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Estimation of Barents Sea uplift by comparison of linear trend lines from well log properties

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Sammendrag

I denne oppgaven har lineære trender fra målte brønnloggsegenskaper blitt sammenliknet for å se om man kan estimere oppløft. Referanse trender fra områder som ikke har blitt løftet opp, brønner 15/9-6, 34/7-1, 34/7-5 og 6608/10-3, har blitt sammenliknet med lineære trender fra områder i Barensthavet som har blitt løfet opp, brønner 7216/11-1 S, 7117/9-1, 7120/5-1 and 7121/4-1.

Brønnloggsegenskaper som har blitt bruk er Vp, Vs, Vp/Vs, Rhob, Rdeep og porøsitet. Alle disse egenskapene kan bruker for å estimere oppløft, bortsett fra Rdeep, som bare kan bli brukt til å si noe om områder har blitt løftet opp eller ikke. Rdeep kan ikke brukes til å få noen verdier på oppløftsestimatet.

Når vi sammenlikner to trendlinjer, burde de ideelt sett ha samme litologi, porøsitet og poretrykk. De burde også være så parallelle som mulig. Hvis disse kriteriene ikke er oppfylt, vil oppløfts estimatet bli feil, og verdiene vil variere veldig.

Brønnene som ligger vest i Barentshavet, 7216/11-1 S og 7117/9-1 viser ingen oppløft, som forventet. De to andre brønnene, viser oppløft på mellom 600 og 1500m, som er verdier som er realistiske. Denne oppgaven viser at metoden fungerer, hvis de overnevnte kriteriene er møtt.

Abstract

Linear trends of measured well log properties have been compared in this thesis, to see if uplift in the Barents Sea can be estimated. Reference trends from areas that have not been uplifted, wells 15/9-6, 34/7-1, 34/7-5 and 6608/10-3, have been compared to linear trends from areas that have been uplifted, wells 7216/11-1 S, 7117/9-1, 7120/5-1 and 7121/4-1, from the Barents Sea.

The well log properties used are Vp, Vs, Vp/Vs, Rhob, Rdeep and porosity. All these properties can be used to get uplift estimates, except for Rdeep, which can only be used to say something about if the are has been uplifted or not. Rdeep cannot be used to get any uplift estimate values.

When comparing two trend lines, they should ideally have the same lithology, porosity and pore pressure. They should also be as parallel as possible. If these criteria are not met, the uplift estimates will be incorrect, and span over a very large range of values.

Wells located to the west in the Barents Sea, 7216/11-1 S and 7117/9-1, show no uplift, which is as expected. The two other wells show uplift from 600 to 1500m, which is a range of values that are realistic. This study shows that the method is working, if the mentioned criteria are met.

Chapter 1 - Introduction

We want to find out if comparing linear trends of measured well log properties can be used to estimate uplift. The Barents Sea has been subject to uplift of various degrees, and being able to quantify the amount of uplift would be useful information to have when exploring for hydrocarbons. The Norwegian Sea and the North Sea has not been subject to uplift, and by comparing linear trends of well log properties from these areas with areas that have been uplifted, we should get uplift estimates.

Four wells from the Norwegian Sea and the North Sea, and four wells from the Barents Sea will be used in this study. There should be enough data from these wells to demonstrate if our problem can be solved or not. If the results are satisfying, and we are able to estimate uplift trend line comparison, people exploring for hydrocarbons would have another tool to increasing the chance to find oil and gas.

When exploring for hydrocarbons, it can be important to know if the area you are exploring has been subject to uplift. Uplift will influence a lot of important factors that play a role when exploring for hydrocarbons. Reservoir seals might fail and start to leak when uplifted, causing hydrocarbons that once were trapped to leak to the sea floor or migrate to another trap.

Decreasing reservoir pressure as a result of uplift might bring gas that has been dissolved in oil out of solution, displacing the oil in the process such that it migrates to the sea floor or into another trap.

Five well log properties will be used in this study, compressional wave velocity (Vp), shear wave velocity (Vs), the ratio between compressional wave velocity and shear wave velocity (Vp/Vs), density (Rhob), deep resistivity measurements (Rdeep) and porosity. It is interesting to find out if the different properties give us different estimates.

Uplift will be estimated in three Barents Sea wells, 7216/11-1 S, 7121/4-1, 7117/9-1 and 7120/5-1. Two of these wells 7216/11-1 S and 7117/9-1 are located in the western part of the Barents Sea, while 7121/4-1 and 7120/5-1 are located more to the east. We have chosen these wells because uplift in the Barents Sea is zero to the east, increasing to the west. We want to see if we can demonstrate this. The reference wells that the Barents Sea trend will be compared too are 15/9-6, 34/7-1, 34/7-5 and 6608/10-3.

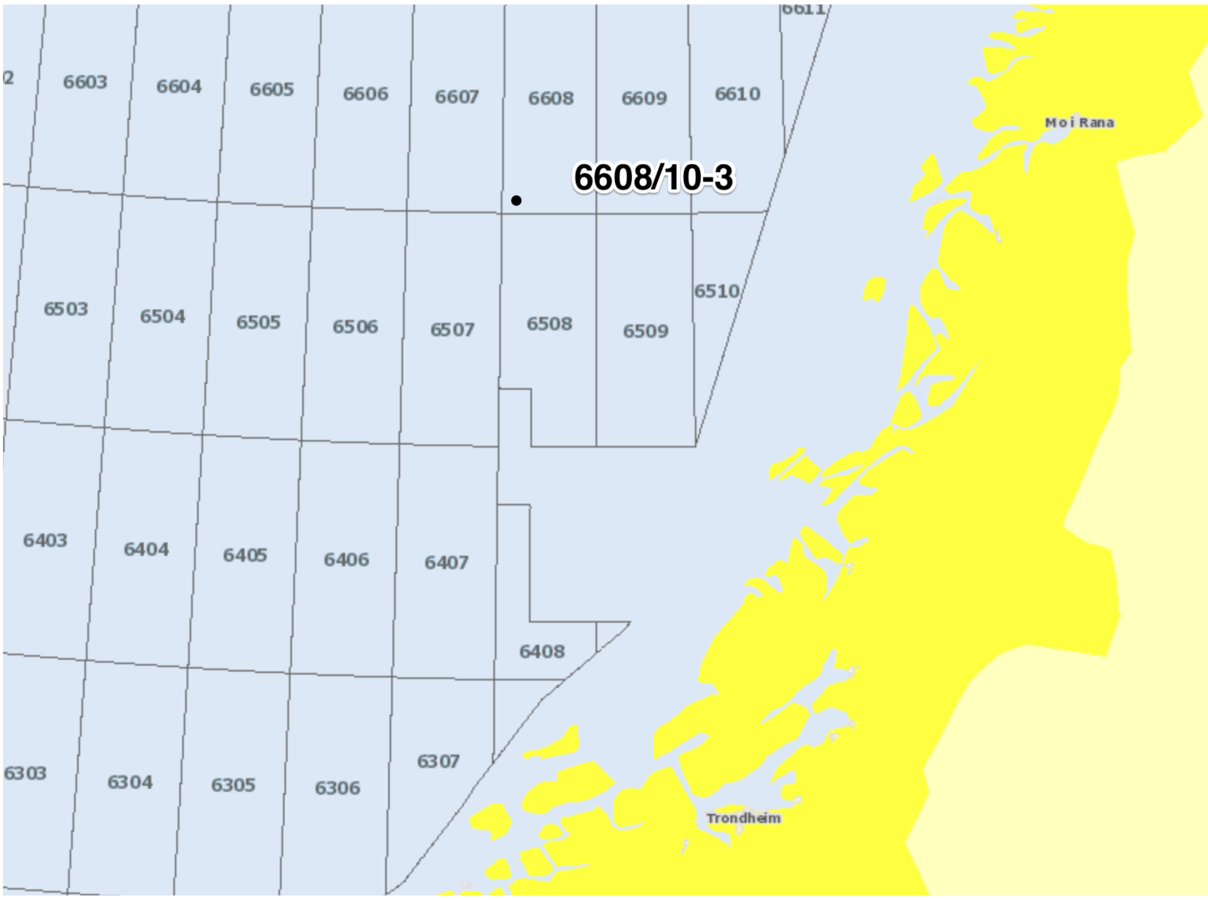

Figure 1 - Map showing reference well 6608/10-3. Map modified from NPD factpages.

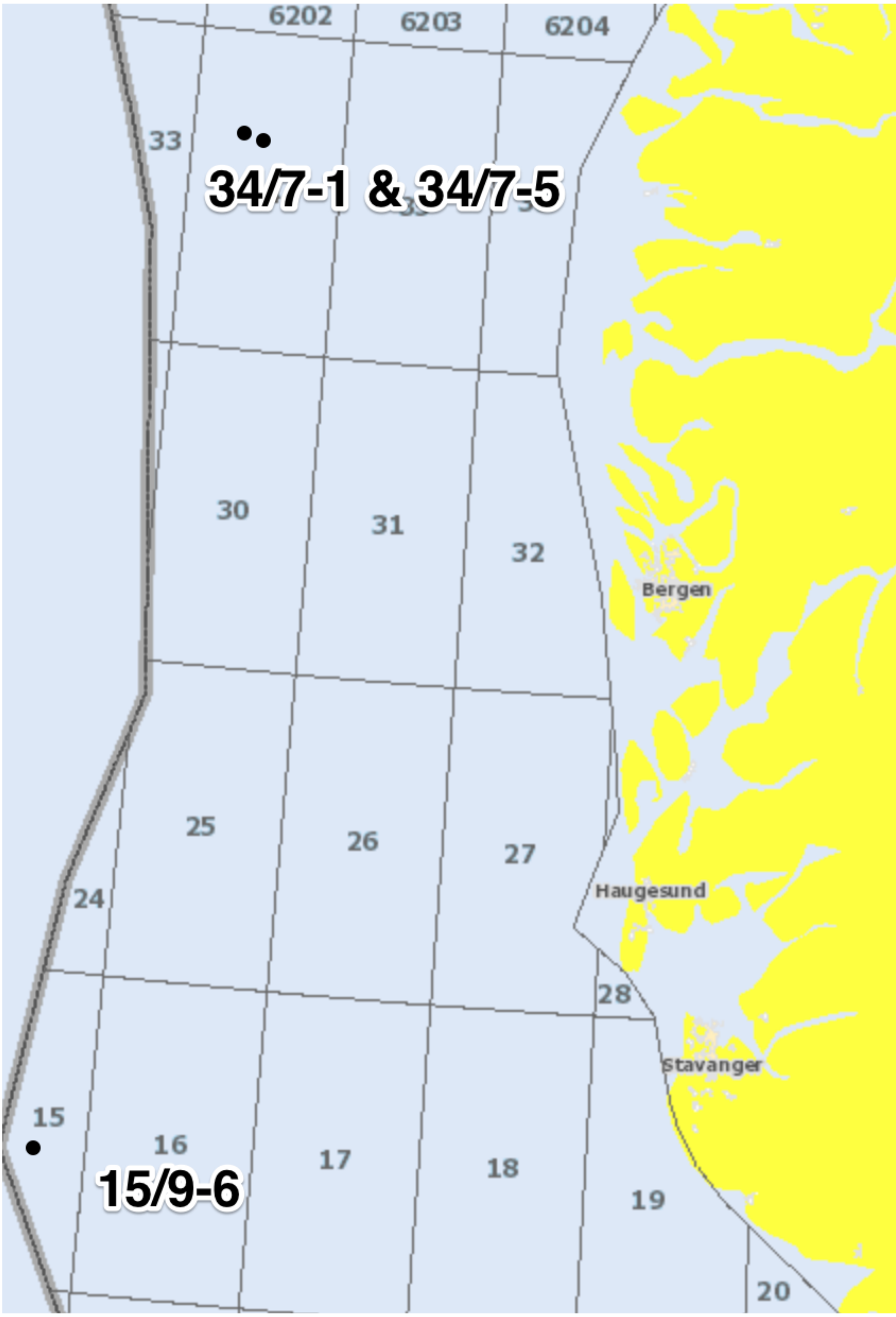

Figure 2 - Map showing 3 out of 4 reference wells. Map modified from NPD factpages.

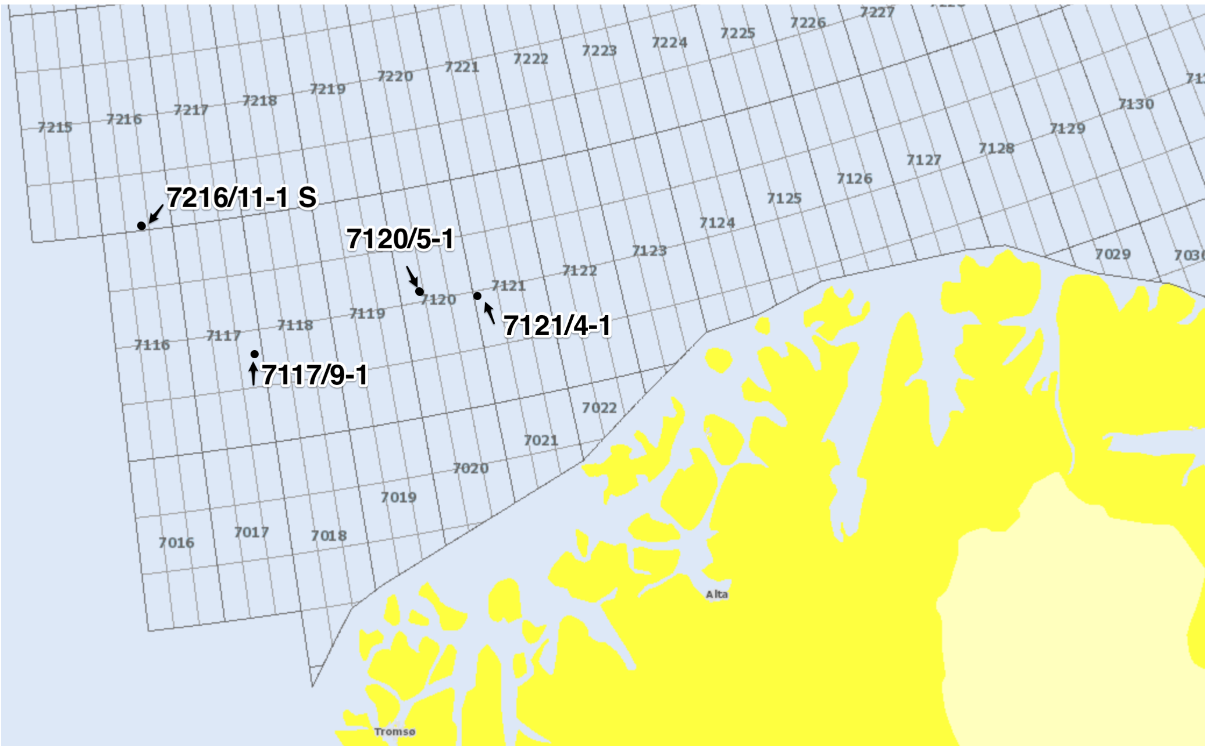

Figure 3 - Map showing the geographical location of the Barents Sea wells used in this study. Map modified from NPD factpages.

Similar studies trying to estimate uplift have been done before, with a focus on compressional wave velocity, temperature data, and other well log properties (D.V. Corcoran et. Al. 2005 & Hansen, S, 1996.)

This thesis will start by explaining the theory we base our analysis on, continuing with an explanation of the methodology, a presentation of the results, analysis of the results and finishing with a conclusion and eventual suggestions for future work. There is an appendix at the end of the document including figures showing raw well log data plotted together with the linear trend lines, for every well and every well log property.

Chapter 2 - Theory

It is well known that parts of the stratigraphy in the Barents Sea have been subject to uplift after the last ice age (Baig et Al, 2016). The icecap was in contact with the seafloor, and the weight of the ice kept the subsurface at a large depth. After the ice caps disappeared, the stratigraphy started moving upwards due to the reduce load from the retreating ice, and the sea became increasingly shallow.

Measured well log properties will be used to create linear trend lines for Vp, Vs, Vp/Vs, Rhob, Rdeep and porosity well log properties. These properties all change with burial depth. This is because increasing burial depth affects the lithology where the properties are being measured. Stress, porosity, temperature, mineralogy etc. all changes with depth, and these features influences the measurements of the well log properties.
We believe that all geological groups in the Barents Sea deposited earlier than the Nordland group have been subject to uplift, and we have chosen to focus on the Sotbakken and Cretaceous sediments when doing uplift estimation.
Because of this uplift, parts of the stratigraphy are now shallower than before. We assume that the measured well log properties at maximum burial depth of these uplifted geological groups are preserved, and that they will show measured values corresponding to a greater burial depth. This assumption can be used to estimate the amount of uplift these geological groups have been subject to.

For instance, Vp data from a geological group that have been uplifted will match the trend line of a geological group in the reference wells that has not been uplifted, and is at a greater depth.

We assume that all measured well log properties vary linearly with depth. While this is not always the case, it is an assumption that is pretty accurate. It makes the uplift estimation easy compared to if we had trend lines that were not linear. Plotting raw data together with the linear trend lines show that this assumption is accurate.

When trying to estimate uplift in a Barents Sea well, we will compare a trend line from a geological group in this well with reference trends from time equivalent geological groups. Not all comparisons can be used to estimate uplift, due to various reasons. This will be discussed later.

Linear trend lines from measured well log properties from two time equivalent geological groups can be compared to estimate the uplift. The trend line of the geological group we want to estimate should be plotted together with reference trends from a time equivalent geological group. The reference trends have to be established from well log data from geological groups that has not been subject to uplift.
For this method to work, the trend line of the group we are estimating has to be located in a plot such that we have to move it down through the sub surface for it to match the reference trend. Ideally, the trends should be parallel, giving us the same uplift estimate regardless of whether we look at the top or the bottom of the group that is to be estimated. However, the trend lines often have different gradients, making them non-parallel. This gives us not one estimated uplift value, but a range of uplift values, depending on whether we estimate uplift from the top or bottom of the group. The boundaries for the estimation will be found at the top or bottom of the geological group that where uplift is being estimated.

The gradients of the trend lines being compared should have the same sign, or else the uplift estimate is going to be infinite at either the top or the bottom of the geological group. See figures 1, 2 and 3 for graphical examples and demonstration of this method.

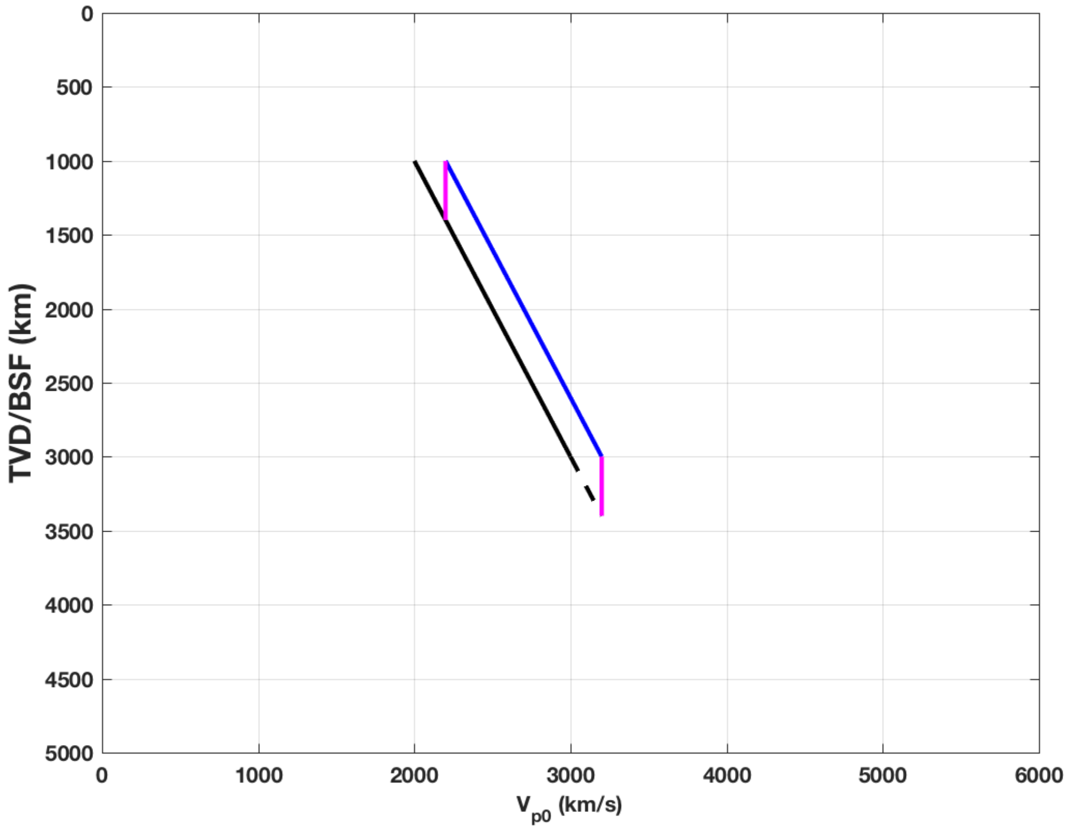

Figure 4 -Figure showing how uplift estimation is done. The blue line represents a trend line from a well where we want to estimate uplift, and the black line represents a reference trend line. The magenta coloured line is the distance the blue trend line has to be shifted to match the black line. The length of the magenta line is then the amount of uplift the group represented by the blue line has gone through. The trend lines are parallel, so the magenta line has the same length both at the top and the bottom of the uplifted group. The black, stapled line is an extrapolation of the reference trend, making it possible to estimate uplift at the bottom of the group represented by the blue trend line

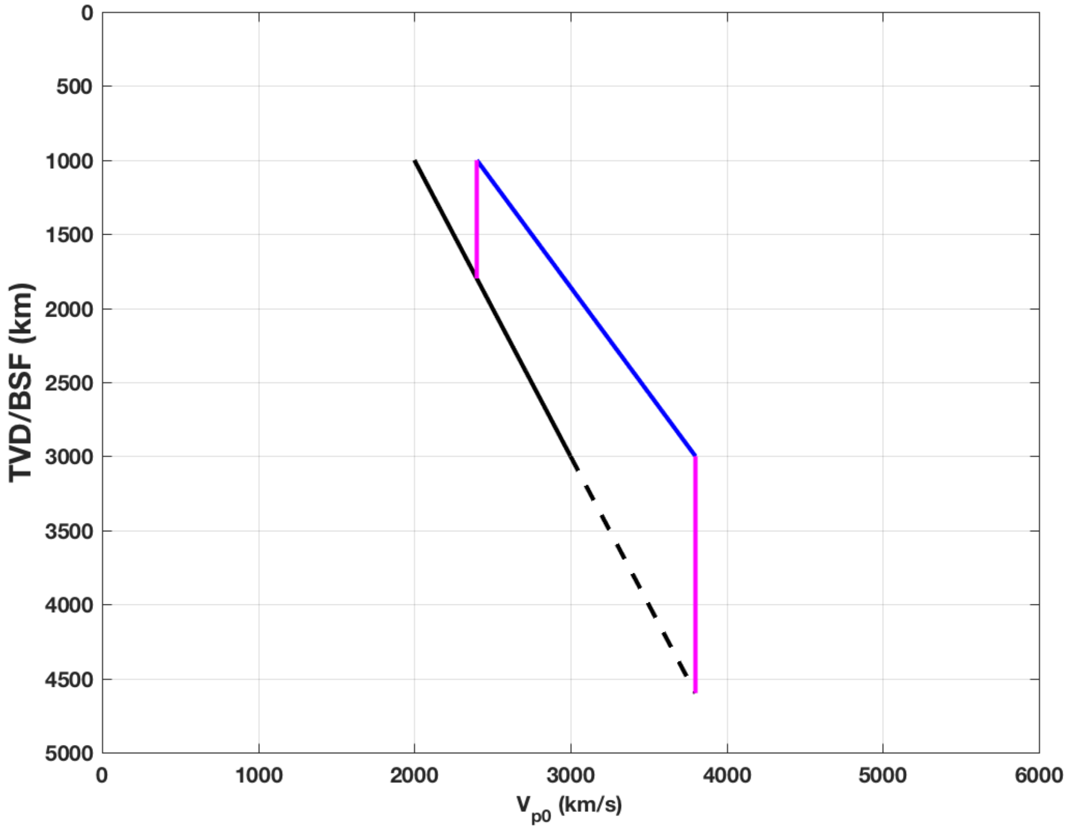

Figure 5 -- Figure showing how uplift estimation is done on two trend lines that are not parallel. The blue line represents a trend line from the Barents Sea that has been subject to uplift, and where uplift is being estimated. The black line represents a reference trend line. This example is more realistic than the one shown in figure 1. We see that we get different uplift values whether we estimate uplift at the top or bottom of the blue trend line. The uplift values will be an interval with the lowest estimate found at the top of the group represented by the blue line, and the highest value found at the bottom of the group represented by the blue line. In this example, the black trend has a higher gradient than the blue trend. If it were the other way around, the lower boundary of the uplift estimate would be found at the bottom of the blue trend line, and the upper boundary of the estimate found at the top of the blue trend line.

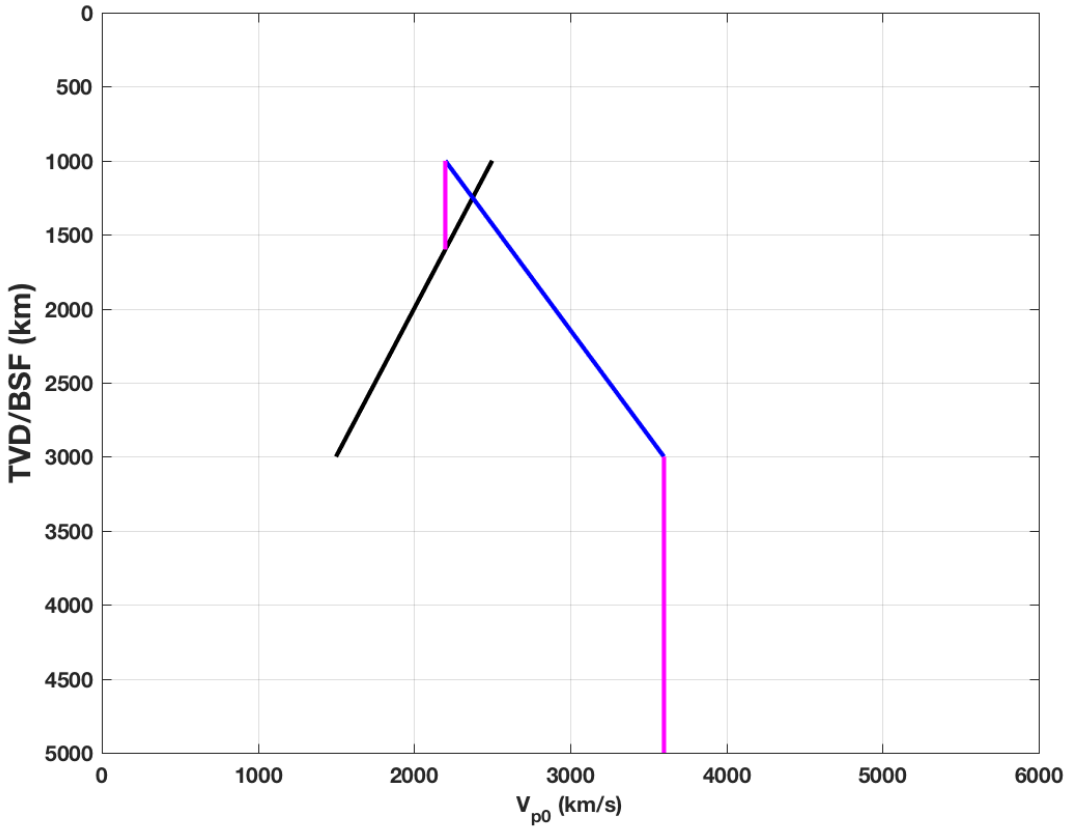

Figure 6 - Figure showing two trend lines with opposite gradient sign. We see that we get a value for uplift at the top of the blue trend line, but and infinite uplift value at the bottom of the same trend line. This shows that it is not possible to compare two trend lines with opposite gradient signs to estimate uplift.

Only trends from time equivalent geological groups will be compared to each other. We have reference trends from the Nordland, Hordaland, Rogaland and Shetland groups, and Barents Sea trends from the Nordland, Sotbakken and Cretaceous sediments. Nordland and Nordland is time equivalent, Hordaland and Rogaland is time equivalent to Sotbakken, and Shetland is time equivalent to the Cretaceous sediments.

Not all trend lines will be useful when estimating uplift. First of all, they have to make physically sense. Trend lines with values below 0 at the sea floor have to be discarded. The reason that we get values below zero at the sea floor and negative gradients is most often because the Vclay filter has removed a lot of data points, such that the trend line is not representative of the data, or that the geological group is so thin that do not get a correct trend line.

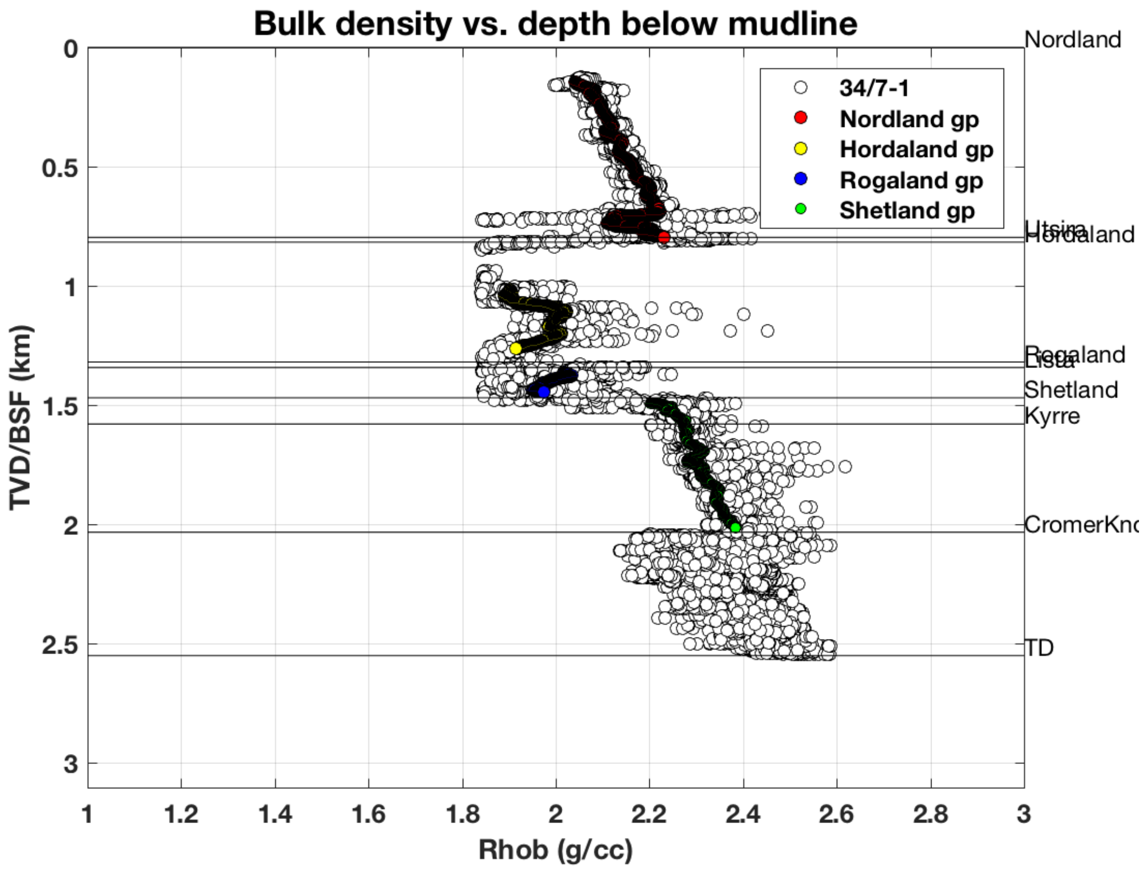

Figure 7 - Figure showing a plot of Rhob vs. depth for well 34/7-1. We see that the Hordaland group (yellow) has a lot of datapoints removed by the vclay filter, and that the Rogaland group (blue) is very thin.

All trend lines are linear and will have an equation like this:

$$V_p = V_{p0} + k * z$$

$$V_s = V_{s0} + k * z$$

$$V_p/V_s = V_{p0}/V_{s0} + k * z$$

$$Rhob = Rhob_0 + k * z$$

$$R_{deep} = R_{deep0} + k * z$$

When comparing two trend lines with each other, it is important that the trend lines come from groups with the same lithology. We will achieve this by applying a vclay filter removing unwanted data points that do not contain enough shale.

We want data points with a Vclay (volume fraction) > 0,5 to be what influences our regression models. This will results in mostly shale, claystones and siltstones creating the fundament of our property models. These lithologies have low porosity, and will not contain as much pore fluids as sandstones and limestones, which both are porous rocks. Pore fluids will influence the values of the measured properties we want to use for our models, and that is not something we want to happen. We want models that can be compared to each other, even though they are from highly different geological areas.

2.1 Vp/Vs

Lithostatic pressure will influence Vp and Vs measurements, and we want to look at the relationship between these two properties because they will to a certain degree cancel the effect that lithostatic pressure has on both properties when looked at individually.

2.2 Vp

All wells have P-wave velocity measurements. We assume that p-wave velocity increases with depth, and that most of the trend lines from both the reference wells and the Barents Sea wells will have positive gradients.

2.3 Vs

We do not have any Vs measurements in any of the wells, so this property has to be estimated from the Vp measurements using the Greenberg-Castagna relationship between compressional waves and shear waves. The Greenberg-Castagna (Rock physics handbook 2nd edition) equation is different for sand stones and shales.

$$Vs_{GC,sandstone} = (0{,}80416 * Vp) - 0{,}85588$$

$$Vs_{GC,shale} = (0{,}76969 * Vp) - 0{,}86735$$

Vs is calculated for every data point in the well. The arithmetic and harmonic mean is then calculated, and weighted based on Vshale values. The final Vs data is then calculated by taking the average of the arithmetic and harmonic mean.

$$Vs_{GC,arithmetic\ mean} = (1 - V_{shale}) * Vs_{GC,sandstone} + V_{shale} * Vs_{Gc,shale}$$

$$Vs_{GC,harmonic\ mean} = (\frac{1 - V_{shale}}{Vs_{GC,sandstone}} + \frac{V_{shale}}{Vs_{GC,shale}})^{-1}$$

$$Vs_{GC} = \frac{Vs_{GC,arithmetic\ mean} + Vs_{GC,harmonic\ mean}}{2}$$

It is difficult to know if the estimated Vs values match what we would get if we measured the property in nature instead, and it is therefore interesting to have a well with measured values of Vs, and compare them to values estimated from Vp in the same well. This has been done for one well, and we see that the estimated values are close to the measured values. Application of the Greenberg-Castagna relationship is robust, and we trust the estimated values for all the wells where Vs have been estimated from Vp.

Well 8/10-4 S has Vs measurements, and can be used to verify that using the Greenberg-Castagna relationship is valid. Unfortunately, it does not have Rhob measurements through the whole well section. Since Vshale is calculated from porosity, which is calculated from Rhob, we only have Vshale values for a short interval of the well. See figure 8.

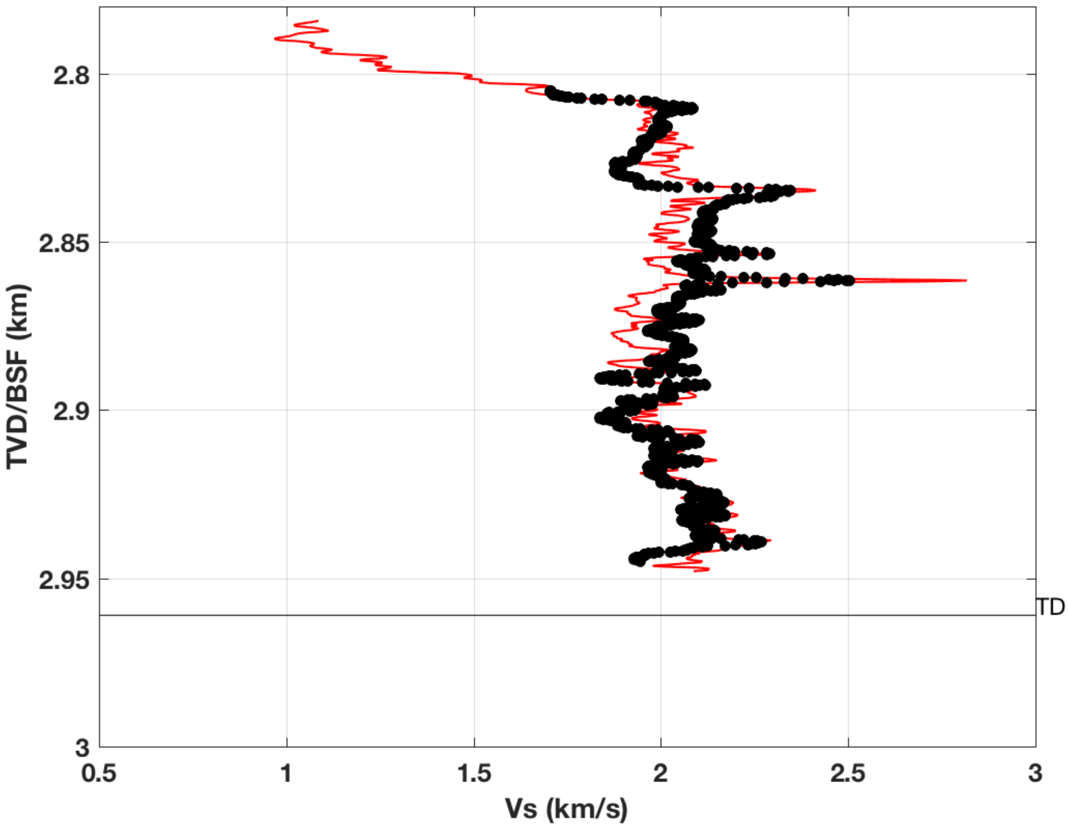

Figure 8 - Comparison between measured Vs data (black) and estimated Vs data from Greenberg-Castagna relationship (red) from well 8/10-4 S. We see that there is a nice match between the two data sets.

2.4 Rhob

All wells have density measurements. We assume that density increases with depth, as compaction increases and packs the sediments closer together, resulting in more grains occupying the same amount of volume. Some wells do not have density measurements through the whole well section, and it has to be estimated from p-wave velocity. The Gardner relationship (Gardner et al, 1974) has been used for rhob estimation.

$$\rho_b = a * {V_p}^m$$

Where a = 0.31, and m=0.25.

It is important to make sure that this approximation is correct, and estimated Rhob values for one well should be plotted together with measured Rhob values. Measured Rhob values for well 34/7-5 have been plotted together with estimated Rhob values using the Gardner relationship. The match is not perfect, but pretty good for some geological groups. It is sufficient for our use.

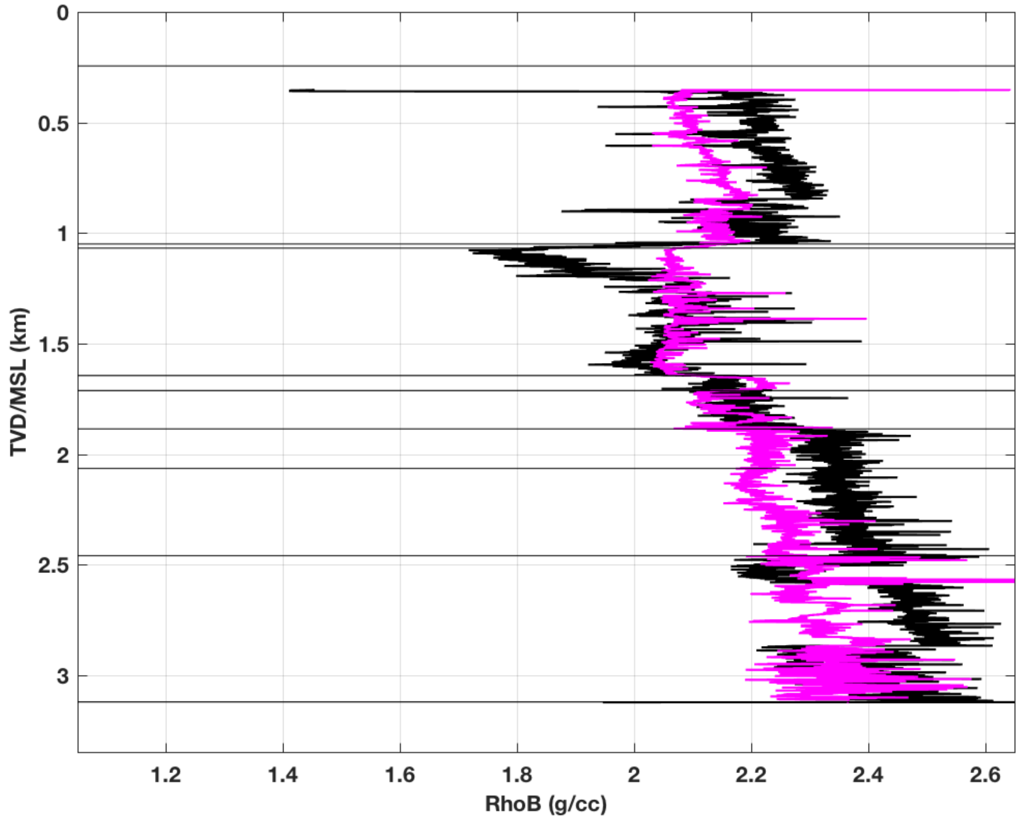

Figure 9 - Measured rhob values (black) from well 34/7-5 plotted together with estimated rhob values (magenta). The match is not perfect, but still pretty good for some geological groups. The values where estimated by using the Gardner relationship.

