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Is it possible to estimate the magnitude of uplift and erosion by the use of check-shot data and average velocity?

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Abstract

This work investigates a new method in quantifying the magnitude of net erosion or net exhumation by using average velocity profiles derived from check-shot data. The fundamental principle is based on finding the same "average lithology" in both uplifted and not uplifted regions. Thus, if two large intervals are found, which have comparable average properties, then they can be used for net exhumation estimates despite consisting of composite lithology. Using a larger lithological interval and average velocity are considered to bear less uncertainty. An essential part of the method revolves around using similar velocity-depth gradients for the uplifted area and not uplifted area, which in turn is believed to be important for accurate net exhumation estimates.

The new methodology is applied on 7 wells in the Barents Sea, then compared to results from standard shale compaction trends using density and sonic well logs. The net exhumation estimates from average velocity are considerably lower than those of sonic (100m-750m less ~ average 450m less), and slightly lower than those of density (-150m-650m less ~ average 200m less). The high net exhumation estimates from the sonic logs might be due to overpressure mainly affecting the sonic log and not the density log. Average velocity might be robust with respect to overpressure, since its believed to correct for such effects when finding the same average lithology/acoustic properties. The check-shot method is also advantageous to use when a lithology is missing/thin since it does not utilize a specific rock type, but instead it uses a larger lithological interval. The methods show steady increase in net exhumation from SW to NE, but the sonic/density show more spiky results possibly due to the smaller depth interval being used, along with varied density/velocity-depth gradients and uncertainty related to lithological control. The main uncertainty for the check-shot method is possibly related to establishing the relevant parameters for the reference trend, and understanding the validity of some assumptions. More research should be done to test the method and the underlying principles. However, if the lower net exhumation estimates are more correct than the those from sonic/density; areas earlier thought to be unfavorable could be reconsidered for further exploration. This work represents an exciting and important front for further work, as using average velocity has not been common to use, and it has widespread availability in seismic data.

Sammendrag

Dette arbeidet undersøker en ny metode for å kvantifisere størrelsen på netto erosjon ved bruk av gjennomsnittshastighet fra «check-shot». Det fundamentale prinsippet er basert på å finne samme «gjennomsnittslitologi» i både oppløfta og ikke oppløfta områder. Hvis to slike store intervaller kan bli funnet, og som har samme gjennomsnittlige egenskaper, da kan de bli brukt for å estimere netto erosjon til tross for å bestå av kompositt litologi. Det å bruke et større litologisk intervall samt gjennomsnittshastighet er betraktet for å bære mindre usikkerhet. En essensiell del av metoden går ut på å bruke cirka samme hastighets-dyp gradienter for både det oppløfta og ikke oppløfta området, da dette trolig er viktig for nøyaktige netto erosjons estimater.

Den nye metoden ble anvendt på 7 brønner i Barentshavet, deretter sammenlignet med resultater fra leire kompaksjons trender ved bruk av hastighet og tetthets logger fra brønndata. Netto erosjons estimatene er vesentlig lavere enn dem fra hastighetslogger (100m-750m mindre ~ gjennomsnitt 450m lavere). og litt lavere enn dem fra tetthetslogger (-150m-650m mindre ~ gjennomsnitt 200m lavere). De høye netto erosjons estimatene kan være et resultat av overtrykk, noe som muligens påvirker hastighetsloggen mer enn tetthetsloggen. Den nye metoden er muligens robust mot overtrykk, siden den trolig korrigerer for slike effekter når man finner den samme gjennomsnittslitologien/akustiske egenskapene. Den nye metoden har også den fordelen når enkelte formasjoner er tynne eller mangler, siden den ikke utnytter en spesifikk litologi, men heller bruker et større litologisk intervall. Alle metodene viser gjevn økning i netto erosjon fra sørvest til nordøst, men hastighetslogger og tetthetslogger viser mer spredte resultat, muligens som en følge av det mindre intervallet som blir brukt, varierte tetthet/hastighet-dyp gradienter. samt usikkerhet assosiert med litologisk kontroll. Den største usikkerheten assosiert med check-shot metoden er trolig relatert til å etablere de relevante parameterne for referanse trenden, samt å forstå validiteten av noen antakelser. Mer forskning bør gjøres for å teste metoden og de underliggende prinsippene. Dersom de lavere oppløfts estimatene er mer korrekte enn dem fra hastighet/tetthet, da impliserer dette at tidligere ikke attraktive områder kan bli revurdert for videre petroleumsleting. Dette arbeidet representer en spennende og viktig front for videre arbeid, delvis fordi gjennomsnittshastighet ikke har blitt mye brukt, samt at det finnes mye av det i seismiske data.

Acknowledgements

I would like to thank my supervisor Kenneth Duffaut for his guidance, data provision and dedication to this project. It has been an exciting journey in unexplored territory with a lot of interesting discussions. I also would like to thank Per Avseth for relevant suggestions during meetings. Thanks to NTNU, NPD and Schlumberger for all the used resources.

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1. Introduction

Uplift and erosion of sedimentary rocks have been studied offshore Norway through several methods, commonly in the Barents Sea. When looking at the magnitude of net exhumation estimates, they show large uncertainties for different methods (Baig et al., 2016, Henriksen et al., 2011a, Corcoran and Doré, 2005, Hansen, 1996). This could be considered the challenge of today; the large variations in net exhumation between methods and uncertainty related to the individual methods. Numerous studies have been carried out to estimate net exhumation. Some studies utilize compaction trends such as porosity, bulk density and interval velocity. Others use temperature data like vitrinite reflectance and apatite fission track analysis, whereas large scale approaches use basin analysis/mass balance studies, or stratigraphic analysis where there is section/seismic correlation (Baig et al., 2016, Henriksen et al., 2011a, Corcoran and Doré, 2005, Hansen, 1996, Holliday, 1993, Richardsen et al., 1993, Nyland et al., 1992). The difference in net exhumation still exceed over 500m in several areas even when based on single methods. (Henriksen et al., 2011a). Most methods are based upon well data, which could be considered a type of point data as opposed to for example mass balance studies or seismic studies (Corcoran and Doré, 2005). In general, more well data decreases the uncertainty and the standard deviations becomes narrower with more methods. From all the different methods, net exhumation estimates from the shale compaction method seems to show the lowest standard deviation. (Henriksen et al., 2011a).

Many basins have been severely uplifted through time, and coincides with the fact that most petroleum reserves are located onshore (Henriksen et al., 2011a). Many studies (e.g Baig et al., 2016, Henriksen et al., 2011a, Storvoll et al., 2005, Nyland et al., 1992) discuss especially the Barents Sea, as it has been well established that there have been severe uplift and subsequent erosion during the Cenozoic removing mostly Neogene and Paleogene sediments. This has mainly affected petroleum systems to give poorer properties than expected prior to knowing about the uplift and erosion. Since higher level of diagenesis is generally associated with deeper burial, this will affect the reservoir properties when uplifted as the diagenesis is considered mainly irreversible. For example, net to gross and porosity is well established to become lower for more deeply buried/compacted rocks, and preserved when uplifted (e.g Corcoran and Doré, 2005). Other effects from uplift and erosion are hydrocarbon leakage from traps due to gas expansion from pressure release (Nyland et al., 1992), cooler source rocks, changed oil/gas migration routes, breached seal capacity due to fractures, enhanced reservoirs due to fractures, and other structural changes (Corcoran and Doré, 2005, Doré and Jensen, 1996). Depending on the situation, net exhumation can thus both be positive and negative regarding hydrocarbon potential. The quest of quantitative exhumation estimates is thus to compare properties in not uplifted regions and uplifted regions, and to establish a link relating prospectivity to the variation in net exhumation estimates. Knowing the net exhumation also provides better understanding of the surrounding petroleum system, and helps to understand the overall geological history more accurately. This could help to maximize petroleum recovery/economy and reduce associated risks (Corcoran and Doré, 2005).

The focus of this work is the implementation of a new methodology in quantifying the magnitude of net exhumation by using compaction data from wells. It is based upon the use of average velocity derived from check-shot data and several lithologies combined, as opposed to one specific lithology. The use of average velocity has until now not been used because of the general agreement of having to choose specific lithology and not composite lithology. Normally net exhumation has been estimated by well-established standard shale compaction methods, based on sonic and density well logs. Those methods have the fundamental difficulty in selecting similar lithology in the uplifted and not uplifted area, along with having enough reliable data. This similar lithology might be thin or absent in some areas, contain stringers of different lithology, and have overpressure which is hard to quantify; Standard methodologies might therefore contain a lot of uncertainty (Corcoran and Doré, 2005). However, the main concept of using average velocity from check-shot data is the robustness associated with the larger scale and the accumulative definition of average velocity. It's therefore less affected by thin abnormal lithology, and sees the bigger picture. In addition, after all, the whole rock column and not just a specific lithology is being uplifted, and could therefore be used for net exhumation studies.

The work investigates how the new method fits among existing compaction methods (density/sonic) to quantitatively estimate the magnitude of net exhumation. Thus, timing of net exhumation will not be investigated. It is studied by creating reference trends from wells in the North-Sea/not uplifted parts in the Barents Sea, and compared with 7 uplifted wells in the Barents Sea. An additional goal is to constrain, understand and limit uncertainty relating to net exhumation estimates. This accounts for both standard methods and the new proposed methodology.

2. Background

2.1 Compaction and diagenesis of sedimentary rocks

It's important to know about compaction and diagenesis of sedimentary rocks because the methods used to measure the magnitude of net exhumation in this study utilizes such compaction properties. It's also important to understand the proxies for compaction (density/velocity) which are being used to measure net exhumation.

