 2800 m respectively.

Velocity versus Depth plot for sandstones, shale and source rocks in wells with location along W-E and N-S cross-section.in SW Barents Sea.

Figure 77 shows velocity versus depth cross – plot for sandstones, shale and source rock in study wells in W-E and N-S cross-section in SW Barents Sea. The interval 1A consists predominantly of shale and shows exponential slope with slightly decreasing in velocity (*Fig. 77* (*a*), (*b*)). The interval 2A (*Figure 77* (*b*)) located at much shallower burial depth then interval 2A in figure 77 (a) and shows high velocity slope gradient. Interval 3A in figure 77 (a), (b) shows high velocity trend (4000 – 6000m/s) in sandstones from Stø, Nordmella and Tubåen Formations. Note that interval 3A in figure 77 (b) located at much shallower burial depth then interval 3A in figure 77 (a).

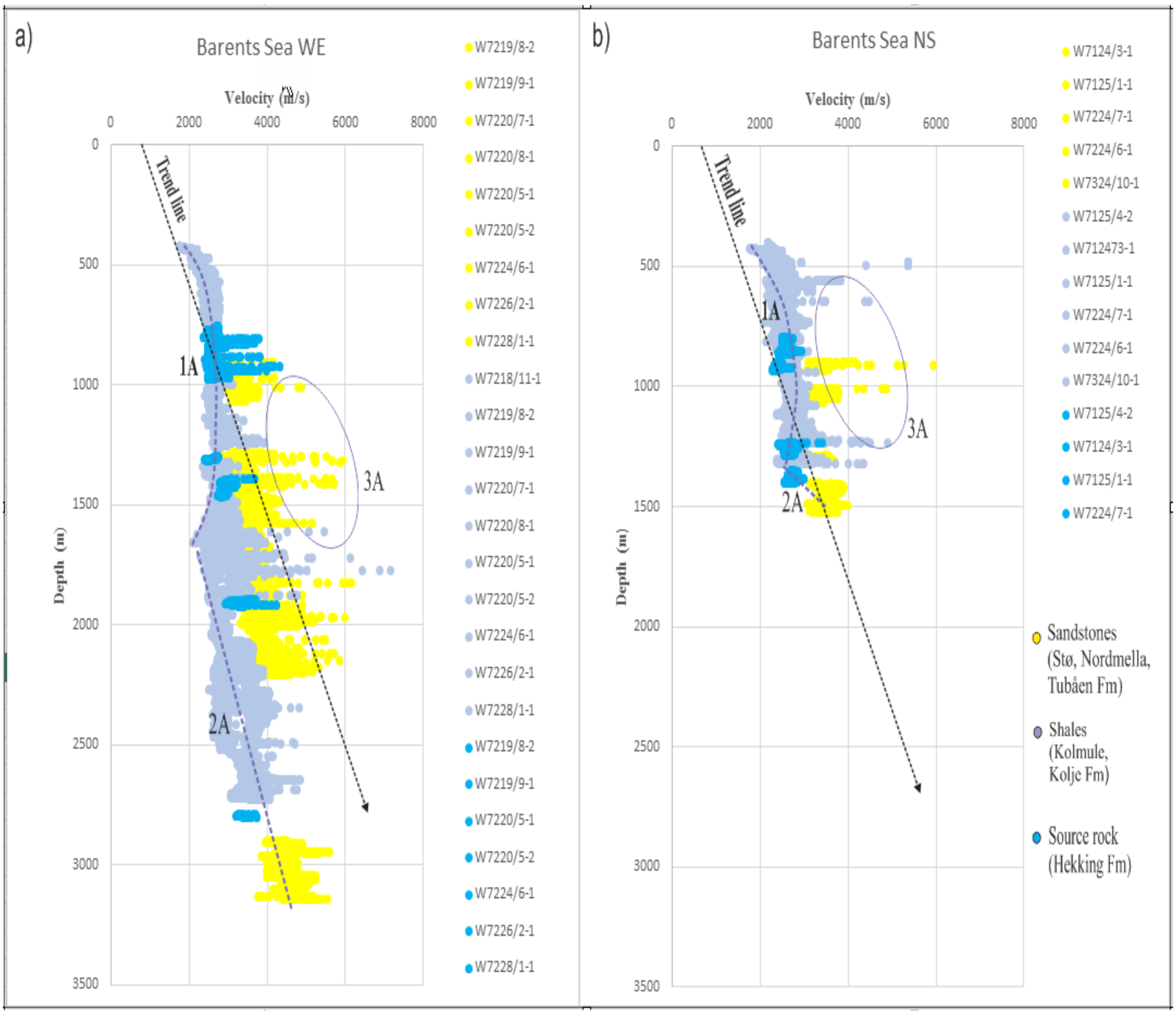


Figure 77. *Cross – plot Velocity versus Depth for study wells with present depth along WE and NS cross-section in the SW Barents Sea. The highlighted area (grey circle) represents anomalous velocity sandstones interval (5000 – 6000m/s). Trend line from published data applied to compare the velocity trend. Sonic velocity measurements every 15cm from wells in the SW Barents Sea.*

Density versus Depth plot for study wells in SW Barents Sea.