2.5 Deep resistivity

All wells have resistivity measurements, both shallow, medium and deep resistivity measurements. We are using the deep resistivity measurements, because these measurements are less influenced by drilling fluids and cuttings, compared to the shallow and medium measurements.

2.6 Porosity

Porosity is calculated from the density log by this equation:

$$\emptyset = \frac{\rho_{ma} - \rho_{bulk}}{\rho_{ma} - \rho_{fl}}$$

Where ρ_{ma} is matrix density, ρ_{bulk} is bulk density and ρ_{fl} pore fluid density.

Chapter 3- Method

We will establish linear trends from well logs in four wells that are located in the Norwegian North Sea and the Norwegian Sea, with one linear trend for each well log property. These wells will be called reference wells, and the trends reference trends. When estimating uplift in a Barents Sea well, we have to compare trend lines from the Barents Sea with reference trends from time equivalent geological group. We have reference trends from the Nordland, Hordaland, Rogaland and Shetland groups, and Barents Sea trends from the Nordland, Sotbakken and the Cretaceous sediments. Nordland and Nordland is time equivalent, Hordaland and Rogaland is time equivalent to Sotbakken, and Shetland is time equivalent to the Cretaceous sediments.

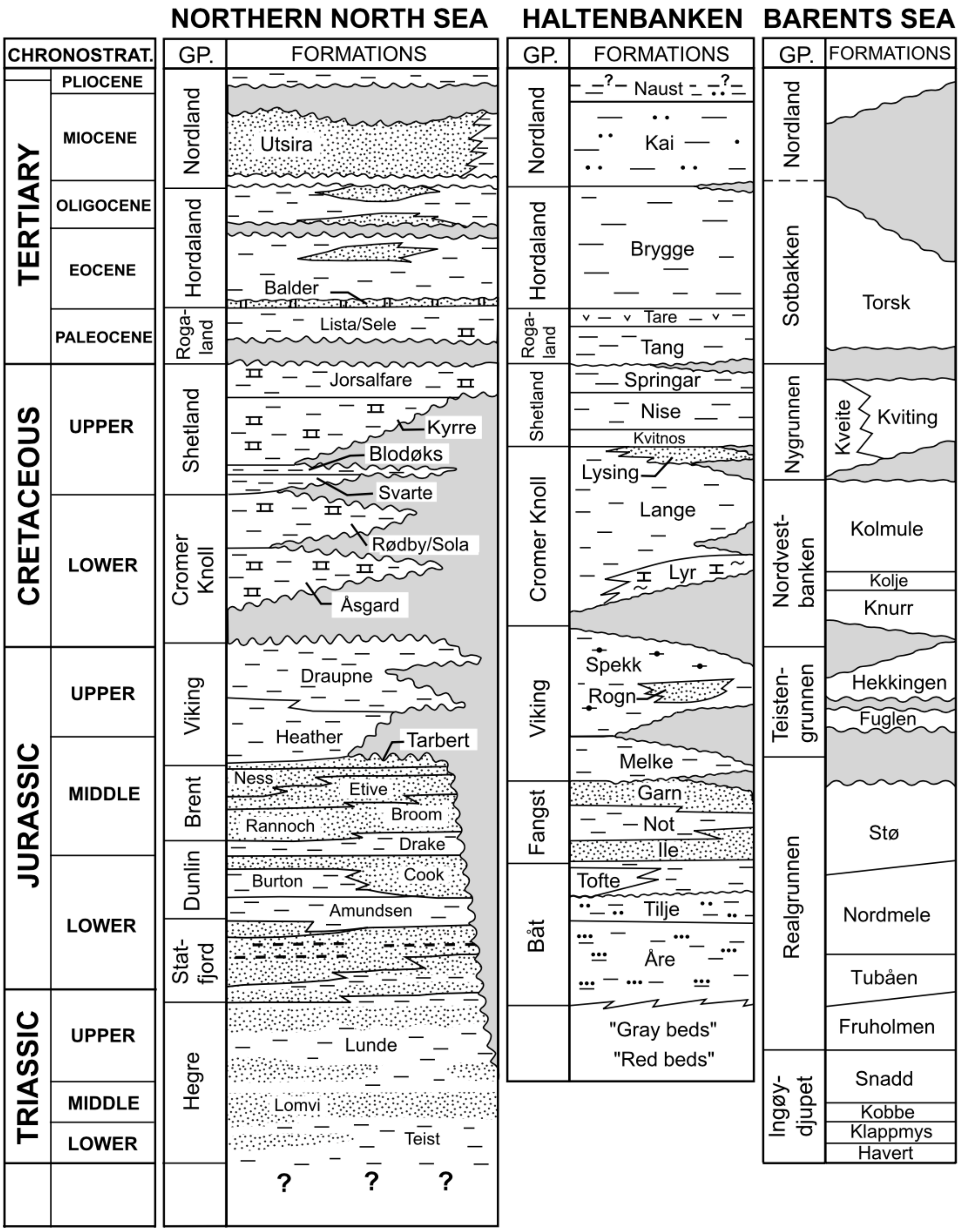

Figure 10 - Figure showing stratigraphy for the Northern North Sea, Norwegian Sea and Barents Sea. Used to find out which geoloigcal groups are time equivalent. From Storvoll et al, 2005.

All data handling will be done in Matlab, and Matlab scripts are created to import well log data from las files, to split data up for each geological group, run relevant filters, plot data perform linear regression on data from each geological group and finally to calculate estimated uplift.

When comparing linear trends, it is important that we try to normalize the data as much as possible. We are only interested in data points from rocks with high shale content, and a vclay cut off filter will therefore be used to filter out unwanted datapoints. The vclay cut off filter has been set to 0.5, resulting in data points from rocks with a vclay below 0.5 to be filtered out. Vclay is in this case volume percentage. Vclay, Vsand and porosity will always add up to 1.

Vclay is calculated from the gamma log, and minimum and maximum GR values have to be picked manually from the well log. Investigation of the GR log together with the completion logs from each well was used to determine min and max GR values. Min GR value should be picked from a clean sandstone, and max GR value should be picked from a clean shale. It is important to look at the completion log from each well to be sure that you are picking GR values from correct lithologies. Other lithologies such as igneous rocks can give off very low GR values, and can mistakenly be thought to be sand. See figure 11.

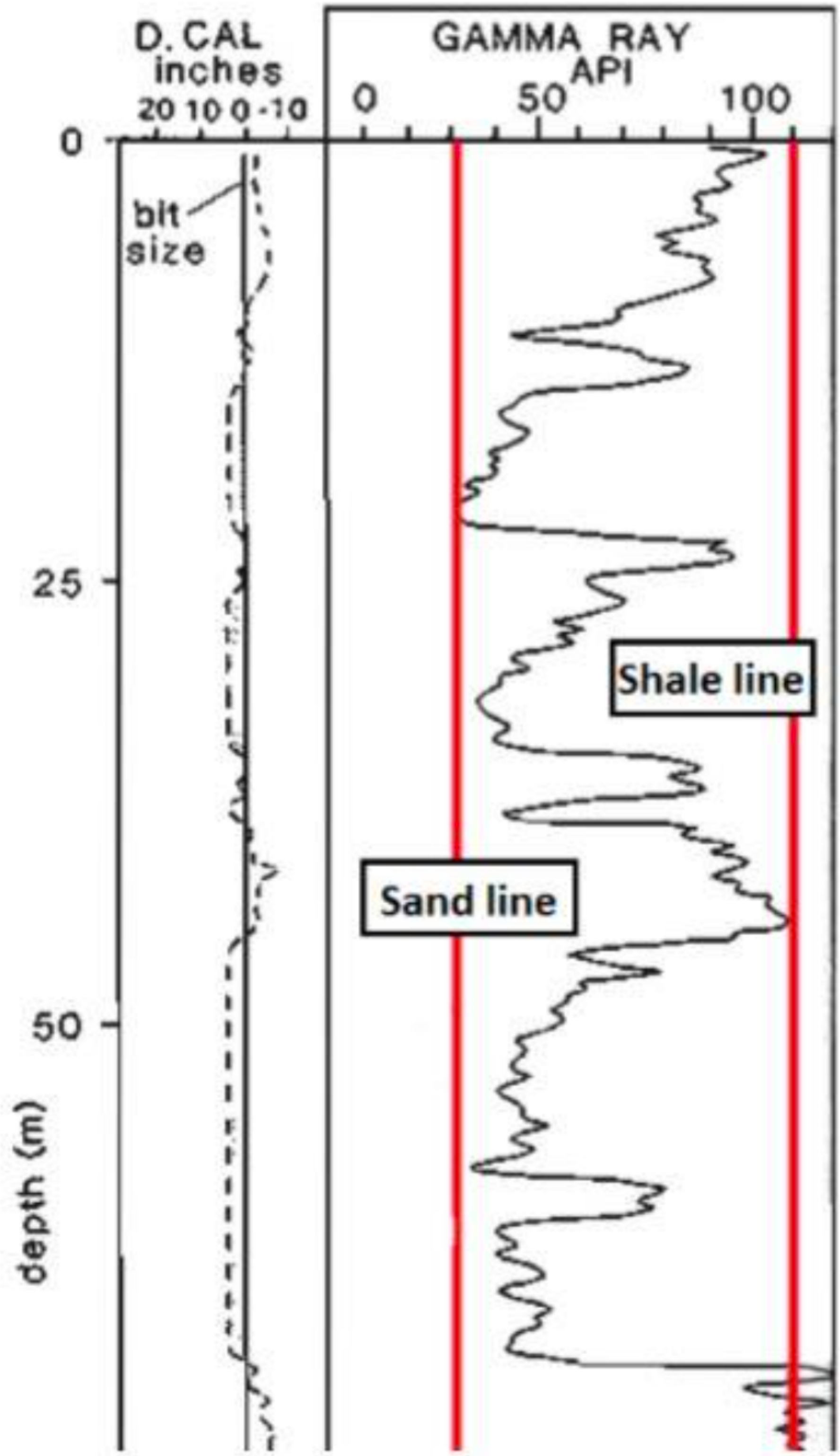

Figure 11 - Gamma ray log showing the sand and shale lines, representing minimum and maximum picked GR values, respectively. Modified from Rider (2000).

A low pass moving average smoothing filter will also be applied to the data for smoothing, with a span of 199.

Running a moving average filter will mess up data point values at the start and end of the geological groups, if there are big changes in measured properties between the two groups, introducing ”tails” to the smoothed curve. If the vclay filter does not remove these tails, they have to be removed manually. This has been done for some groups in some wells. Some groups also have data points from the Nordand group manually removed due to them clearly being outliers. These outliers are mostly a result of well log measuring errors influenced by shallow lithology, conductor etc.

After the data has been split up with respect to geological groups and filtered to remove unwanted data points, regression is run to establish linear trends for each measured property, for each geological group.

All four reference trends from one geological group and one well log property is plotted together with the trend line from a time equivalent geological group and same well log property from a Barents Sea well. Trend lines that have the same gradient sign can be compared to estimate uplift, but the trend from the well that has been uplifted needs to be positioned in the plot so that it can be moved to a greater depth to match the reference trend lines. See figures 1, 2 for demonstration of this method.

Chapter 4 - Results

We want to compare the reference trend lines from wells 15/9-6, 34/7-1, 34/7-5 and 6608/10-3 in the North Sea with trend lines from the Barents Sea wells 7216/11-1 S, 7117/9-1 and 7121/4-1 to estimate uplift. Time equivalent geological groups will be compared. The Nordland group from the reference wells and the Nordland group in the Barents Sea are time equivalent. The Hordaland and Rogaland groups from the reference wells and the Sotbakken group from the Barents Sea are time equivalent. The Shetland group from the reference wells and the Cretaceous sediments from the Barents Sea are time equivalent. The Cromer Knoll group, which can be found in the reference wells, is also of Cretaceous age, but it is too thin to give us a good trend line.

The Nordland group has not been subject to uplift in the Barents Sea (Baig et al, 2016), but we will compare trend lines anyway because it is interesting to find out if we can see the effects of zero uplift on the trend lines. The Nordland trends from the reference wells and the Barents Sea should be nearly identical. The trend lines from Hordaland are very different than those from Sotbakken, making it impossible to estimate uplift by comparing the two. See appendix.

The Rogaland group is very thin, and will not give us a good trend line because it contains too few data points. It is not possible to use this group for uplift estimation,

We are left with one geological group that can be used to estimate uplift, the Shetland group. It will be compared to the Cretaceous sediments in the Barents Sea wells. These are the geological groups we will compare for the rest of the wells.

Plots showing raw data and reference trend lines for the other well log properties can be found in the appendix.

4.1 7216/11-1 S

Well 7216/11-1 S consists of the Nordland and Sotbakken groups, and no older geological groups have been penetrated. As discussed earlier, Sotbakken cannot be compared to either Rogaland or Hordaland reference trends. Due to the well being so far east in the Barents Sea, we expect the uplift to be minimal. The Nordland trends can be plotted together to demonstrate this.

4.1.1 Vp

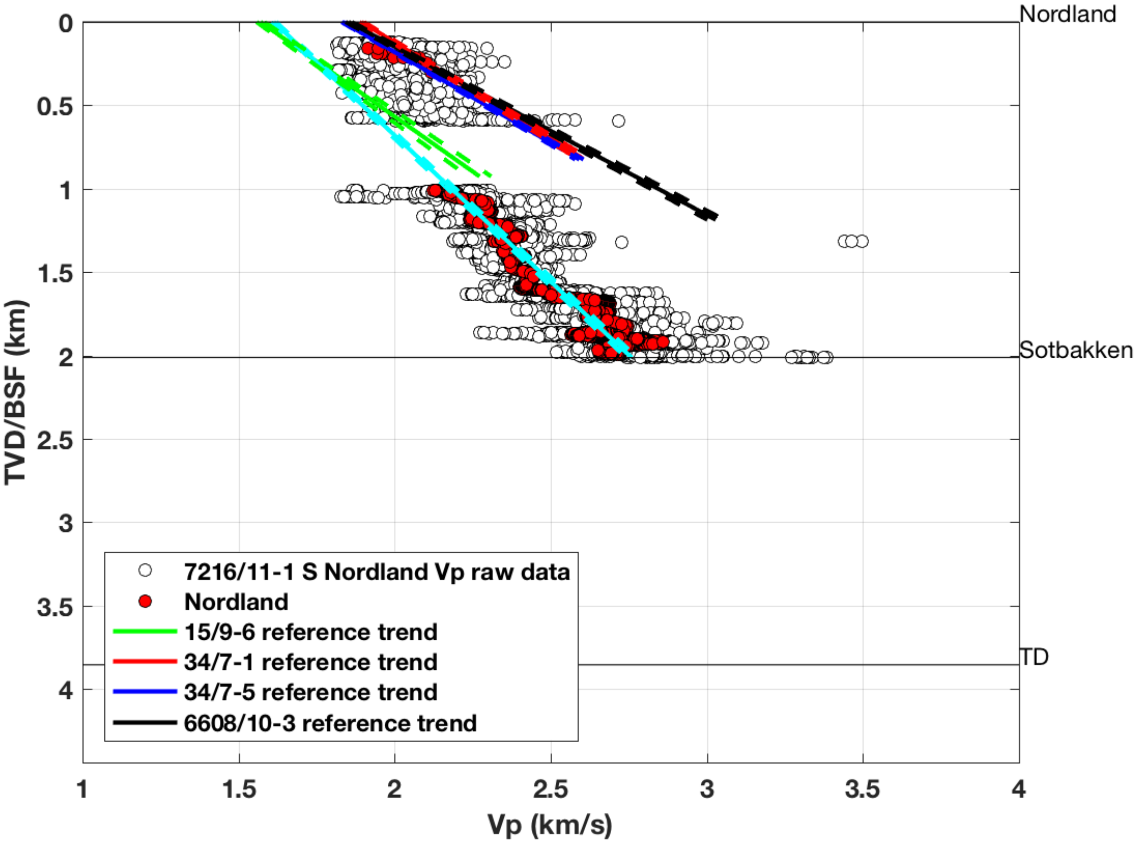

Figure 12 - Plot showing raw Vp data from the Nordland group in well 7216/11-1 S, represented by white dots. The smoothed data is shown in red. The reference trend lines are also found in the plot. The cyan line is the trend line representing the Vp data from well 7216/11-1 S. The stapled lines show the range of the uncertainty for the linear trend lines.

There is a good match between the Nordland group in 15/9-6 and 7216/11-1 S, and between the rest of the trends. Why this is the case will be discussed in the discussion section.

Well	Vp0	K(z)
15/9-6	1,57	0,76
34/7-1	1,89	0,87
34/7-5	1,83	0,92
6608/10-3	1,89	0,89
7216/11-1 S	1,61	0,57

Table 1 - Table showing the equations for the Nordland reference trends, and the Nordland trend from 7216/11-1 S.

4.1.2 Vs

Vs values are calculated from Vp data, so we should see the same relationship between trends as we did for the Vp data.

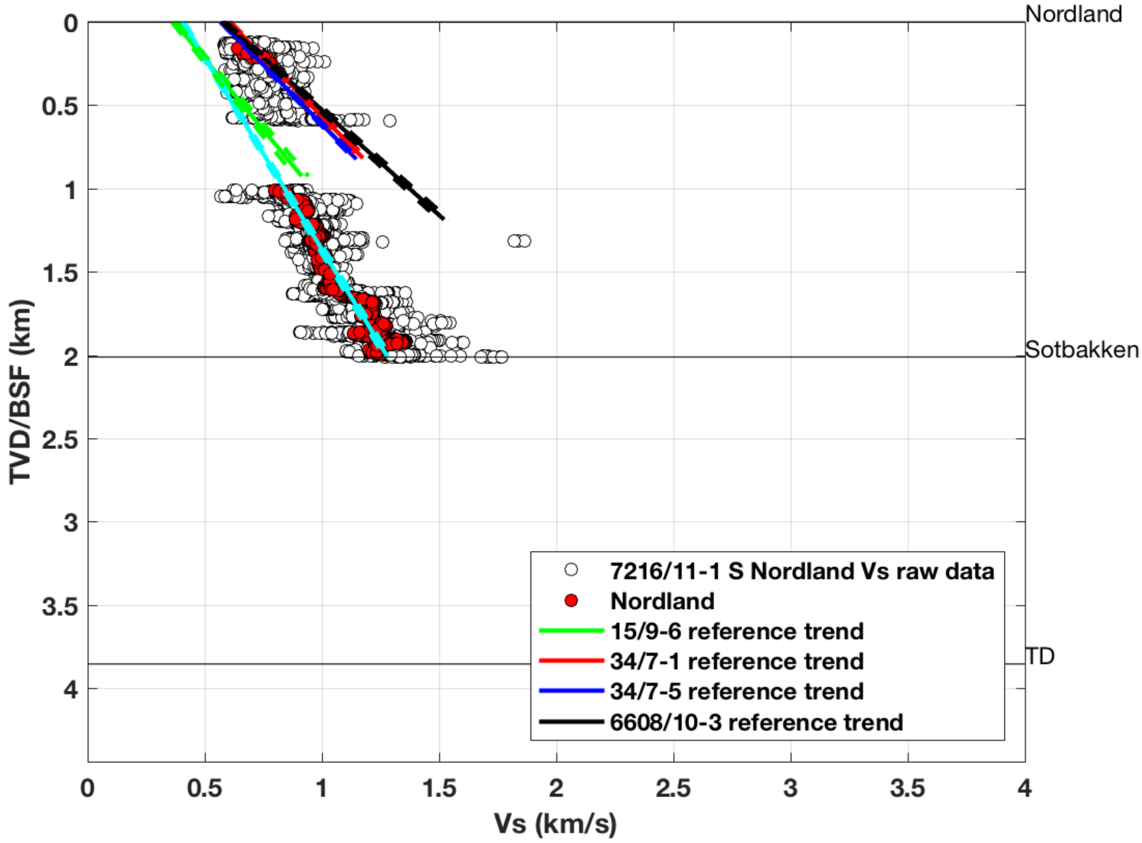

Figure 13 - Plot showing raw Vs data from the Nordland group in well 7216/11-1 S, in white. The smoothed data is shown in red. The reference trend lines are also found in the plot. The cyan line is the trend line representing the Vs data from well 7216/11-1 S. The stapled lines show the range of the uncertainty for the linear trend lines.

This plot looks like the Vp plot, and the relationship between the Vs trends are the same as well.

Well	Vs0	K(z)
15/9-6	0,37	0,59
34/7-1	0,60	0,7
34/7-5	0,57	0,70
6608/10-3	0,58	0,79
7216/11-1 S	0,41	0,44

Table 2 - Table showing the equations for the Nordland reference trends, and the Nordland trend from 7216/11-1 S.

4.1.3 Vp/Vs

The Vp/Vs ratio is expected to behave as the Vp and Vs data as well, because it is a ratio between the two.

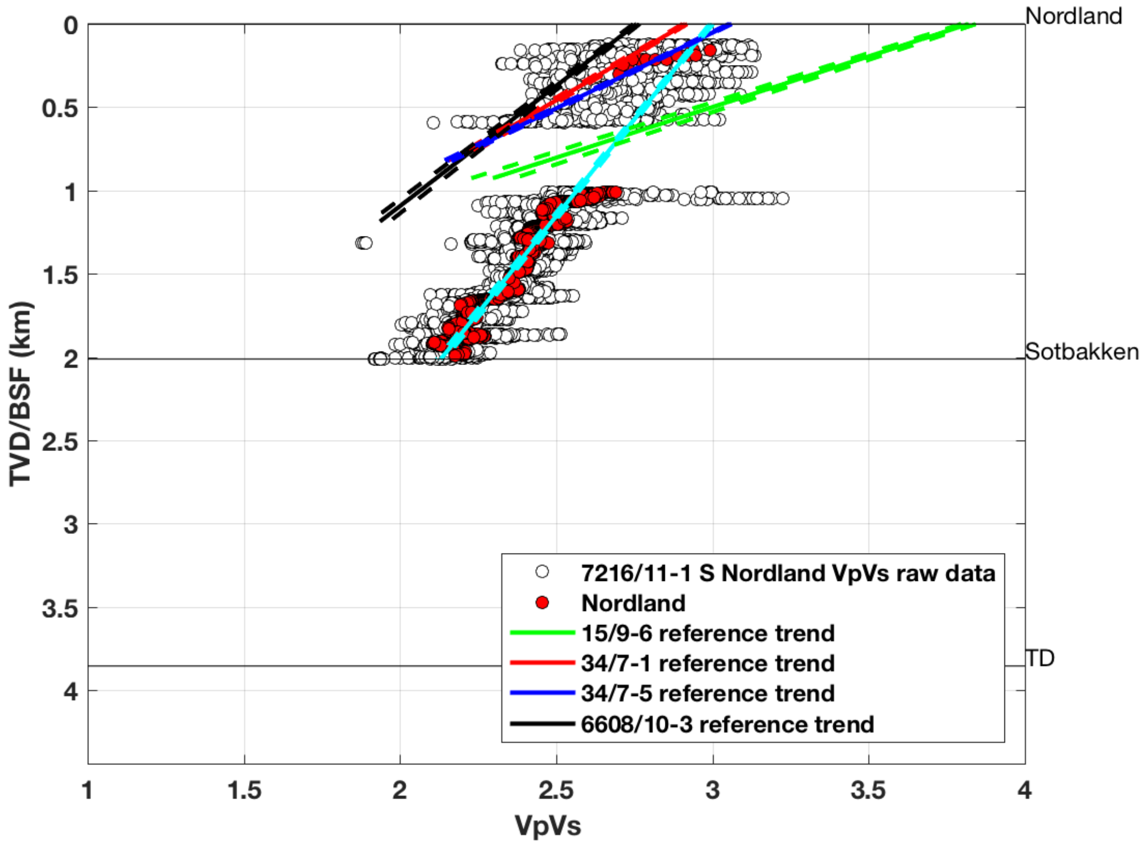

Figure 14 - Plot showing raw Vp/Vs data from the Nordland group in well 7216/11-1 S, in white. The smoothed data is shown in red. The reference trend lines are also found in the plot. The cyan line is the trend line representing the Vp/Vs data from well 7216/11-1 S. The stapled lines show the range of the uncertainty for the linear trend lines.

The relationship between the trends is similar to the Vp and Vs plots, but 15/9-6 is different. This is probably because the filters have removed a lot of shallow data points in this well.

Well	Vp/Vs0	K(z)
15/9-6	3,82	-1,64
34/7-1	2,91	-0,9
34/7-5	3,1	-1,1
6608/10-3	2,76	-0.69
7216/11-1 S	3	-0,43

Table 3 - Table showing the equations for the Nordland reference trends, and the Nordland trend from 7216/11-1 S.

4.1.4 Rhob

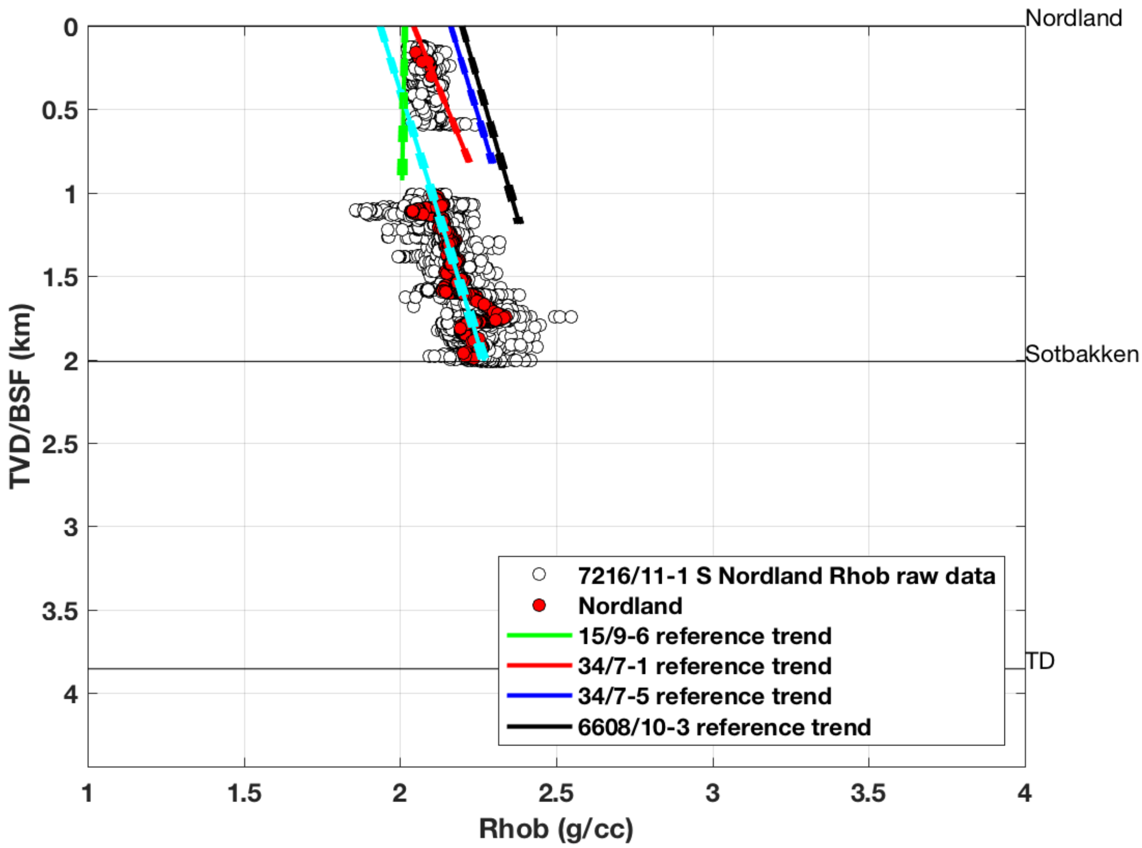

Figure 15 - Plot showing raw rhob data from the Nordland group in well 7216/11-1 S, in white. The smoothed data is shown in red. The reference trend lines are also found in the plot. The cyan line is the trend line representing the rhob data from well 7216/11-1 S. The stapled lines show the range of the uncertainty for the linear trend lines.

We see the same relationship between the trend lines in this plot as in the Vp, Vs, Vp/Vs plots. The differences between the trend lines are most likely due to different lithology and porosity, both parameters influencing density measurements.

Well	Rhob0	K(z)
15/9-6	2,01	-0,01
34/7-1	2,04	0,22
34/7-5	2,16	0,16
6608/10-3	2,2	0,15
7216/11-1 S	1,94	0,17

Table 4 - Table showing the equations for the Nordland reference trends, and the Nordland trend from 7216/11-1 S.

4.1.5 Rdeep

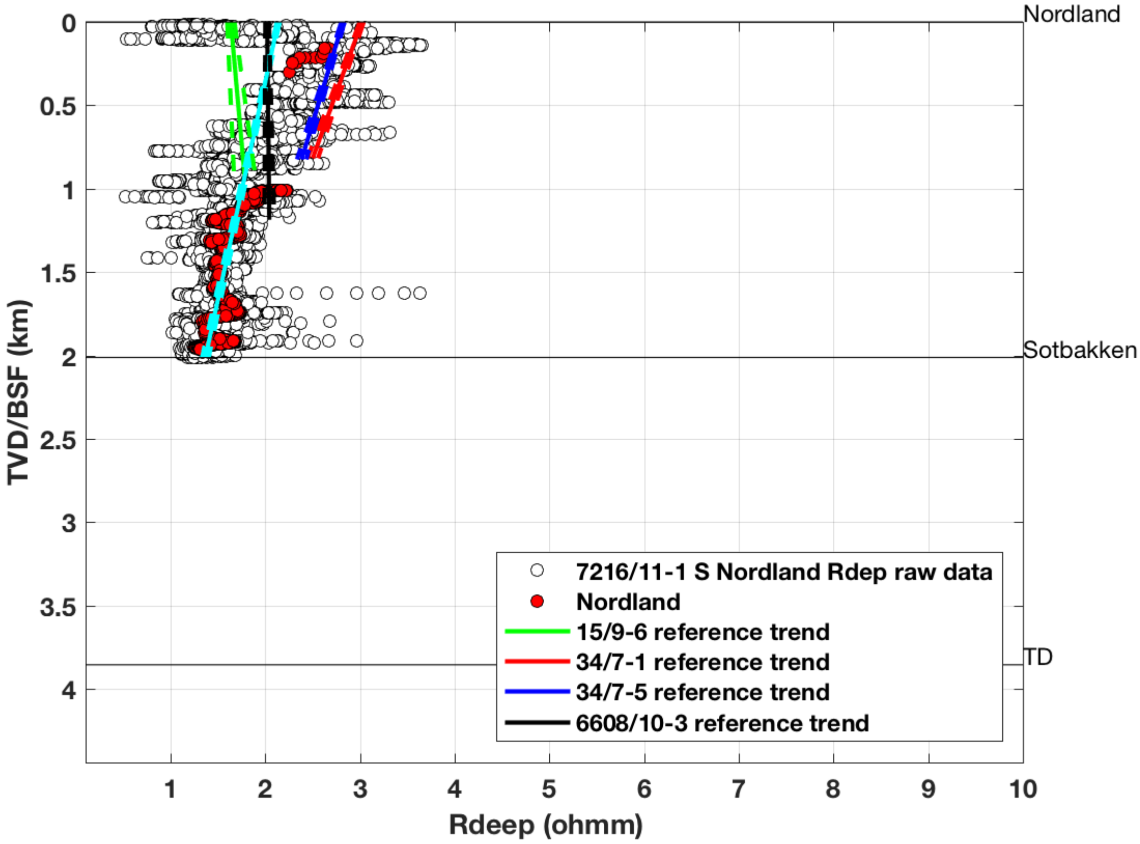

Figure 16 - Plot showing raw rdeep data from the Nordland group in well 7216/11-1 S, in white. The smoothed data is shown in red. The reference trend lines are also found in the plot. The cyan line is the trend line representing the rdeep data from well 7216/11-1 S. The stapled lines show the range of the uncertainty for the linear trend lines.

The relationship between the trend lines in this plot look similar to the 4 previous plots, but with some differences that are most likely a result of different lithology.

Well	Rdeep0	K(z)
15/9-6	1,63	0,16
34/7-1	3,02	-0,63
34/7-5	2,81	-0,53
6608/10-3	2,02	0,02
7216/11-1 S	2,14	-0,38

Table 5 - Table showing the equations for the Nordland reference trends, and the Nordland trend from 7216/11-1 S.

4.1.6 Porosity

Porosity is calculated from density, so we can assume that the relationship between the trend lines to be similar to the rhob plot.

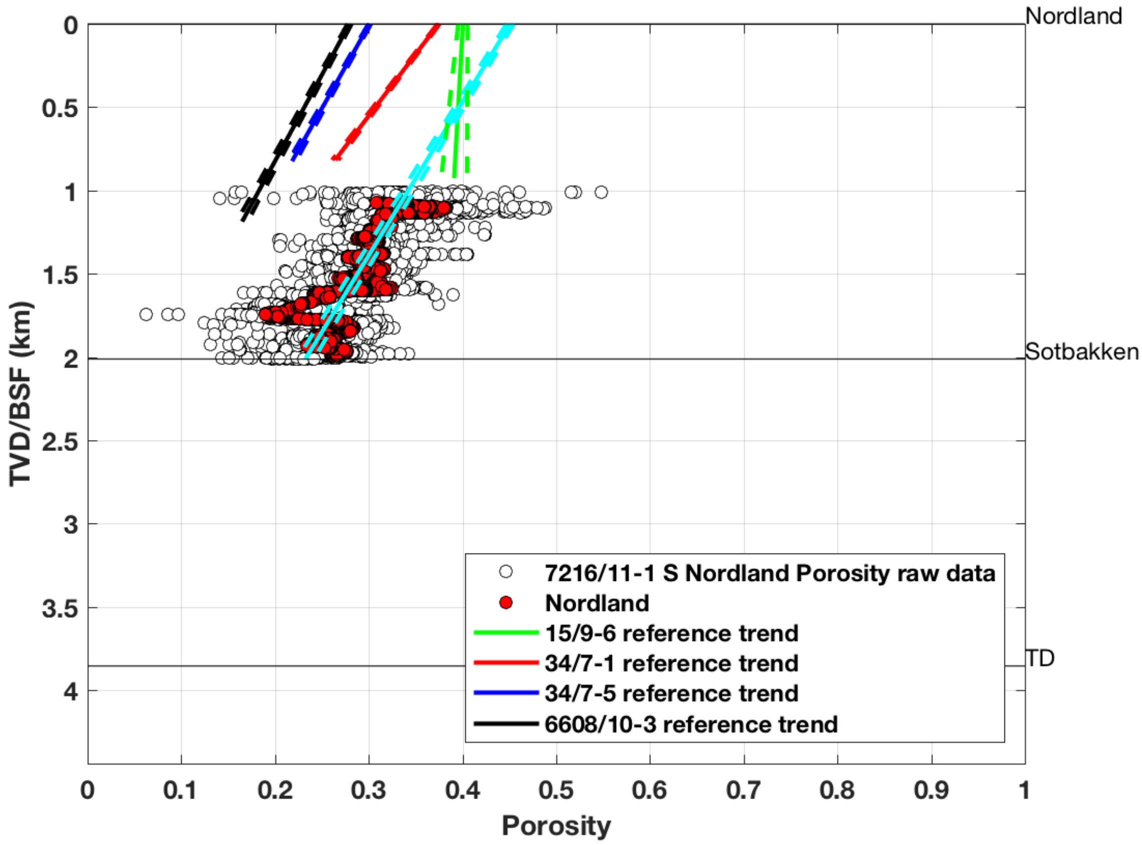

Figure 17 - Plot showing raw porosity data from the Nordland group in well 7216/11-1 S, in white. The smoothed data is shown in red. The reference trend lines are also found in the plot. The cyan line is the trend line representing the porosity data from well 7216/11-1 S. The stapled lines show the range of the uncertainty for the linear trend lines.

This plot looks like the inverse of the rhob plot. Differences between the trend lines are most likely a result of different lithology.

Well	Porosity0	K(z)
15/9-6	0,4	-0,01
34/7-1	0,37	-0,14
34/7-5	0,3	-0,1
6608/10-3	0,28	-0,1
7216/11-1 S	0,44	-0,1

Table 6 - Table showing the equations for the Nordland reference trends, and the Nordland trend from 7216/11-1 S.

4.2 7117/9-1

Well 7117/9-1 is also located far to the east in the Barents Sea, and we expect the uplift to be minimal.

4.2.1 Vp

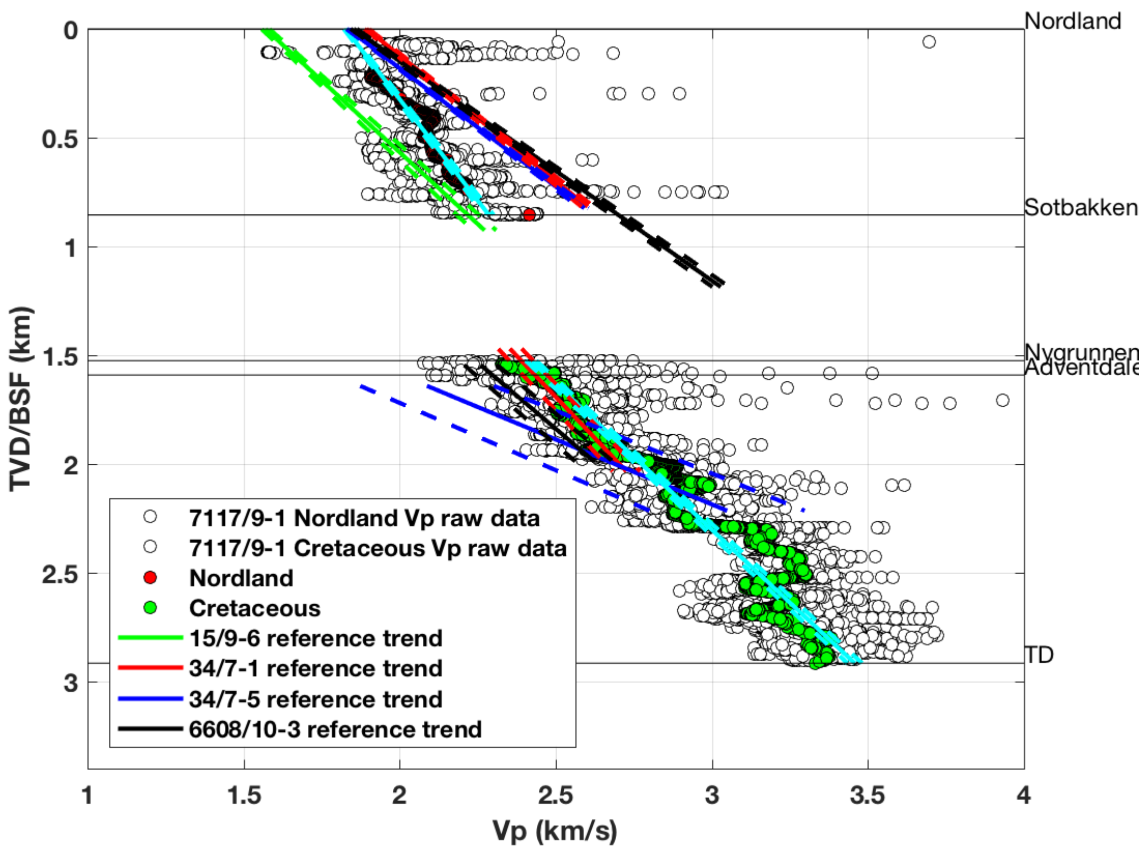

Figure 18 - Plot showing raw Vp data from the Nordland group and the Cretaceous sediments in well 7117/9-1, in white. The smoothed data of the two groups are shown in red and blue, respectively. The reference trend lines are also found in the plot. The cyan lines are the trend lines representing the Vp data from well 7117/9-1. The stapled lines show the range of the uncertainty for the linear trend lines.

The data and trend lines from the Nordland group looks very much like the same plot for well 7216/11-1 S. This makes sense, as the two wells are close to each other.

There is overlap between the trend lines from Shetland and the Cretaceous sediments when the uncertainty is included. Because the trend lines overlap, we can conclude that the Cretaceous sediments in well 7117/9-1 have been subject to minimal uplift.

Well	Vp0	K(z)
15/9-6	1,57	0,76
34/7-1	1,89	0,87
34/7-5	1,83	0,92
6608/10-3	1,88	0,89
7117/9-1	1,83	0,54

Table 7 - Table showing the equations for the Nordland reference trends, and the Nordland trend from 7117/9-1.

Well	Vp0	K(z)
34/7-1	1,38 ± 0,02	0,67 ± 0,01
34/7-5	-0,66 ± 0,12	1,68 ± 0,06
6608/10-3	1,64 ± 0,03	0,43 ± 0,02
7117/9-1	1,28 ± 0,01	0,75 ± 0,004

Table 8 - Table showing the equations for the Shetland reference trends, and the Cretaceous trend from 7117/9-1.

4.2.2 Vs

Vs values are calculated from Vp data, so we should see the same relationship between trends as we did for the Vp data.