As sediments are buried they compact mechanically when the effective stress (generally depth) increases. This is a result of the overburden and it changes the physical properties of the rocks. Porosity and total rock volume is thus reduced with increasing burial/compaction, and bulk density/velocity is increased (figure 2.1). Mechanical compaction is basically strain from different stresses, and based upon different mineralogy and composition it varies greatly. This not only accounts for how a certain composition is affected by increasing effective stress, but the initial properties are also very different between various types of sediments (Bjørlykke, 2014). For

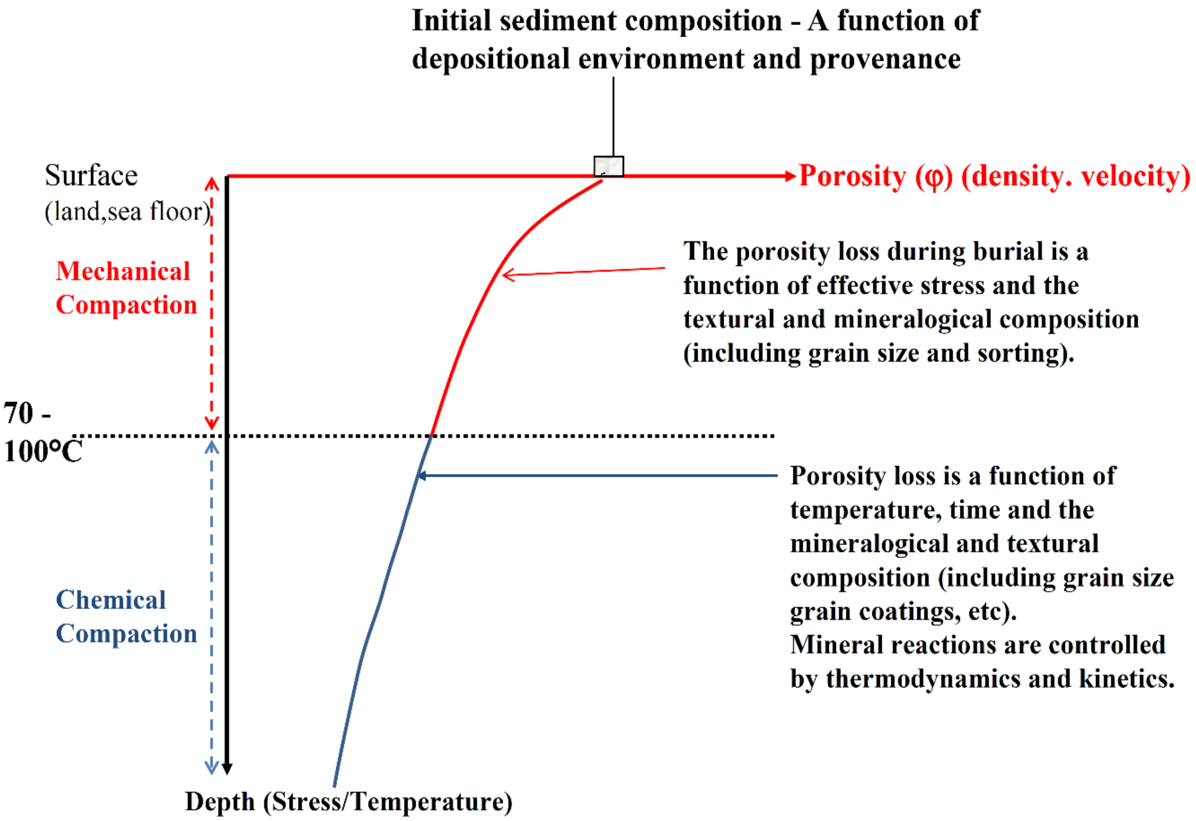


Figure 2.1: Compaction of sediments as a function of depositional environment and provenance. Porosity decrease with depth, whereas velocity and bulk density increase. From Bjørlykke (2014).

example, porosity for seabed sediments can range from 38% (coarse sand) to 85.8% (clay) (Hamilton, 1971). This implies different compaction routes regarding porosity as a function of depth.

Chemical compaction revolves around precipitation and dissolution of minerals which leads to reduced porosity and increased density. In general, the main principles differ from those of mechanical compaction and it usually follows after mechanical compaction (Storvoll et al., 2005). For sandstone the main part of quartz cementation starts at the temperature of 75-80° Celsius, and it is considered to respond exponentially to temperature, implying the time interval exposed to higher temperature is very important (Walderhaug, 1994). A stable framework is usually created at these higher temperatures and the cement overgrowth will prevent further mechanical compaction. The chemical compaction is however a function of temperature, time and mineralogy since different cement types exist (Bjørlykke, 2014).

Clay minerals are the most common material in sedimentary basins (Mondol et al., 2008). The abundance of Smectite is thought to have a significant impact on compaction trends as discussed by several authors (Marcussen et al., 2009, Mondol et al., 2008, Mondol et al., 2007, Storvoll et al., 2005); Kaolinite and Smectite are considered end members of the clay minerals because of their very different properties. Smectite has low permeability and large surface area whereas kaolinite has relatively high permeability. Experimental mechanical compaction shows that at 20Mpa effective pressure, pure smectite has around 40% porosity whereas pure kaolinite has around 20% porosity. The velocity is subsequently considerably lower at the higher porosity, however it is also different at the same porosity (Mondol et al., 2007). It indicates that knowing the initial composition and mineralogy is very important in order to know the cause of a given compaction (porosity, velocity and density), and not just knowing the effective stress. This differs from the reply of Japsen (2006) to Storvoll et al. (2005), where he concluded that the velocity of shale could mainly be expressed as function of effective stress.

Storvoll et al. (2005) investigated velocity depth trends in the North Sea (figure 2.2), the Norwegian Sea and the Barents Sea for Mesozoic and Cenozoic sediments, and concluded that no clear general velocity depth trend is found. Despite this, he created a first order approximation, $V(z) = 1477m/s + 0.57*(1/s)*z$ (V in m/s, z in meters, s in seconds) for all the Cenozoic and

Mesozoic sediments from over 50 wells, which are mostly influenced by shale (They excluded salt and carbonate). Smaller trends are also shown (trends marked N and S). For example, the low velocity and inverse compaction trends in parts of the Northern North-Sea (figure 2.2 a, 2N Hordaland Group) has been thought to be associated with a high smectite content and overpressure, and thus low velocity. The trend 1N (Nordland Group) has a high gradient due to easily compacted poorly sorted sand and silt, and thus the velocity and compaction increases rapidly with depth (Marcussen et al., 2009, Storvoll et al., 2005). Other important observations from figure 2.2 is the generally lower velocity of source rocks (green) and higher velocity of sandstones/carbonates (red and purple respectively). The density log would follow similar patterns as shown by the velocity (Storvoll et al., 2005).

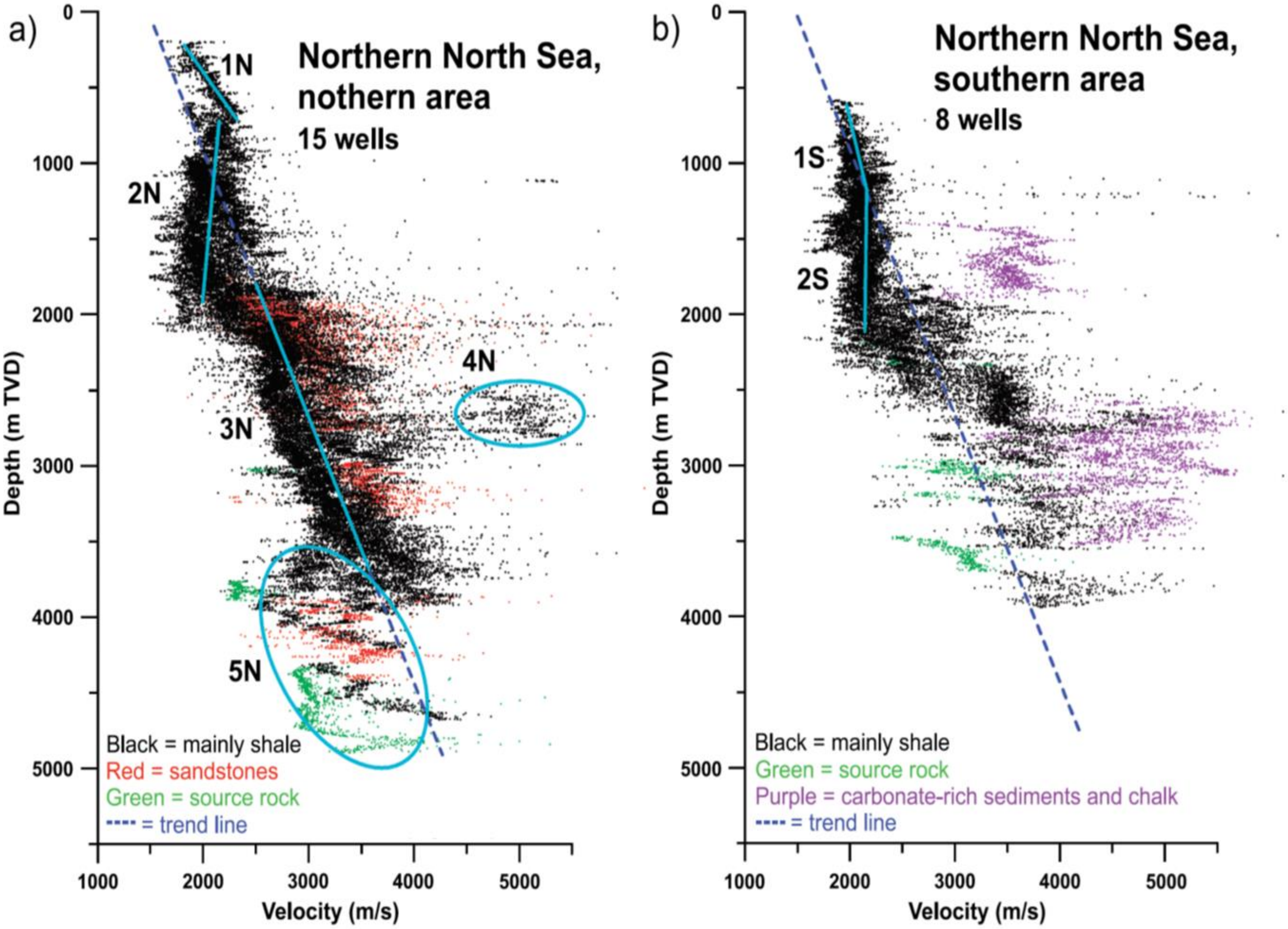


Figure 2.2: Velocity depth trends in the North Sea. a) Northern North Sea northern area. b) Northern North Sea southern area. The stippled blue line represents the general trend line of Vp = 1477m/s + 0.57*(1/s)*z. It matches the Shetland Group (3N) very well. Smaller trends are marked "N" and "S". From Storvoll et al. (2005).