Figure 78 (a) shows variation in density in Triassic – Cenozoic sediments at present burial depth in study wells. After correcting for exhumation (*Fig. 78(b)*) density, especially in sediments in wells 7216/11-1S, 7219/9-1, 7220/7-1 and 7219/9-1 increasing more rapidly.

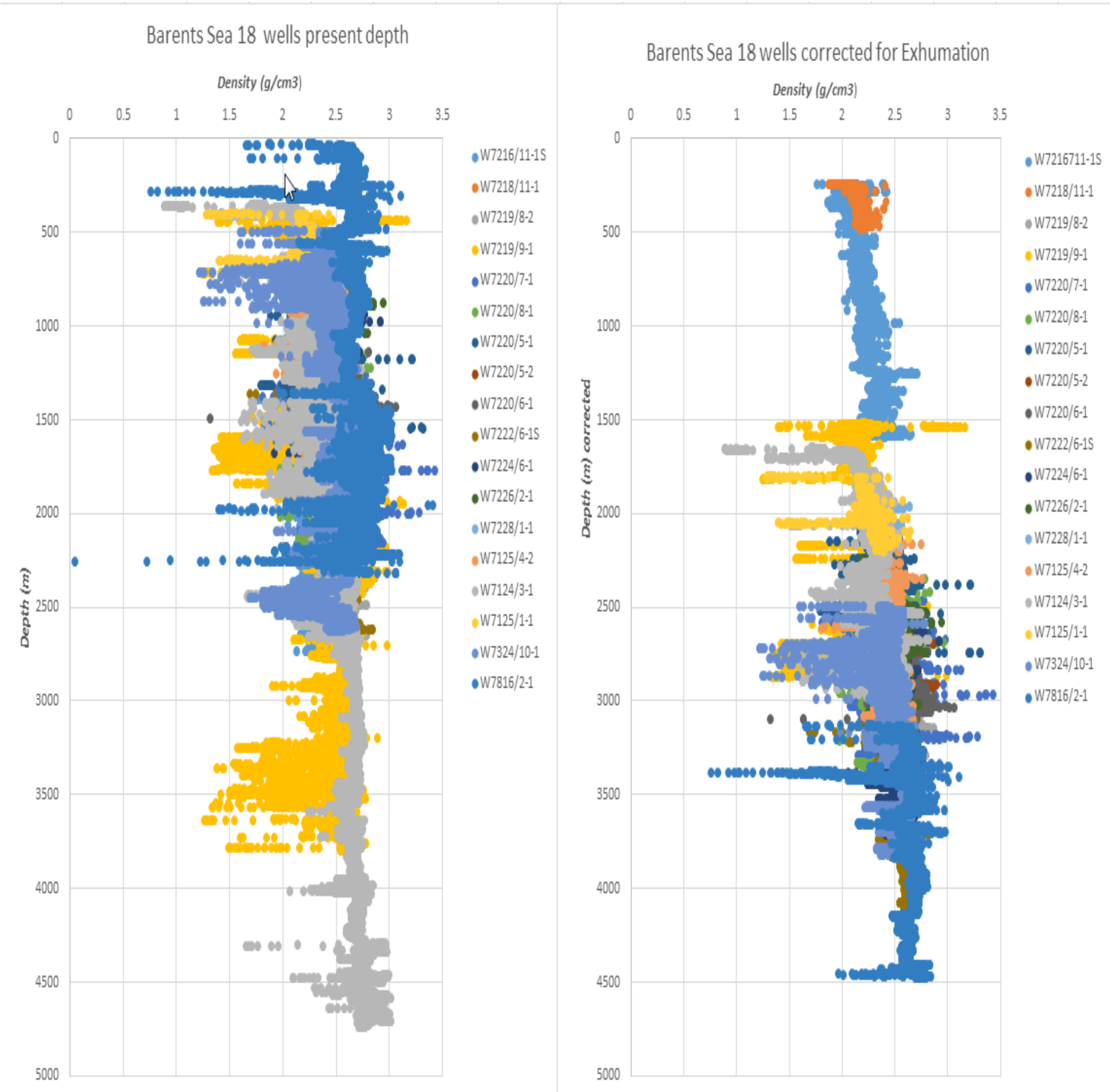


***Figure 78**. Cross – plot Density versus Depth for study wells with present and edited depth in SW Barents Sea.*

5 Discussion

Uplift and erosion have been classified as exhumation (Riis, 1992). It knowing fact that porosity reduced with depth due to compaction processes. This is the reason in increasing velocity in rocks. Compaction is irreversible process that means that in uplifted rocks, porosity has the same velocity then it was at buried depth (Storvoll, 2005).

Velocity data derived from well logs is a crucial for evaluation of sedimentary basins. It serves as a significant tool to identify lithology compositions, intervals with fluid, hydrocarbons contain and areas with overpressure. Velocity data is significant due to estimation of exhumation and temperature conditions (Storvoll et al., 2005).

General trend in study wells has been compared with estimated trend line (*Fig.20*) based on previous velocity studies (Storvolll at al., 2005).