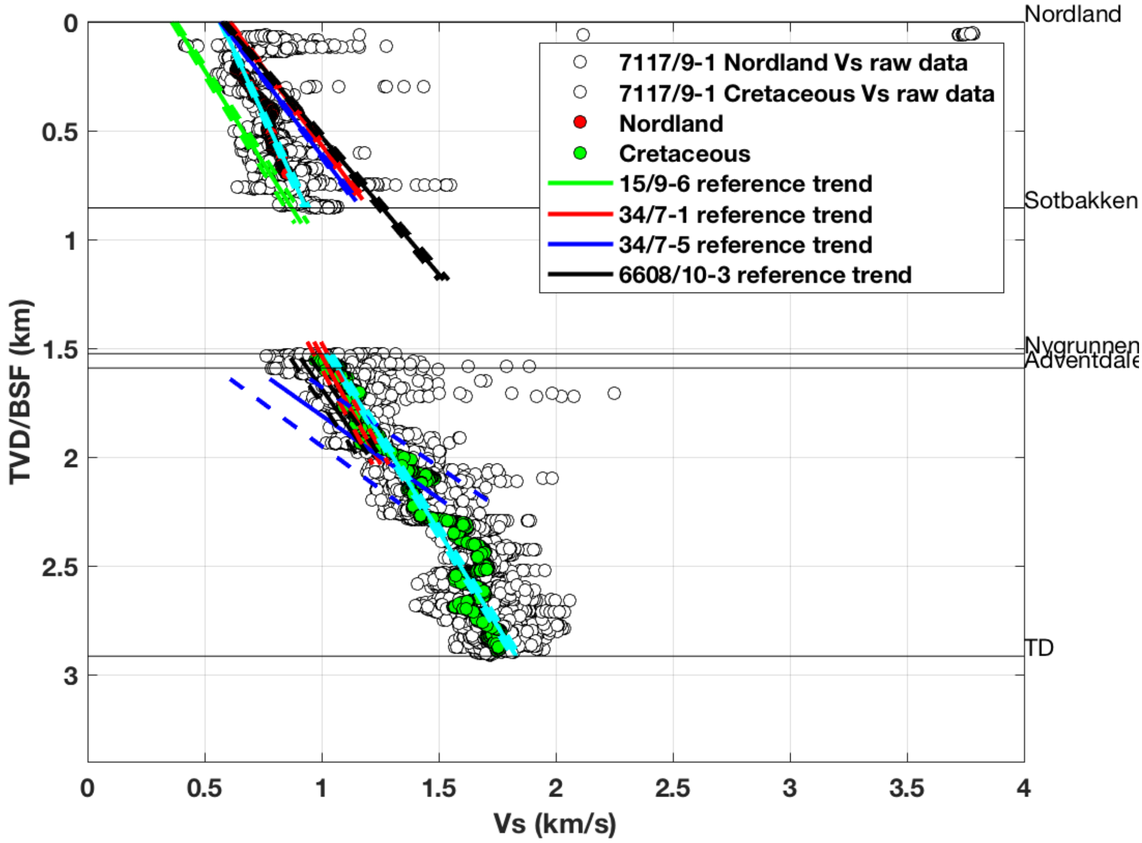

Figure 19 - Plot showing raw Vs data from the Nordland group and the Cretaceous sediments in well 7117/9-1, in white. The smoothed data of the two groups are shown in red and blue, respectively. The reference trend lines are also found in the plot. The cyan lines are the trend lines representing the Vs data from well 7117/9-1. The stapled lines show the range of the uncertainty for the linear trend lines.

The data and trend lines from the Nordland group looks very much like the same plot for well 7216/11-1 S. This makes sense, as the two wells are close to each other, and can expect the Nordland group to have the same lithology in both wells.

There is overlap between the trend lines from Shetland and the Cretaceous sediments when the uncertainty is included. Because the trend lines overlap, we can conclude that the Cretaceous sediments in well 7117/9-1 have been subject to minimal uplift.

Well	Vs0	K(z)
15/9-6	0,37	0,59
34/7-1	0,6	0,7
34/7-5	0,57	0,7
6608/10-3	0,58	0,79
7117/9-1	0,57	0,42

Table 9 - Table showing the equations for the Nordland reference trends, and the Nordland trend from 7117/9-1.

Well	Vs0	K(z)
34/7-1	0,23 ± 0,015	0,5 ± 0,01
34/7-5	-1,37 ± 0,1	1,31 ± 0,05
6608/10-3	-0.09 ± 0,02	0,65 ± 0,01
7117/9-1	0,15 ± 0,008	0,57 ± 0,003

Table 10 - Table showing the equations for the Shetland reference trends, and the Cretaceous trend from 7117/9-1.

4.2.3 Vp/Vs

The Vp/Vs ratio is expected to behave as the Vp and Vs data as well, because it is a ratio between the two.

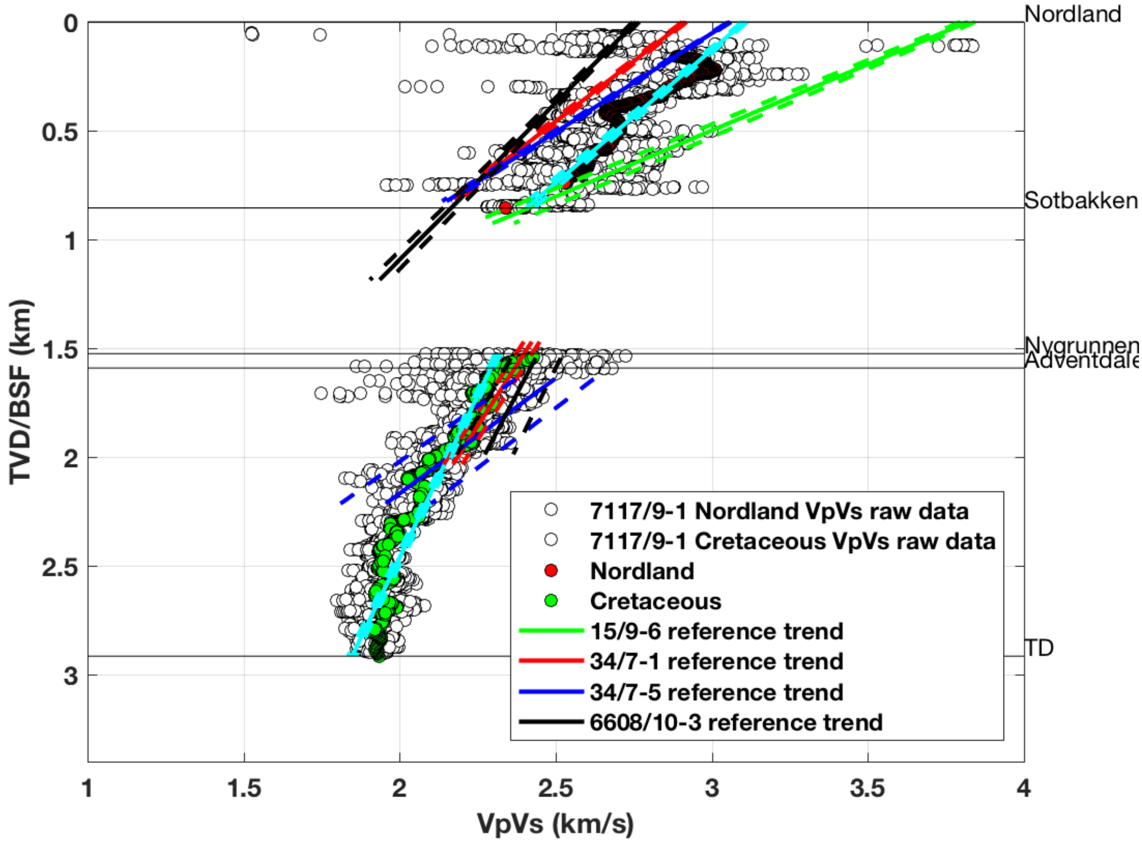

Figure 20 - Plot showing raw Vp/Vs data from the Nordland group and the Cretaceous sediments in well 7117/9-1, in white. The smoothed data of the two groups are shown in red and blue, respectively. The reference trend lines are also found in the plot. The cyan lines are the trend lines representing the Vp/Vs data from well 7117/9-1. The stapled lines show the range of the uncertainty for the linear trend lines.

The data and trend lines from the Nordland group looks very much like the same plot for well 7216/11-1 S. This makes sense, as the two wells are close to each other.

There is overlap between the trend lines from Shetland and the Cretaceous sediments when the uncertainty is included. Because the trend lines overlap, we can conclude that the Cretaceous sediments in well 7117/9-1 have been subject to minimal uplift.

Well	Vp/Vs0	K(z)
15/9-6	3,82	-1,64
34/7-1	2,91	-0,9
34/7-5	3,05	-1,1
6608/10-3	2,75	-0,69
7117/9-1	3,1	-0,82

Table 11 - Table showing the equations for the Nordland reference trends, and the Nordland trend from 7117/9-1.

Well	Vp/Vs0	K(z)
34/7-1	3,08 ± 0,013	-0,45 ± 0,007
34/7-5	4,05 ± 0,07	-0.94 ± 0,03
6608/10-3	3 ± 0,04	-0,37 ± 0,02
7117/9-1	2,83 ± 0,005	-0,34 ± 0,003

Table 12 - Table showing the equations for the Shetland reference trends, and the Cretaceous trend from 7117/9-1.

4.2.4 Rhob

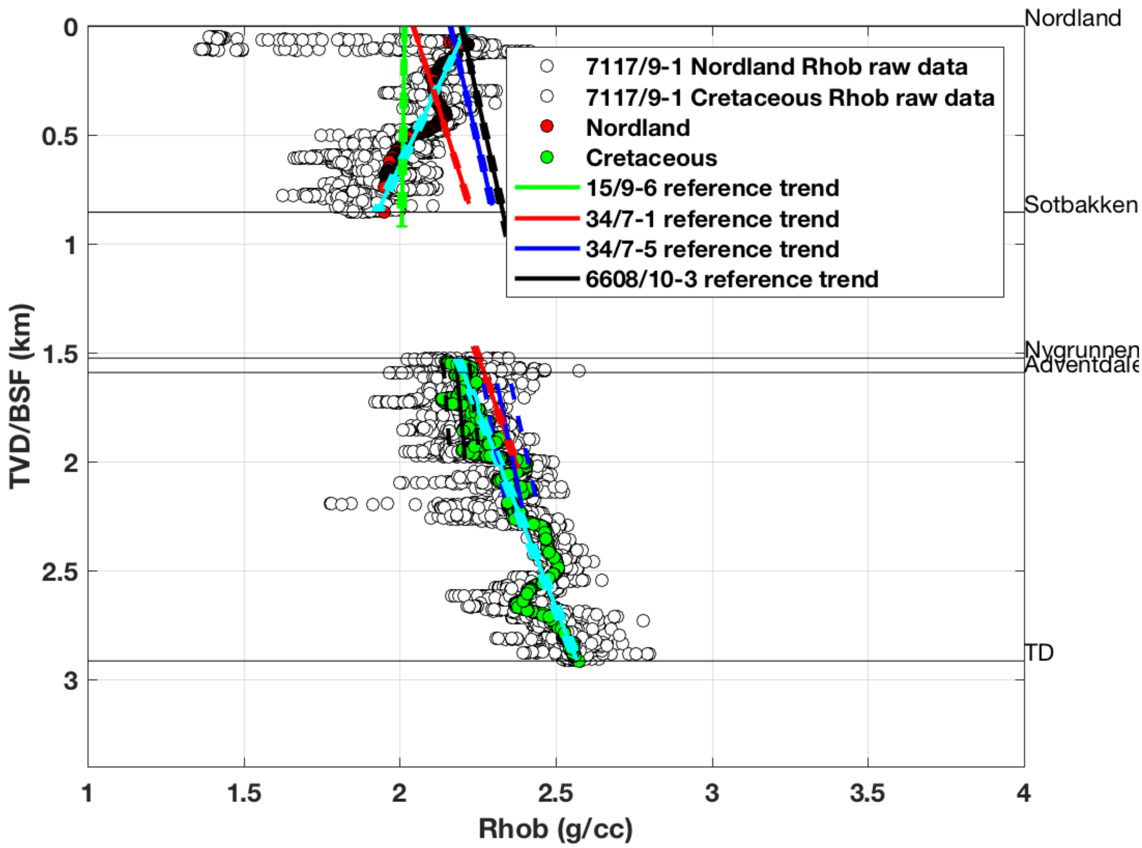

Figure 21 - Plot showing raw rhob data from the Nordland group and the Cretaceous sediments in well 7117/9-1, in white. The smoothed data of the two groups are shown in red and green, respectively. The reference trend lines are also found in the plot. The cyan lines are the trend lines representing the rhob data from well 7117/9-1. The stapled lines show the range of the uncertainty for the linear trend lines.

The rhob trend in Nordland in well 7117/9-1 is negative, which is counter intuitive. Density should increase with depth. There might be incorrect measurements leading to this, or it might be that the porosity is decreasing with depth as well, which explains why density does that as well. The relationship between the Nordland trends is similar to the relationship between the Vp, Vs and Vp/Vs trends, the 7117/9-1 trend falls in between the others.

Again, there is overlap between the Shetland and Cretaceous trends, indicating that uplift is minimal.

Well	Rhob0	K(z)
15/9-6	2,02	-0,01
34/7-1	2,04	0,22
34/7-5	2,16	0,16
6608/10-3	2,2	0,15
7117/9-1	2,22	-0,34

Table 13 - Table showing the equations for the Nordland reference trends, and the Nordland trend from 7117/9-1.

Well	Rhob0	K(z)
34/7-1	1,87 ± 0,003	0,25 ± 0,002
34/7-5	2,08 ± 0,02	0,14 ± 0,01
6608/10-3	2,08 ± 0,02	0,06 ± 0,01
7117/9-1	1,77 ± 0,004	0,27 ± 0,002

Table 14 - Table showing the equations for the Shetland reference trends, and the Cretaceous trend from 7117/9-1.

4.2.5 Rdeep

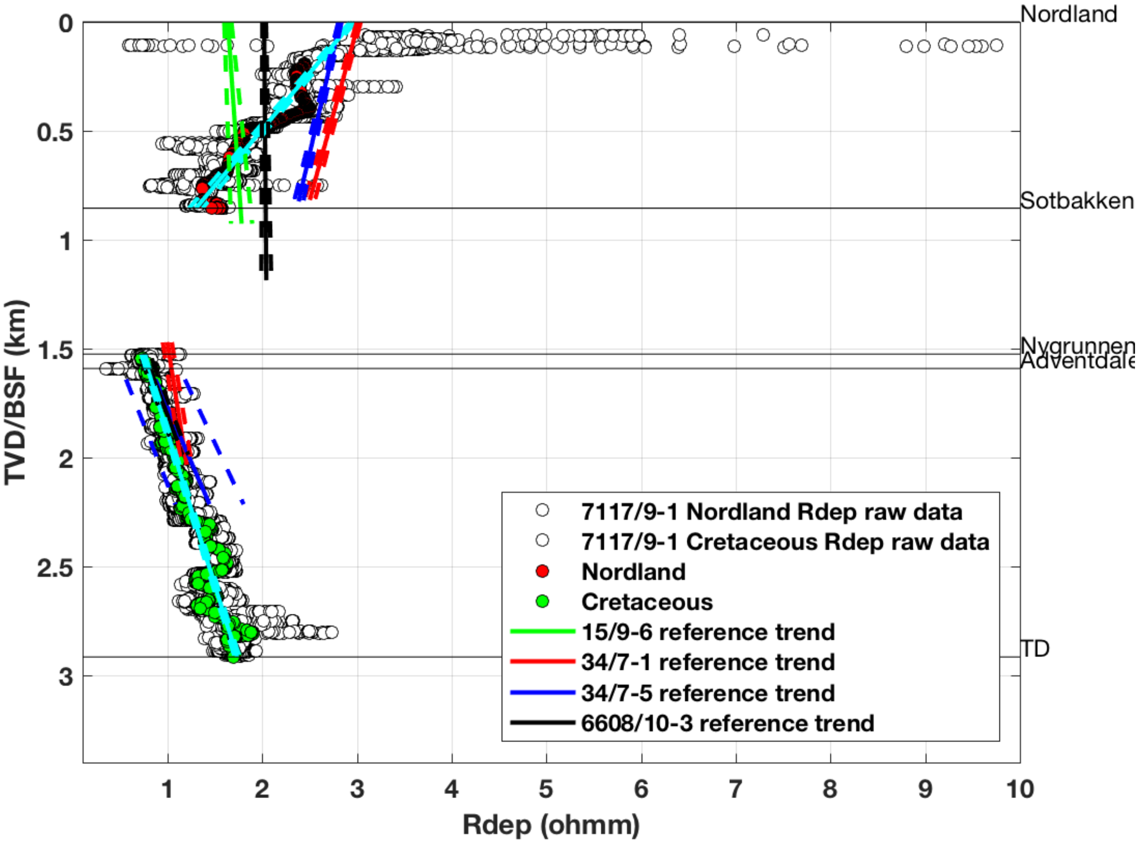

Figure 22 - Plot showing raw Rdeep data from the Nordland group and the Cretaceous sediments in well 7117/9-1, in white. The smoothed data of the two groups are shown in red and green, respectively. The reference trend lines are also found in the plot. The cyan lines are the trend lines representing the Rdeep data from well 7117/9-1. The stapled lines show the range of the uncertainty for the linear trend lines.

The relationship between the Nordland trends is again similar to the relationship between the other trends.

The trend lines for Shetland and the Cretaceous sediments overlap, indicating minimal uplift.

Well	Rdeep0	K(z)
15/9-6	1,63	0,16
34/7-1	3,02	-0,63
34/7-5	2,82	-0,53
6608/10-3	2,02	0,02
7117/9-1	2,95	-1,93

Table 15 - Table showing the equations for the Nordland reference trends, and the Nordland trend from 7117/9-1.

Well	Rdeep0	K(z)
34/7-1	0,46 ± 0,03	0,36 ± 0,014
34/7-5	-0,76 ± 0,17	0,96 ± 0,09
6608/10-3	-0,55 ± 0,03	0,86 ± 0,017
7117/9-1	-0,35 ± 0,01	0,71 ± 0,005

Table 16 - Table showing the equations for the Shetland reference trends, and the Cretaceous trend from 7117/9-1.

4.2.6 Porosity

Porosity is calculated from density, so we can expect the porosity trend lines to behave like the density trends.

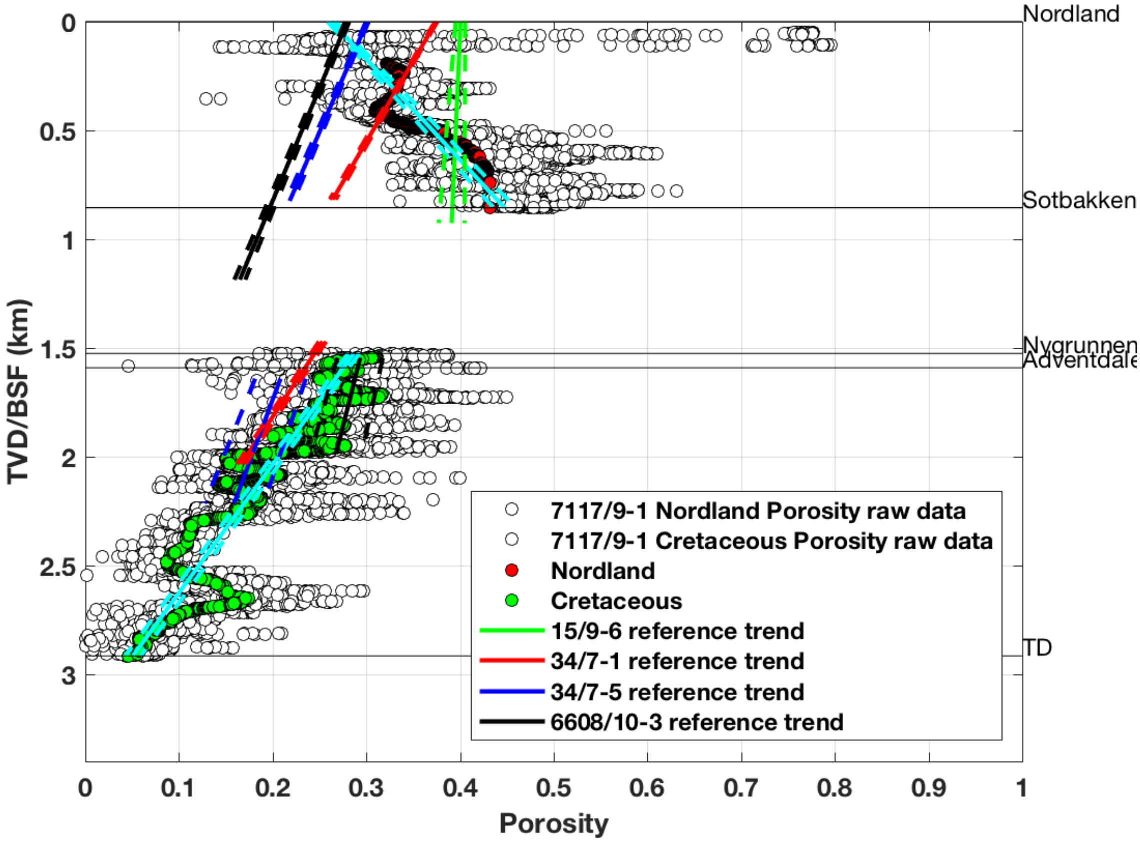

Figure 23 - Plot showing raw porosity data from the Nordland group and the Cretaceous sediments in well 7117/9-1, in white. The smoothed data of the two groups are shown in red and green, respectively. The reference trend lines are also found in the plot. The cyan lines are the trend lines representing the porosity data from well 7117/9-1. The stapled lines show the range of the uncertainty for the linear trend lines.

The porosity plots are very similar to the density plots, as expected. Again, we see overlap for the Shetland and Cretaceous sediments trend lines.

Well	Porosity0	K(z)
34/7-1	0,48 ±	-0,15
34/7-5	0,35	-0,09
6608/10-3	0,38 ± 0,013	-0,06 ± 0,0073
7117/9-1	0,55 ± 0,004	-0,17 ± 0,002

Table 17 - Table showing the equations for the Shetland reference trends, and the Cretaceous trend from 7117/9-1.

4.3 7120/5-1

Well 7121/4-1 lies further to the east than the other wells, but not as far east as 7121/4-1. The subsurface have been subject to more uplift than the more western located wells. In this well, the Nordland group is very thin, making it impossible to use it to estimate uplift. Sotbakken is present, but as discussed earlier, we cannot use this group to estimate uplift. The Cretaceous sediments are thick, and they can be used to estimate uplift.

4.3.1 Vp

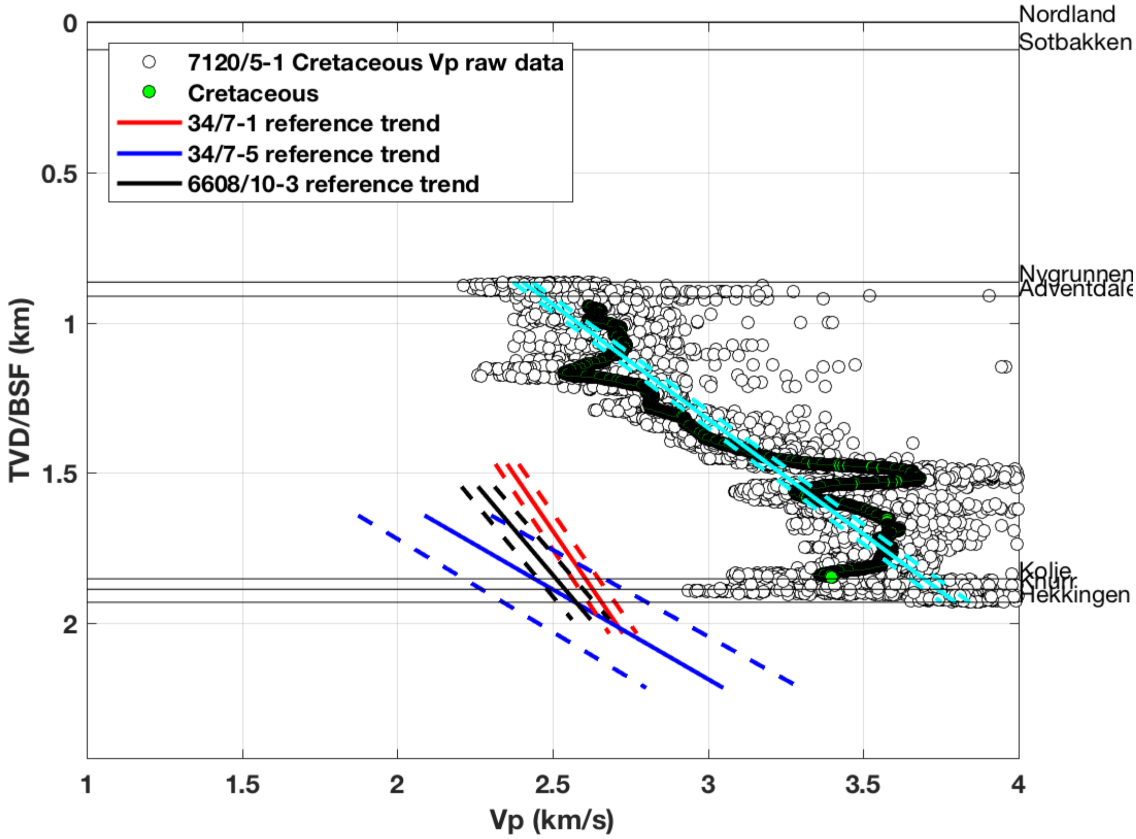

Figure 24 - Plot showing raw Vp data from the Cretaceous sediments in well 7120/5-1, in white. The smoothed data is shown in green. The reference trend lines are also found in the plot. The cyan line is the trend line representing the Vp data from well 7120/5-1. The stapled lines show the range of the uncertainty for the linear trend lines.

We see clearly that the Cretaceous sediments have been subject to uplift. Depending on which reference trend we use for comparison, we would get different ranges of uplift estimates. The Vclay filter has removed a lot of data points in well 34/7-5, so it is a lithological effect that makes it so different from the trend line of the neighbouring well, 34/7-1. Because of the reduced amount of data points in well 34/7-5, the uncertainty range is larger then for the other reference trends, resulting in an uplift estimate using this well being less accurate than using the other reference trends.

Well	Vp0	K(z)
34/7-1	1,38 ± 0,02	0,67 ± 0,01
34/7-5	-0,66 ± 0,12	1,68 ± 0,06
6608/10-3	1,64 ± 0,03	0,43 ± 0,02
7120/5-1	1,27±0,02	1,31±0,01

Table 18 - Table showing the equations for the Shetland reference trends, and the Cretaceous trend from 7120/5-1.

Well used for comparison	Max uplift (m)	Min uplift (m)
34/7-1	1721,4 ± 57	680,89 ± 57
34/7-5	964,53 ± 127	731,42 ± 127
6608/10-3	1490,2 ± 65	855,42 ± 65

Table 19 - Table showing the estimated uplift values for a comparison between the Shetland reference trends, and the Cretaceous trend from well 7120/5-1.

4.3.2 Vs

Vs values are calculated from Vp data, so we should see the same relationship between trends as we did for the Vp data.

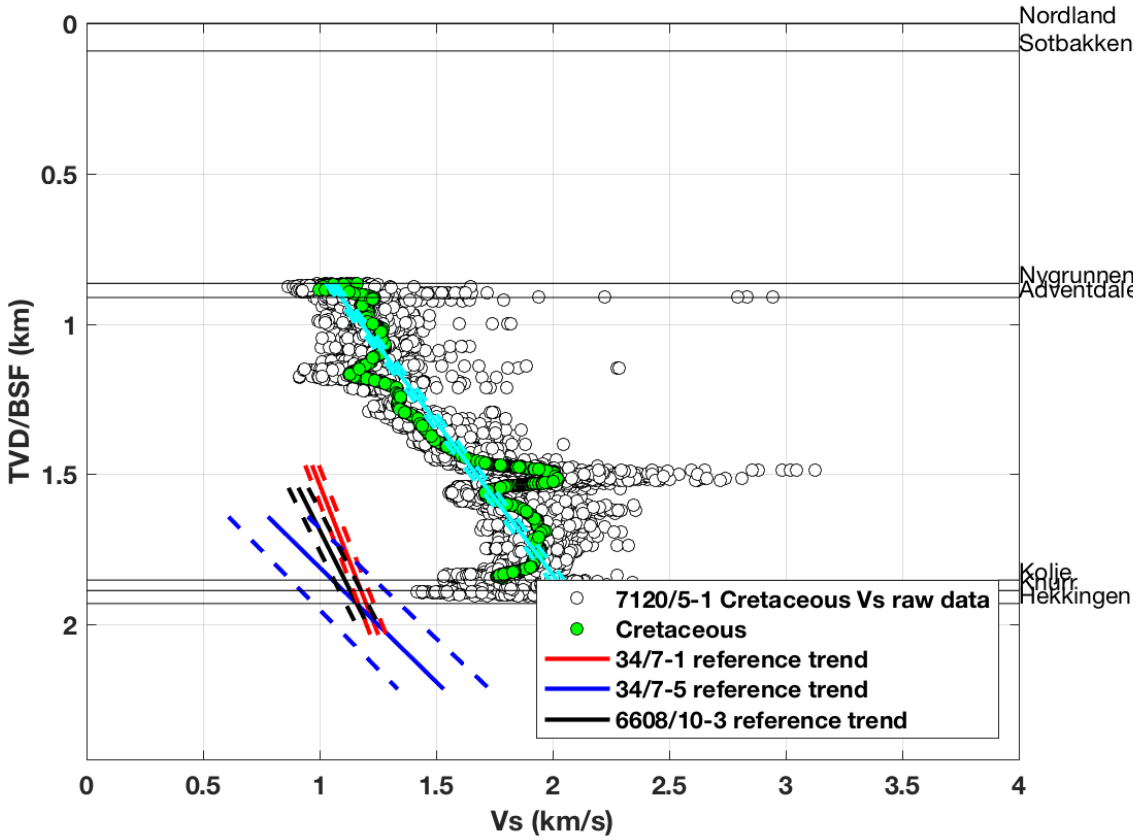

Figure 25 - Plot showing raw Vs data from the Cretaceous sediments in well 7120/5-1, in white. The smoothed data is shown in green. The reference trend lines are also found in the plot. The cyan line is the trend line representing the Vs data from well 7120/5-1. The stapled lines show the range of the uncertainty for the linear trend lines.

The Vs plot looks like very much like the Vp plot, and here it is also the Vclay filtering that results in the 34/7-5 trend being different from the 34/7-1 trend. This will result in the same inaccuracy when estimating uplift.

Well	Vs0	K(z)
34/7-1	0,23 ± 0,015	0,5 ± 0,01
34/7-5	-1,37 ± 0,1	1,31 ± 0,05
6608/10-3	-0.09 ± 0,02	0,65 ± 0,01
7120/5-1	0,2±0,01	0,98±0,01

Table 20 - Table showing the equations for the Shetland reference trends, and the Cretaceous trend from 7120/5-1.

Well used for comparison	Max uplift (m)	Min uplift (m)
34/7-1	1774,5 ± 57	762,42 ± 57
34/7-5	980,34 ± 127	713,67 ± 127
6608/10-3	1438,7 ± 65	892,21 ± 65

Table 21 - Table showing the estimated uplift values for a comparison between the Shetland reference trends, and the Cretaceous trend from well 7120/5-1.

4.3.3 Vp/Vs

The Vp/Vs ratio is expected to behave as the Vp and Vs data as well, because it is a ratio between the two.

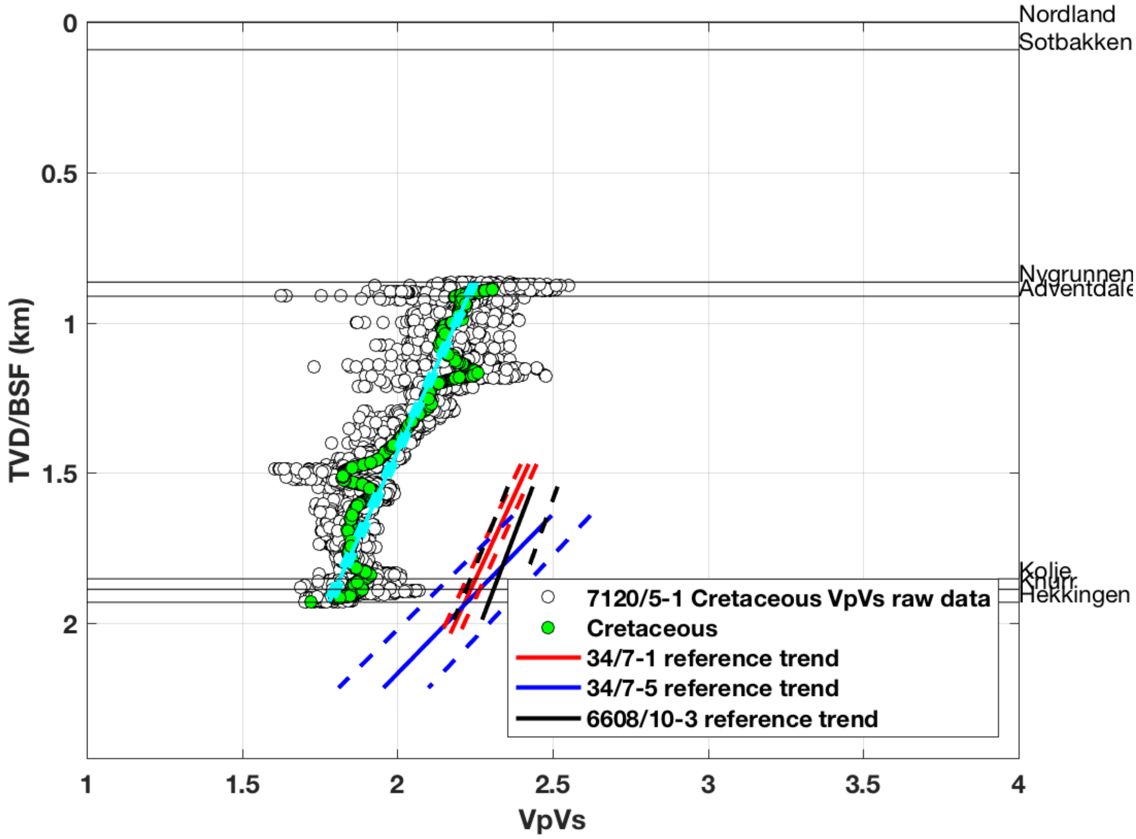

Figure 26 - Plot showing raw Vp/Vs data from the Cretaceous sediments in well 7120/5-1, in white. The smoothed data is shown in green. The reference trend lines are also found in the plot. The cyan line is the trend line representing the Vp/Vs data from well 7120/5-1. The stapled lines show the range of the uncertainty for the linear trend lines.

The Vp/Vs plot is almost identical to the Vp and Vs plots, as expected. The trend line from well 6608/10-3 is more parallel to the Cretaceous trend line than for Vp and Vs, but the uncertainty range is bigger.

Well	Vp/Vs0	K(z)
34/7-1	3,08 ± 0,1	-0,45 ± 0,007
34/7-5	4,05 ± 0,07	-0.94 ± 0,03
6608/10-3	3 ± 0,04	-0,37 ± 0,02
7120/5-1	2,63 ± 0,006	-0,43 ± 0,004

Table 22 - Table showing the equations for the Shetland reference trends, and the Cretaceous trend from 7120/5-1.

Well used for comparison	Max uplift (m)	Min uplift (m)
34/7-1	995,56 ± 56	975,17 ± 56
34/7-5	1039,4 ± 132	470,84 ± 132
6608/10-3	1395,4 ± 216	1189,5 ± 216

Table 23 - Table showing the estimated uplift values for a comparison between the Shetland reference trends, and the Cretaceous trend from well 7120/5-1.

4.3.4 Rhob

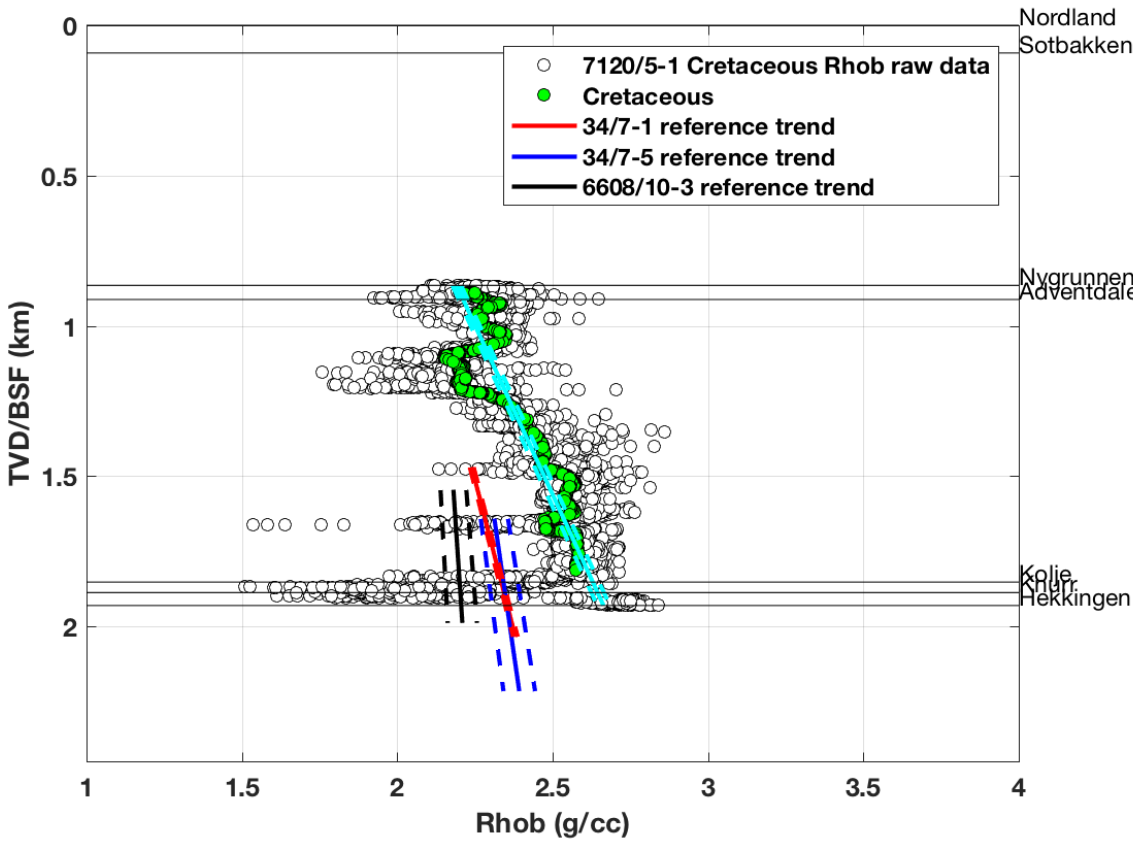

Figure 27 - Plot showing raw rhob data from the Cretaceous sediments in well 7120/5-1, in white. The smoothed data is shown in green. The reference trend lines are also found in the plot. The cyan line is the trend line representing the rhob data from well 7120/5-1. The stapled lines show the range of the uncertainty for the linear trend lines.

The density trend lines for the two neighbouring wells, 34/7-1 and 34/7-5 are almost identical, and would yield uplift estimates that are close to each other. They are much more similar than for Vp, Vs and Vp/Vs, and a reason might be that there are some lithological property that influences the Vp, Vs and Vp/Vs data.

Well	Rhob0	K(z)
34/7-1	1,87 ± 0,003	0,25 ± 0,001
34/7-5	2,08 ± 0,02	0,14 ± 0,01
6608/10-3	2,08 ± 0,02	0,06 ± 0,01
7120/5-1	1,81 ± 0,008	0,44 ± 0,006

Table 24 - Table showing the equations for the Shetland reference trends, and the Cretaceous trend from 7120/5-1.

Well used for comparison	Max uplift (m)	Min uplift (m)
34/7-1	1241,3 ± 28	410,81 ± 28
34/7-5	2223,6 ± 313	0 ± 313
6608/10-3	7060,9 ± 413	843,63 ± 413

Table 25 - Table showing the estimated uplift values for a comparison between the Shetland reference trends, and the Cretaceous trend from well 7120/5-1.

4.3.5 Rdeep

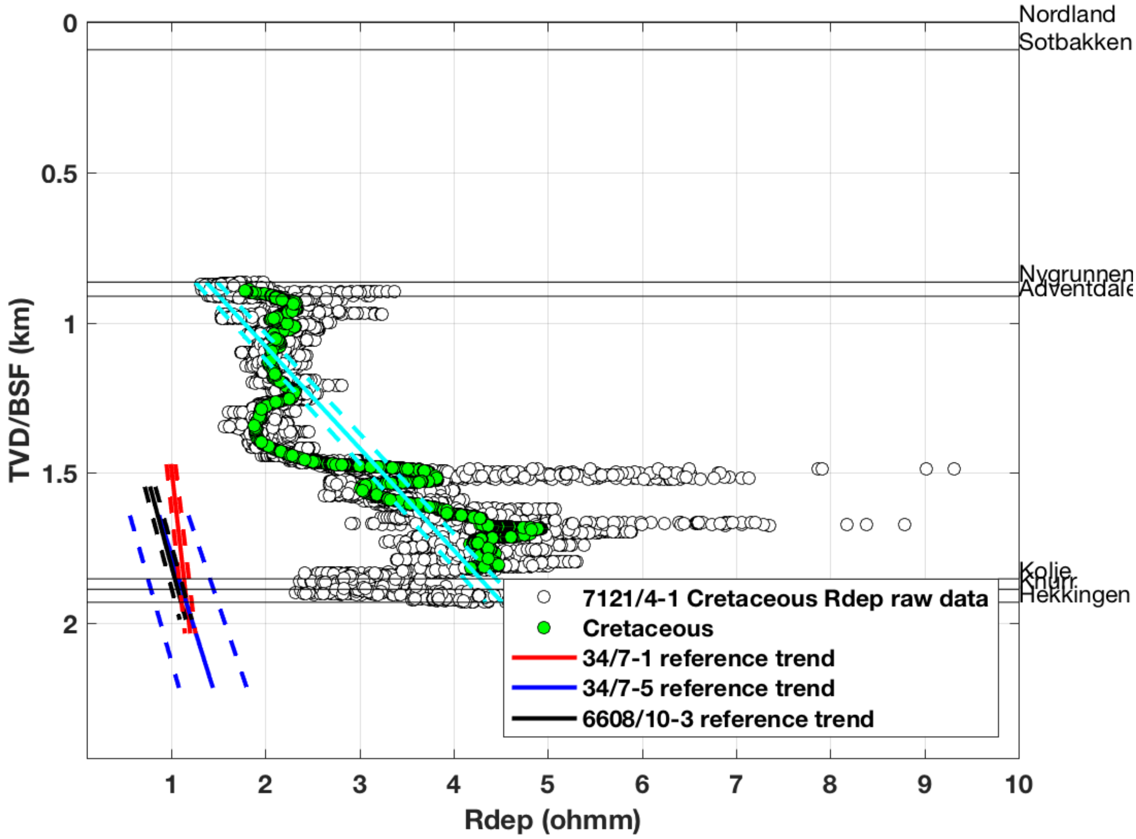

Figure 28 - Plot showing raw rdeep data from the Cretaceous sediments in well 7120/5-1, in white. The smoothed data is shown in green. The reference trend lines are also found in the plot. The cyan line is the trend line representing the rdeep data from well 7120/5-1. The stapled lines show the range of the uncertainty for the linear trend lines.