Figure (2.2) emphasizes the complexity in creating a "general" compaction trend used for various compaction studies (e.g net exhumation); since depending on different lithology, burial history, temperature and pore pressure; a lot of different trends (1N-3N) are possible. The trends being marked 2N and 3N are for instance both shale dominated, but 2N is smectite dominated (Storvoll et al., 2005). Exponential trends could for example also exist depending on the interval.

2.2 Defining net exhumation

It is important to establish a good terminology regarding terms relating to uplift and erosion. Many terms have been used among various authors, but are often considered overlapping and sometimes not specific enough (Corcoran and Doré, 2005). Simply exhumation is used to describe the removal of material by any means from a basin such that previously buried rocks are exposed (Doré et al., 2002). It is therefore a shorthand often used for uplift and erosion. Also, the term exhumation is more general than uplift, it could for instance be removal of sediments in a dynamic datum (for example seabed) as opposed to "uplift" referring to a static datum (like geoid). Uplift is strictly restricted to plate scale tectonic processes and regional lithospheric processes (Corcoran and Doré, 2005).

Net exhumation and gross exhumation are the two most important (Corcoran and Doré, 2005). Gross exhumation is the amount of uplift and erosion at a particular unconformity prior to re-burial. Net exhumation is then defined as the difference between the present burial depth of a unit of reference and its maximum burial prior to exhumation (figure 2.3). Net exhumation is the property measured by the methods in this study, and is more accurate than "uplift and erosion". Gross exhumation is not quantified when measuring net exhumation by compaction methods, since eroded sediments are masked by equivalents amount of new sediments. Net exhumation is equivalent to the common term net uplift (Riis and Jensen, 1992) or net erosion (Henriksen et al., 2011a). There are several other terms in the literature relating to uplift and erosion as well (Corcoran and Doré, 2005). The effects of net exhumation on petroleum systems are summarized in figure 2.4 by Henriksen et al. (2011a). These effects are not studied in any detail, but it's very important to be aware of the motivation for studying net exhumation.

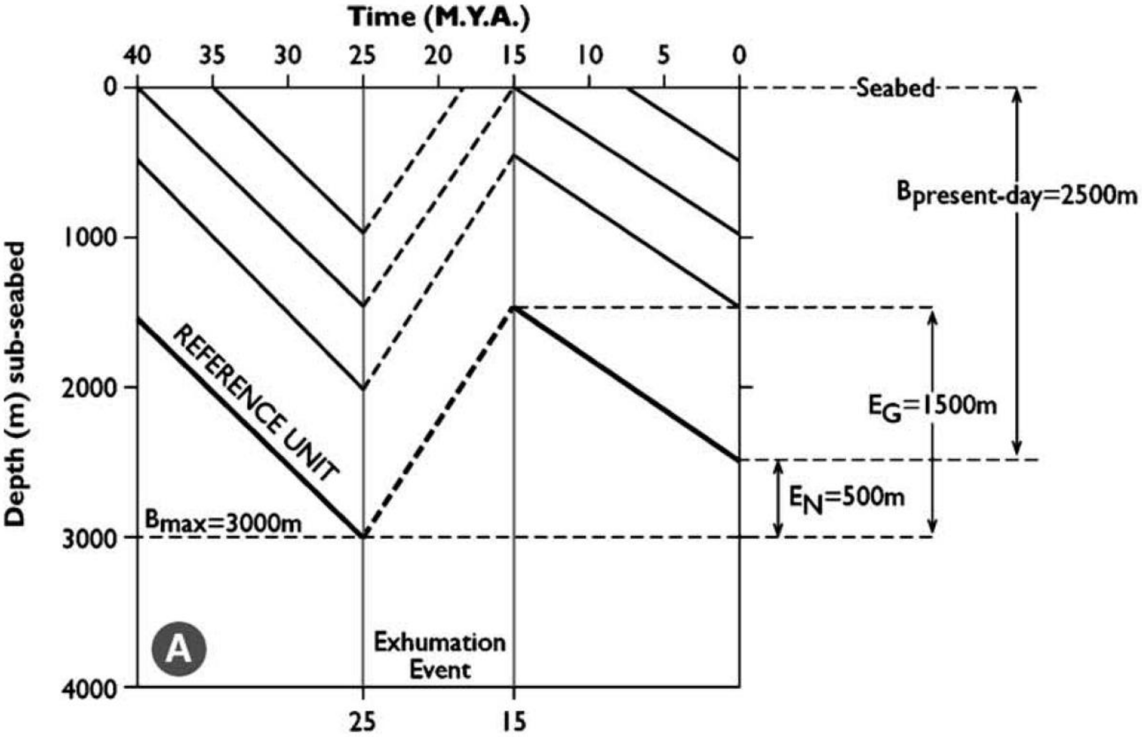


Figure 2.3: Concept of net exhumation (E_N) and gross exhumation (E_G). Other terms are B_{max} (max burial) and $B_{present\text{-}day}$ (burial present day). Note how the total amount of uplift and erosion would be 1500m (E_G), whereas when using the compaction methods in this study, we would measure the net exhumation being 500m. New sediments would mask the previously eroded sediments. Net exhumation is a better definition of the vaguer term being uplift and erosion. From Corcoran and Dore (2005).

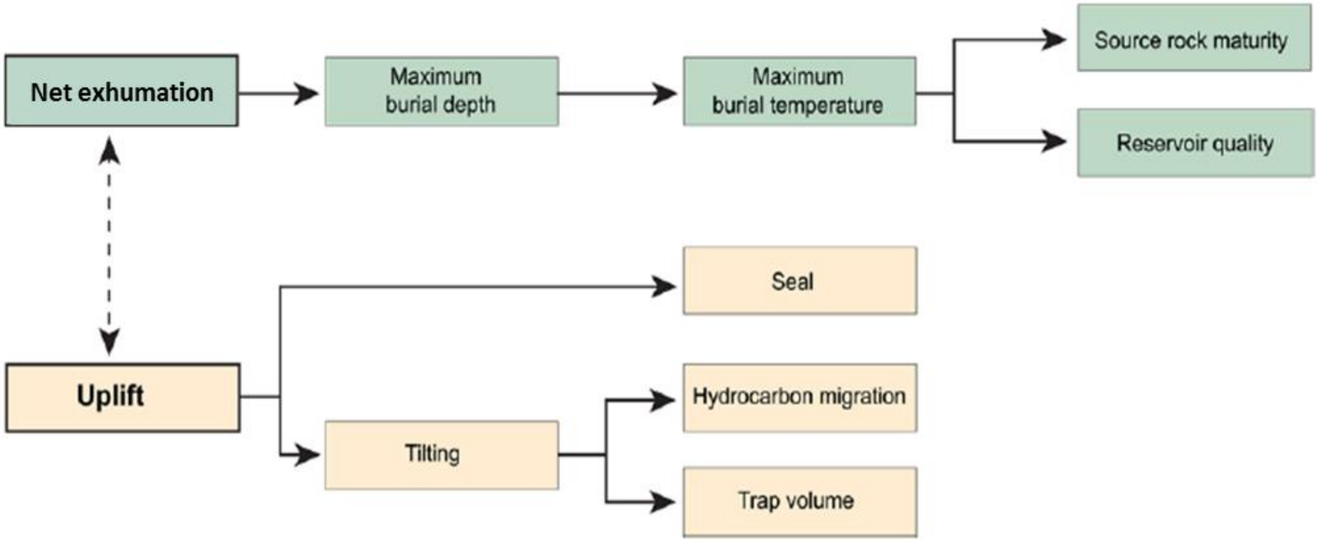


Figure 2.4: Effects of uplift and net exhumation on petroleum systems. Modified from Henriksen et al. (2011a)

3. Theory and methodology

This section will highlight details of the theory and methodology associated with estimating net exhumation from compaction related methods, first standard methods then the new method.

3.1 Net exhumation from standard compaction methods

Since the chosen standard methods to estimate the magnitude of net exhumation utilize interval velocity (using primary wave) and bulk density, it is important to properly define them as seen in equation 1 and 2. In equation 1, t is two way traveltime for layer i and z is the thickness of layer i. Equation 2 shows bulk density (ρb) as a function matrix density (ρm), fluid density (ρf) and porosity ϕ.

$$V\mathrm{int,i} = \frac{2\Delta z\mathrm{i}}{\Delta t\mathrm{i}} \qquad \text{(Equation 1)}$$

$$\rho b = (1 - \phi) * \rho m + \phi * \rho f \qquad \text{(Equation 2)}$$

Since the compaction of sedimentary rocks is considered mainly irreversible regarding mechanical expansion when subject to uplift and erosion and less effective stress; a given lithology is thus uplifted to a new lower depth, with its compaction properties (density/sonic) mostly preserved. It has “memory” of its deepest burial and we can measure the net exhumation. (Baig et al., 2016, Corcoran and Doré, 2005). There is a need for statistical data as both the density and sonic logs are full of measurement fluctuations from different small beds and borehole conditions. Therefore, trend lines (similar to figure 2.2) as opposed to raw data are needed when measuring net exhumation. Some additional assumptions are made when estimating net exhumation from interval velocity and bulk density:

i) Velocity/density-depth trends increase with depth and are linear. Other trends exist, but due to the large amounts of available trends the linear is the simplest. The gradient of the linear regression would approximate infinity if the regression is based upon very deeply buried sediments (or “infinity” depth), and be less steep further up in the subsurface (Storvoll et al., 2005). This would possibly also provide problems for other types of trend lines. However, more shallow sediments are dealt with.

ii) The rocks in both the uplifted and reference area have similar and comparable physical properties. These would be influenced by lithology, sorting, grain size, average mineralogy, burial/thermal history, pore-pressure and so on. Ideally it is a homogenous formation with an extensive depth range which only have hydrostatic pressure (Corcoran and Doré, 2005).