Log data from study wells plotted with present depth and depth corrected for exhumation. Estimated trend line applied for comparing of velocity trend (*Fig. 20*). After correcting for exhumation, one can see that velocity increase more rapidly with depth.

5.1 Chemical compaction and velocity.

Interval 4A starts at depth 2500 m in figure 76 (b). It comprises sandstones from Stø, Nordmella formations of Early to Middle Jurassic age and shale from Kolje, Kolmule formations. One can see that velocity increase and anomaly high (5000 – 6000 m/s) at depth interval between 2500 – 3100 m. It can be explained by chemical compaction of shale and sandstones. Chemical compaction gives a sharp increase in velocity due to shear modulus increases in shale and sandstones (Vernik, 1992).

Velocity in shale can vary due to local lithology and content of silt and clay can affect it in that way that velocity increase with higher contain of silt. Figure 76 (b) shows high velocities in shale: 3000 -5000 at depth 2000 m and 6000 – 7000 at depth 2800 m. This is probably of high silt contain in the unit. Interval 1A in figure 77 (a) consists of velocities from shale from Kolmule og Kolje formations and shows slightly decreasing in velocity. This is can be related to fluid or gas contain in shale.

5.2 Time, temperature, quartz cementation and velocity.

According Storvoll (2005) sediments in the Barents Sea shows higher velocity to compare with sediments in the North Sea, for example (Storvoll et al., 2005). This is can we see in cross-plot in figure 73 and 74. Velocity rapidly increase with depth in study wells to compare with estimated trend line, what is also including well data from the North Sea. The reason to increasing in velocity associates with quarts cementation in sediments. Quarts cementation is sensitive to temperature and occurs at 70 – 80^{0} that correspond 2000 m depth. The Barents Sea sediments have been experienced high temperature, more then 100C^{0} at 3000 km depth for 12 millions years ago (Storvoll et al., 2005). This caused high rate of quartz cementation and following significant reduction in porosity and increasing in velocity.

Figure 73 (b) shows study wells with depth corrected for exhumation. Interval between 2500 – 4000 m indicates rapidly increasing in velocity. This is can be explained by quartz precipitation, timing and temperature that sediments have been subjected under maximum burial (Storvoll et al, 2005).

It seems that velocity increase more rapidly in sediments in N-S cross-section (*Fig.77*(*b*)) then in sediments in W-E cross-section (*Fig. 77* (*a*)). Comparing to the estimated trend line, velocity in N-W sediments increase more then in sediments in W-E area.
Interval 1A in figure 77 (a), (b) is mainly made up of shales of Kolmule, Kolje formations and source rock of Hekking Formation shows exponential trend with slightly decreasing in velocity. The Kolmule Formation consists of claystone ,shales, silt interbeds and strings of limestone and dolomite (Npd, 2017). Kolje Formation consists mainly of shale and claystone with interbeds of limestone, dolomite, sandstone and siltstone. Depositional environment refers to open marine. (Npd, 2017).
The Hekking Formation was deposited in anoxic, marine environment, and comprise predominantly shale and claystone (Npd, 2017).
The velocity increases with depth throughout the 2A interval in both W-E and N-S cross-sections. Note, that slope of the trend line in interval 2A (N-S section) shows high velocity gradient (*Fig 77* (*b*)).
Interval 3A shows anomaly velocity in figure 77 (a) and (b) which is made up of sandstones of Stø (progradating coastal environment) and Nordmella (tidal flat/ flood plain environment) formations (Npd, 2017).

From figure 76 (a), (b), and 77 (a), (b) it seems that velocity increase rapidly in sandstones then in shale. Quartz cementation and compaction are the main reasons in velocity increasing in sandstones while present of silt strings in shale can explain decreasing in velocity.

Note that in figure 76 (b) interval 5A (3700 – 3900 m) shows reduced velocity. According Storvoll (2005) all sediments that located at stratigraphic level more then 4000 m was deposited in Triassic (corrected for exhumation depth) have a low velocities. Triassic rocks from the Barents Sea comprise source and reservoir rocks (*Figure 7*). Low velocities in Triassic formations and in interval 5A can be explained by overpressure and gas contain in the formations (Storvoll, 2005).

6 Summary and conclusion

The objective of the thesis was to analyse main velocity – depth trend in study wells located in SW Barents Sea and how it behaves due to changing lithology and burial history.

- Analysis of density, resistivity and P-velocity log data from 20 study wells was performed for the purpose to investigate velocity – depth trends in the sedimentary units in the south – western part of the Barents Sea that characterised as function of petro physical properties of sediments, compaction rate, porosity, burial processes.

- Variation in GR, DEN, NEU and Pvel value with depth can be explained by different lithological units what wells penetrated and compaction trend connected to exhumation processes in the Barents Sea.

- The most of study wells showing high velocity/depth trend that can be associated with the burial processes in the area and the quarts cementation in the Barents Sea sediments.

- Some of the wells have low velocity. It can be explained by content of soft kerogen in source rock that lead to anisotropy in velocity and explained why source rocks tend to have lower velocity to compare velocity in sandstones and shales at the same depth.

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