With the trend lines being close to vertical, any uplift estimate using rdeep data would yield very high, incorrect values. We see however that the trend for the Cretaceous sediments are shifted to the right, so we might use this trend line comparison to say something about if uplift have happened or not, but not by how much.

Well used for comparison	Max uplift (m)	Min uplift (m)
34/7-1	0,46 ± 0,02	0,36 ± 0,01
34/7-5	-0,76 ± 0,16	0,96 ± 0,08
6608/10-3	-0,55 ± 0,03	0,86 ± 0,01
7120/5-1	-1,18± 0,07	2,95 ± 0,05

Table 26 - Table showing the equations for the Shetland reference trends, and the Cretaceous trend from 7120/5-1.

4.3.6 Porosity

Porosity is calculated from density, so we can expect the porosity trends to behave like the density trends.

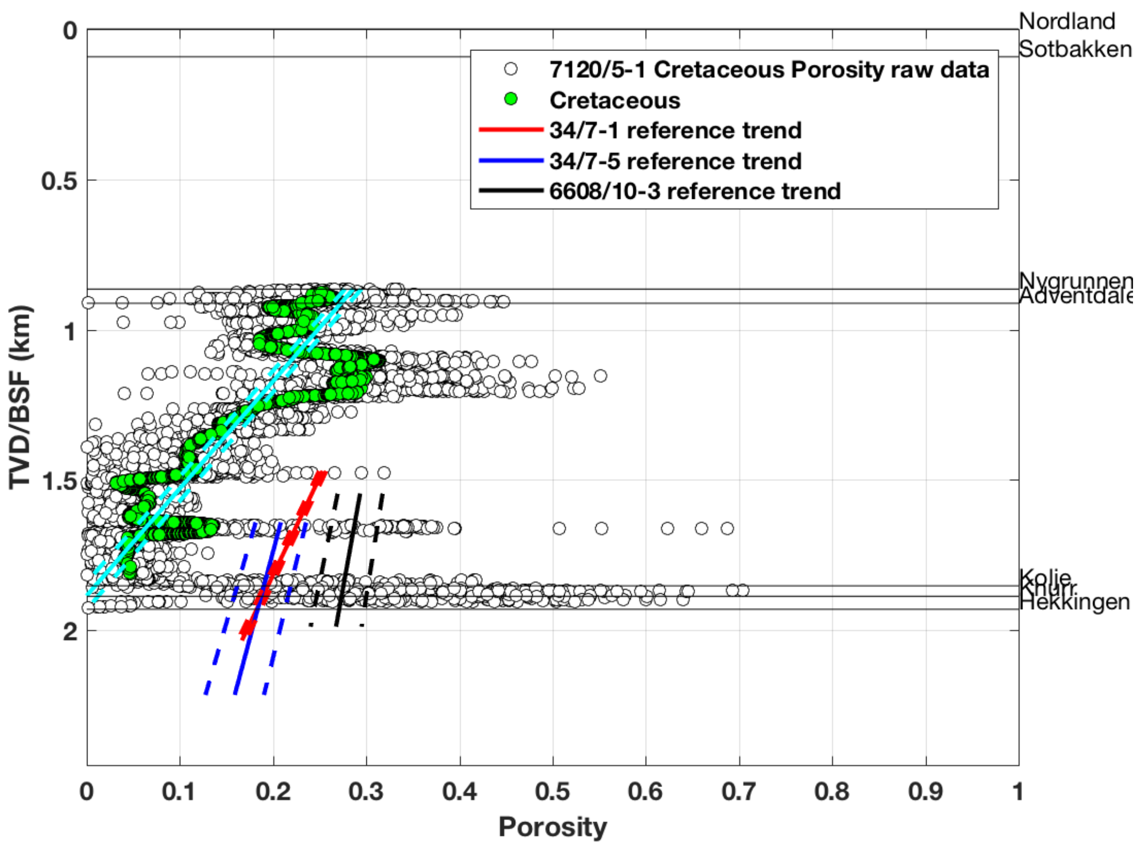

Figure 29 - Plot showing raw porosity data from the Cretaceous sediments in well 7120/5-1, in white. The smoothed data is shown in green. The reference trend lines are also found in the plot. The cyan line is the trend line representing the porosity data from well 7120/5-1. The stapled lines show the range of the uncertainty for the linear trend lines.

This plot is very similar to the density plot, just mirror imaged. Using this plot might help explain the trend we see in the density plot.

Well	Porosity0	K(z)
34/7-1	0,37 ± 0,002	-0,14 ± 0,001
34/7-5	0,35 ± 0,01	-0,09 ± 0,007
6608/10-3	0,39 ± 0,01	-0,06 ± 0,007
7120/5-1	0,53±0,005	-0,28±0,004

Table 27 - Table showing the equations for the Shetland reference trends, and the Cretaceous trend from 7120/5-1.

Well used for comparison	Max uplift (m)	Min uplift (m)
34/7-1	1267,5 ± 26	392,54 ± 26
34/7-5	2269,2 ± 314	0 ± 314
6608/10-3	4854,8 ± 413	808,82 ± 413

Table 28 - Table showing the estimated uplift values for a comparison between the Shetland reference trends, and the Cretaceous trend from well 7120/5-1.

4.4 7121/4-1

Well 7121/4-1 lies further to the east than the other wells, where the subsurface have been subject to more uplift than the more western located wells. In this well, the Nordland group is very thin, making it impossible to use it to estimate uplift. Sotbakken is present, but as discussed earlier, we cannot use this group to estimate uplift. The Cretaceous sediments are thick, and they can be used to estimate uplift.

4.4.1 Vp

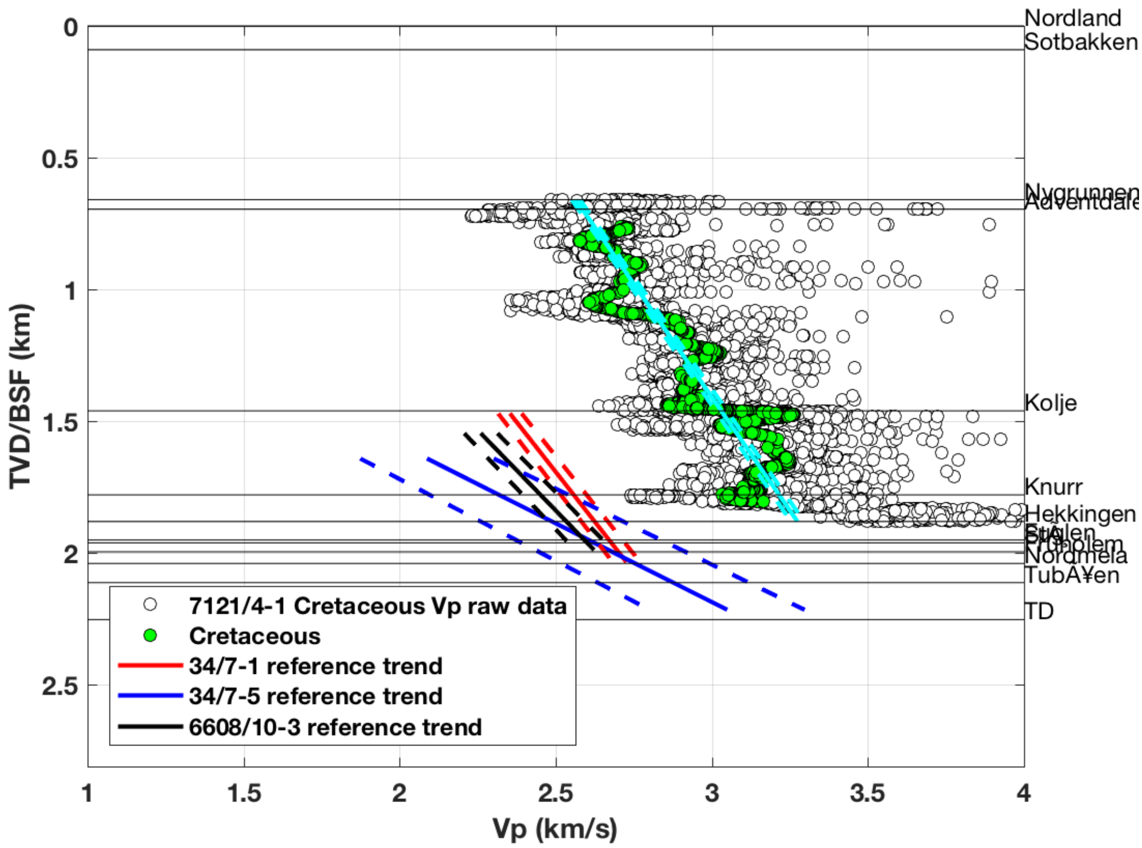

Figure 30 - Plot showing raw Vp data from the Cretaceous sediments in well 7121/4-1, in white. The smoothed data is shown in green. The reference trend lines are also found in the plot. The cyan line is the trend line representing the Vp data from well 7121/4-1. The stapled lines show the range of the uncertainty for the linear trend lines.

We see clearly that the Cretaceous sediments have been subject to uplift. Depending on which reference trend we use for comparison, we would get different ranges of uplift estimates. The differences between the reference trends are a result of different pore pressure and porosity. The Vclay filter has removed a lot of data points in well 34/7-5, so it is a lithological effect that makes it so different from the trend line of the neighbouring well, 34/7-1. Because of the reduced amount of data points in well 34/7-5, the uncertainty range is larger then for the other reference trends, resulting in an uplift estimate using this well being less accurate than using the other reference trends.

Well	Vp0	K(z)
34/7-1	1,38 ± 0,02	0,67 ± 0,01
34/7-5	-0,66 ± 0,12	1,68 ± 0,06
6608/10-3	1,64 ± 0,03	0,43 ± 0,02
7121/4-1	2,18 ± 0,008	0,58 ± 0,006

Table 29 - Table showing the equations for the Shetland reference trends, and the Cretaceous trend from 7121/4-1.

Well used for comparison	Max uplift (m)	Min uplift (m)
34/7-1	1130,3 ± 56	982,06 ± 56
34/7-5	1266,7 ± 127	470,2 ± 127
6608/10-3	1894,9 ± 64	1474,5 ± 64

Table 30 - Table showing the estimated uplift values for a comparison between the Shetland reference trends, and the Cretaceous trend from well 7121/4-1.

4.4.2 Vs

Vs values are calculated from Vp data, so we should see the same relationship between trends as we did for the Vp data.

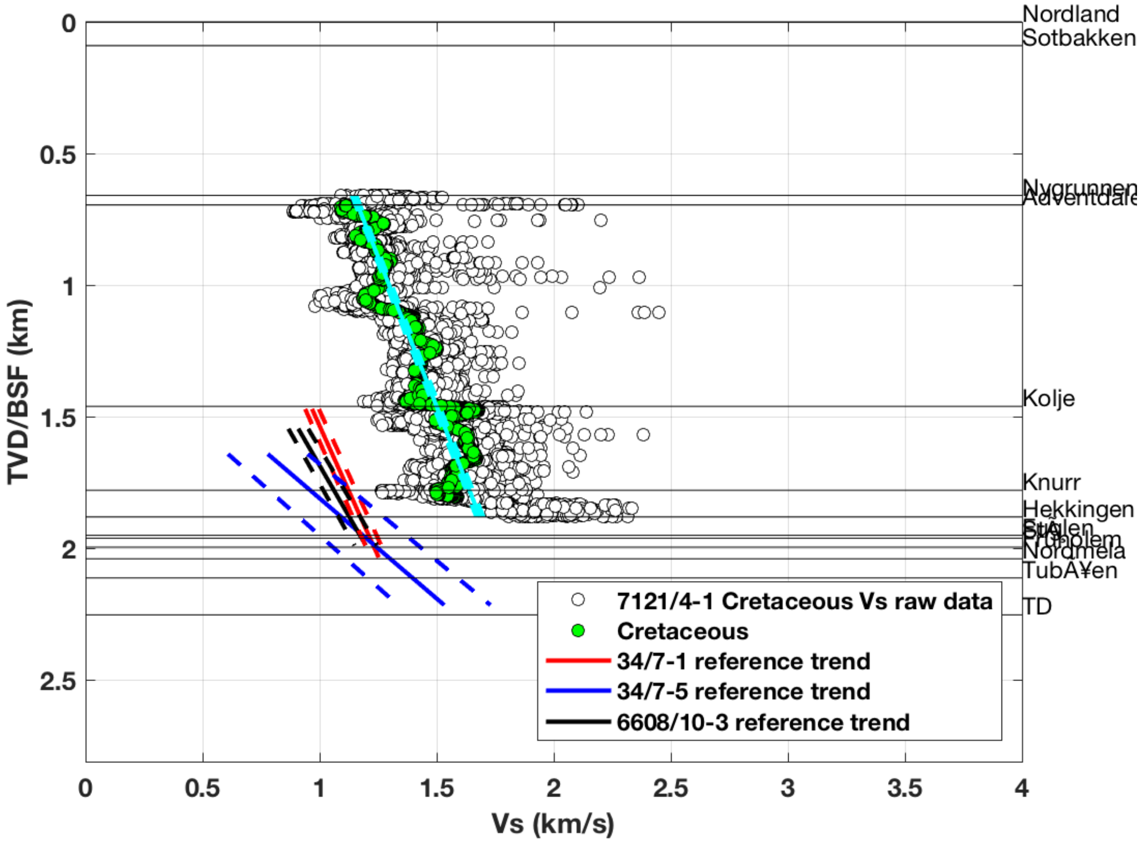

Figure 31 - Plot showing raw Vs data from the Cretaceous sediments in well 7121/4-1, in white. The smoothed data is shown in green. The reference trend lines are also found in the plot. The cyan line is the trend line representing the Vs data from well 7121/4-1. The stapled lines show the range of the uncertainty for the linear trend lines.

The Vs plot looks like very much like the Vp plot, and here it is also the Vclay filtering that results in the 34/7-5 trend being different from the 34/7-1 trend. This will result in the same inaccuracy when estimating uplift.

Well	Vs0	K(z)
34/7-1	0,23 ± 0,015	0,5 ± 0,01
34/7-5	-1,37 ± 0,1	1,31 ± 0,05
6608/10-3	-0.09 ± 0,02	0,65 ± 0,01
7121/4-1	0,86 ± 0,006	0,44 ± 0,004

Table 31 - Table showing the equations for the Shetland reference trends, and the Cretaceous trend from 7121/4-1.

Well used for comparison	Max uplift (m)	Min uplift (m)
34/7-1	1166,6 ± 58	1011 ± 58
34/7-5	1262,5 ± 129	451,74 ± 129
6608/10-3	1251,9 ± 65	857,85 ± 65

Table 32 - Table showing the estimated uplift values for a comparison between the Shetland reference trends, and the Cretaceous trend from well 7121/4-1.

4.4.3 Vp/Vs

The Vp/Vs ratio is expected to behave as the Vp and Vs data as well, because it is a ratio between the two.

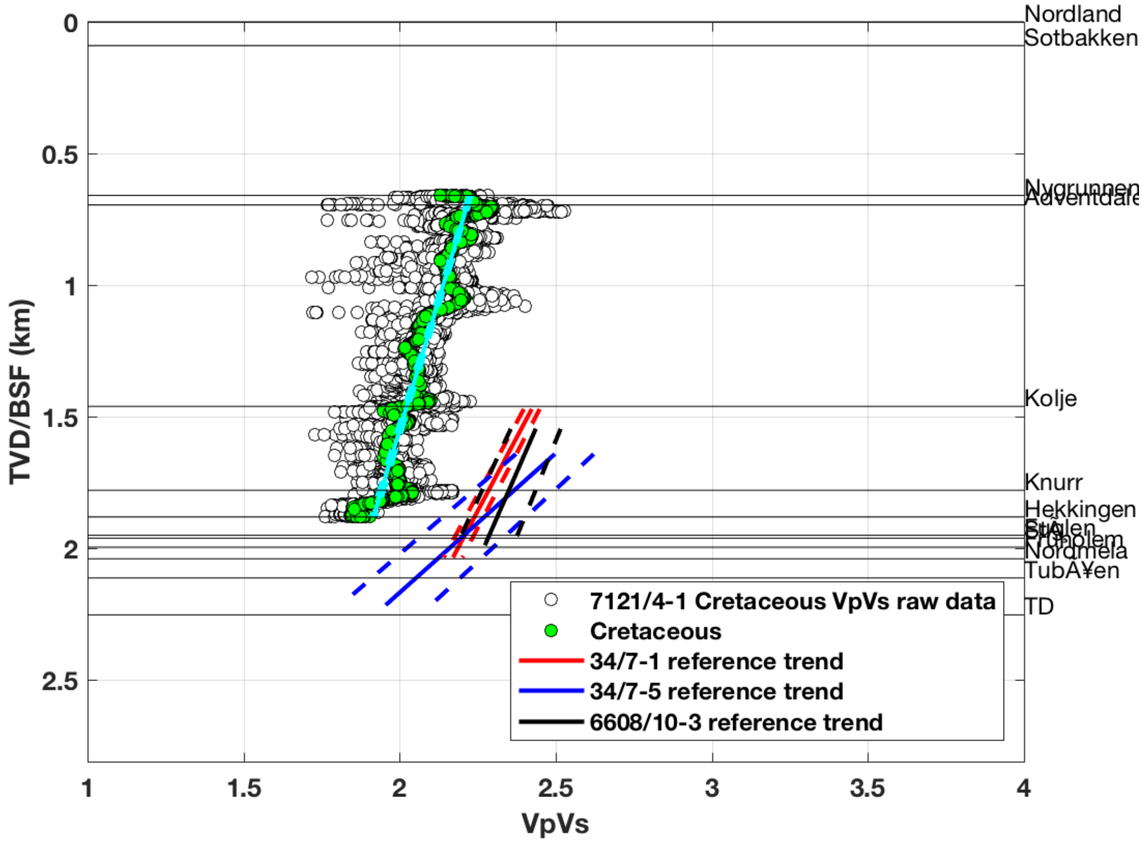

Figure 32 - Plot showing raw Vp/Vs data from the Cretaceous sediments in well 7121/4-1, in white. The smoothed data is shown in green. The reference trend lines are also found in the plot. The cyan line is the trend line representing the Vp/Vs data from well 7121/4-1. The stapled lines show the range of the uncertainty for the linear trend lines.

The Vp/Vs plot is almost identical to the Vp and Vs plots, as expected. The trend line from well 6608/10-3 is more parallel to the Cretaceous trend line than for Vp and Vs, but the uncertainty range is bigger.

Well	Vp/Vs0	K(z)
34/7-1	3,08 ± 0,1	-0,45 ± 0,007
34/7-5	4,05 ± 0,07	-0.94 ± 0,03
6608/10-3	3 ± 0,04	-0,37 ± 0,02
7121/4-1	2,39 ± 0,003	-0,25 ± 0,002

Table 33 - Table showing the equations for the Shetland reference trends, and the Cretaceous trend from 7121/4-1.

Well used for comparison	Max uplift (m)	Min uplift (m)
34/7-1	1252,5 ± 56	723,4 ± 56
34/7-5	1269,6 + 132	377,7 ± 132
6608/10-3	1457,5 ± 216	1078,1 ± 216

Table 34 - Table showing the estimated uplift values for a comparison between the Shetland reference trends, and the Cretaceous trend from well 7121/4-1.

4.4.4 Rhob

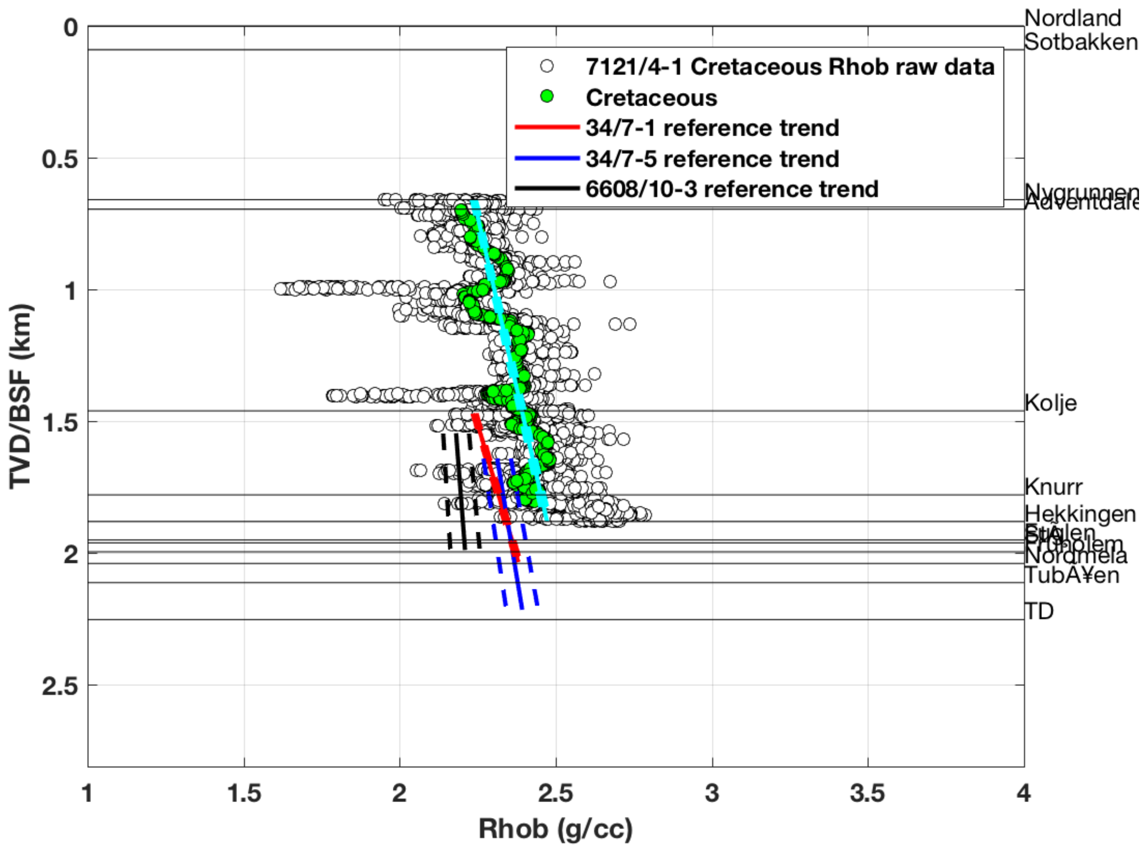

Figure 33 - Plot showing raw rhob data from the Cretaceous sediments in well 7121/4-1, in white. The smoothed data is shown in green. The reference trend lines are also found in the plot. The cyan line is the trend line representing the rhob data from well 7121/4-1. The stapled lines show the range of the uncertainty for the linear trend lines.

The density trend lines for the two neighbouring wells, 34/7-1 and 34/7-5 are almost identical, and would yield uplift estimates that are close to each other. They are much more similar than for Vp, Vs and Vp/Vs, and a reason might be that there are some lithological property that influences the Vp, Vs and Vp/Vs data.

Well	Rhob0	K(z)
34/7-1	1,87 ± 0,003	0,25 ± 0,001
34/7-5	2,08 ± 0,02	0,14 ± 0,01
6608/10-3	2,08 ± 0,02	0,06 ± 0,01
7121/4-1	2,11 ± 0,004	0,19 ± 0,003

Table 35 - Table showing the equations for the Shetland reference trends, and the Cretaceous trend from 7121/4-1.

Well used for comparison	Max uplift (m)	Min uplift (m)
34/7-1	802,6 ± 28	523,5 ± 28
34/7-5	903,2 ± 313	446,8 ± 313
6608/10-3	4155,1 ± 639	1763,7 ± 639

Table 36 - Table showing the estimated uplift values for a comparison between the Shetland reference trends, and the Cretaceous trend from well 7121/4-1.

4.4.5 Rdeep

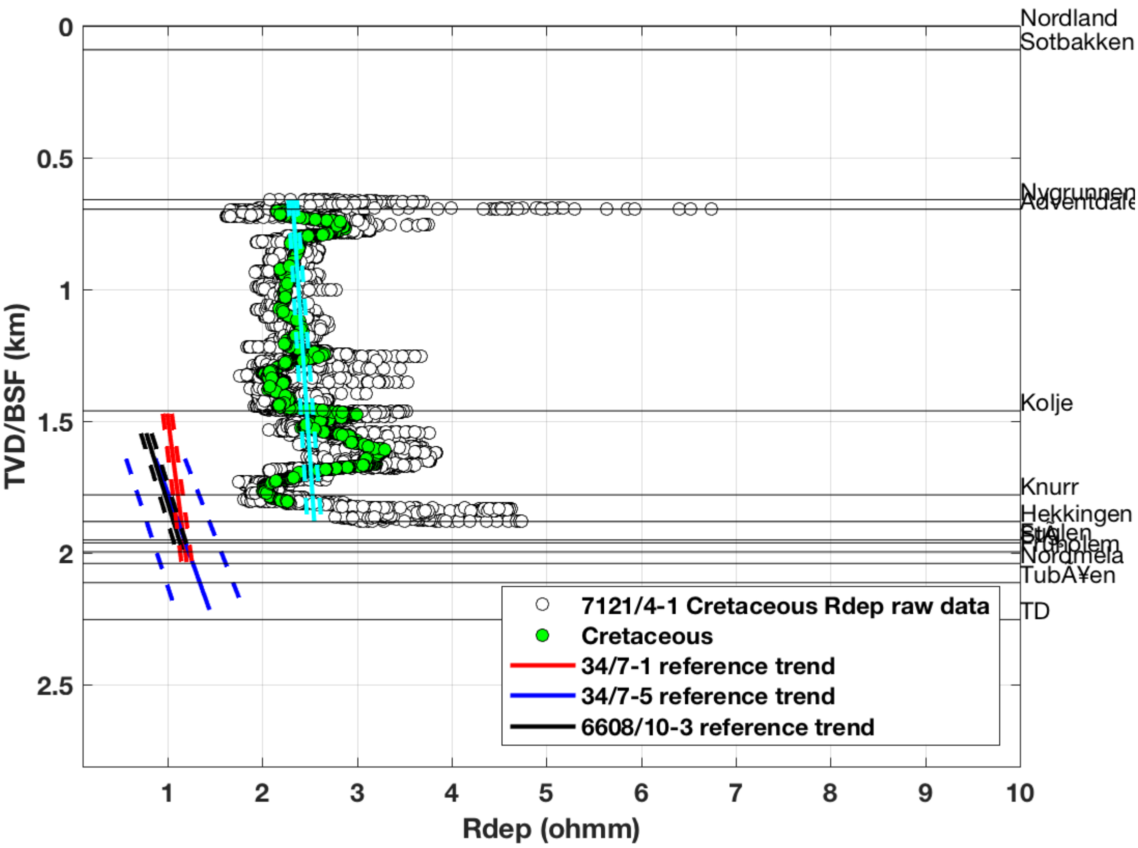

Figure 34 - Plot showing raw rdeep data from the Cretaceous sediments in well 7121/4-1, in white. The smoothed data is shown in green. The reference trend lines are also found in the plot. The magenta line is the trend line representing the rdeep data from well 7121/4-1.

With the trend lines being close to vertical, any uplift estimate using rdeep data would yield very high, incorrect values. We see however that the trend for the Cretaceous sediments are shifted to the right, so we might use this trend line comparison to say something about if uplift have happened or not, but not by how much.

Well	Rdeep0	K(z)
34/7-1	0,46 ± 0,02	0,36 ± 0,01
34/7-5	-0,76 ± 0,16	0,96 ± 0,08
6608/10-3	-0,55 ± 0,03	0,86 ± 0,01
7121/4-1	2,2 ± 0,03	0,18 ± 0,02

Table 37 - Table showing the equations for the Shetland reference trends, and the Cretaceous trend from 7121/4-1.

4.4.6 Porosity

Porosity is calculated from density, so we can expect the porosity trends to behave like the density trends.

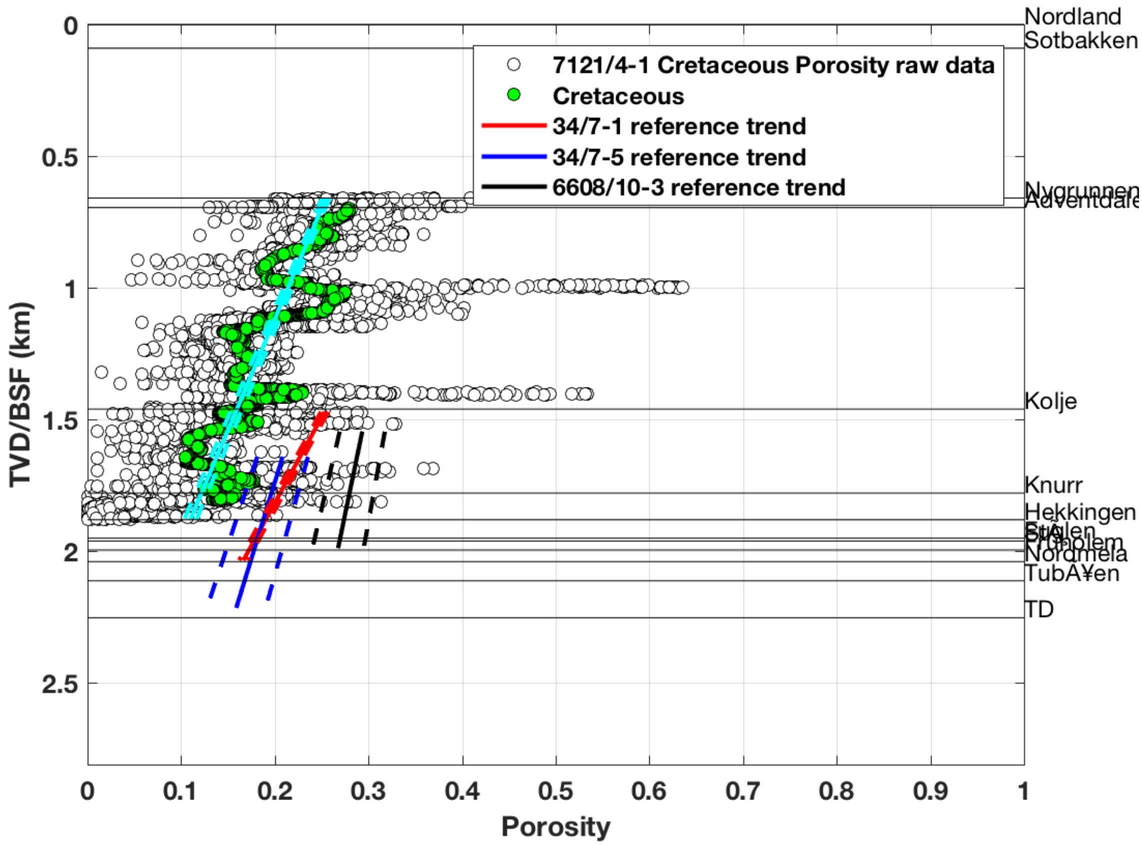

Figure 35 - Plot showing raw porosity data from the Cretaceous sediments in well 7121/4-1, in white. The smoothed data is shown in green. The reference trend lines are also found in the plot. The cyan line is the trend line representing the porosity data from well 7121/4-1. The stapled lines show the range of the uncertainty for the linear trend lines.

This plot is very similar to the density plot, just mirror imaged. Using this plot might help explain the trend we see in the density plot.

Well	Porosity0	K(z)
34/7-1	0,48 ± 0,002	-0,15 ± 0,001
34/7-5	0,35 ± 0,01	-0,09 ± 0,007
6608/10-3	0,38 ± 0,013	-0,06 ± 0,0073
7121/4-1	0,33 ± 0,002	-0,12 ± 0,002

Table 38 - Table showing the equations for the Shetland reference trends, and the Cretaceous trend from 7121/4-1.

Well used for comparison	Max uplift (m)	Min uplift (m)
34/7-1	802,6 ± 26	524,39 ± 26
34/7-5	901,79 ± 314	446,76 ± 314
6608/10-3	2806,9 ± 413	1552,8 ± 413

Table 39 - Table showing the estimated uplift values for a comparison between the Shetland reference trends, and the Cretaceous trend from well 7121/4-1.

Chapter 5 - Discussion

We see differences between the trend lines show in the plots in the previous section. These differences can be explained with differences in pore pressure, porosity and lithology. By looking at the completion logs and reading articles, it is easy to find out what lithology the different geological groups consist of. Porosity plots are included in the results section, making it easy to find out the porosity for the different geological groups. Pore pressure values are found by looking at the mud weight on the Norwegian Petroleum Directorate's fact pages. Saying something about the pore pressure from these values is not the most accurate method to use, but when we do not have accurate pore pressure values measured with tools in the borehole, this is the way to go.

5.1 7216/11-1 S

Only the Cretaceous sediments are thick enough to be studied in this well.

5.1.1 Vp

Looking at the Vp plot for the Nordland group (figure x), we see that the reference trends from 34/7-1, 34/7-5 and 6608/10-3 are identical. They are located more to the north than well 15/9-6. The trend lines from 15/9-6 and 7216/11-1 S are also identical. We see a difference between the trends because the lithology is different. The Nordland lithology in the southern North Sea is more is more smectite rich compared to the Nordland lithology in the northern North Sea. Nordland in well 15/9-6 and 7216/11-1 S have the same lithology. This shows that the Vclay filter is not doing what we want it to do. It filters out all data points with a Vclay below 0,5. Ideally, we should be left with data points that represent the same lithology, and therefore all the trend lines should lie on top of each other, but this is not the case. The Nordland group in all the wells have not been subject to uplift either, which also is an argument why the trend lines should lie on top of each other. The pressure is also hydrostatic, which further strengthens that they should lie on top of each other.

However, we see that the porosity in these wells is different (figure x). The porosity in well 7216/11-1 S is higher than in the others, and this explains why the Vp values are lower. The porosity in well 15/9-6 is the highest of all the reference wells, and this also explains why the vp values are lower. However, it does not change with depth. This is probably because the lithology is different.

To summarize, the differences between the trend lines is a result of differences in the lithology and porosity.

5.1.2 Vs

The Vs is almost identical to the Vp plot, and the differences between the trend lines are also because of differences in lithology and porosity.

5.1.3 Vp/Vs

The Vp/Vs is almost identical to the Vp and Vs plots, and the differences between the trend lines are also because of differences in lithology and porosity.

5.1.4 Rhob

The differences between the trend lines in this plot are because of lithology and porosity. The wells with the highest porosity also have the lowest density. This connection is in line with the explanation why Vp, Vs and Vp/Vs trend lines are different. 15/9-6 has a vertical trend line, which is not something one should expect.

5.1.5 Rdeep

Resistivity varies with temperature and higher temperature decreases the resistivity. This means that resistivity should decrease with depth, as temperature increases with depth. Nordland from well 7216/11-1 S is the thickest, and show the lowest resistivity values, as expected.

The differences between the deep resistivity trends are purely lithological, because these measurements do not vary with porosity and pore pressure. The two neighbouring wells, 34/7-1 and 34/7-5 have almost identical trend lines, as expected since the lithology is the same. 15/9-5 is highly different from the two, also as expected since the lithology is different.

5.1.6 Porosity

Porosity directly influences density measurements, as lower porosity should lead to higher density. Porosity also influences Vp and Vs data, and lower porosity should lead to increased VP and Vs velocities. All Vp, Vs and Rhob trends confirm this.

5.2 7117/9-1

Both the Nordland group and the Cretaceous sediments are thick enough to be studies in this well.

5.2.1 Nordland group

5.2.1.1 Vp

The trend line from well 7117/9-1 is more similar to 34/7-1, 34/7-5 and 6608/10-3 in this well, compared to 7216/11-1 S where it is more similar to the 15/9-6 trend line. The lithology in well 7117/9-1 is probably similar to the wells that have similar trend lines. The pore pressure is higher than for the reference wells, but this should result in the trend line being more to the right in the plot. The porosity in 7117/9-1 increases with depth, and should result in decreasing density with depth. This should lead to slower increasing Vp with depth, and might explain why the 7117/9-1 trend have a smaller gradient than 34/7-1, 34/7-5 and 6608/10-3. The difference we see is a lithological and porosity effect.

5.2.1.2 Vs

The Vs plot is almost identical to the Vp plot, and the differences between the trend lines are because of differences in lithology and porosity.

5.2.1.3 Vp/Vs

The Vp/Vs is almost identical to the Vp and Vs plots, and the differences between the trend lines are also because of differences in lithology and porosity.

5.2.1.4 Rhob

The density trend for well 7117/9-1 decreases with depth. This is something one should not expect, but the porosity increases with depth in this well, so the data shown is probably correct. The difference between the trend lines is a lithological and porosity effect.

5.2.1.5 Rdeep

The rdeep trends are very different, and this is probably a lithology effect.

5.2.1.6 Porosity

The porosity plot looks like the density plot, but mirror imaged.

5.2.2 Cretaceous sediments

5.2.2.1 Vp

The vp trend lines of Shetland and the Cretaceous sediments are similar. 34/7-5 stands out, because the vclay filter has removed a lot of data points in this well. The trend line from 34/7-5 standing out is a lithological effect. The trends, when uncertainty is included overlap, showing that uplift has been minimal, as expected.

5.2.2.2 Vs

The Vs plot is almost identical to the Vp plot, and the differences between the trend lines are because of differences in lithology.

5.2.2.3 Vp/Vs

The Vp/Vs is almost identical to the Vp and Vs plots, and the differences between the trend lines are also because of differences in lithology.

5.2.2.4 Rhob

The density trend lines overlap as well, and show that minimal uplift has happened. If we look at the porosity plot, we see that the trend lines with the highest porosity show the lowest density, and opposite. This is as expected.

5.2.2.5 Rdeep

The resistivity trend lines overlap as well, indicating minimal uplift.

5.2.2.6 Porosity

The porosity trend lines overlap as well, and show that minimal uplift has happened. If we look at the density plot, we see that the trend lines with the highest density show the lowest porosity, and opposite. This is as expected.

5.3 7120/5-1

Vp

We see a clear uplift trend on this plot. The reference trends are different from each other, and this is a result of lithology and porosity. The pore pressures are the same, so that is not an influencing factor. The porosity is much higher in well 7120/5-1, so the uplift estimates are probably a bit too high, since reducing the porosity would increase the Vp values, moving the 7120/5-1 trend line to the left in the plot.

Vs

The Vs plot is almost identical to the Vp plot, and the differences between the trend lines are the same as the reasons behind the differences for the Vp plot.

Vp/Vs

The Vp/Vs plot is almost identical to the Vp and Vs plots, and the differences between the trend lines are the same as the reasons behind the differences for the Vp and Vs plots.

Rhob

We see a clear uplift trend on the density plot as well. The trend from 7120/5-1 have a gradient that is different from the reference trends, resulting in the uplift estimates spanning over large values. The porosity of the trend are different, with the Cretaceous sediments from well 7120/5-1 being the lowest, followed by 34/7-5, 34/7-5 and then 6608/10-3. This leads to the uplift estimates from rhob being too high.

Rdeep

We see a clear uplift trend in the resistivity plot as well. The trend lines are close to parallel, and almost vertical, making it difficult to estimate uplift values. It is however possible to identify that uplift has happened, but not by how much.

Porosity

The porosity plot looks like the density plot, but mirror imaged.

5.3 7121/4-1

5.3.1 Vp

We see a clear uplift trend on this plot (figure x). The reference trends are different from each other, and this is a result of lithology, and porosity. The reference wells have a higher pore pressure than the Cretaceous sediments in well 7121/4-1, which should result in the vp values from the reference trends being higher than if they were hydrostatically pressured, or had the same pressure as well 7121/4-1. This will result in the uplift estimate being too low, because the reference trends would move to the left in the plot if the pressure were the same. The porosity is different as well, with 7121/4-1 having the lowest, followed by 34/7-5, 34/7-5 and then 6608/10-3. Increased porosity leads to reduced vp values. The differences in the porosities influences the uplift estimates. If the porosity in 7121/4-1 was higher and closer to the reference wells, we would see lower vp values. This results in the uplift estimates being a bit too high.

The uncertainty range of each of the reference trends will influence the values of the uplift estimate.

5.3.2 Vs

The Vs plot is almost identical to the Vp plot, and the differences between the trend lines are the same as the reasons behind the differences for the Vp plot.

5.3.3 Vp/Vs

The Vp/Vs plot is almost identical to the Vp and Vs plots, and the differences between the trend lines are the same as the reasons behind the differences for the Vp and Vs plots.