The linear trend can be written as a function of z to give out velocity/density, represented by equation 3 (Storvoll et al., 2006, Al-Chalabi, 1997, Hamilton, 1979, Slotnick, 1936). This will give rise to a V_0 and a k. V_0 represents where the trend line crosses for z = 0 (z is true vertical depth below seafloor), and k represents the gradient. This means all data is plotted relative to seafloor. This part and net exhumation is exemplified with velocity as a conceptual model (figure 3.1). 1 denotes the not uplifted reference and 2 denotes uplifted area.

$$V(z) = V_0 + k(z) \qquad \text{(Equation 3)}$$

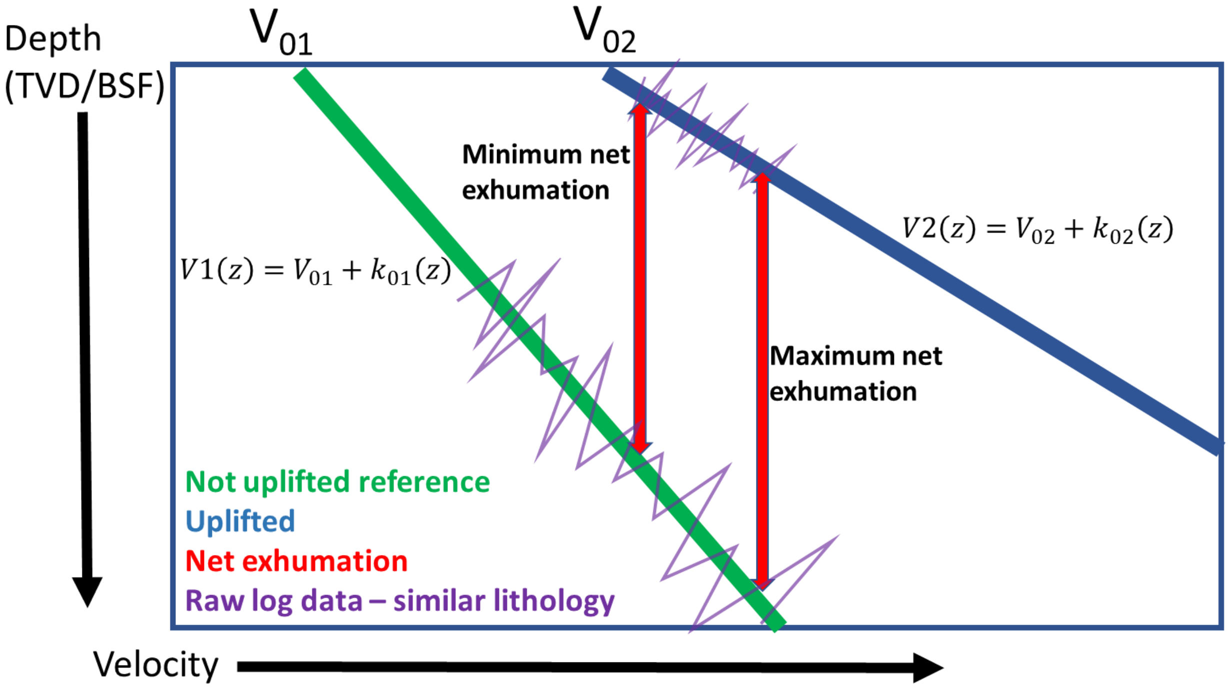


Figure 3.1: Concept of two linear trend lines made from velocity data points, in blue (uplifted) and green (reference). Subtraction between them for a given velocity would yield net exhumation. Notice that the depth is below seafloor for all data points. All the same concepts account for density as well.

The uplifted trend line (blue) is only considered valid over the data which was input to its regression (purple data). This means the net exhumation is taken between the top and base of the data in the uplifted area (minimum and maximum net exhumation in figure 3.1). It will not be the same net exhumation magnitude if the trend lines (blue and green) have different gradients. This is shown by the two red arrows; thus the average net exhumation is used.

The reason for applying shale compaction to estimate net exhumation, as opposed to for example sandstone, is that shale intervals are often much thicker and more abundant than sandy intervals (NPD, 2017). However, a reference compaction trend could also be established for other lithology, and is in theory equally valid when compared with similar uplifted intervals.

A volume clay cutoff based upon the gamma ray well log (equation 4) was done in order to have mainly shale (e.g Marcussen et al., 2009). It’s well established that shale show higher gamma ray values than sandstone due to the higher content of radioactive elements. The input is the value of the gamma ray log at a given depth (gr log value), gr min (gamma ray value corresponding to the minimum sand line) and gr max (gamma ray value believed to correspond to 100% shale). The volume clay cutoff was typically chosen between 50% and 80% for each well, mainly in a way where it excluded sandy peaks, but not to the extent where the data points became very scattered and thus the regression unreliable. The input data was also smoothed to lessen the effect of spikes, after these steps we could do linear regression on the data.

$$V\ clay = \frac{\text{gr log value} - \text{gr min}}{\text{gr max} - \text{gr min}} \qquad \text{(Equation 4)}$$

Summarized steps:

1. Select similar shales in the not uplifted area as the uplifted, all data (velocity/density) relative to seafloor.

2. Do volume clay cutoff to exclude sandy peaks and smoothing (optional)

3. Perform linear regression on both datasets, subtract the depth difference for a given velocity/density and it will yield the magnitude of net exhumation. Use the average net exhumation if they have different gradients (k). This would be based on the linear interval velocity/density in the middle of the uplifted lithology.

3.2 Average velocity

3.2.1 Basic concepts

The check-shot is based upon using an air gun for a marine survey, and for zero offset check-shots it's placed as near to the wellbore as possible (figure 3.2). Having a geophone in the well at various depths will give out the time it takes for an acoustic signal to travel the path between the source (air gun in water) and the receiver (geophone). The check-shot will give out a certain number of OWT (one way time) and depth pairs, depending on how many shots were taken. Both check-shots and VSP data have been used, mainly differing in the data point spacing. TWT (two-way time) can be calculated by multiplying OWT by 2. Having the check-shots almost vertical over the wells removes anisotropy effects associated with wave propagation. Average velocity (from primary wave) is the accumulative thickness divided by the accumulative time (equation 5). In equation 5, z_i is the thickness of layer i, whereas t is two-way travel time for layer i. The chosen datum was the seafloor. This means each shot shows the overburden. (Herron and Latimer, 2011)

$$Vavg = \frac{2\sum \Delta zi}{\sum \Delta ti} \qquad \text{(Equation 5)}$$

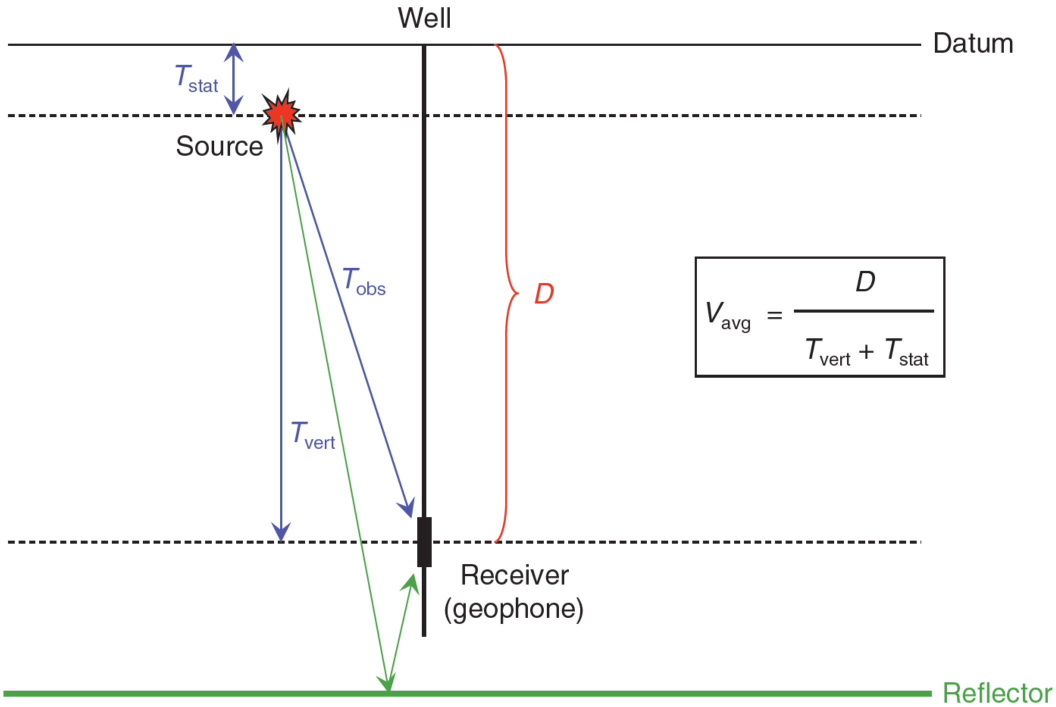


Figure 3.2: Concept of check-shot, figure from Herron and Latimer (2011).