5.3.4 Rhob

We see a clear uplift trend on the density plot as well. The trend lines are close to parallel, and would yield good uplift estimates. The porosity of the trend are different, with the Cretaceous sediments from well 7121/4-1 being the lowest, followed by 34/7-5, 34/7-5 and then 6608/10-3. This leads to the uplift estimates from rhob being too high.

5.3.5 Rdeep

We see a clear uplift trend in the resistivity plot as well. The trend lines are close to parallel, and almost vertical, making it difficult to estimate uplift values. It is however possible to identify that uplift has happened, but not by how much.

5.3.6 Porosity

The porosity plot looks like the density plot, but mirror imaged.

Chapter 6 - Conclusion

It is clear that comparing reference trend lines from geological groups in areas that have not been subject to uplift with trend lines from time equivalent geological groups in areas that have been subject to uplift is a method that can be helpful when trying to estimate uplift.

However, there are some criteria that need to be fulfilled for the method to work properly. The trend lines should represent rocks of the same lithology, with the same pore pressure and porosity. They also need to have the same gradient sign, or else it would be impossible to estimate uplift. All these factors influence the measured well log properties, and if they differ too much, the trend lines will be difficult to compare, leading to incorrect uplift estimates. If the pore pressure, porosity and lithology is the same, the trend lines would be more parallel, giving better uplift estimate values. This has to be kept in mind when using this method.

It is also important that the geological groups being included in the uplift estimates are thick enough to give us trend lines that represent the real world. In the reference wells, the Rogaland group was too thin to be used for uplift estimation. We believed that the trends from Hordaland and Rogaland could be used to estimate uplift, but it turned out that they could not.

Looking at figures 33 – 34, we se a summary of the estimated uplift values from well 7120/5-1. The max estimates (figure 33) are consistent for Vp, Vs, Vp/Vs, Rhob and porosity, and show more or less the same values. Rhob and porosity estimates from well 6608/10-3 show estimates that are too high, and they are considered outliers. Uplift estimate from Rdeep data is not possible, as discussed in the discussion section. We see the same trend of consistency when looking at the minimum uplift estimates (figure 34).

Looking at figures 34-35, we see a summary of the estimated uplift values from well 7121/4-1. The max estimates (figure 34) are consistent for Vp, Vs, Vp/Vs, Rhob and porosity, and show more or less the same values. Estimates from well 6608/10-3 for rhob and porosity show uplift estimates that are too high, and they are considered outliers. Uplift estimate from Rdeep data is not possible, as discussed in the discussion section. We see the same trend of consistency when looking at the minimum uplift estimates (figure 35).

The uplift estimates for these two wells are almost identical, which is something one would expect since they are so geographically close to each other. Most trend lines comparisons show uplift in the range 600 – 1500m.

From the more eastern located wells, we find that the uplift is zero, which is what we expected. This is also a good confirmation that the method works.

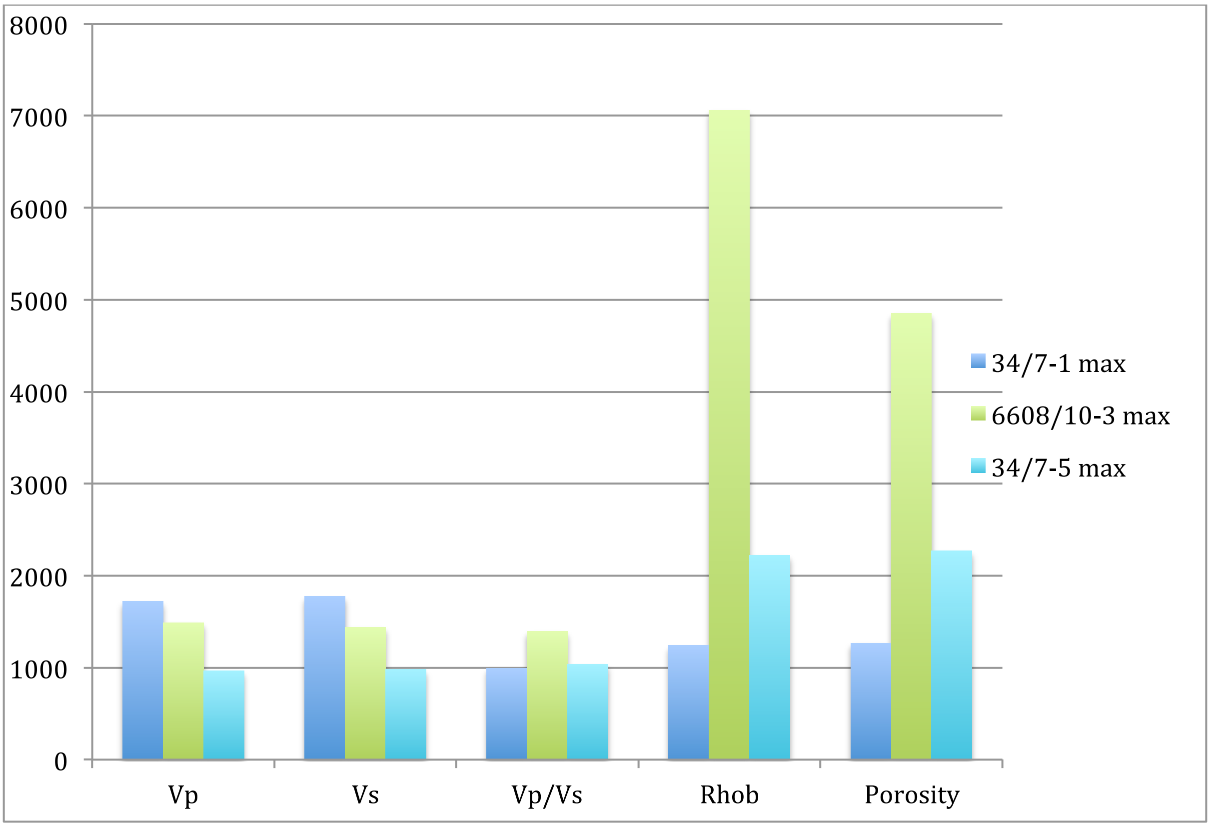

Figure 36 - Figure showing the maximum estimated uplift values in meters for the Cretaceous sediments in well 7120/5-1.

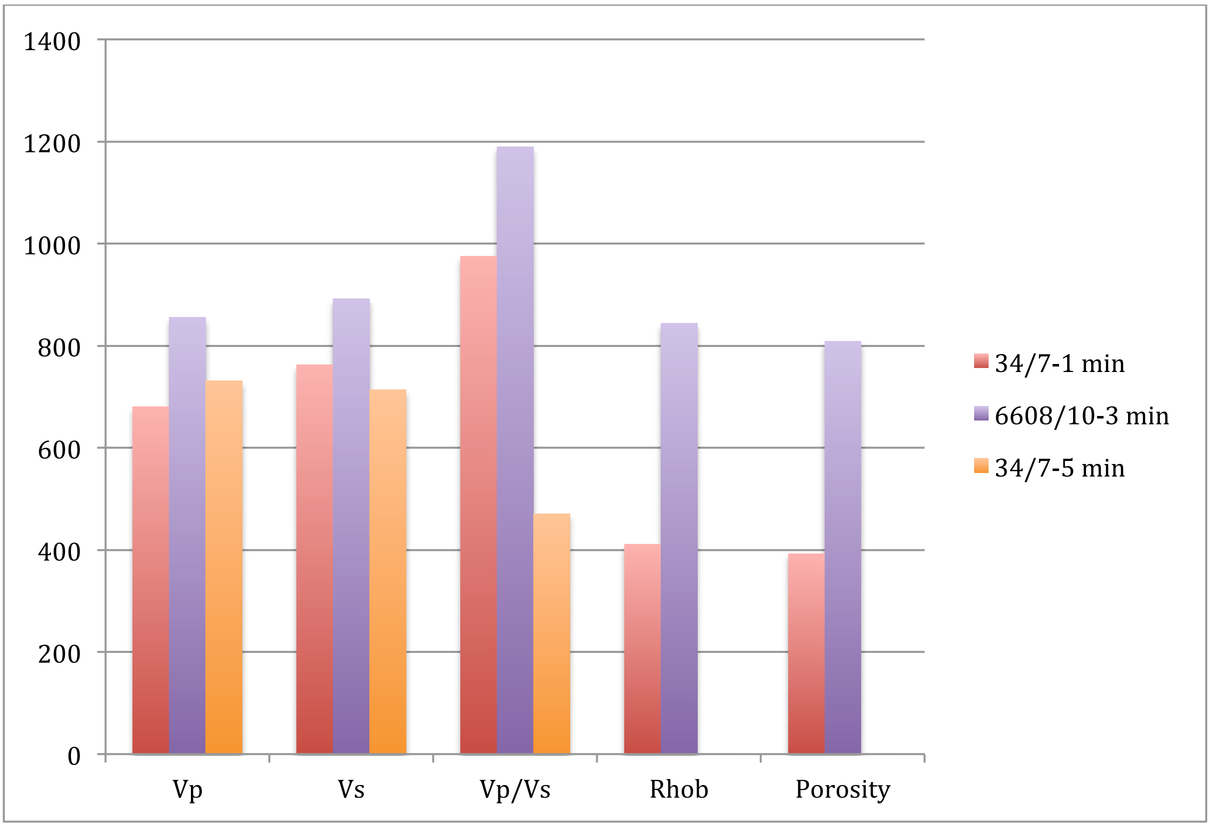

Figure 37 - Figure showing the minimum estimated uplift values in meters for the Cretaceous sediments in well 7120/5-1.

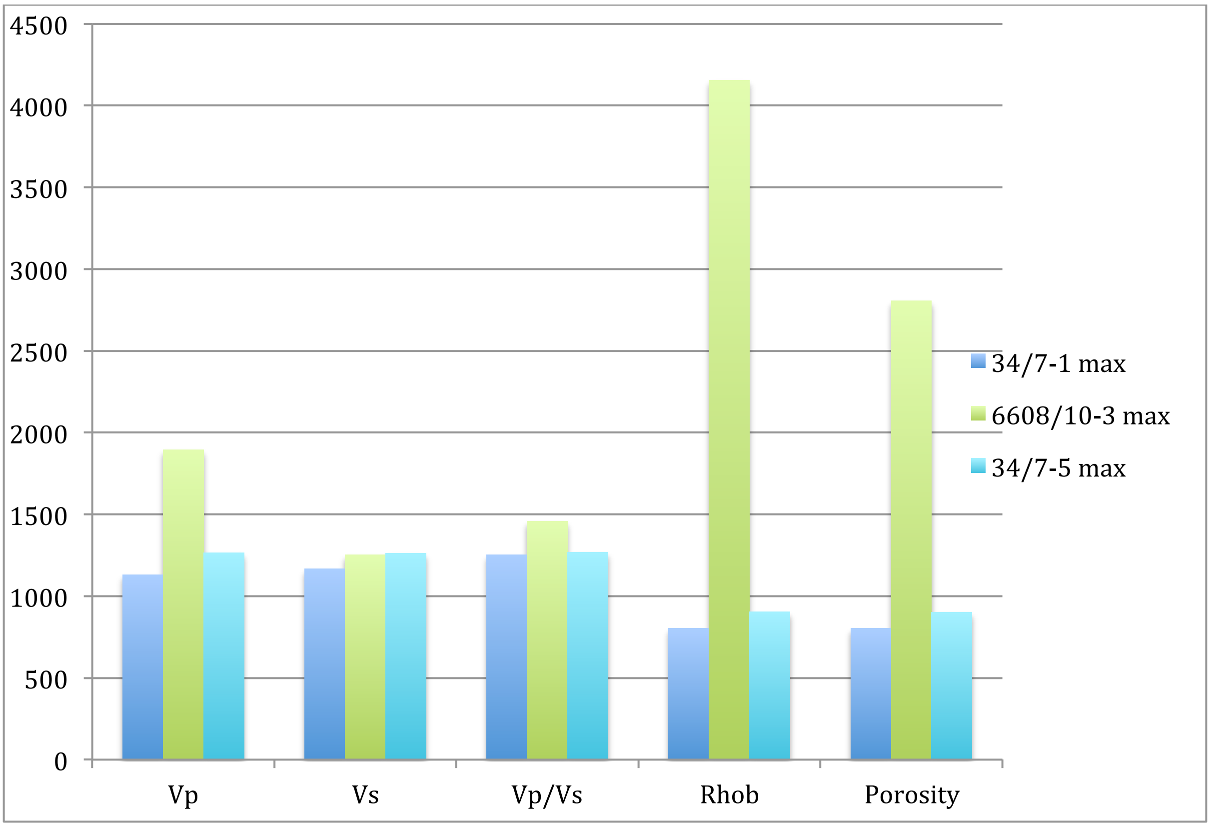

Figure 26 - Figure showing the maximum estimated uplift values in meters for the Cretaceous sediments in well 7121/4-1.

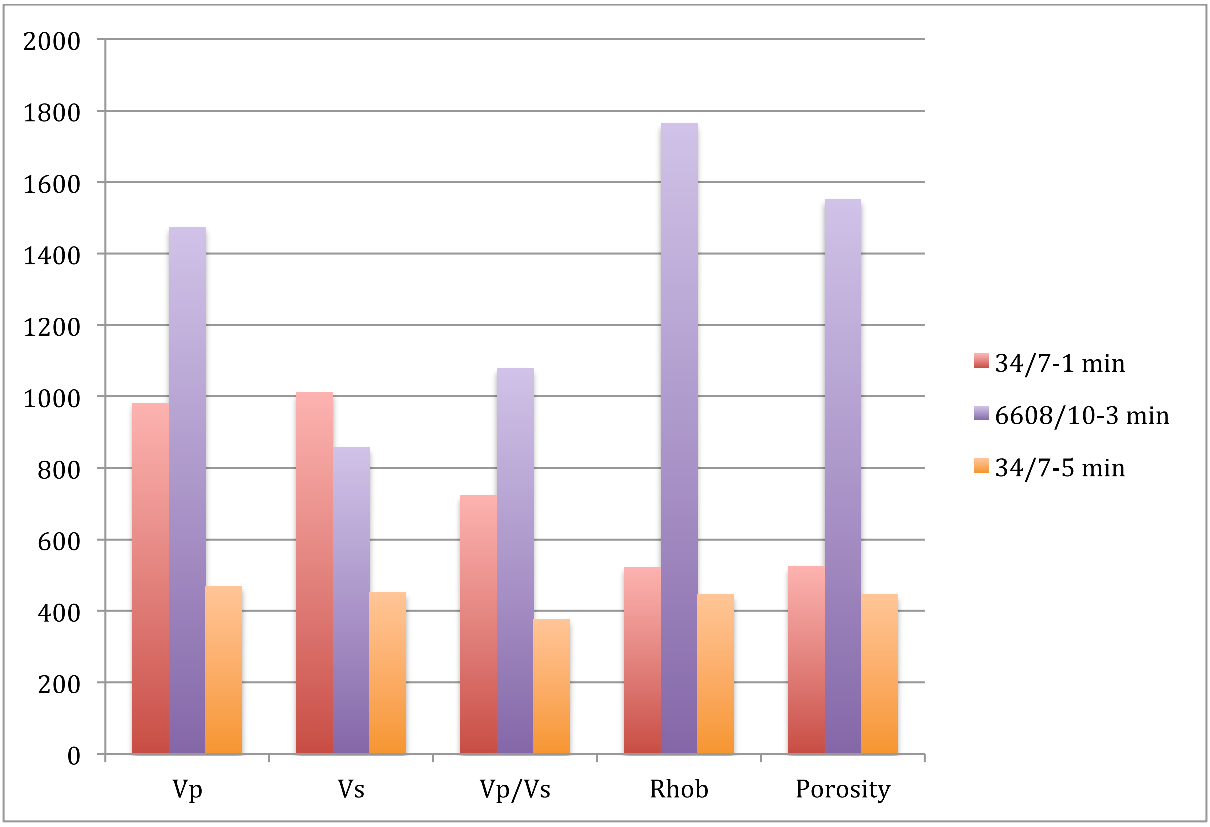

Figure 27 - Figure showing the minimum estimated uplift values in meters for the Cretaceous sediments in well 7121/4-1.

Chapter 7 – Suggestions for future work

I suggest that more wells from the Barents Sea should be used to estimate uplift, to further investigate if the trend of increasing uplift from west to east exists. It is important that these wells have thick sections of Cretaceous sediments, since this is the only lithology that can be used to estimate uplift when we use the reference wells that have been used in this study. Having reference wells with the Shetland group intact is also important. It is also important to use reference wells where Shetland is not limestone, as it is in well 15/9-5.

I would suggest more reference wells to be used. A problem with the reference wells in this study is that the Hordaland and Rogaland groups cannot be used to estimate uplift, due to them being of a different lithology, and too thin, respectively. Sotbakken in the Barents Sea well is thick, and consists of a lot of data points, resulting in trend lines that are a good representation of the data. It is too bad that Sotbakken's uplift cannot be estimated.

Finding a better method to filter out data points representing lithology we do not want, than the Vclay filter is also something that could be done. The Vclay filter removes data points, but if it worked perfectly, all trend lines from geological groups not subject to uplift would lie on top of each other, because the Vclay only leaves data points of the same lithology. This is not the case.

Finding methods that also filters data points based on pore pressure and porosity values would also be smart, as these parameters also influences the well log properties.

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Baig et al, 2016
Storvoll et al, 2005

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Hansen et al, 1996

Matlab documentation (https://se.mathworks.com/help/matlab/)

Completion logs for well 15/9-6, 34/7-1, 34/7-5, 7117/9-1, 7121/4-1 & 7120/5-1.

Acknowledgments

I would like to thank my supervisor Kenneth Duffaut (NTNU) for constructive feedback, interesting discussion, and especially his patience. My family and girlfriend are also to be thanked, for supporting me while working on this thesis.