3.2.2 Basic assumptions for using average velocity:

The assumptions and ideas behind using average velocity to estimate the magnitude of net exhumation are explained below.

i) The average lithology for a large depth interval could be assumed to be somewhat similar in various areas. High/low velocity anomalies would possibly neutralize each other over such an extensive range. Also, no matter the lithology, the whole rock column and not just a specific lithology is being uplifted. This means a larger lithological interval could be used to quantify net exhumation, assuming you can find the same average lithology/acoustic properties in the compared areas. The acoustic properties are here related to the lithology, and obviously it does not mean the actual velocity, since these must be different in the uplifted/not uplifted areas.

ii) When using a linear velocity model, both the average velocity (check-shot) and interval velocity can be assumed to have the same velocity at seabed (V_0). This will be showed in a model in the next section.

iii) Average velocity from check shot data represents a larger scale compared to interval velocities. Interval velocity from well data are affected a lot by the logging operation and thin beds//lithology variation, which may give rise to velocity spikes. Any form of linear regression thus has relatively large uncertainty. On the other hand, the average velocity from check-shot is less affected by such small-scale features since it is accumulative, and not that affected by borehole conditions. Such effects are thus smeared out and the main lithology/acoustic properties of the overburden will dominate. Any form of linear regression on average velocity is therefore considered more consistent, and with less uncertainty.

iv) Dispersion effects, meaning the low frequency of the check-shot velocity compared to sonic velocities, are considered to have minimal impact on net exhumation estimates. In general, many authors notice positive drift between integrated sonic time and check-shot time (often at least 2.0 ms/300m), meaning the average velocity from check-shot show slightly lower velocity than the average velocity derived from the sonic log (Stewart et al., 1984). Such differences are not further quantified in this work. However, due to only using check-shot data, and not mixing the sonic/VSP scales, the effects would be present in both the uplifted area and not uplifted area; therefore most likely neutralizing such effects on net exhumation estimates. The use of seismic data is also considered better for the calculation of an accurate average velocity, as opposed to doing the same calculation from the sonic log (integrated sonic log). This also relates to when performing well-tie where the check shot is considered more accurate as a time-depth relation compared to the sonic log (e.g Simm et al., 2014). The different types of velocity are exemplified in figure 3.3 on well 34/7-1. Notice how the average velocity is following the same pattern as the interval velocity, but it is smeared out due to including the overburden. As expected the average velocity from check-shot is lower than the average velocity from sonic logs (dispersion). Furthermore, sonic logs often lack data close to the seafloor, this might also explain the higher average velocity from sonic. It’s not reliable since different wells would start the sonic log at different depths, thus it’s not anymore average velocity from seabed, but from an arbitrary datum.

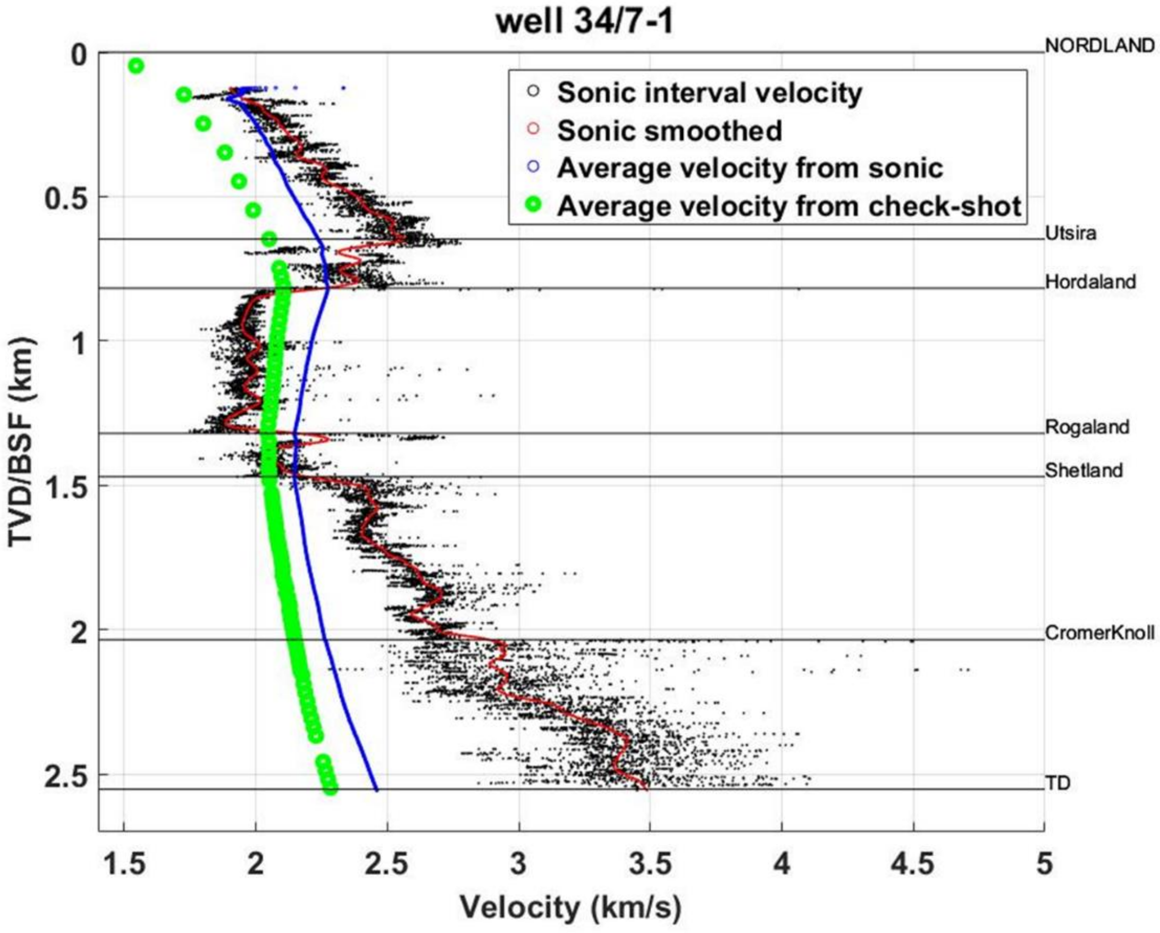


Figure 3.3: Velocity versus depth for well 34/7-1. It shows how the different velocities are related to each-other, and that the average velocity from check-shot is lower than the average velocity from the integrated sonic log. This is due to both different datums and probably dispersion.

3.2.3 Linear velocity model

Before showing the methodology of estimating net exhumation from check-shots in detail, it is important to understand more about the relationship between interval velocity and average velocity, and how each are affected by uplift and erosion. It is also a desire to test the assumption of using the same V_0 for the interval velocity and the average velocity (assuming a linear model for both). This lead to the creation of a linear velocity model which was simulated for 3 scenarios; a not uplifted area (V_{01}), an uplifted area without erosion, and a scenario with uplift and erosion (V_{02}). These are showed with green, red and blue colors respectively (figure 3.4), where dashed lines are average velocity (check-shot) and solid lines are interval velocity. The blue horizontal line is the "pretended" seafloor. 1 is reference, 2 is uplifted with erosion, "V" is Velocity.

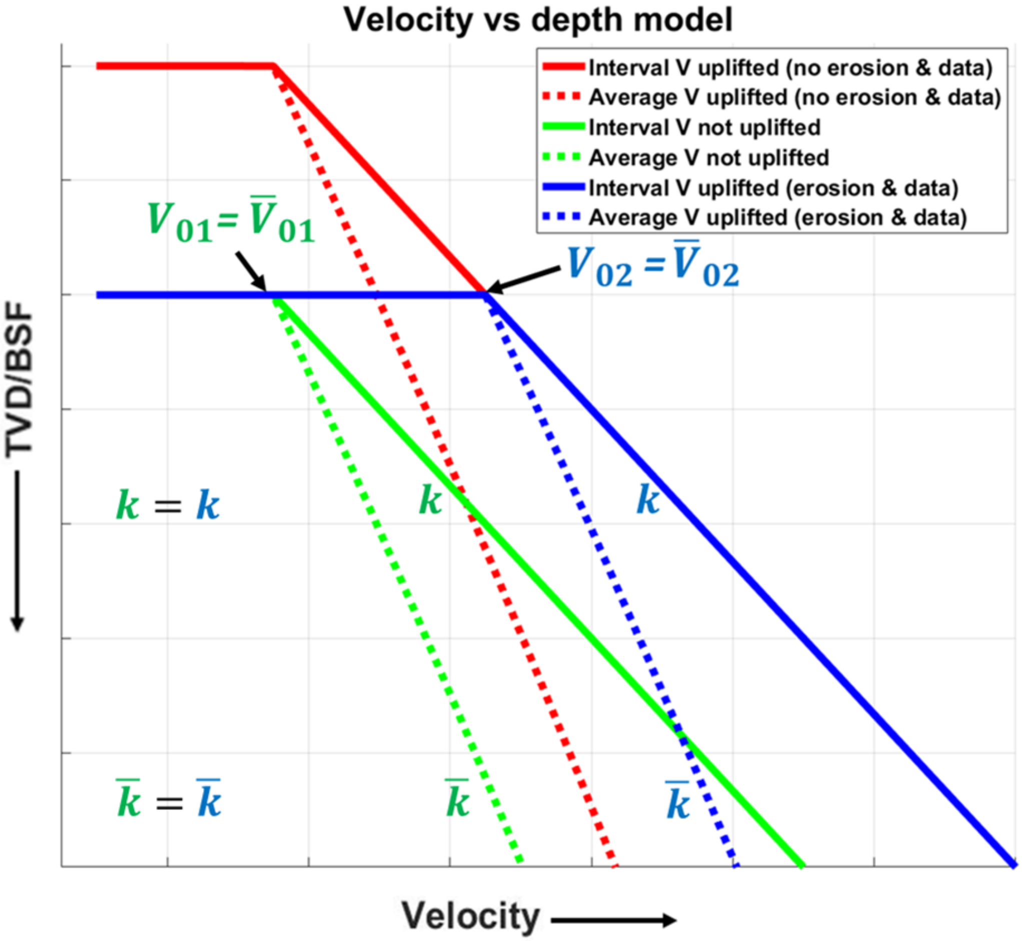


Figure 3.4: Velocity versus depth model. Green colors are for the not uplifted area, blue colors are for the uplifted area exposed to uplift and erosion, and the red colors demonstrate uplift without erosion (i.e a mountain). k is the gradient for the interval velocity lines. Regression on each of the average velocity profiles yields a $\overline{k}$, and a $\overline{V}_0$ approximately similar to the V_0 from the interval velocity profiles, thus $V_{01} = \overline{V}_{01}$ and $V_{02} = \overline{V}_{02}$. All k values are identical, whereas the $\overline{k}$ values are very similar between the areas.

The interval velocity trend lines are computed from equation 3, with a chosen set of values for V_0 and *k*; *k* is the same for all the three scenarios; thus raw data and model coincide. The average velocity is calculated by equation 5. This explains why it starts at the same V_0 as the interval velocity (for each color). It plots very linear although being directly created by equation 5.

This first idea was to look at the possibility of estimating net exhumation by looking at a given average velocity, and extracting the depth difference. We assume the two interval velocity trend lines yields the net exhumation, equivalent to the standard methods. The vertical distance between the interval velocity profiles being green and blue, is equivalent to the vertical distance between the average velocity profiles being green and red. This means if there is no erosion, but simply just uplift, the average velocity could yield net exhumation in a comparable way as when utilizing interval velocity.

However, if there is uplift and erosion (blue curves), it becomes more complicated. The average velocity plotted from V_{02} starts right under rocks which has been eroded away. The start value for the blue average velocity is equivalent to the interval velocity at that point (V_{02}). And since the interval velocity has a higher gradient than the average velocity, it makes the start value too high for the blue average velocity. It is too high by the amount corresponding to the horizontal distance between where the red average velocity crosses the seabed and $V_{02.}$ Net exhumation for a given average velocity (blue vs green) thus gives a net exhumation estimate much higher than the correct value. This is obviously wrong, and it simply relates to the different gradients.

All the average velocity profiles look linear, but are as mentioned slightly curved since they are from equation 5. Linear regression on parts of the average velocity data yields two $\bar{V}0$ values, and two corresponding $\bar{k}$ values (equation 6). No matter the points being input to regression, it only makes minor difference on $\bar{k}$ and $\bar{V}0$ since the raw average velocity data all plot almost linear. After regression, any difference between a $\bar{V}_0$ and V_0 (for each color) is thus minimal. The regression was tested but not showed in figure 3.4 to not clutter the plot. The $\bar{k}$ values are also very similar in both the uplifted area and the reference. This demonstrates how a linear model for both the average/interval velocity and the assumption of $V_0 = \bar{V}_0$ are reasonable.

$$\bar{V}(z) = \bar{V}_0 + \bar{k}(z) \qquad \text{(Equation 6)}$$

3.2.4 Net exhumation from average velocity

The final methodology is presented in this section. From equations 3 and 6, it is as mentioned possible to assume the same V_0 and $\bar{V}_0$. Setting V_0 = $\bar{V}_0$ yields equation 7.

$$V(z) = \bar{V}_0 + (k)\,z \qquad \text{(Equation 7)}$$

By using equation 7, the interval velocity (and not average velocity) is used when estimating net exhumation. However, it differs with the $\bar{V}_0$ being derived from regression on average velocity from check-shot. In practice, it also represents the composite of several lithologies as opposed to a specific lithology. This is also a necessary consequence of the check-shot not being able to filter lithology (i.e. gamma ray cutoff), and it would always include data from the start of the seabed.

However, on real check-shots the raw average velocity data does not plot linearly with depth as in the model (see figure 3.3 vs figure 3.4), which means performing regression on all the average velocity points would have little physical basis. For instance, the average velocity often changes more rapidly at shallow depth compared to greater depths. Also, since all average velocity data points represent the overburden above its depth, it should not be necessary to use all the points as input for linear regression. Therefore, by doing regression on smaller intervals, the changes in average velocity gradients are better represented; this would be the $\overline{k}$.

Furthermore, since check-shots are arbitrary sampled, and due to some bad shots; this means performing linear regression on all the average velocity data would provide further inconsistency. The average velocity is thus interpolated to have a dense sampling and slightly smoothed (figure 3.5). Then linear regression is then performed on small depth intervals, and subsequently by moving a small increment downwards for each regression. An example could be: 500m-700m -> regression, 505m – 705m -> regression; each such regression yields a $\bar{V}_0$ and a $\overline{k}$ (figure 3.5). Now minor changes in average velocity, $\overline{k}$, and $\bar{V}_0$ are represented more smoothly. This is done on the entire range of average velocities given by each check-shot. The smoothing and length of the regression interval (for example 150m vs 200m vs 250m) are chosen so to create a smoothly varying gradient, but not to the extent where the smoothing would ignore, not respect or extrapolate the data significantly. An example of a $\overline{k}$ is created from the black area at the bottom of figure 3.5. This would represent the particular $\overline{k}$ corresponding to the green value on the $\overline{k}$ color scale (a), and the $\bar{V}_0$ corresponding to the blue color (b). The black area (around average depth for $\bar{k}$) is the data being input for regression.

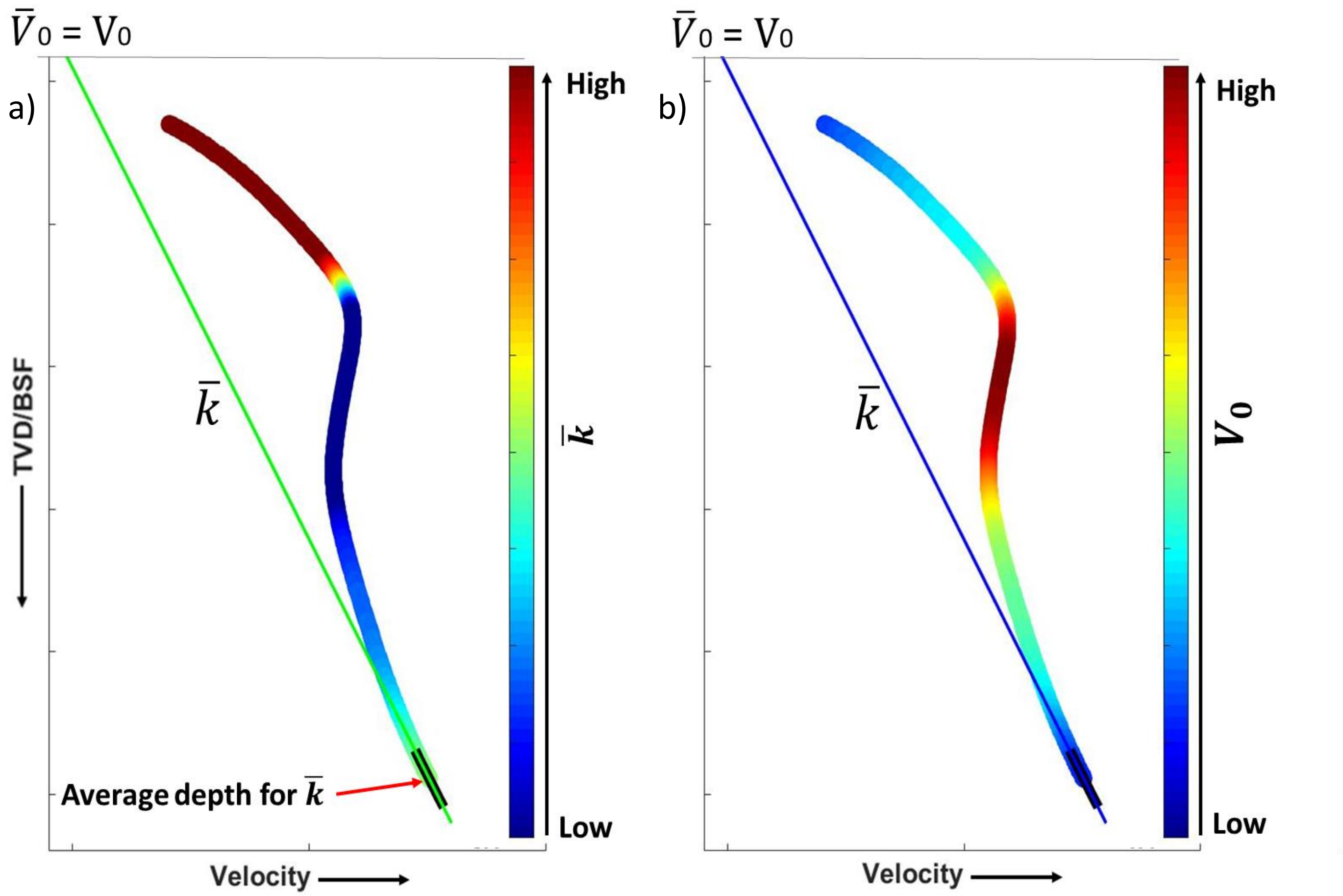


Figure 3.5: Average velocity from check-shots relative to seafloor superimposed with $\bar{k}$ (a) and V_0 (b). Notice how the average velocity is interpolated and then smoothed to have smoothly varying average velocity; then V_0 and $\bar{k}$ is also smooth. Regression on the black area around the average depth for $\bar{k}$ yields the $\bar{k}$ corresponding to the green color (a) and the V_0 corresponding to the blue color (b).

The physical meaning of $\overline{k}$ is the gradient of average velocity with depth, sort of a derivative of the average velocity. It differs from an interval velocity gradient since it's also affected by all the overburden. The $\overline{k}$ would change as a function of how the interval velocity is different relative to the average velocity at the depth. A certain thickness is of course needed to change the gradient significantly as the regression is performed on relatively large intervals (200m was used). It is now postulated that a similar $\overline{k}$ in the uplifted area as the not uplifted area could represent a somewhat similar average lithology. As already seen visually in the model (figure 3.4), the $\overline{k}$ is mostly unaffected by uplift and erosion. This is also the case when using well data, changes in $\overline{k}$ are considered minimal when subject to uplift and erosion, mainly changing V_0. This means the total range, for example $\overline{k}$ = 0.1-0.5, would be mostly preserved in both areas.