Appendix

15/9-6

Vp

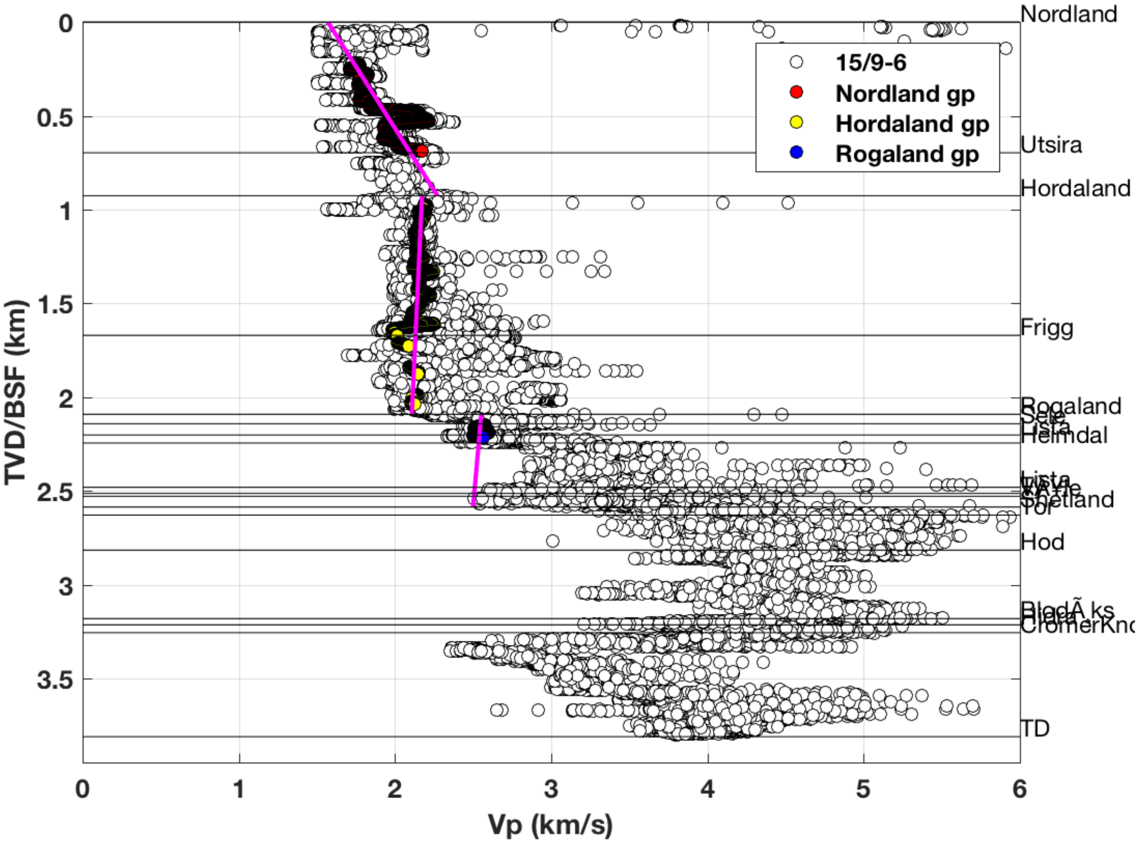

Figure 38 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Vs

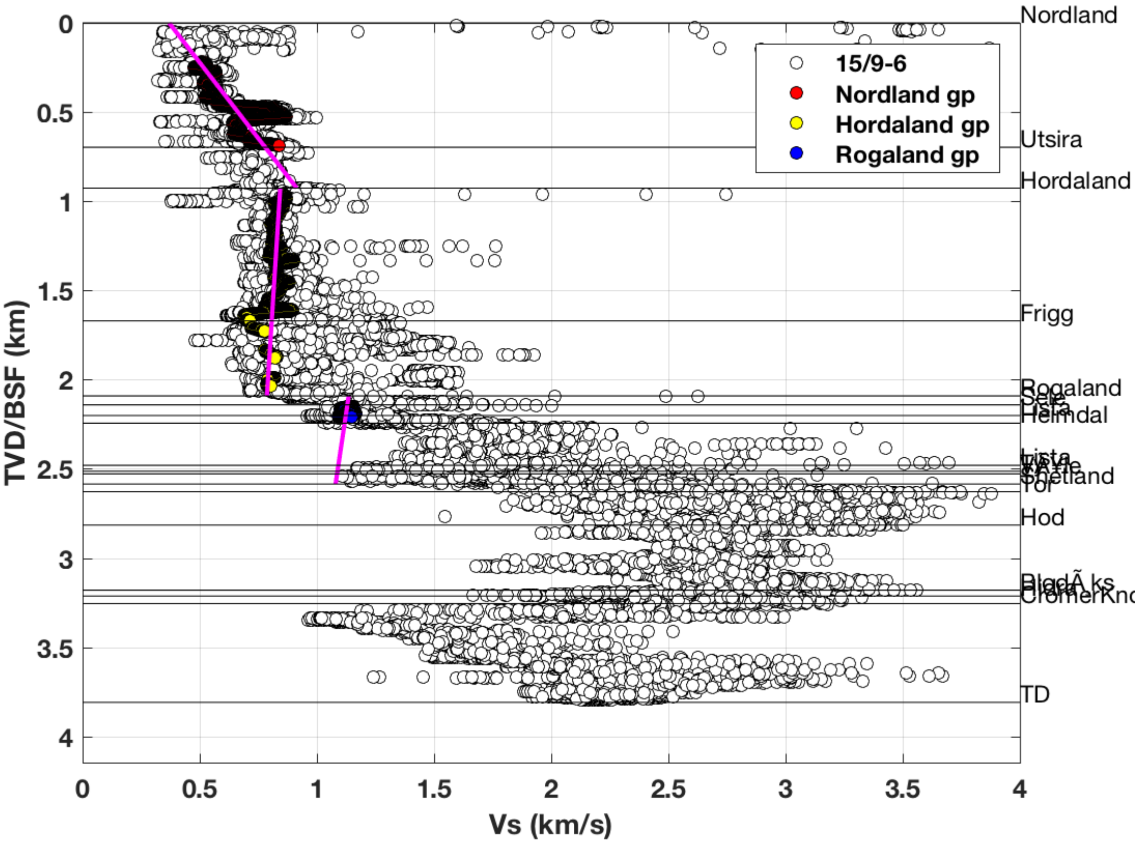

Figure 39 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Vp/Vs

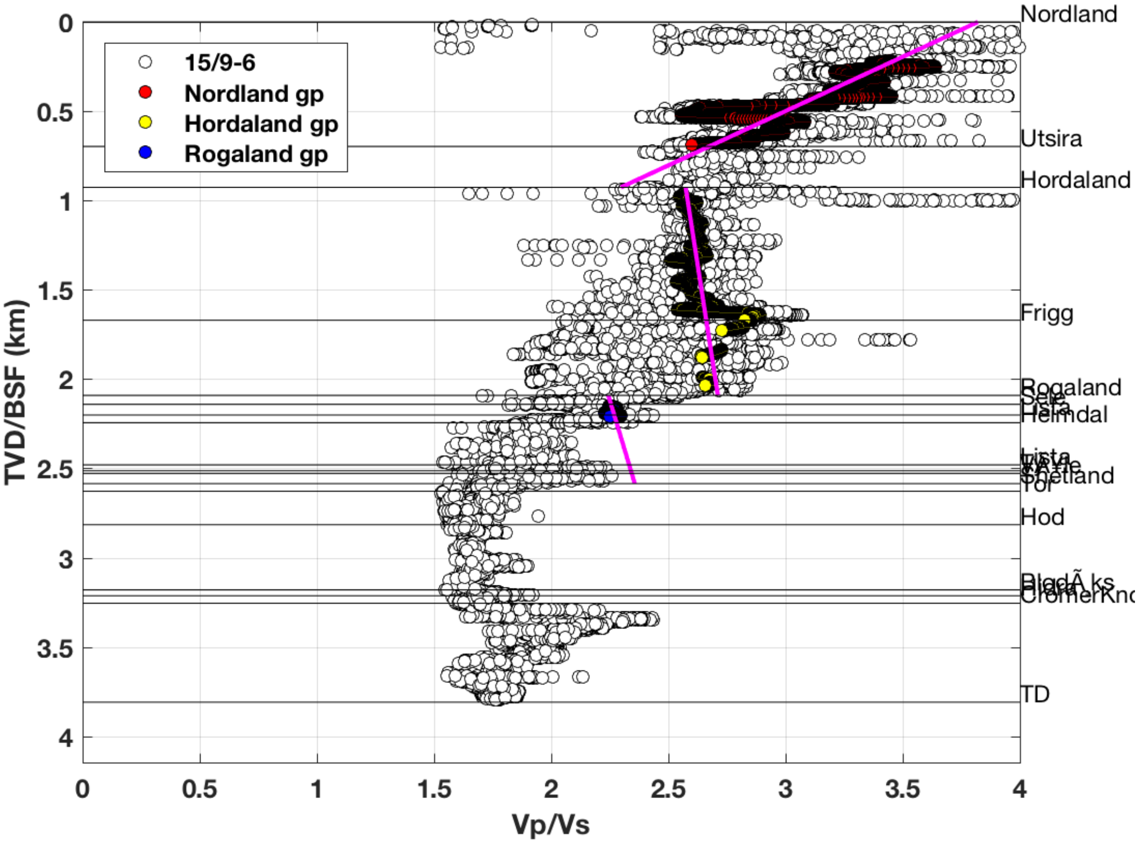

Figure 40 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Rhob

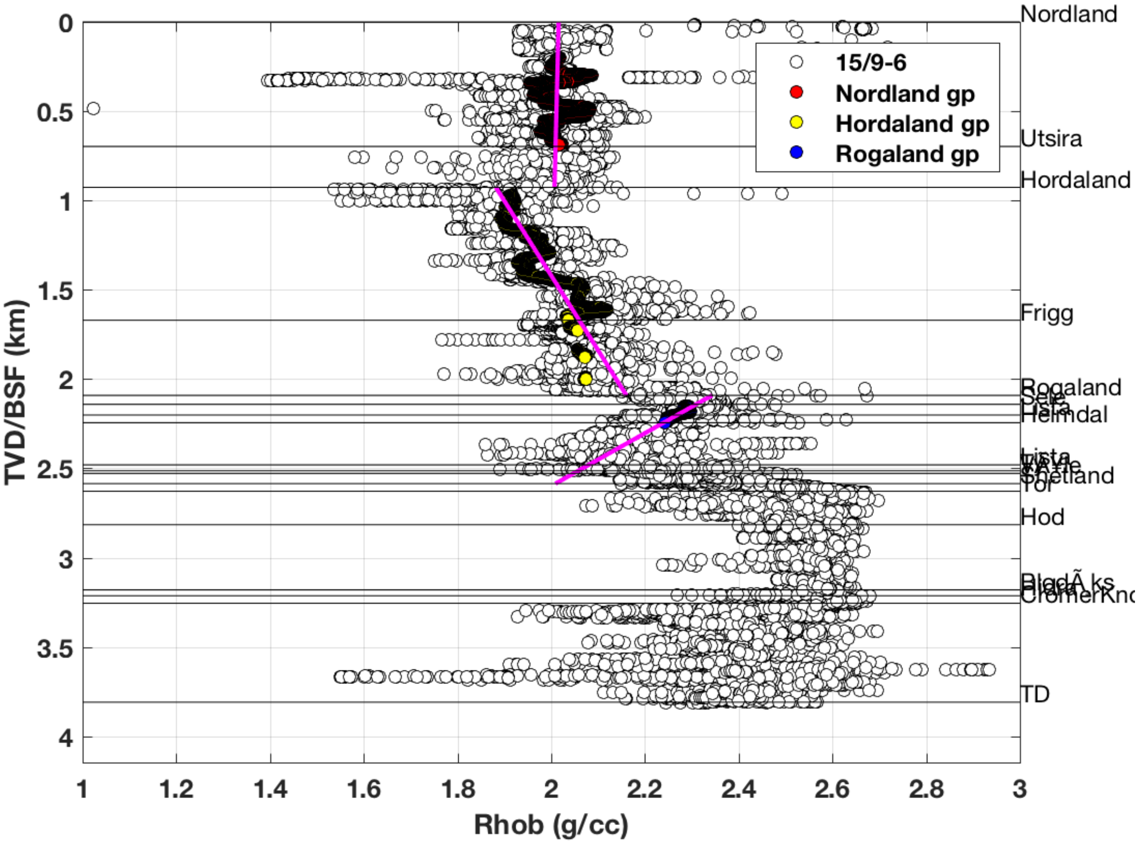

Figure 41 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Rdeep

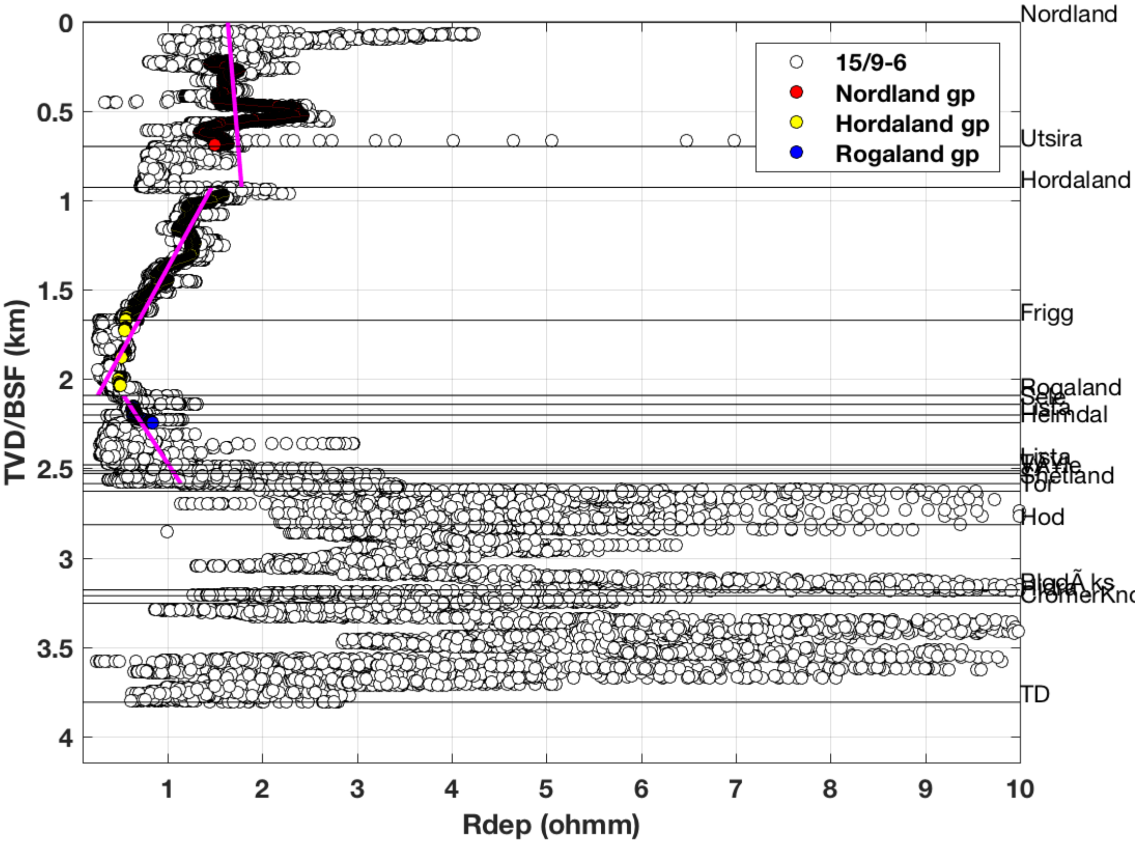

Figure 42 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Porosity

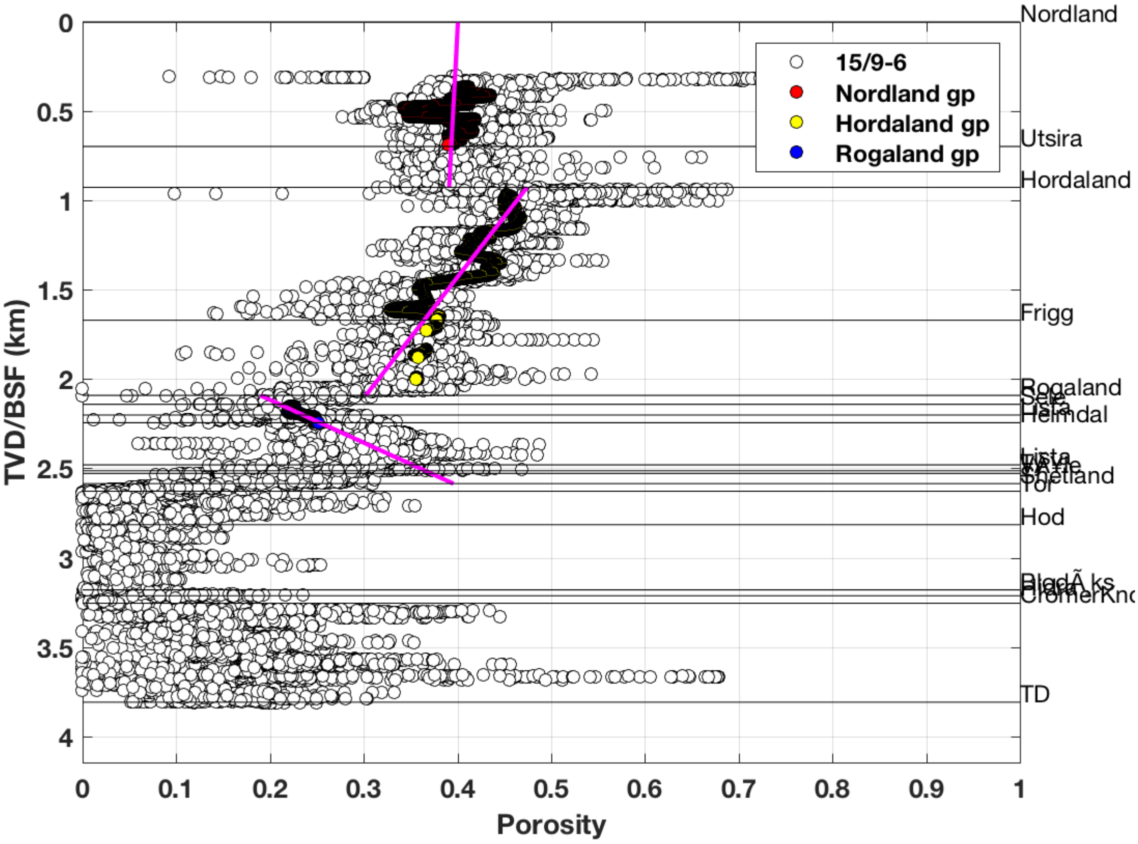

Figure 43 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

34/7-1

Vp

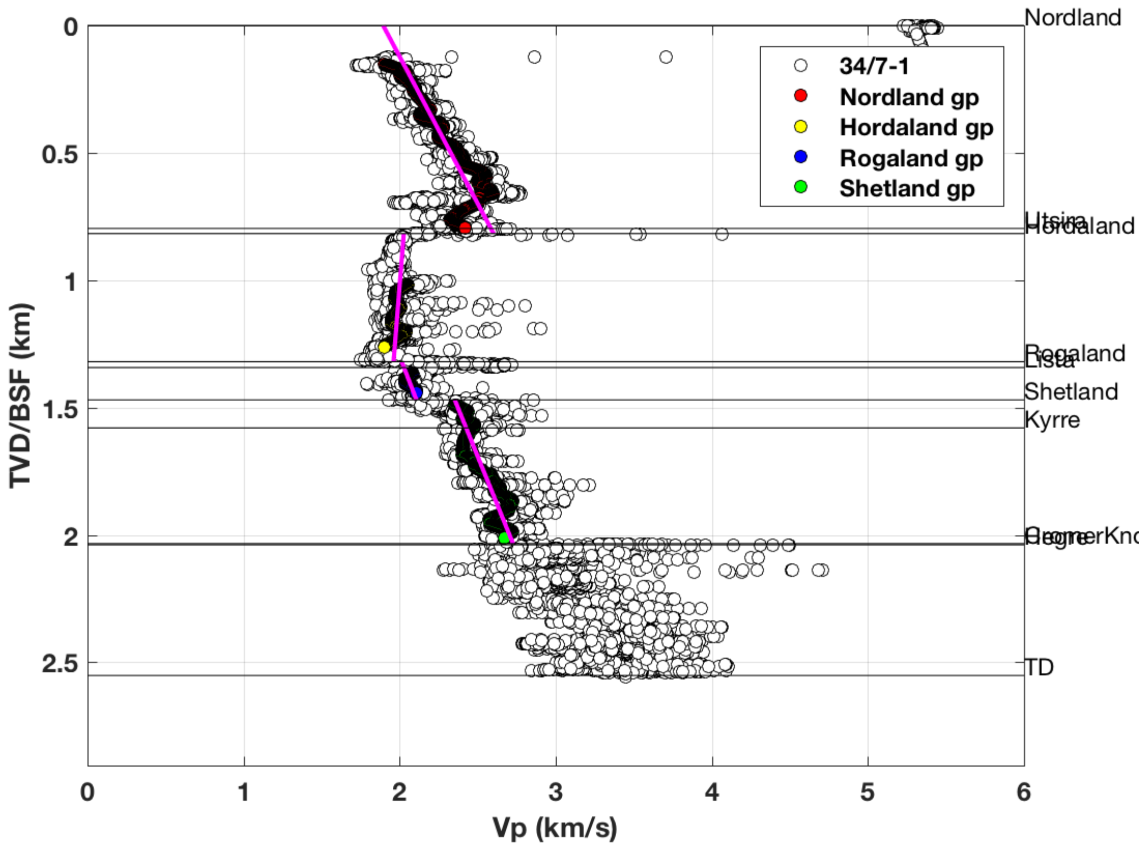

Figure 44 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Vs

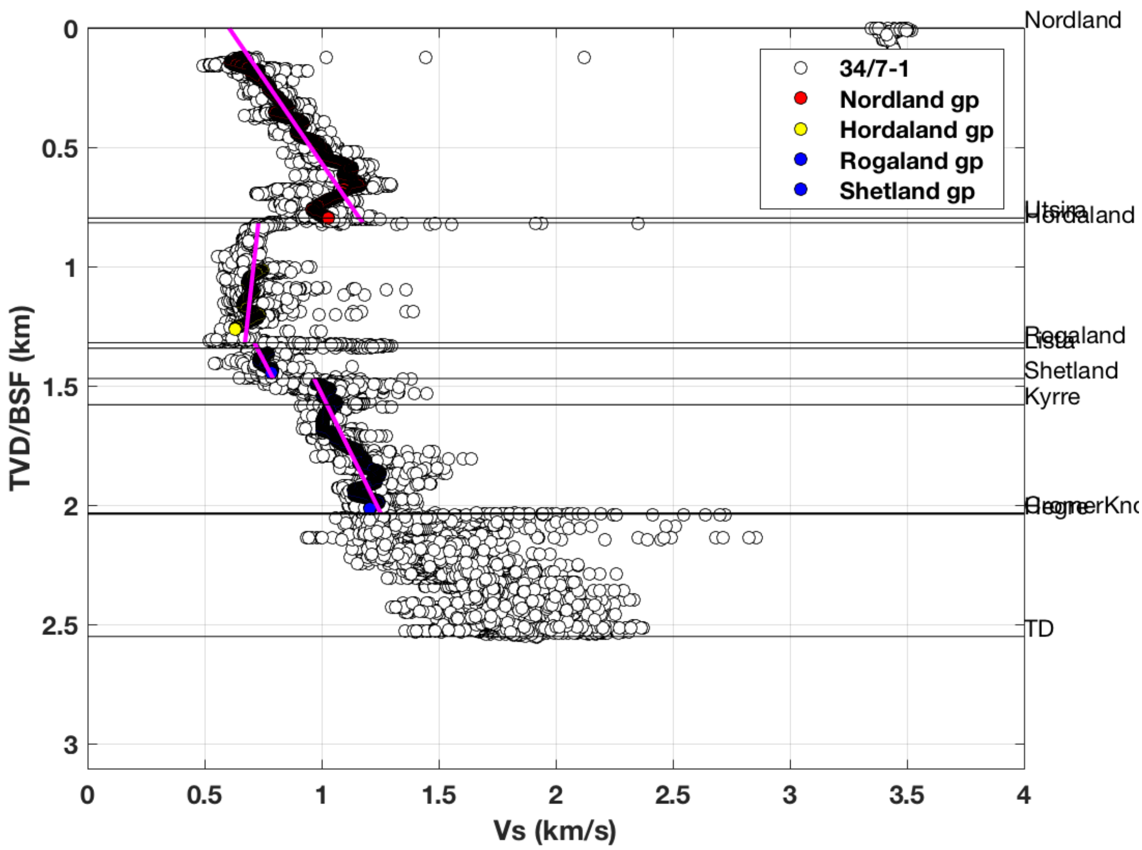

Figure 45 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Vp/Vs

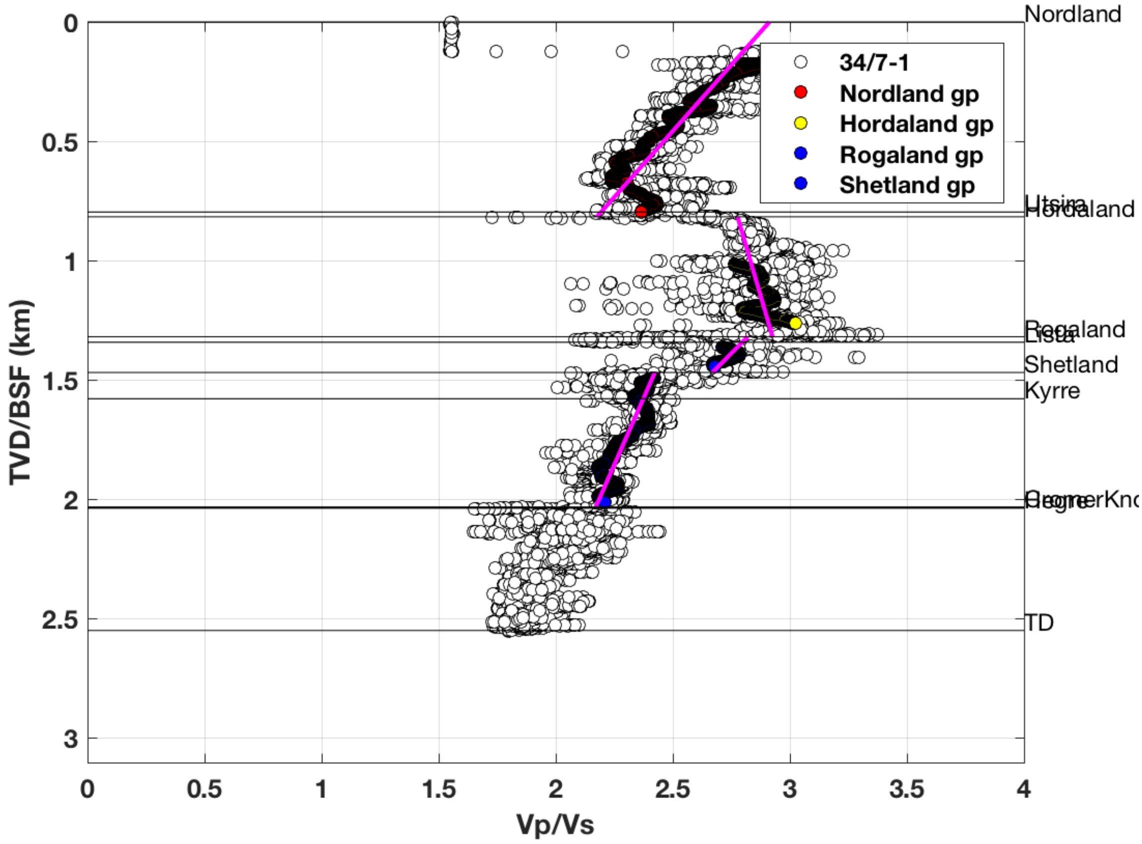

Figure 46 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Rhob

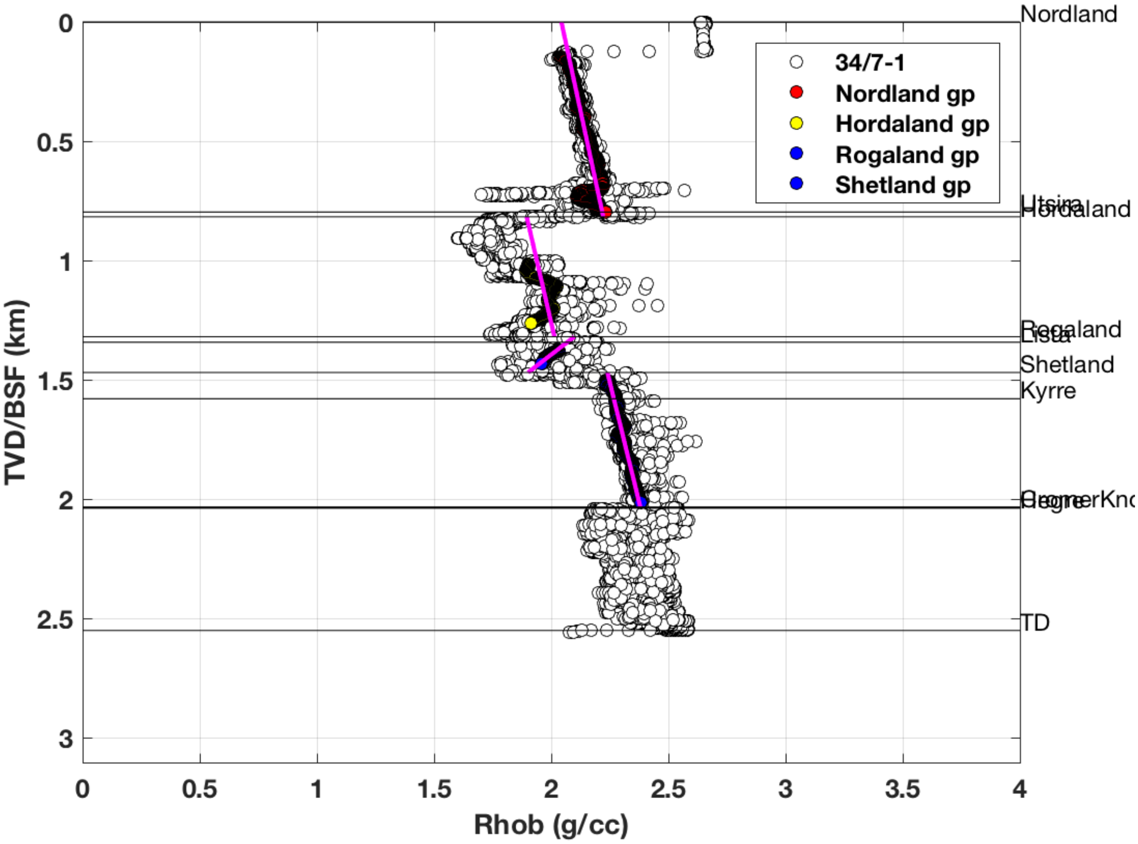

Figure 47 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Rdeep

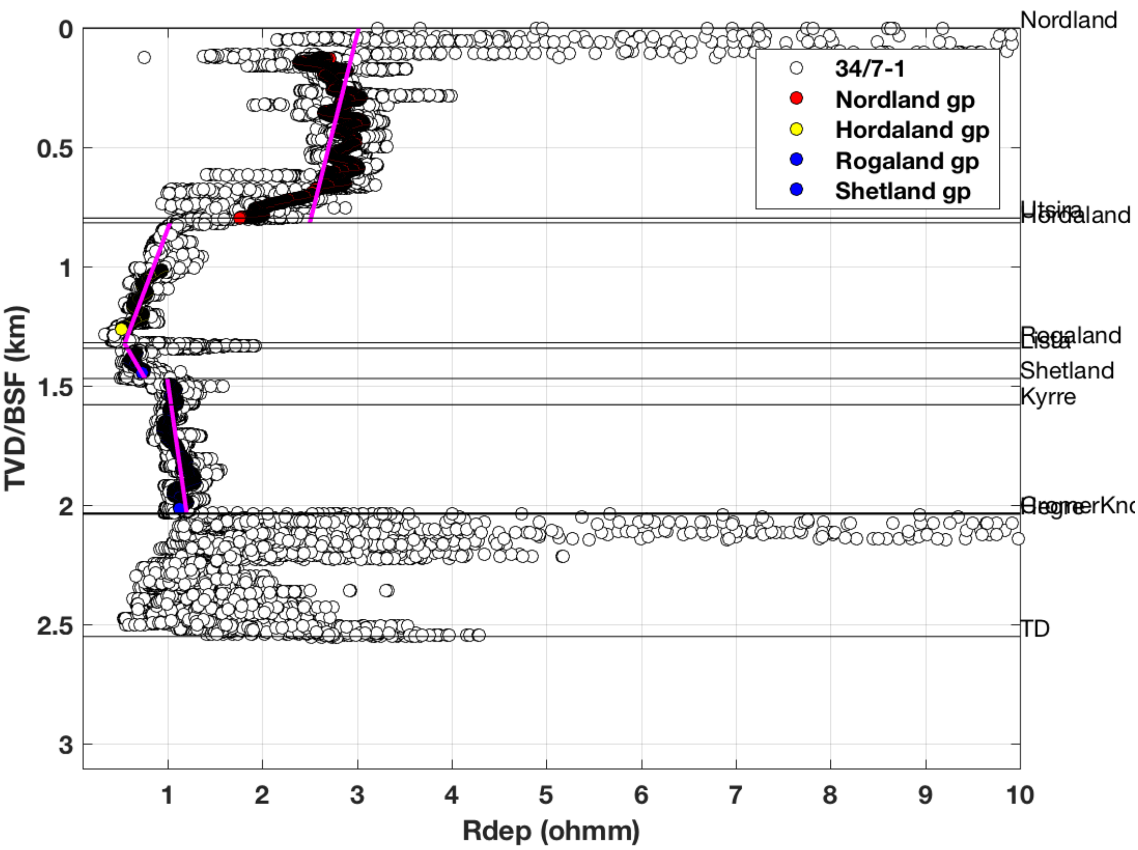

Figure 48 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Porosity

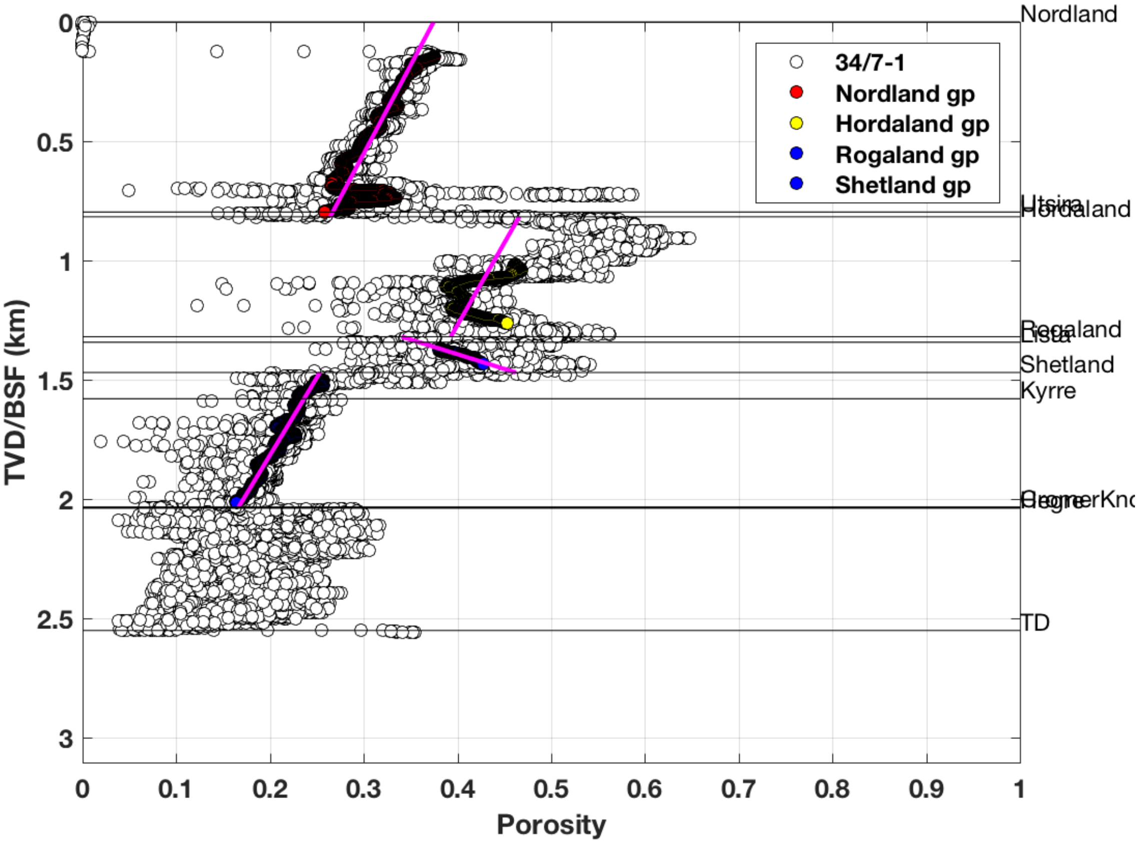

Figure 49 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

34/7-5

Vp

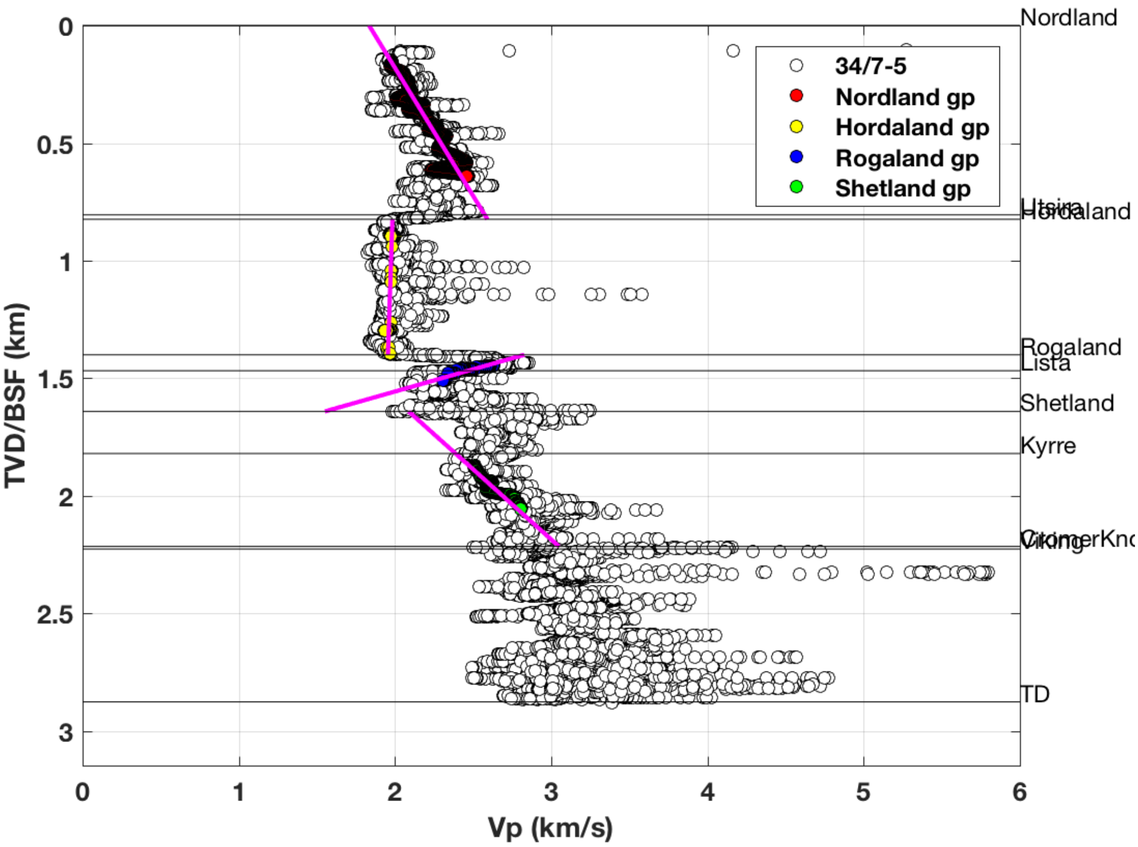

Figure 50 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Vs

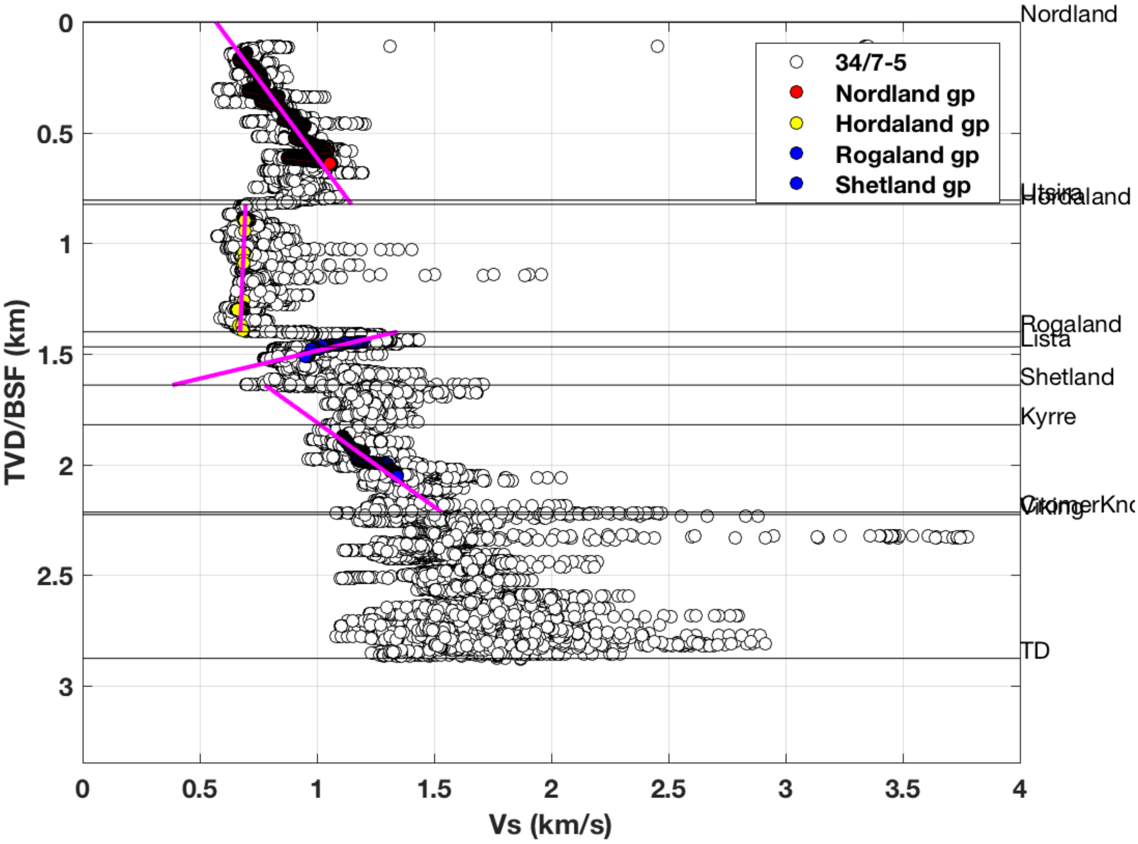

Figure 51 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Vp/Vs

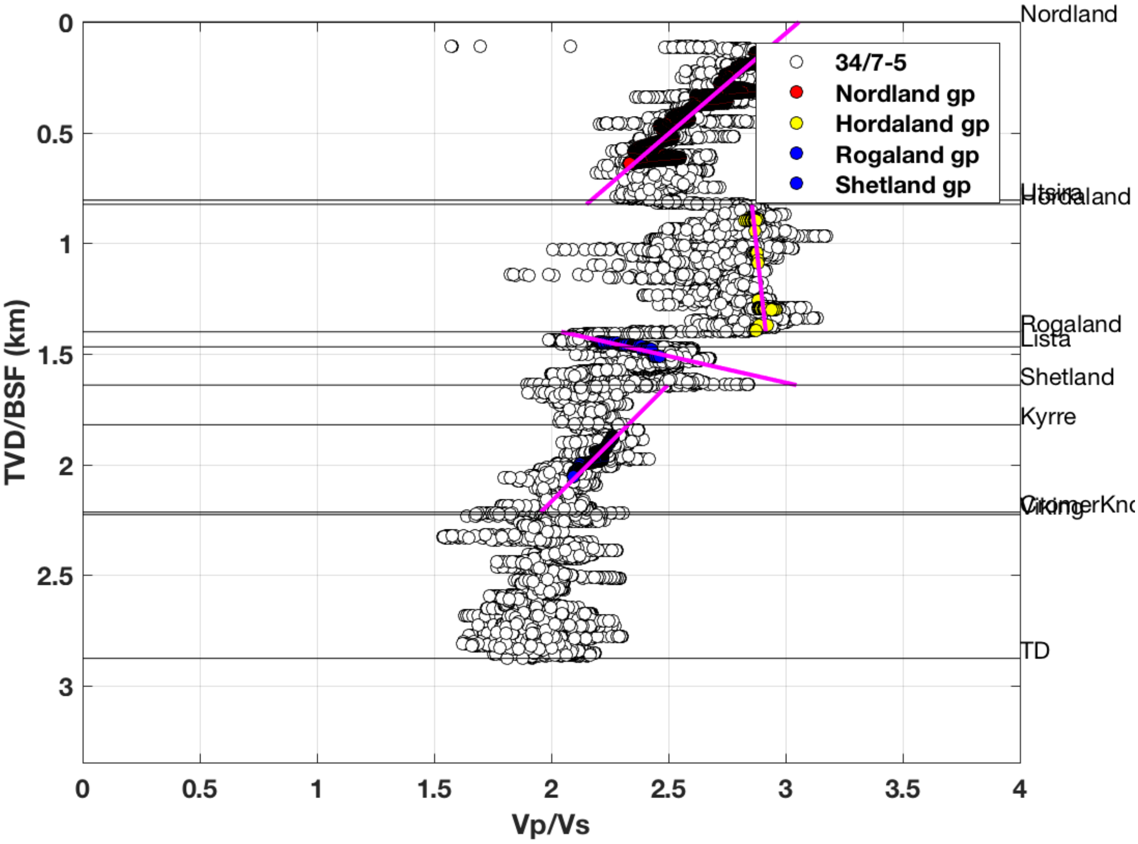

Figure 52 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Rhob

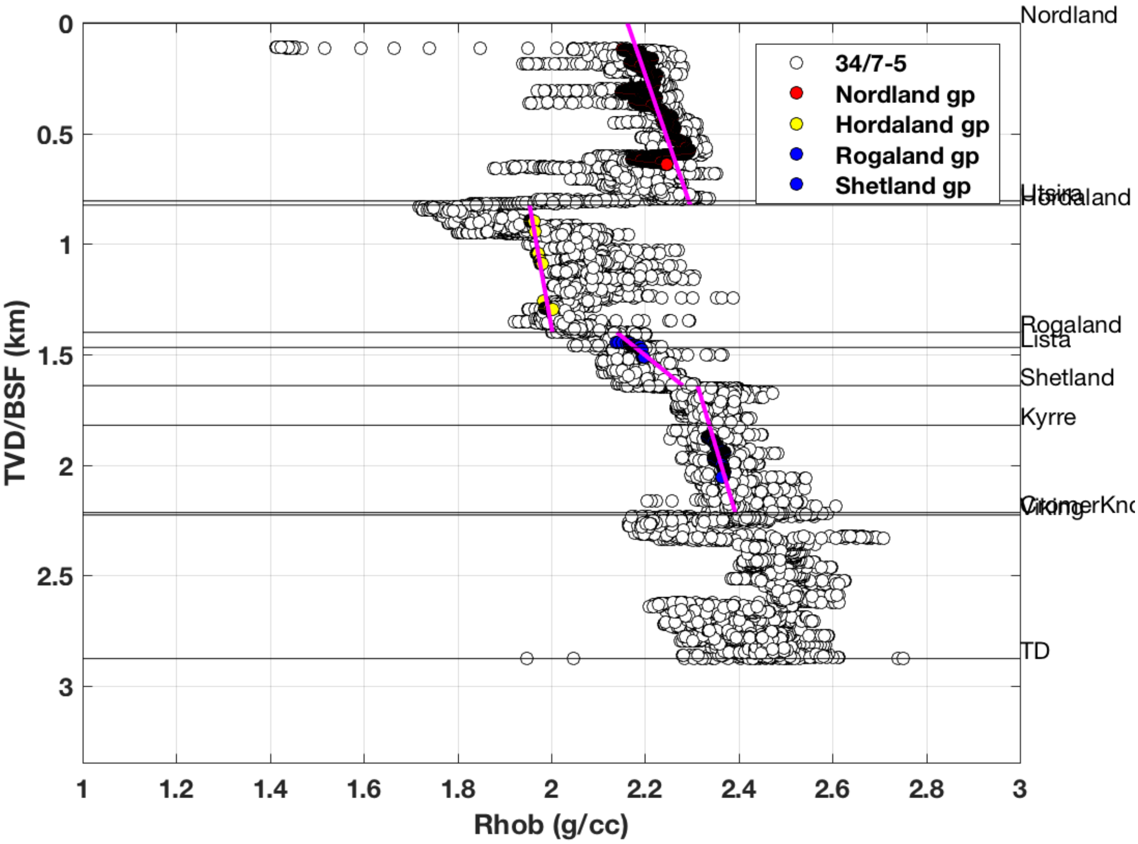

Figure 53 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Rdeep