Finding $\overline{k}$ also means the corresponding $\overline{V}_0/V_0$ is found. Now it is necessary to find the gradient *k*. Equation 8 relates time and depth for a linear interval velocity model (e.g Japsen, 1993), here T is two way travel time below seafloor, z is depth below seafloor, and V_0 is the parameter found from the previously performed regression from $\overline{k}$. Only *k* is unknown (the raw check-shot has all the time and depth pairs). Thus, after solving the integral (equation 8 through 10), equation 10 can be solved for *k* for the time/depth corresponding to the average depth for $\overline{k}$ (figure 3.6). A best fit algorithm is used to find the *k*, as it cannot be found analytically. The *k* now matches the TWT/mean depth value corresponding to the average depth for $\overline{k}$, this can be seen in figure 3.6. *k* is typically a little bit over twice the value of $\overline{k}$. A linear trend line for the interval velocity can therefore be found by only using check-shot data. Equation 10 would generally yield a higher *k* for a lower V_0. Note that all the input terms are relative to seafloor.

$$T = 2\int_0^z \frac{dz}{(V_0 + k(z))} \qquad \text{(Equation 8)}$$

$$T = \frac{2}{k}\int_{V_0}^{V_0+k(z)} \frac{du}{u} \qquad \text{(Equation 9)}$$

$$T = \frac{2}{k} ln\left(\frac{V_0+k(z)}{V_0}\right) \qquad \text{(Equation 10)}$$

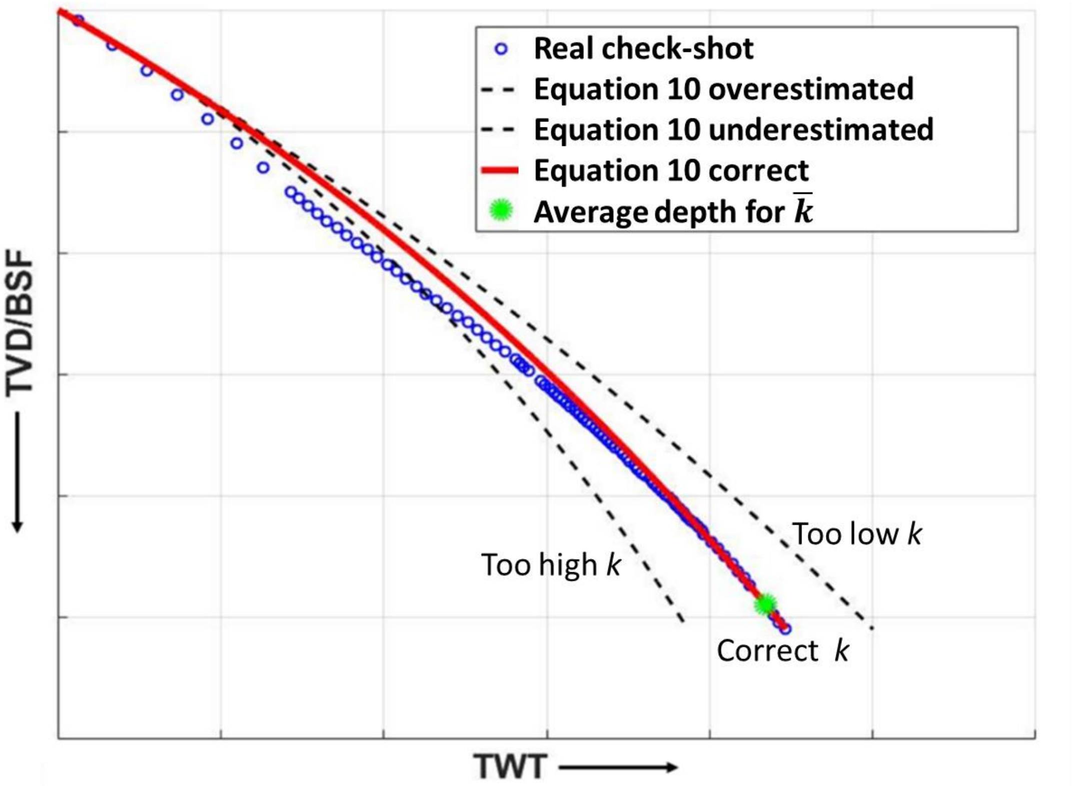


Figure 3.6: Procedure of finding correct *k* in the TWT-depth domain from equation 10. Blue color indicates the real check-shot, whereas the red and two black stippled lines resemble synthetic data created with equation 10. Red is the correct synthetic with the k value which will match the depth/TWT corresponding to the average depth for $\bar{k}$.

Doing this procedure of finding k for the same $\bar{k}$ from both the uplifted area and the reference yields two interval velocity trend lines. These can be subtracted from each another in the same way as the standard methods, and it gives the net exhumation estimate (figure 3.7). The criterion is to use the same $\bar{k}$ for each well. As the *k*/ $\bar{k}$ ratio is a little bit over 2 for most cases, this means the *k* is also fairly similar for the uplifted/not uplifted area for a given $\bar{k}$. A similar *k* is thus the goal in this method, and then the net exhumation does not vary significantly depending on the investigated velocity. In the case of a small difference in *k*, the average net exhumation is used, in a comparable way as in the standard methods. This corresponds to the depth difference at the velocity between the V_0 in the uplifted area and the velocity at the average depth of the regression input for $\bar{k}$ (in the uplifted area). However, the impact of this is minimal due to the very similar *k*. By using gradients as a criterion, this differs from standard methods. In the standard methods, a similar lithology etc. is chosen, and then the *k* is hopefully/often assumed to be similar between the two areas, but it is not a criterion.

Being realistic, choosing $\bar{k}$ when it is very low or high would create absurd V_0 values and unrealistic net exhumation estimates. We believe $\bar{k}$ should be chosen to yield V_0 values around 1500m/s in the not uplifted areas. This is in accordance with the trends of Storvoll et al. (2005) and Johansen (2016), and the standard reference trend in this work. This also implies that we assume V_0 is a somewhat physical value as opposed to a statistical artifact. V_0 around 1500m/s is also a realistic value when looking at the velocity of seabed sediments dominated by clay (Hamilton, 1971). Although the check-shot derived data is not only utilizing strictly clay dominated lithology, the main lithology would probably be dominated by clay, thus V_0 values around 1500m/s should be realistic. As showed later when creating the reference trends, $\bar{k}$ = 0.3 (1/s) seems to yield such realistic V_0 values for all the not uplifted reference wells. Differences in net exhumation estimates

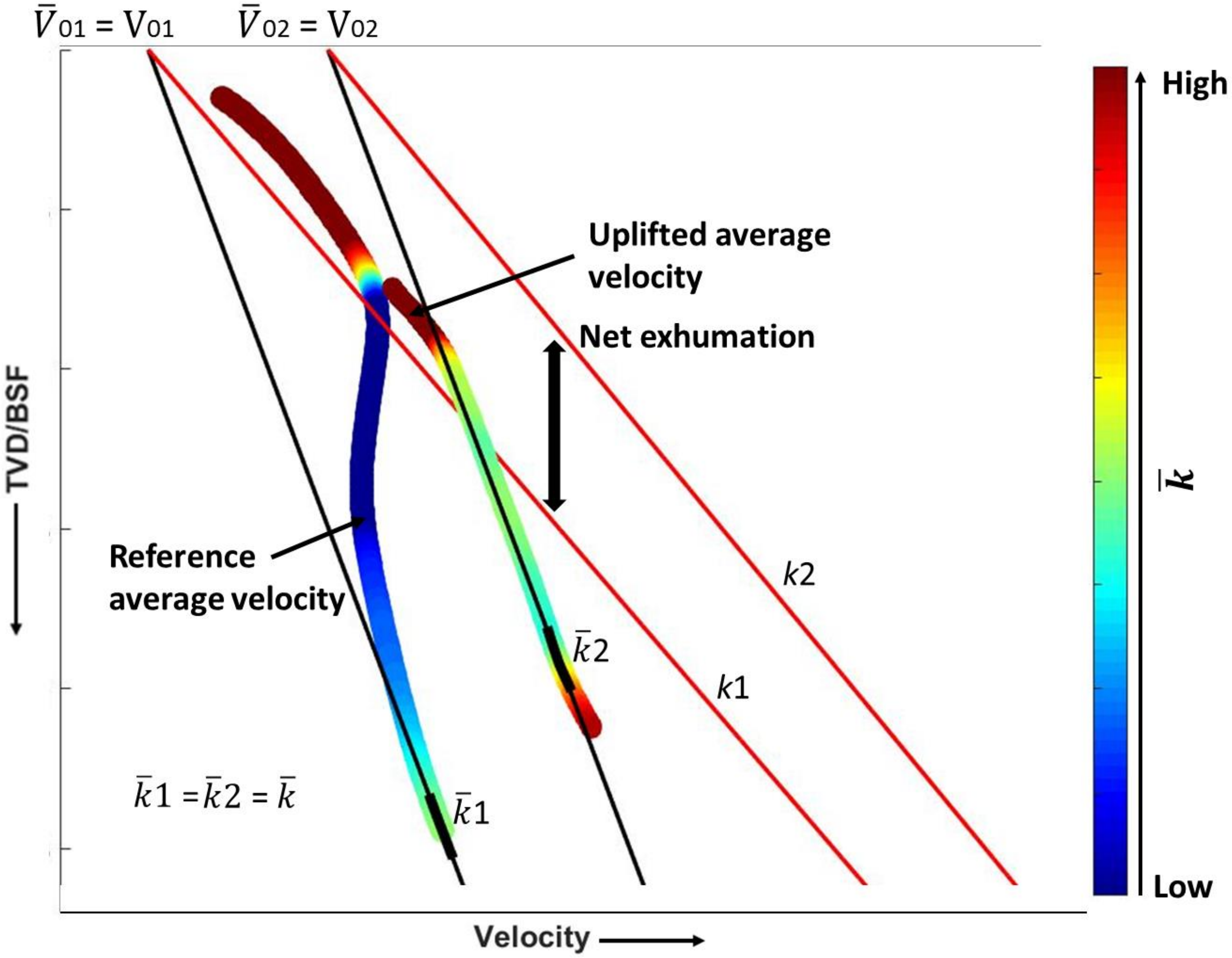


Figure 3.7: Summarized procedure for net exhumation estimates from the check-shot method. 1 denotes not uplifted reference, whereas 2 denotes area with uplift and erosion. In this example, the green color for $\bar{k}$ is the chosen $\bar{k}$ value for both areas. The regression comes from the black small line in each area. $k1$ and k2 are slightly different due to slightly different k/$\bar{k}$ ratios.

from varying $\bar{k}$ are presented later. However, for now we believe $\bar{k}$ values around 0.3 yields the most realistic net exhumation estimates. Due to rapid changes in $\bar{k}$ at shallow burial, it was decided to look at $\bar{k}$ values at relatively greater depths (e.g. larger than 1500m). The likelihood of having the same average lithology would probably also increase by looking at larger rock columns. Then lithology effects are smeared out as much as possible and the main lithology of the overburden will dominate. Additionally, it was attempted to use approximately the same average depths for $\bar{k}$ as much as possible. This was especially the case if a given $\bar{k}$ could be found at multiple depths.