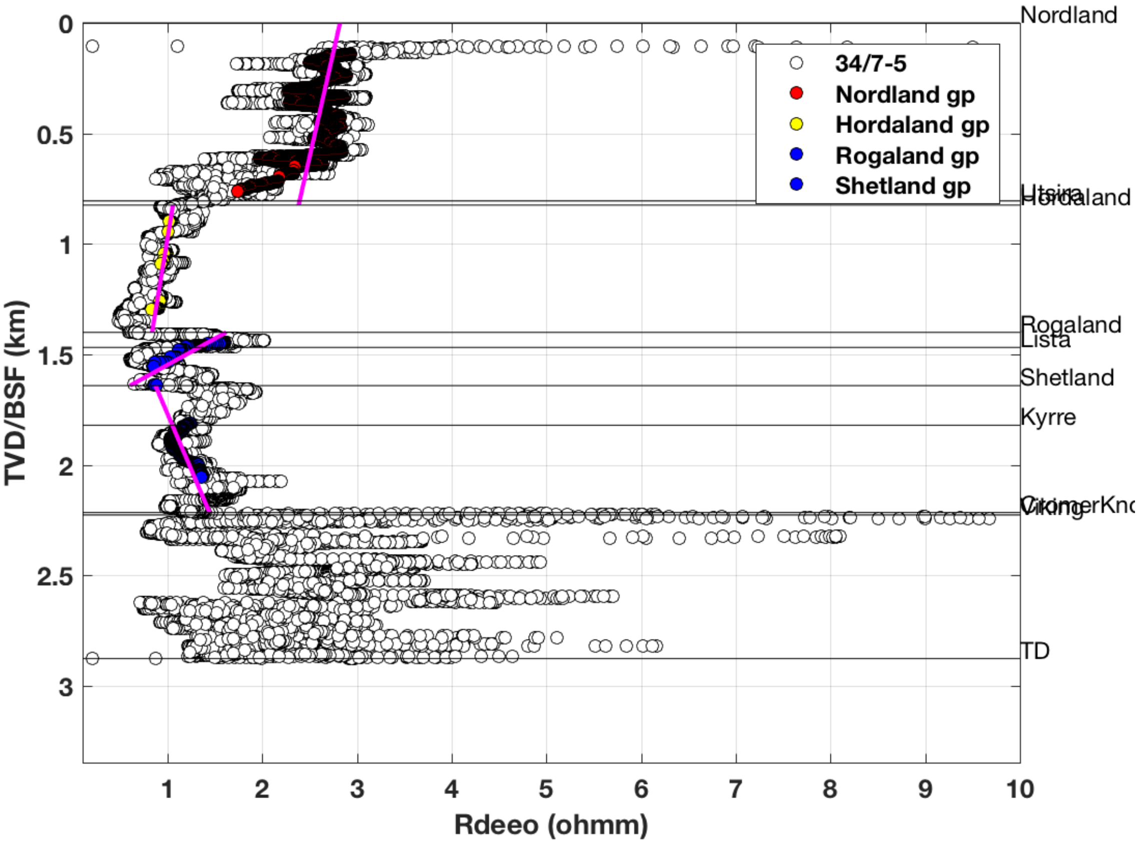

Figure 54 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Porosity

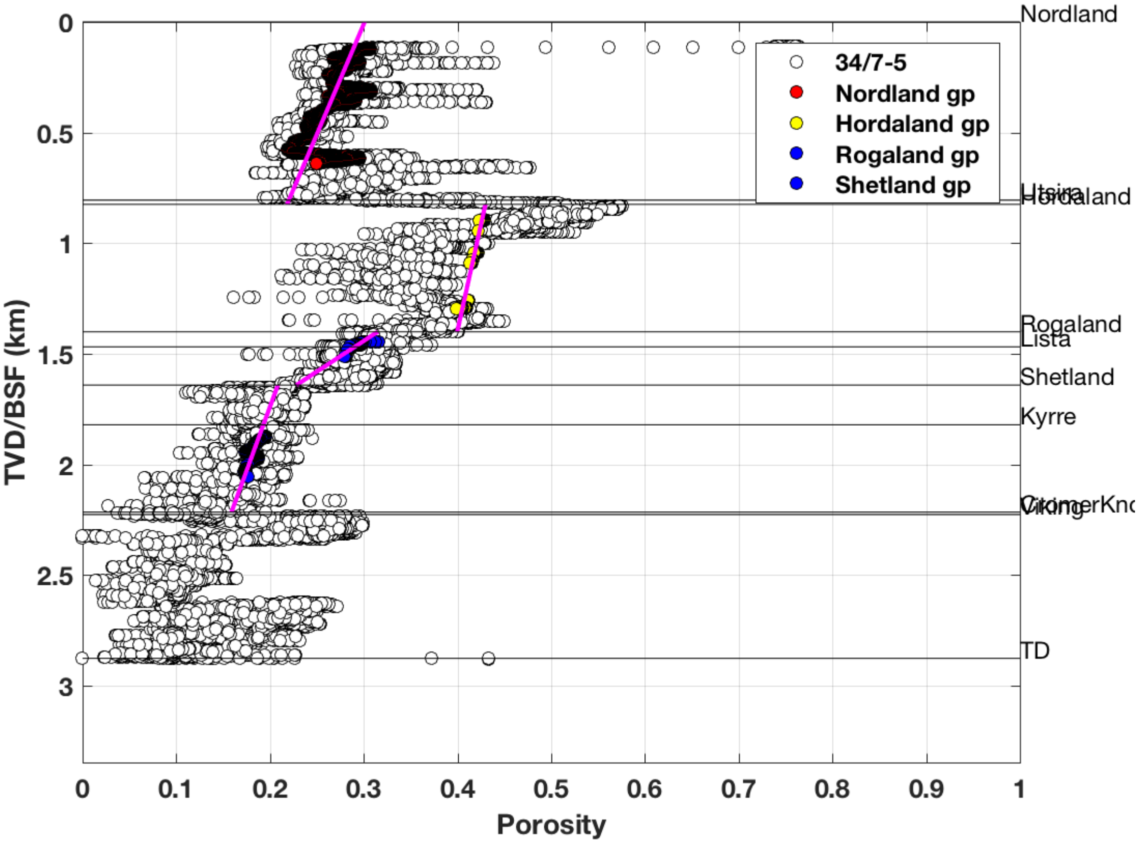

Figure 55 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

6608/10-3

Vp

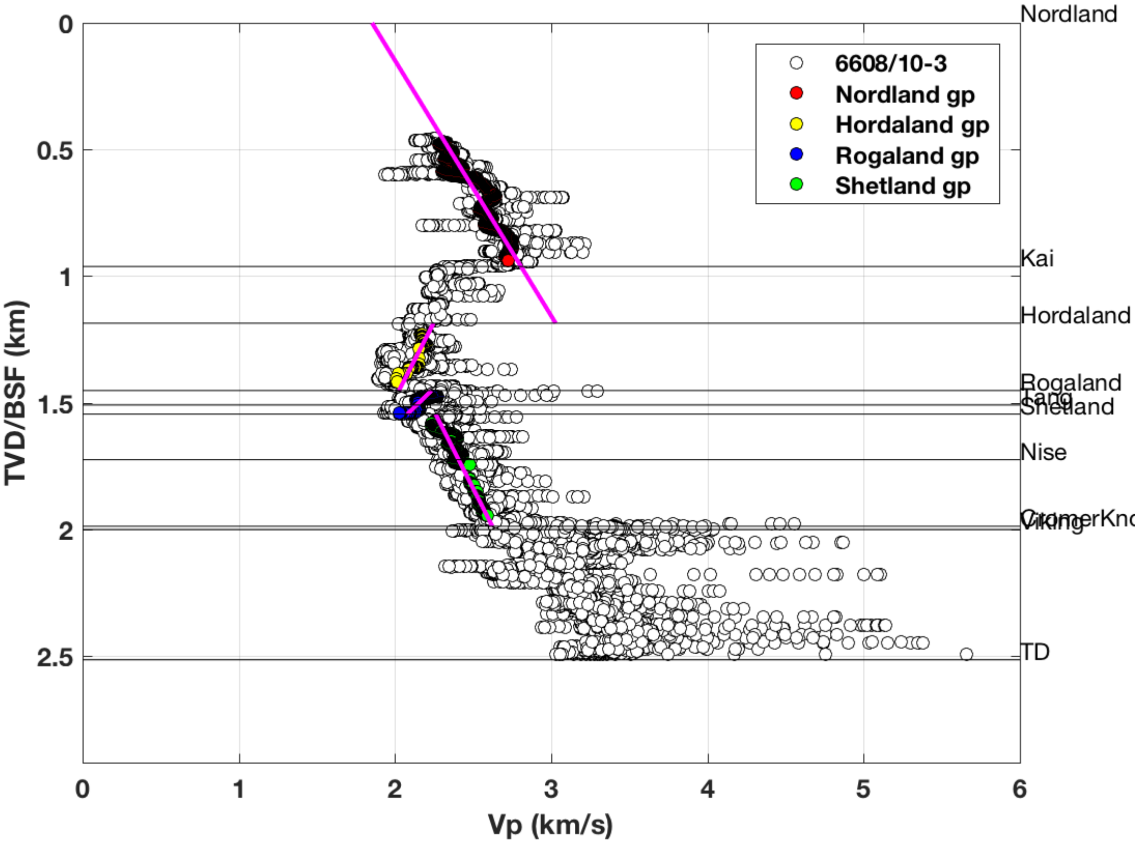

Figure 56 -

Vs

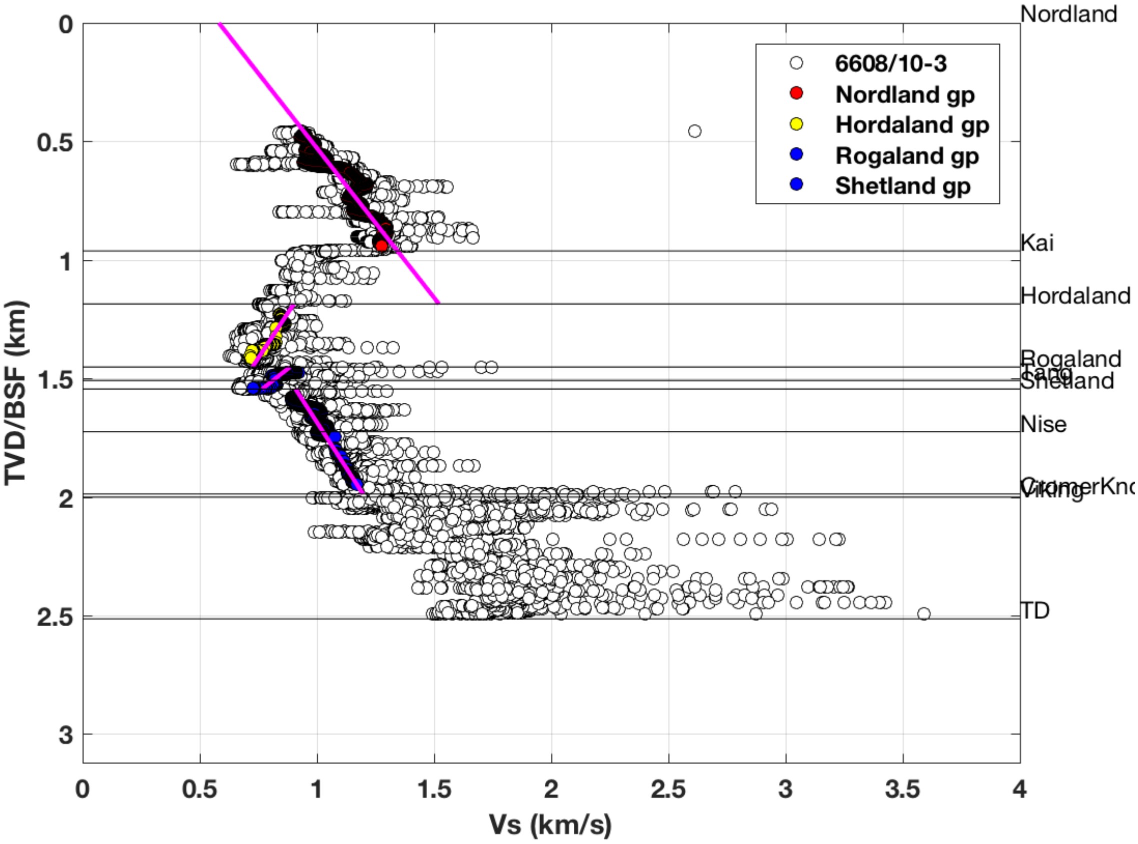

Figure 57 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Vp/Vs

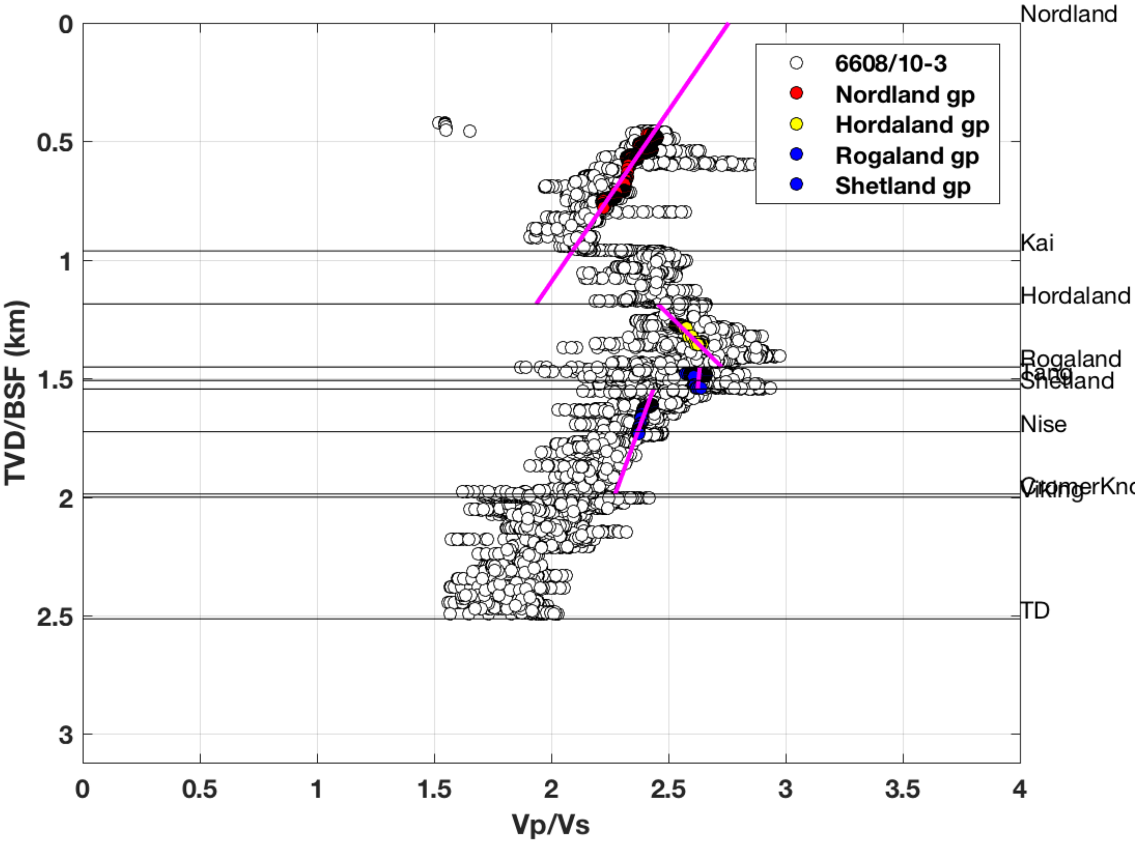

Figure 58 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Rhob

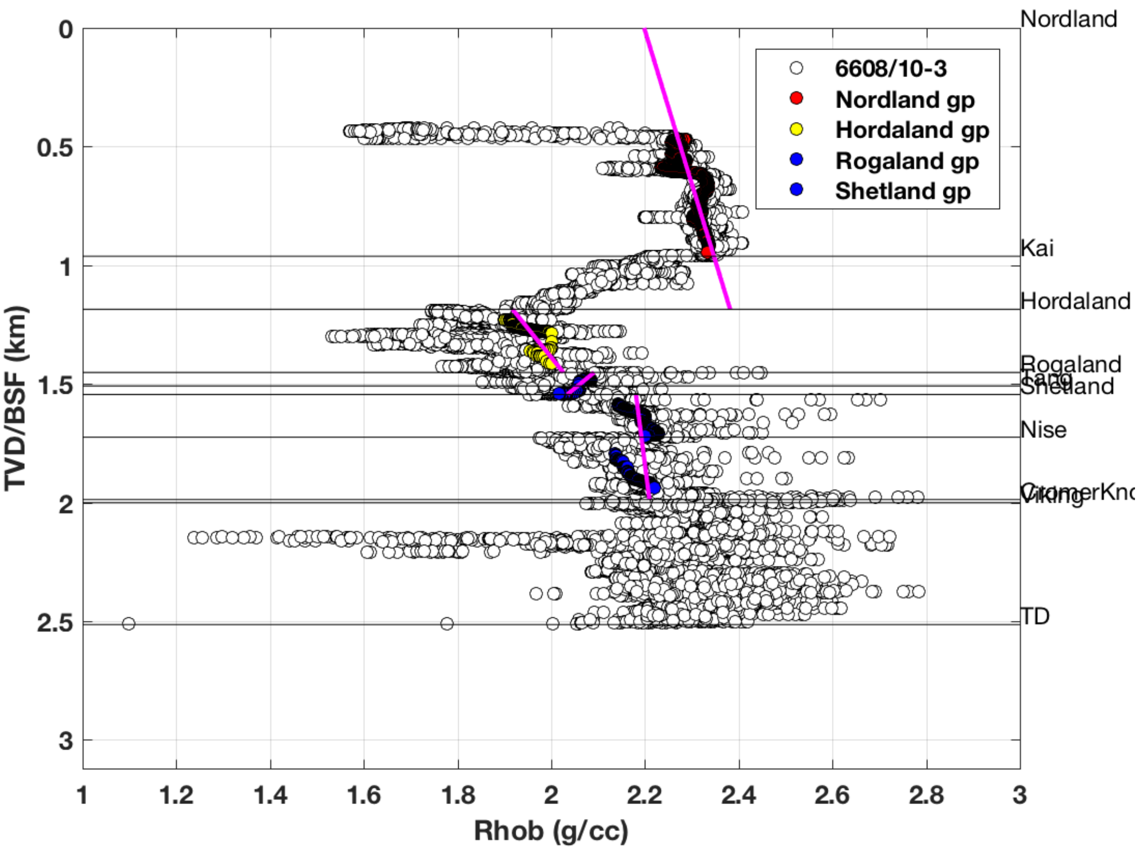

Figure 59 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Rdeep

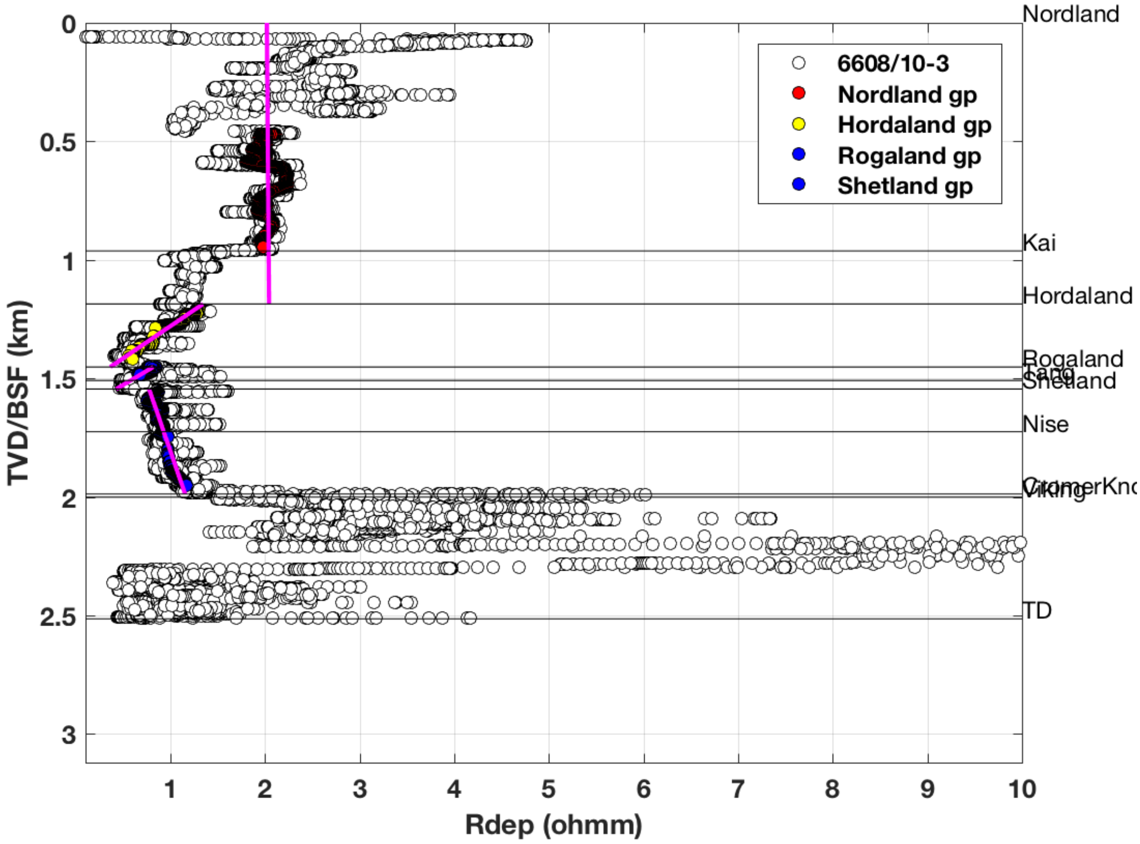

Figure 60 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Porosity

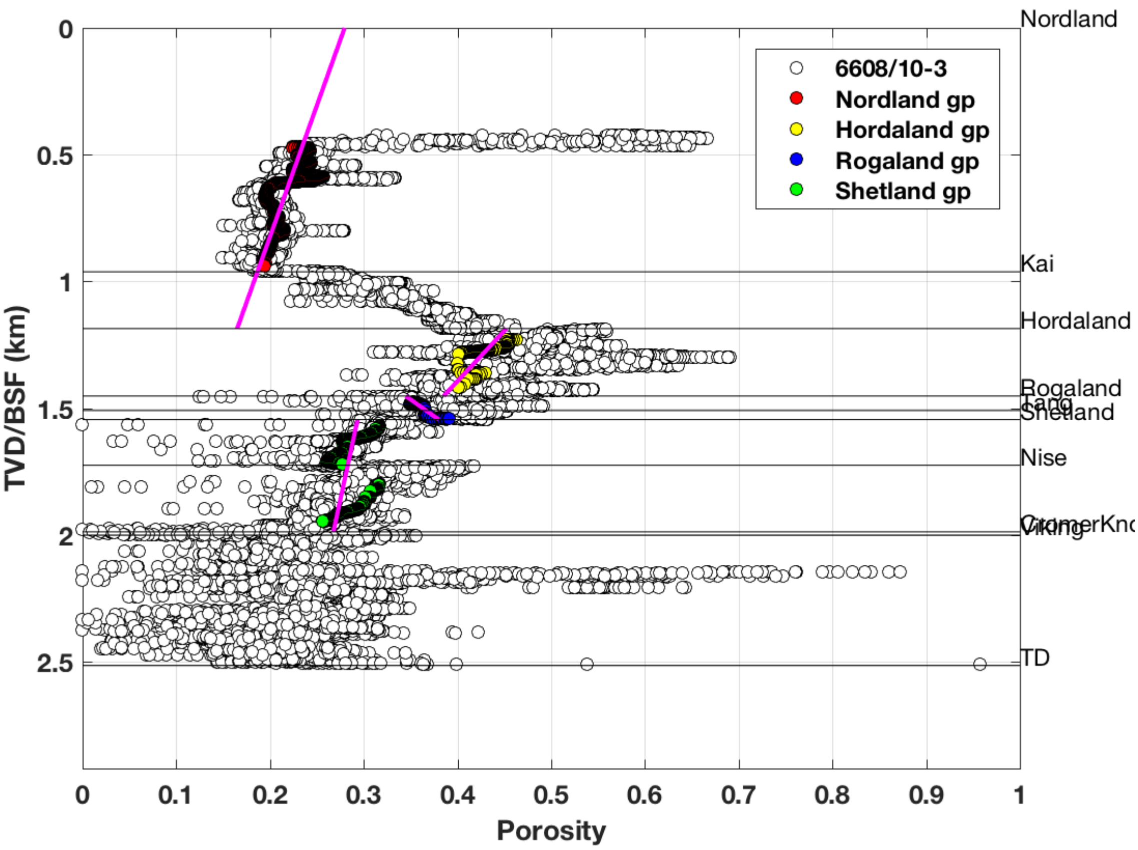

Figure 61 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

7216/11-1 S

Vp

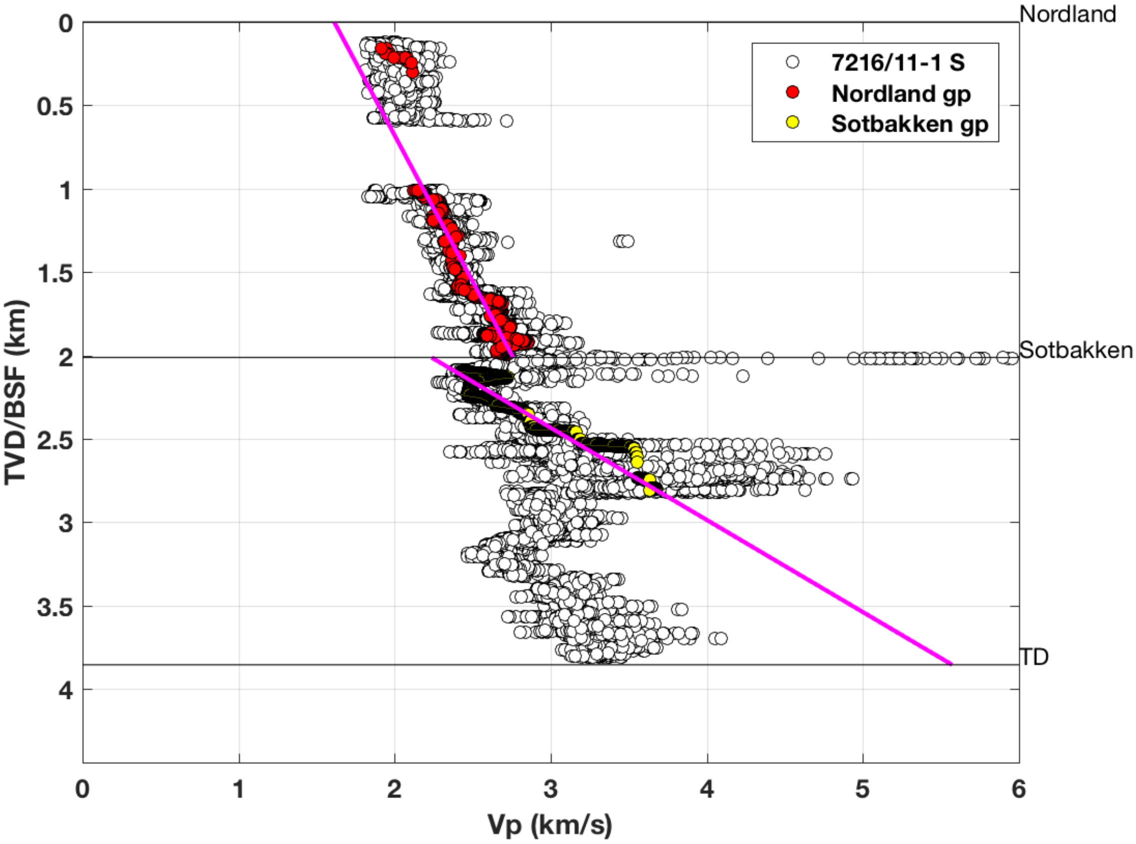

Figure 62 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Vs

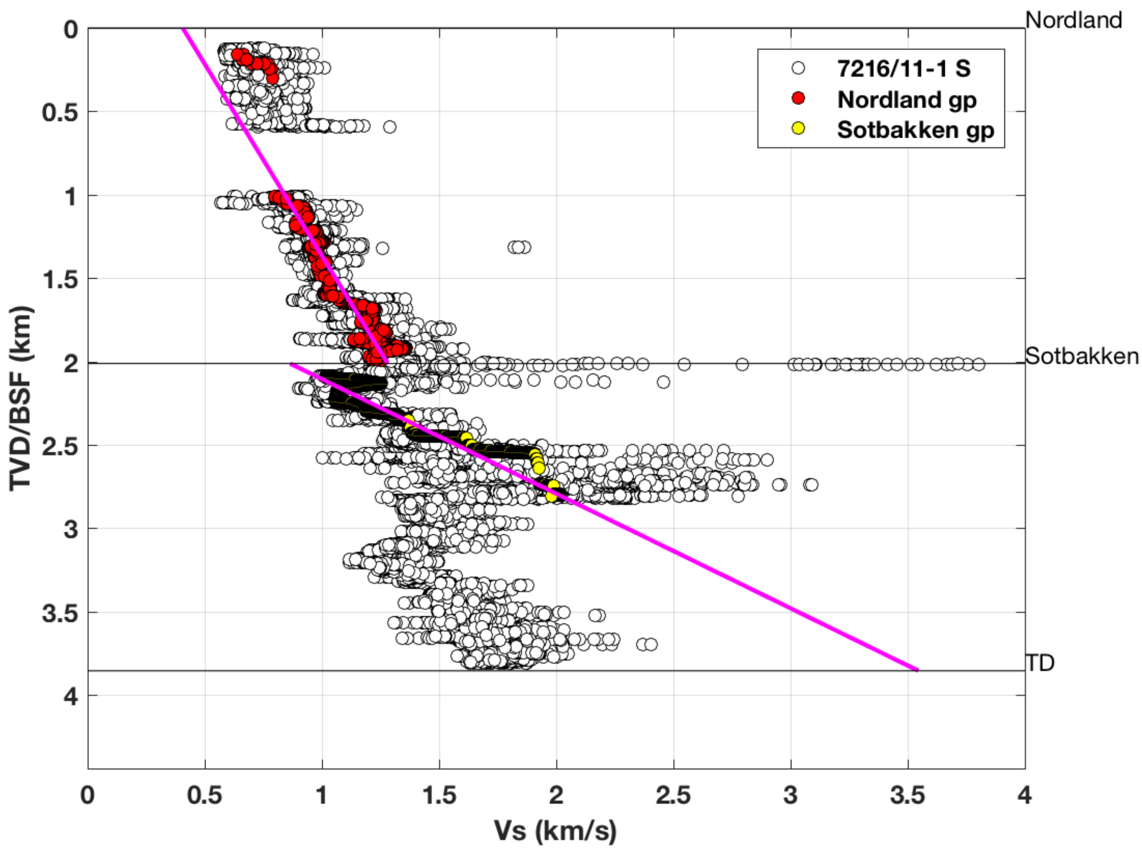

Figure 63 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Vp/Vs

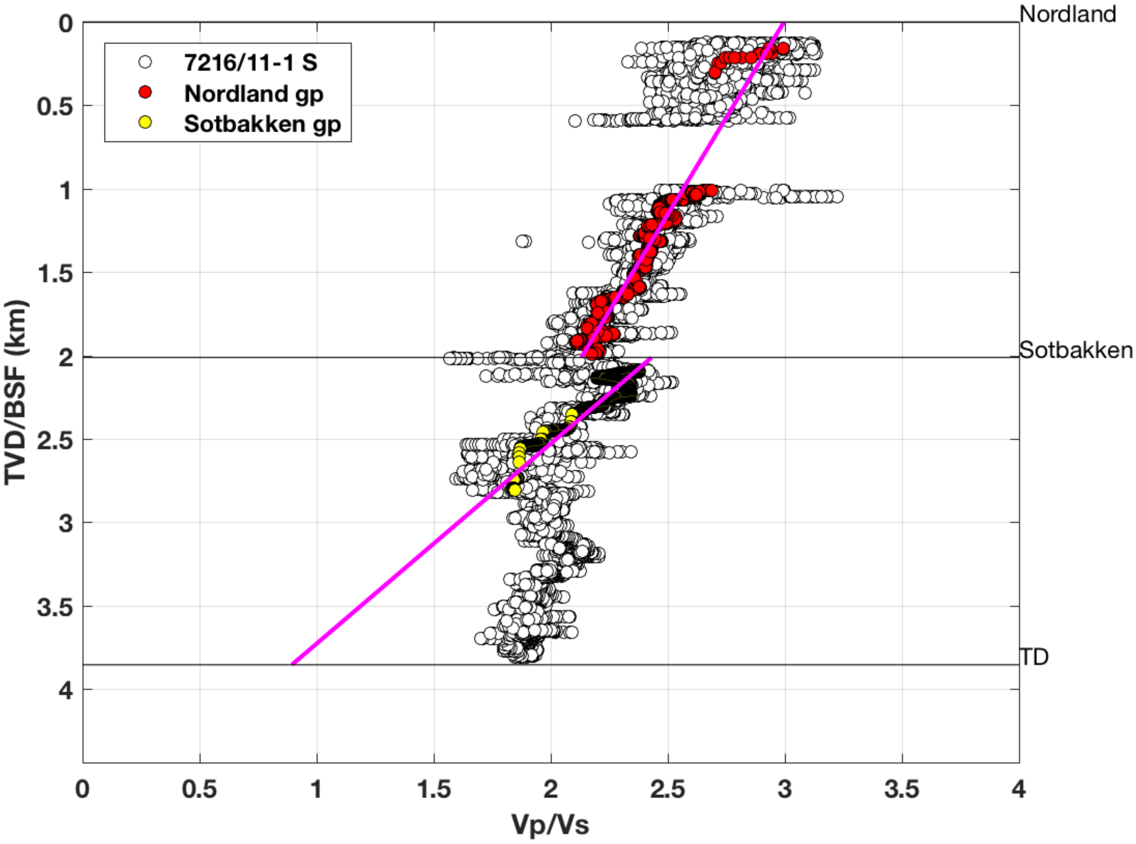

Figure 64 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Rhob

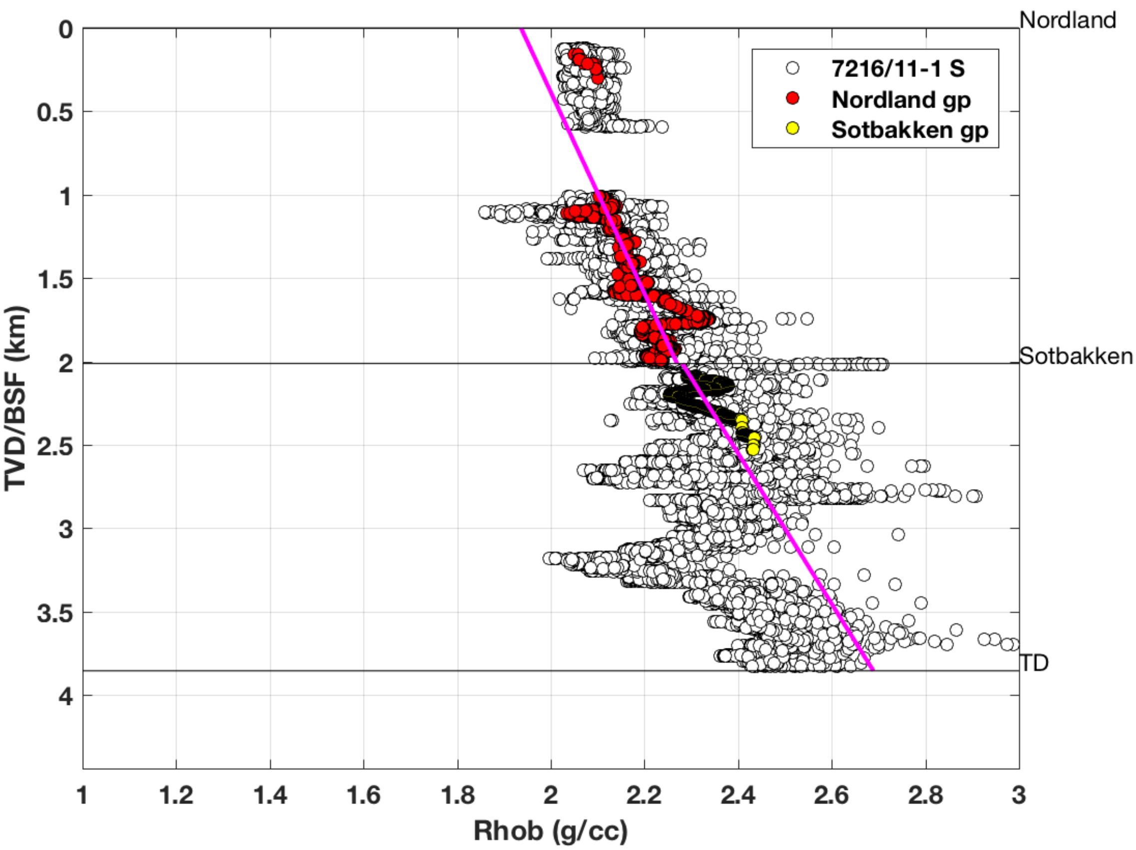

Figure 65 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Rdeep

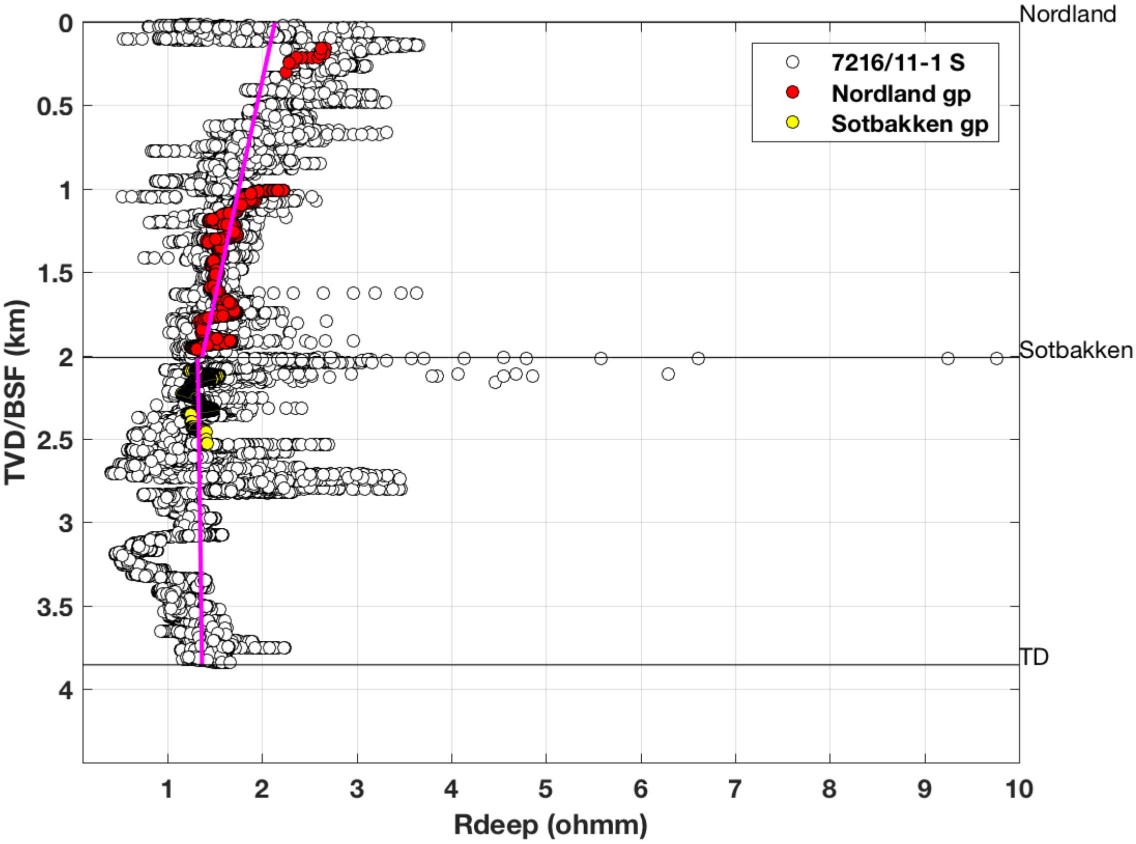

Figure 66 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Porosity

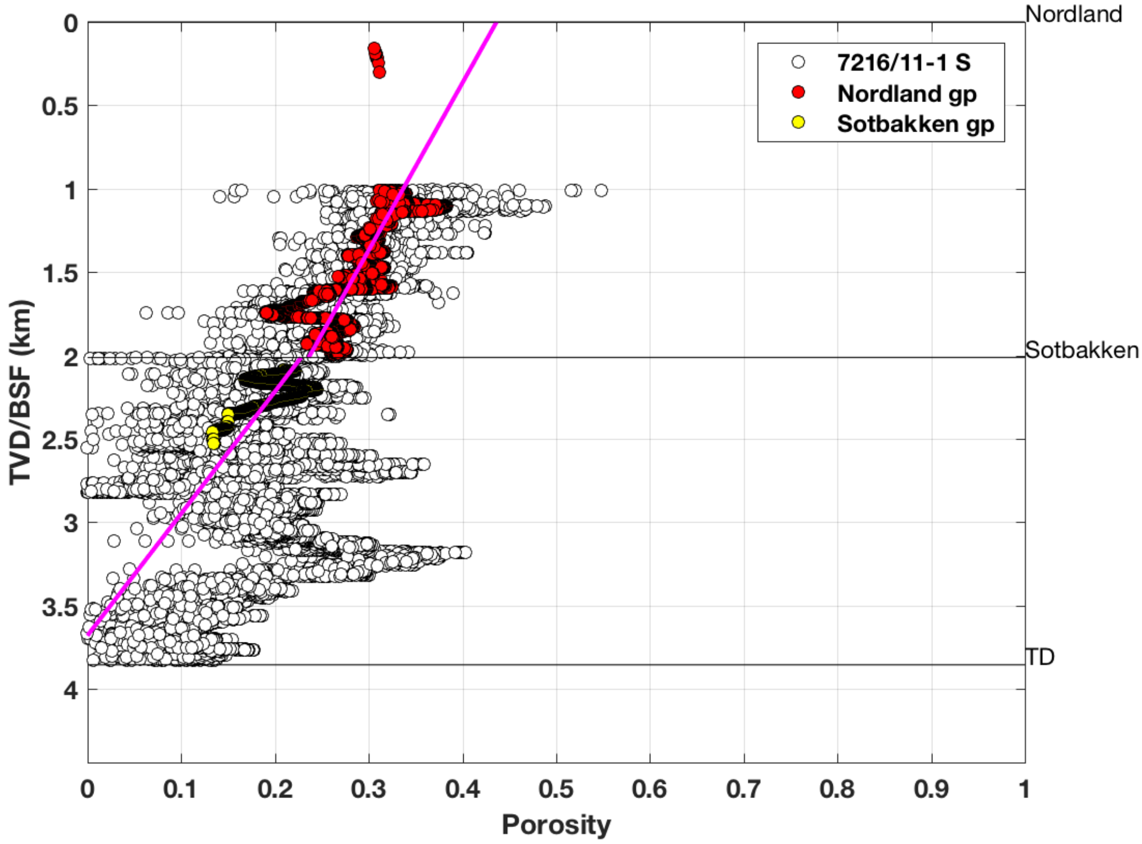

Figure 67 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

7117/9-1

Vp

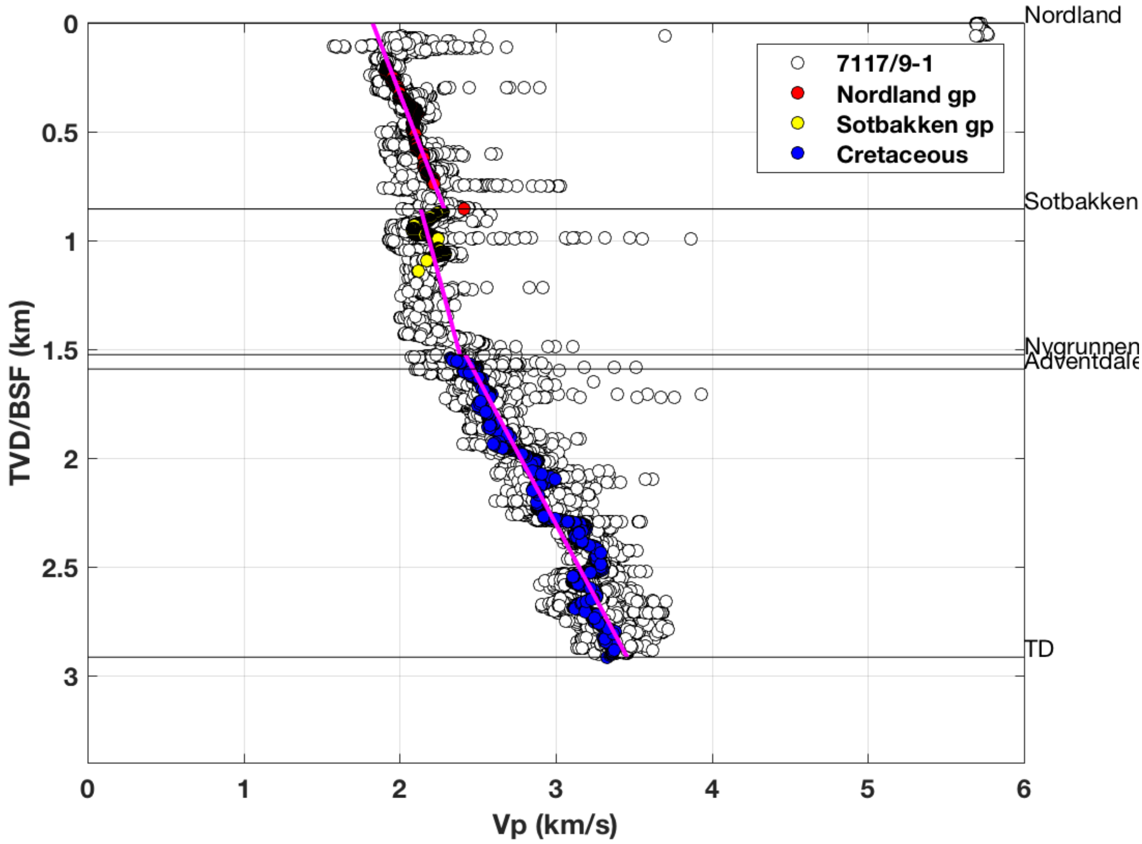

Figure 68 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Vs

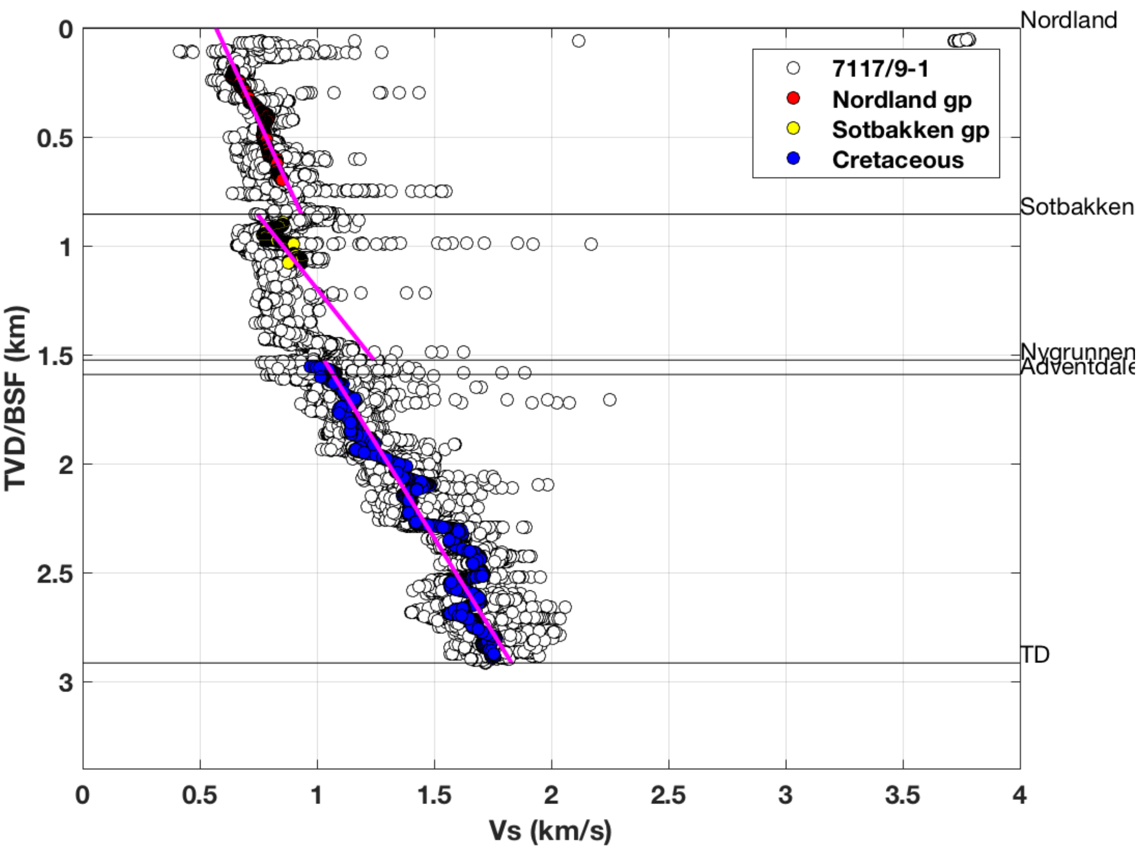

Figure 69 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Vp/Vs

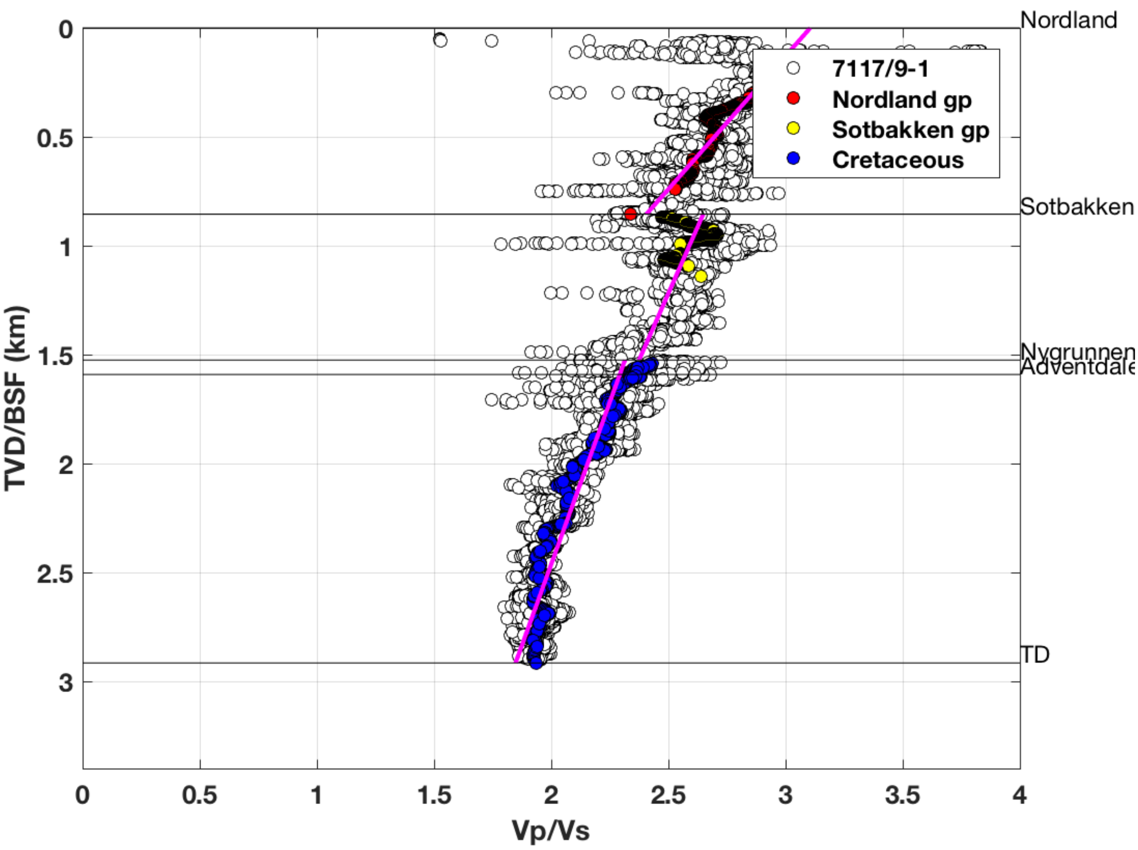

Figure 70 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Rhob

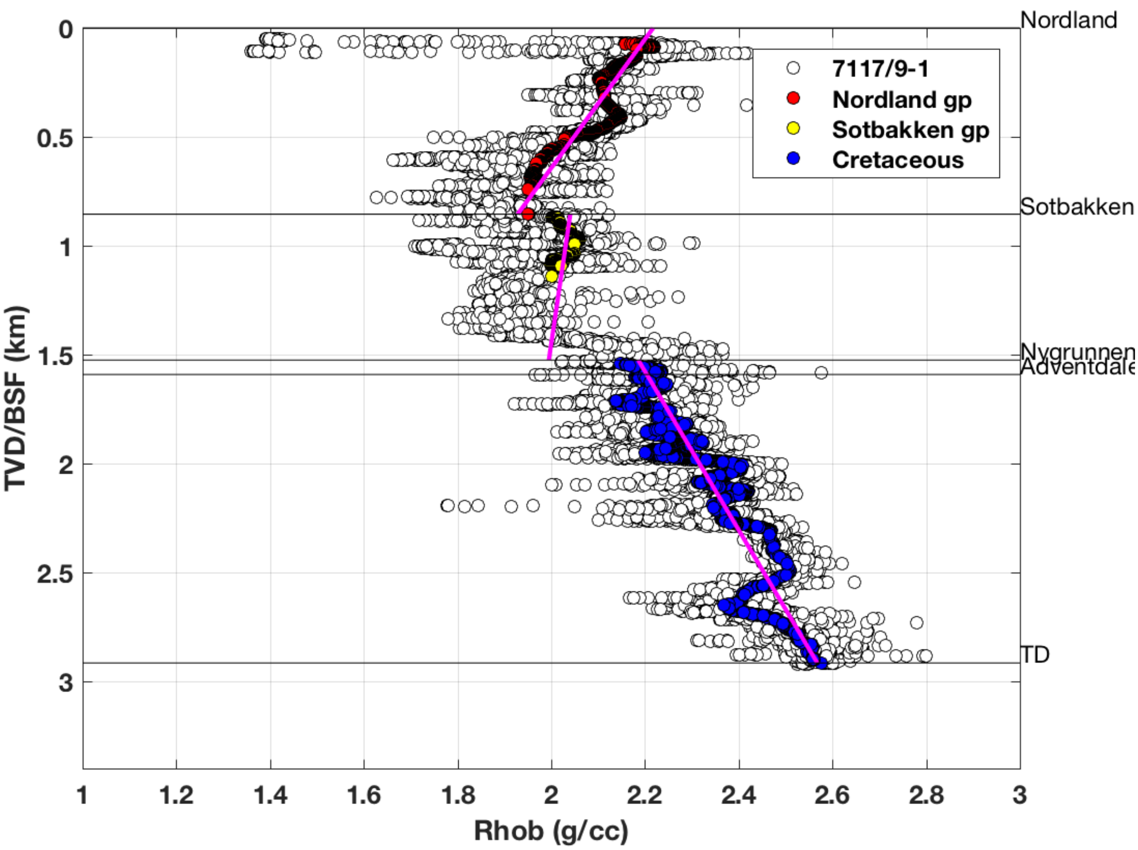

Figure 71 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Rdeep

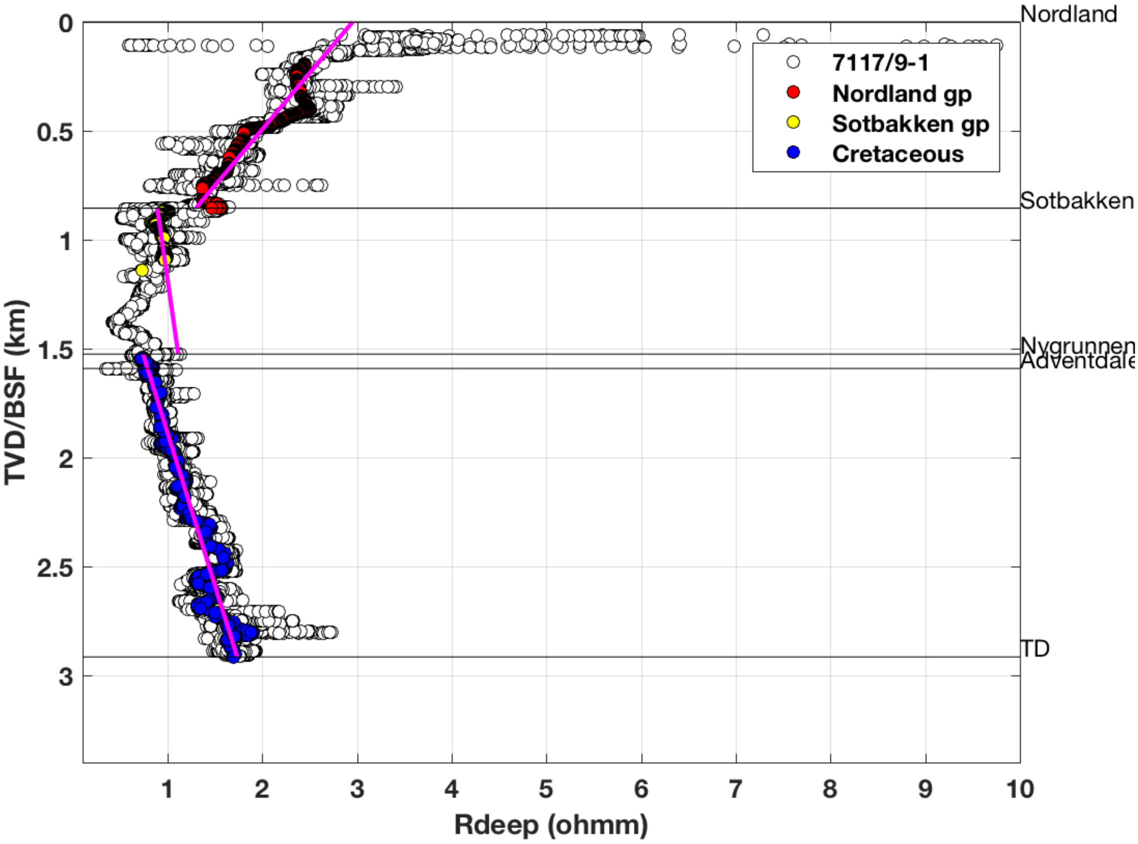

Figure 72 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Porosity

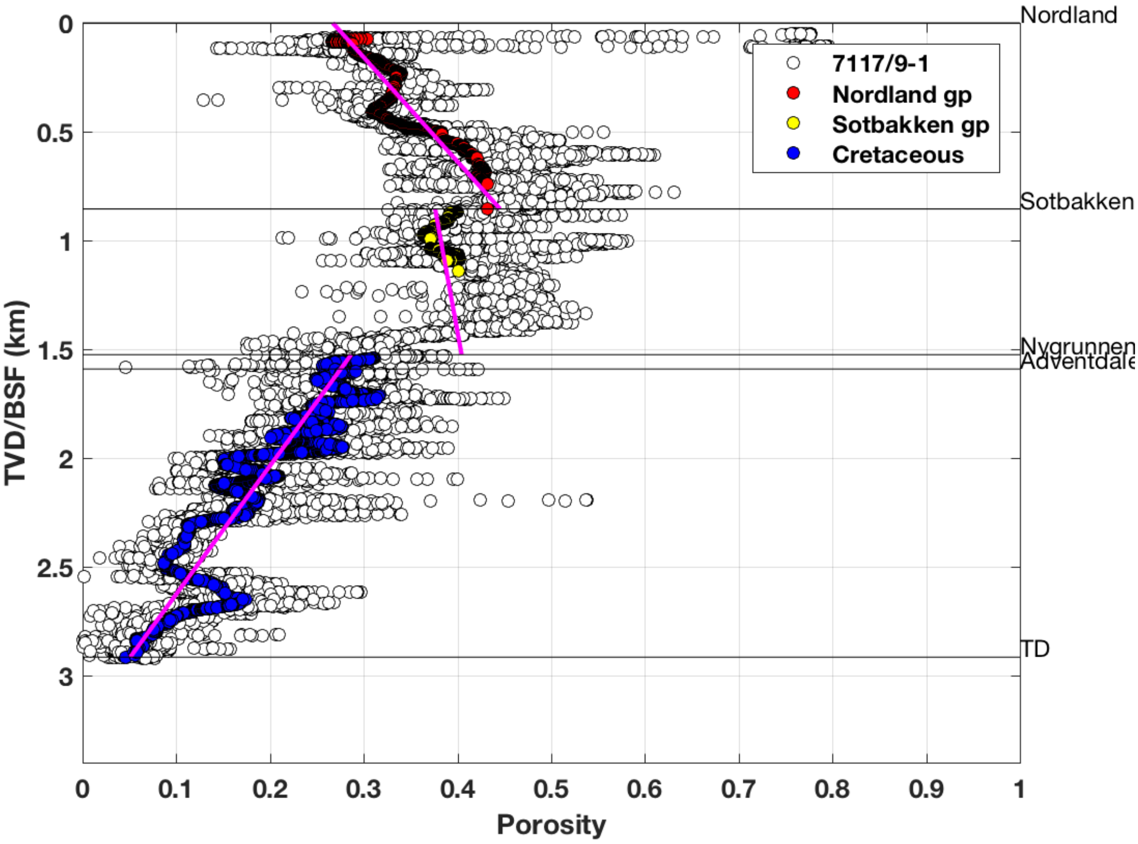

Figure 73 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

7120/5-1

Vp

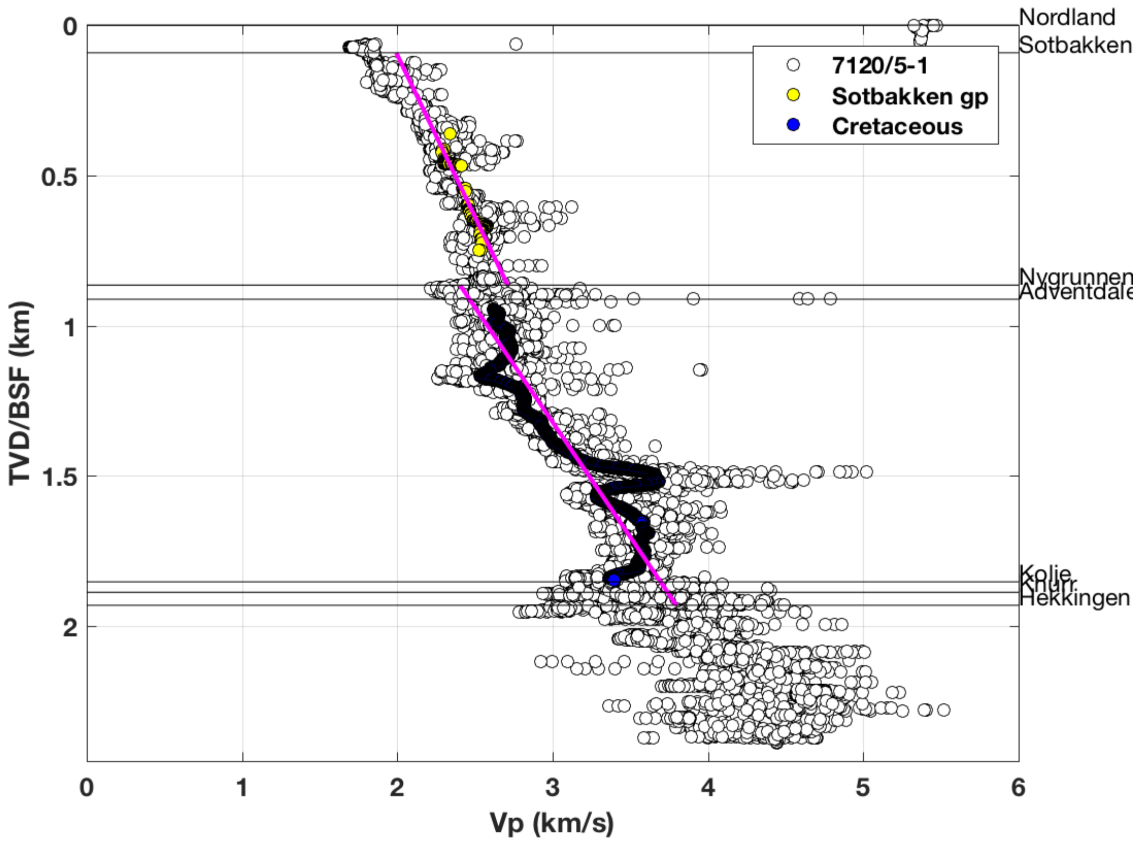

Figure 74 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Vs

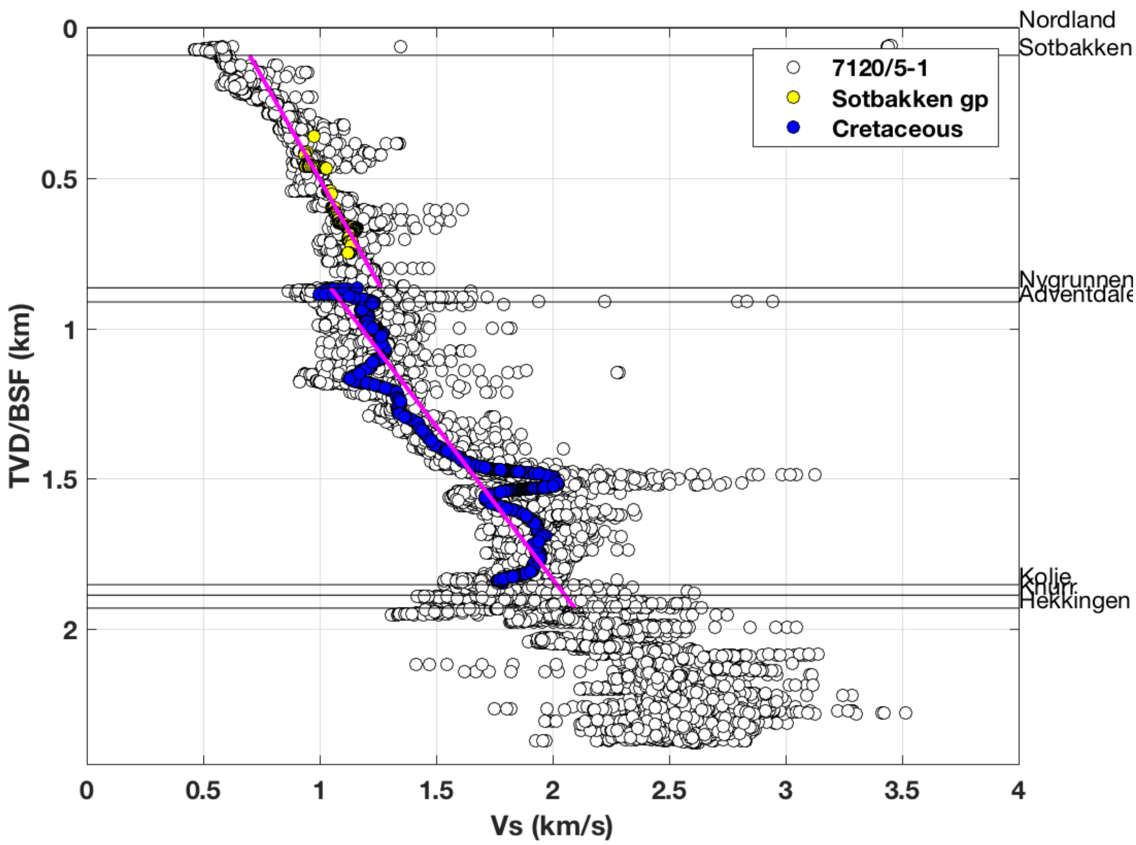

Figure 75 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Vp/Vs

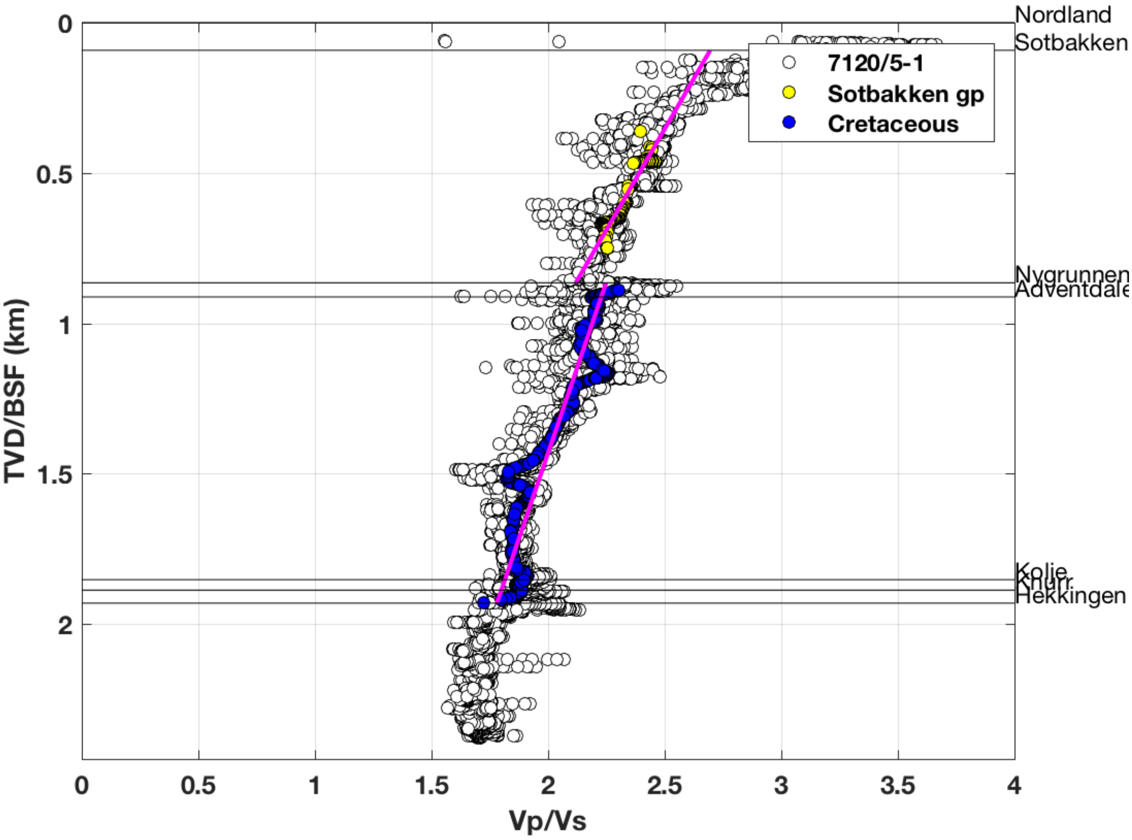

Figure 76 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Rhob

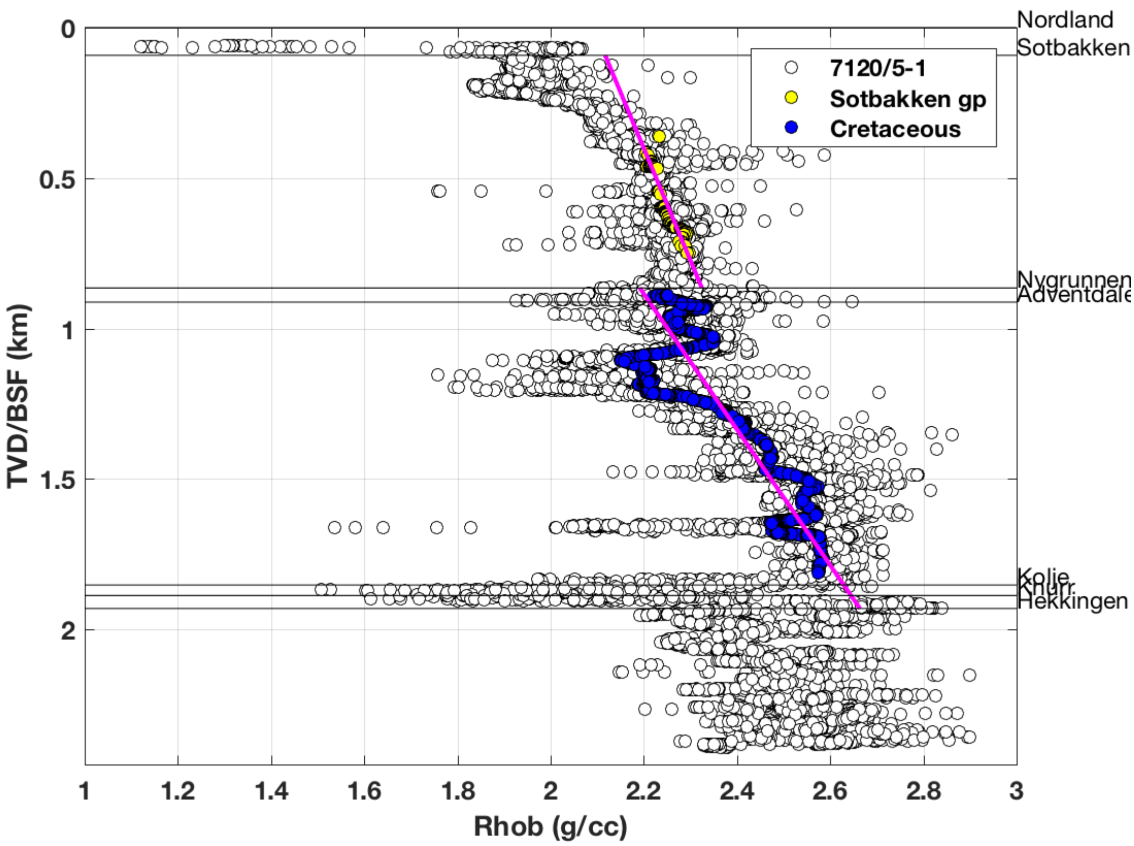

Figure 77 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Rdeep

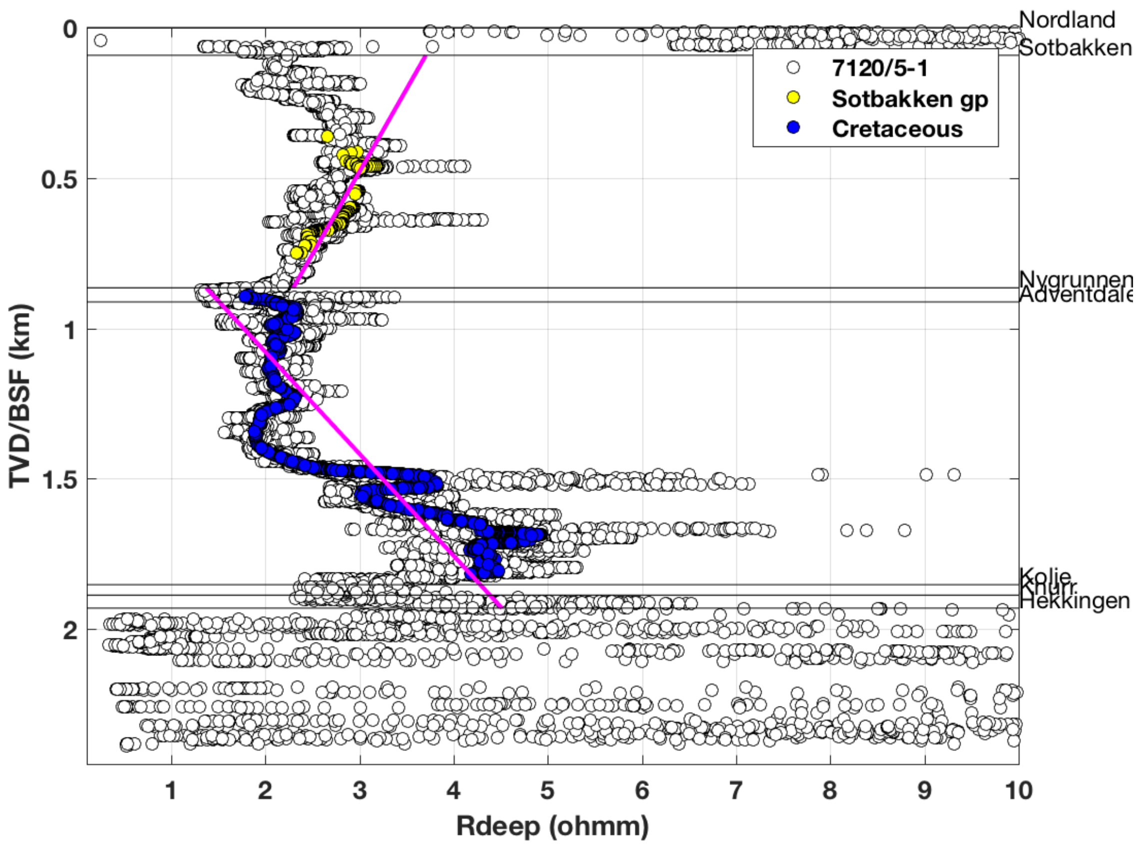

Figure 78 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Porosity

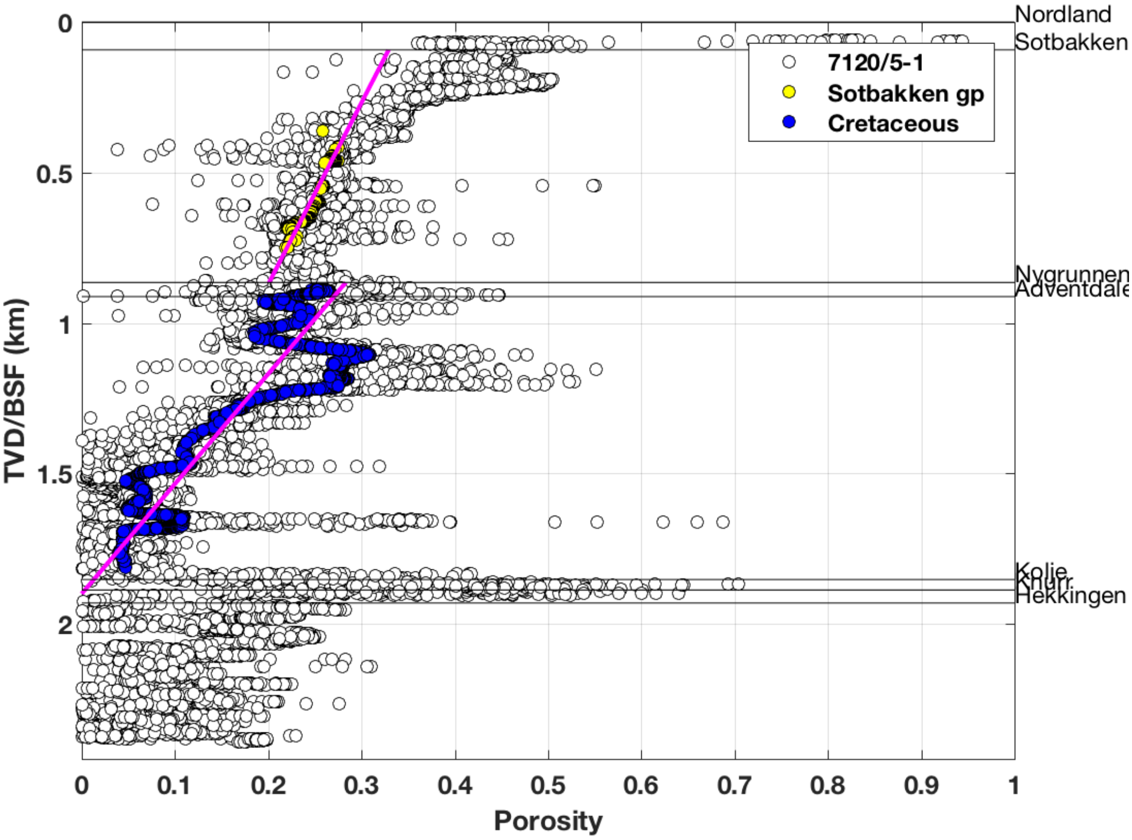

Figure 79 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

7121/4-1

Vp

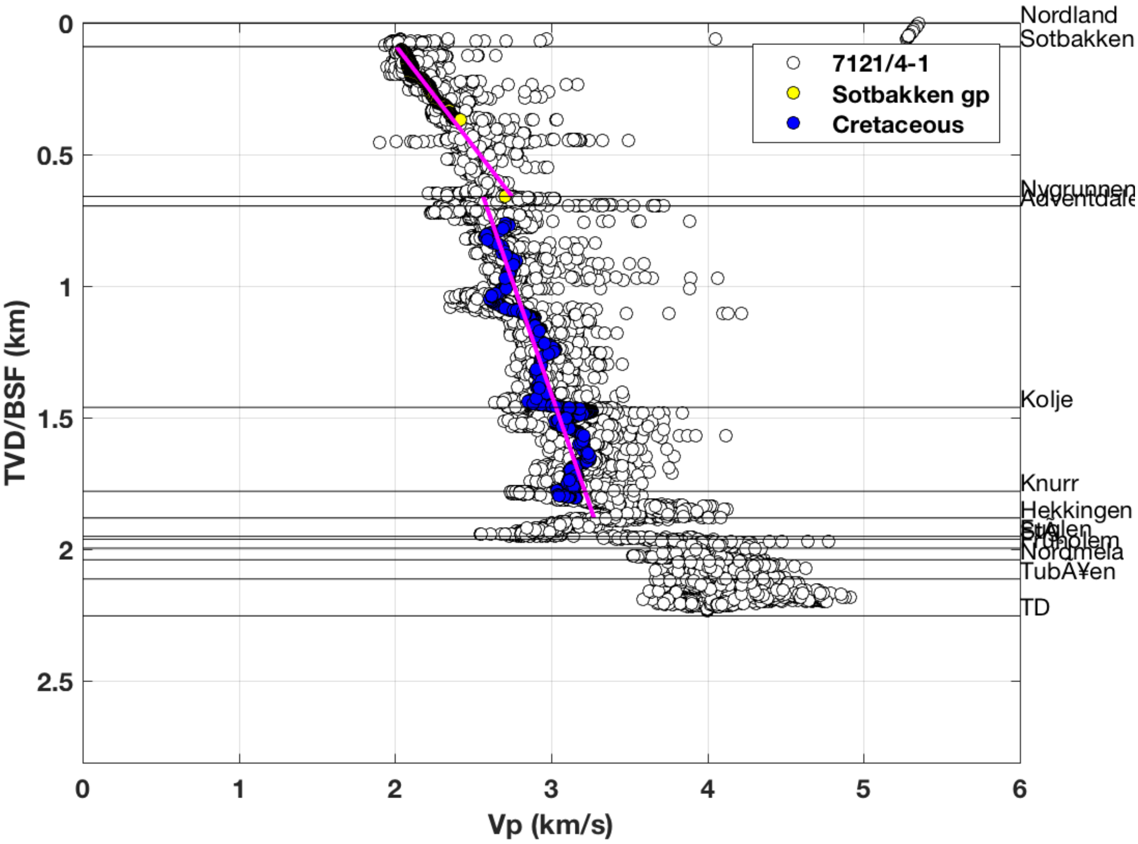

Figure 80 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Vs

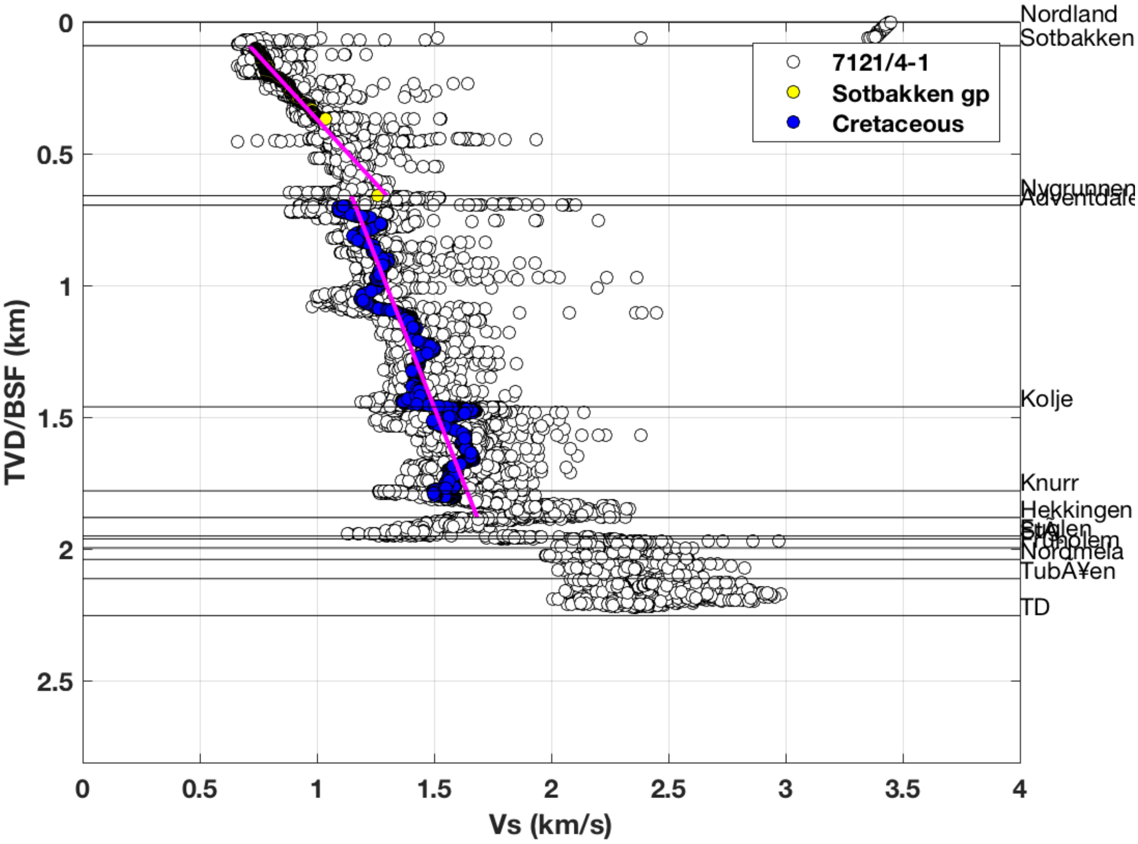

Figure 81 – Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Vp/Vs

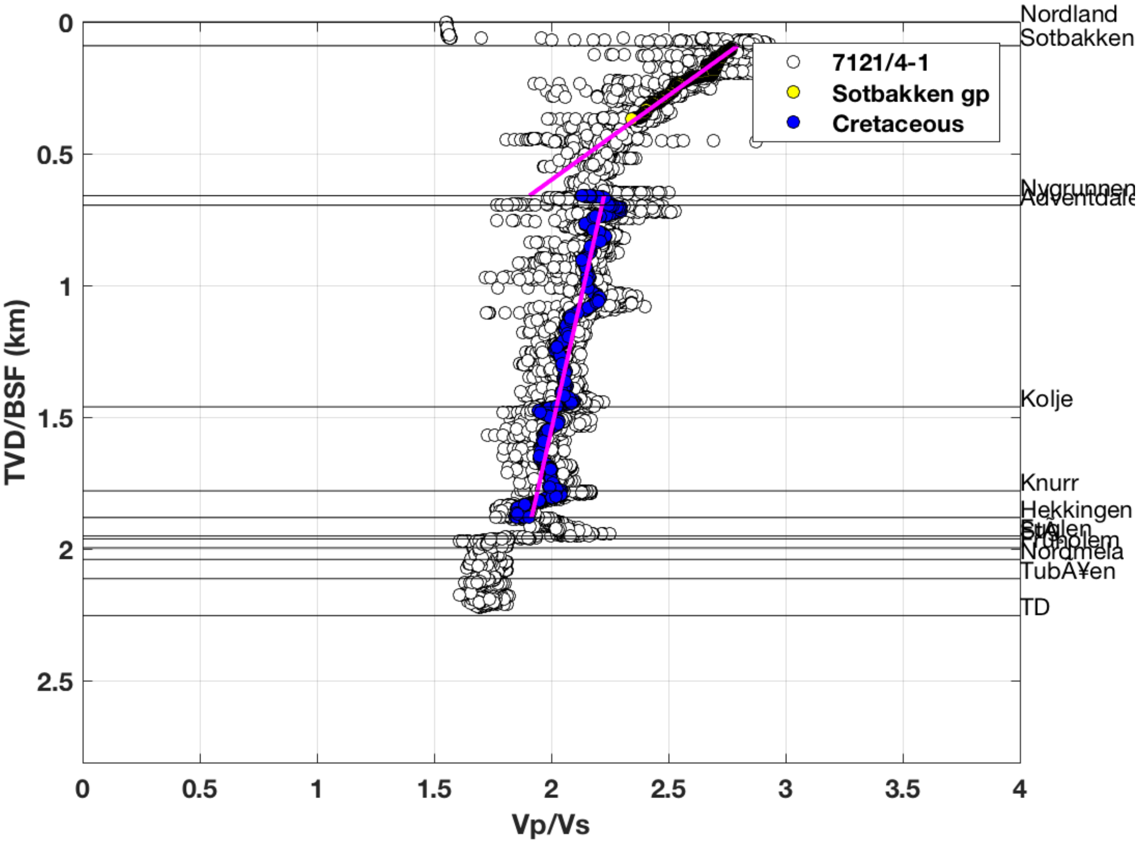

Figure 82 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Rhob

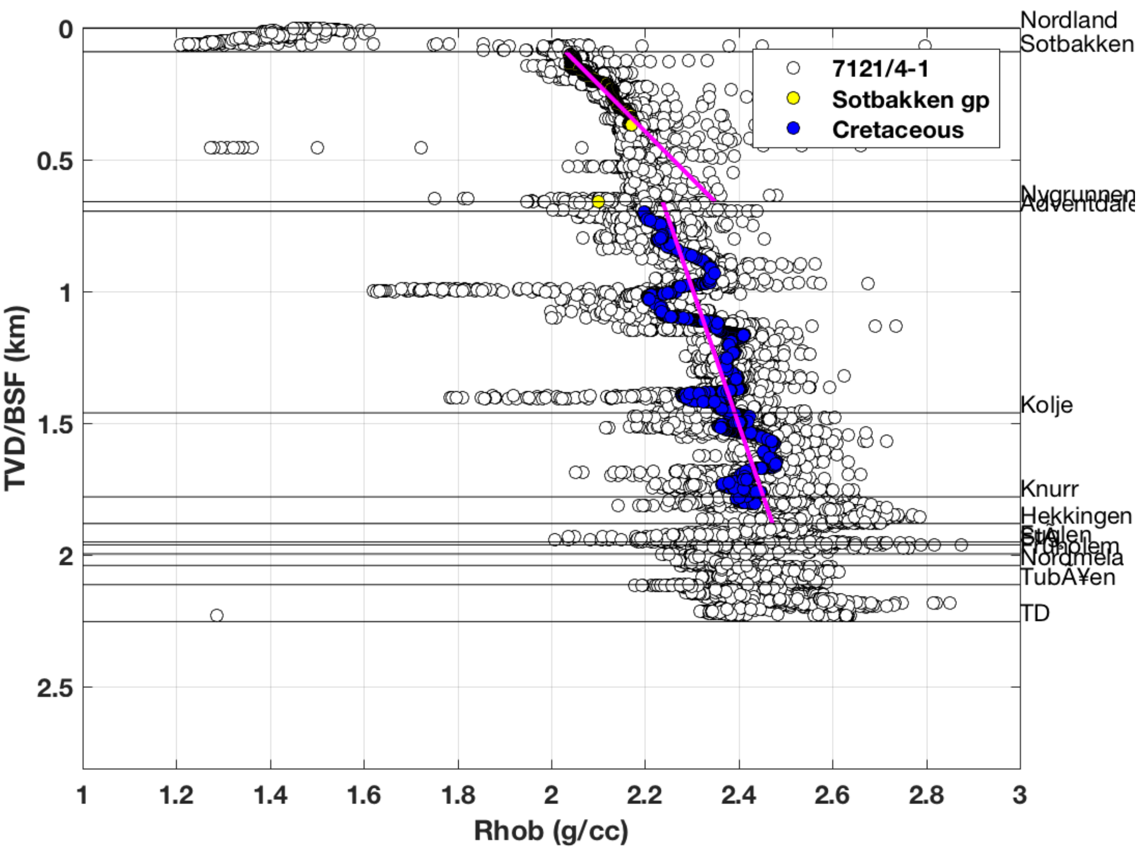

Figure 83 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Rdeep

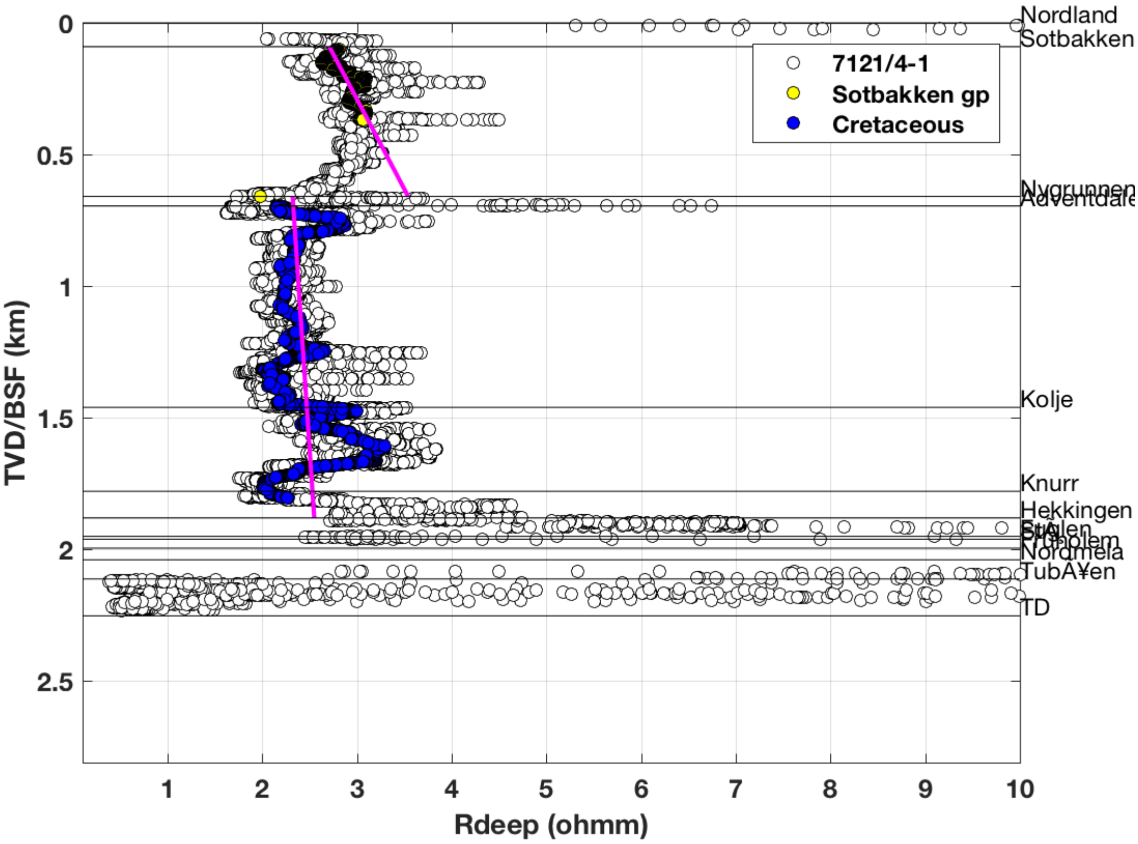

Figure 84 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.

Porosity

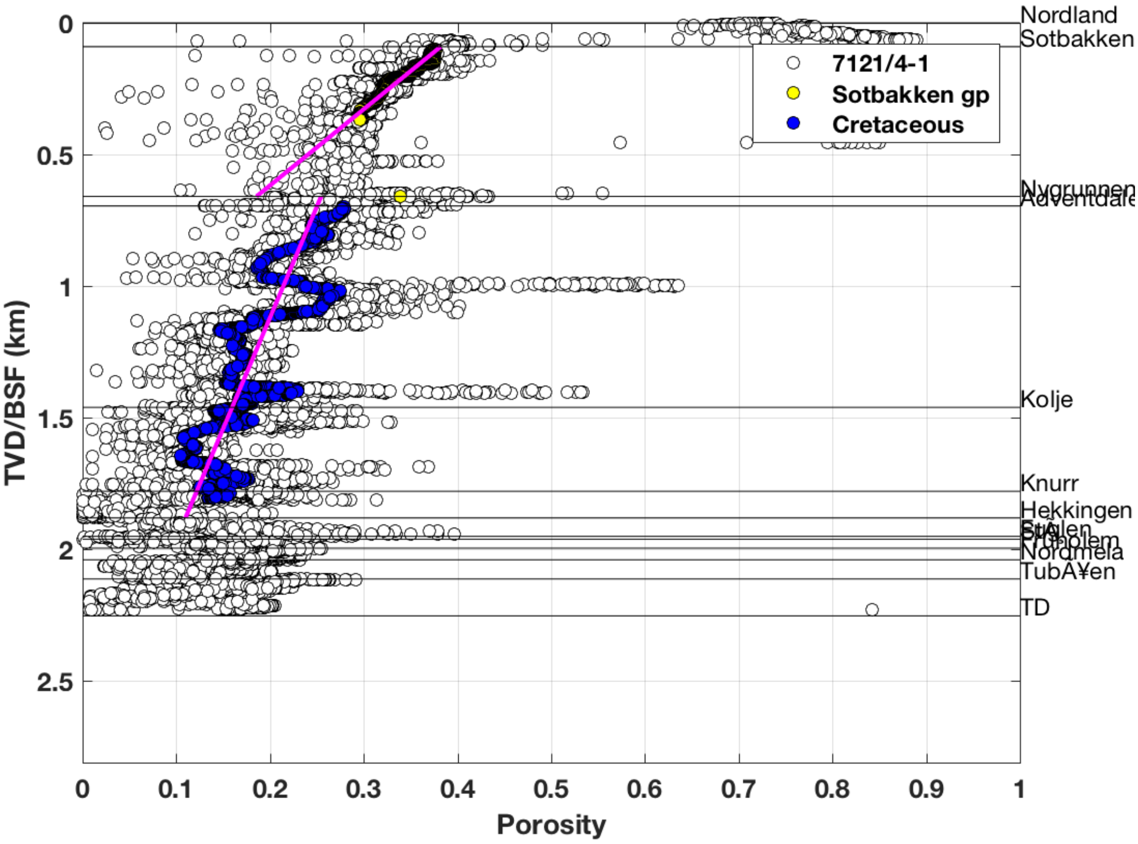

Figure 85 - Figure showing raw data (white dots with black border) vs. trend lines calculated using linear regression.