Summarized steps

1. Plot average velocity from check-shots relative to seafloor. Interpolate and smooth to have a smoothly varying velocity. Do this for both the reference area and uplifted area.

2. Find similar $\bar{k}$ values in both areas where $\bar{k}$ is the gradient of average velocity. It can be found by doing regression on small intervals of the average velocity, for example 500m-700m -> regression, 505m – 705m -> regression. Each such interval yields a $\bar{k}$ and $V_{0.}$ $\bar{k}$ ~ 0.3 (1/s) yields representative V_0 values (~1500m/s) in the reference, thus should be used for both uplifted/not uplifted areas. The V_0 from average velocity can be used since we assume similar V_0 for average velocity and interval velocity. Use equation 10 to estimate *k*. It can be found since we have V_0 and time/depth from check-shot corresponding to the average depth for $\bar{k}$.

3. Net exhumation can be found as the depth difference for a given interval velocity between the created interval velocity trends in the uplifted and not uplifted area. Use the average if they have slightly different gradients. Plot it down to the data which created $\bar{k}$ in the uplifted area.

3.2.5 Advantages/disadvantages by using average velocity

Advantages:

- No need for sonic/density often affected by borehole conditions and poor logging runs.
- No need for specific lithological control. There is no need for the presence of a specific group/formation as utilized by standard methods.
- Since the method uses a large rock column (~2km), there should be a smooth increase in net exhumation from well to well, not influenced by regression uncertainty because a formation is thin/not present.
- The same average lithology is believed to be found in both areas by finding the same $\overline{k}$, hence a "correction" for abnormal effects such as overpressure is possibly included when finding the compared rock columns. There is no significant difference in k, on the other hand this is a problem in standard methods.

Disadvantages:

- Lack of complete understanding in the physical meaning of $\overline{k}$ and why it works. As for now its seems to be a very large-scale approximation, but where it lacks the same physical simplicity and determinism as other methods. Other methods look at compaction more directly whereas this method investigates it through more complicated parametrization and composite lithology.
- Would not work with completely different average geologies, for example a hypothetical "95% carbonate" basin cannot be compared to a "95% shale" basin. We assume around the same average lithology might be present at a large depth interval in the compared basins.
- It's hard to know the proper selection of a $\overline{k}$ (and V_0) in the reference, and why one value should be chosen as opposed to another. The same is the case if a $\overline{k}$ is present at various depths. This induces some uncertainty for each net exhumation estimate.
- Need for VSP/average velocity data, preferably over an extensive depth range with dense sampling.

4. Geological setting & data

Only a brief overview will be given of the geology in the Barents-sea and in the North-Sea, and will focus on the structural elements and information which is most central to uplift and erosion. The wells/data being used are also showed in this section.

4.1 Barents Sea.

Currently most of the exploration in the Barents Sea on the Norwegian sector has revolved around the Hammerfest Basin being in the western part of the Barents Sea (figure 4.1). Several gas discoveries have been made in this basin. In Norwegian waters, only small accumulations of hydrocarbons have been discovered outside this basin. In general, the petroleum systems are influenced by many different source rocks all the way from the Silurian to the Cretaceous, and the Barents Sea is considered to be a multi-sourced area. (Henriksen et al., 2011b).

The Barents Sea is bounded by a young passive margin in the west and north, developed because of the Cenozoic opening of the Norwegian-Greenland Sea and the Eurasia Basin. Between the Svalbard Platform and the Norwegian mainland there are several sub-basins and highs with more marked structural relief going westwards. Here mostly Cretaceous-Jurassic sediments are preserved in the basins. West of the Harstad Basin, entering deeper waters, more Paleocene-Eocene sediments are preserved. In the western Barents Sea the geological history after the Caledonian is dominated by three large rift phases. These are the Late Devonian?-Carboniferous (1), Middle Jurassic-Early Cretaceous(2), and Early Tertiary(3). In the first one the Barents Sea was mostly affected by crustal extension. In the later phases, there is a general westward migration of the rift systems; in addition well-defined rifts and pull-apart basins were generated in the southwest, and generation of strike-slip faults in the north. Except for late epeirogenic movements, which produced present data elevation differences, areas outside the south-western Barents-sea have been mainly stable. This accounts for example for the Svalbard Platform. The well-known late Cenozoic uplift and erosion removed most of the Cenozoic sediments, and in some places even older strata. This means there is a domination of Mesozoic units. The erosion is known to be most extensive in the western Barents Sea, and especially around the area in the north of Svalbard, where it's been suggested that more than 3000m of rocks have been removed. However, in the south-western Barents Sea (e.g Hammerfest Basin), most current estimates of net exhumation are around 1000-

1500m, whereas in the east little work has done underdone to quantify the magnitude. The Neogene and quaternary rocks rests unconformably on Mesozoic and Paleogene rocks, and these younger rocks thickens significantly at the margin (Faleide et al., 2010). The wells used to quantify the net exhumation are also showed in figure 4.1. The profile goes mostly from southwest to north/northeast and show increasing net exhumation in this direction. Note that well 7316/5-1 is used as a reference thought to have no uplift and erosion in the Barents Sea (Baig et al., 2016). A 2D profile from Henriksen et al. (2011a) shows the general increase in net exhumation eastward in figure 4.2. Names and formations corresponding to the different ages are showed in figure 4.3.

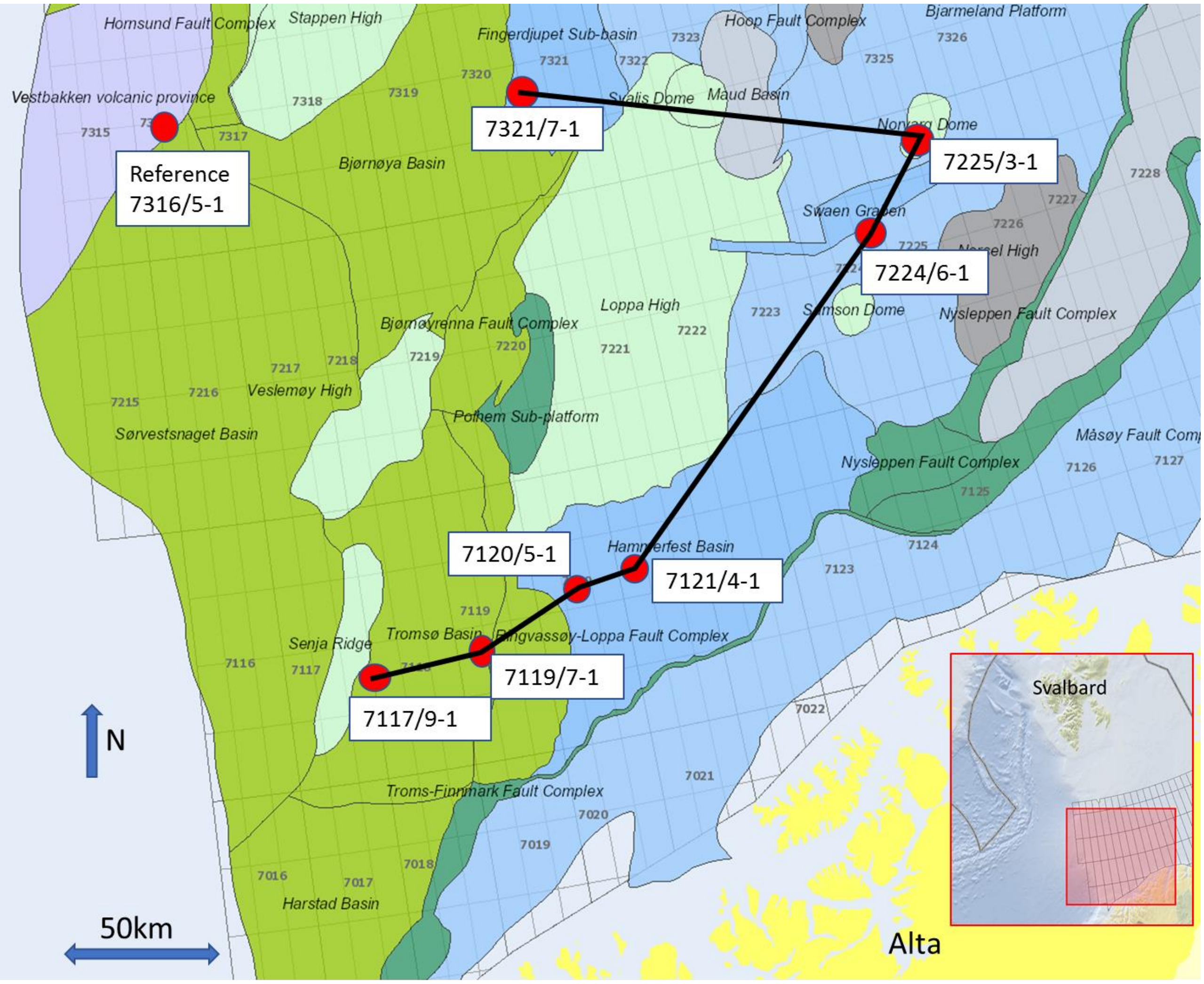


Figure 4.1: Map over the main structural elements in the western Barents Sea along with the wells used in the study. The wells being used are highlighted in red, and the profile is highlighted by the black line. It coincides mostly with increasing net exhumation from SW to NE A reference well (7316/5-1) in the NW is also showed. Modified from NPD (2017).

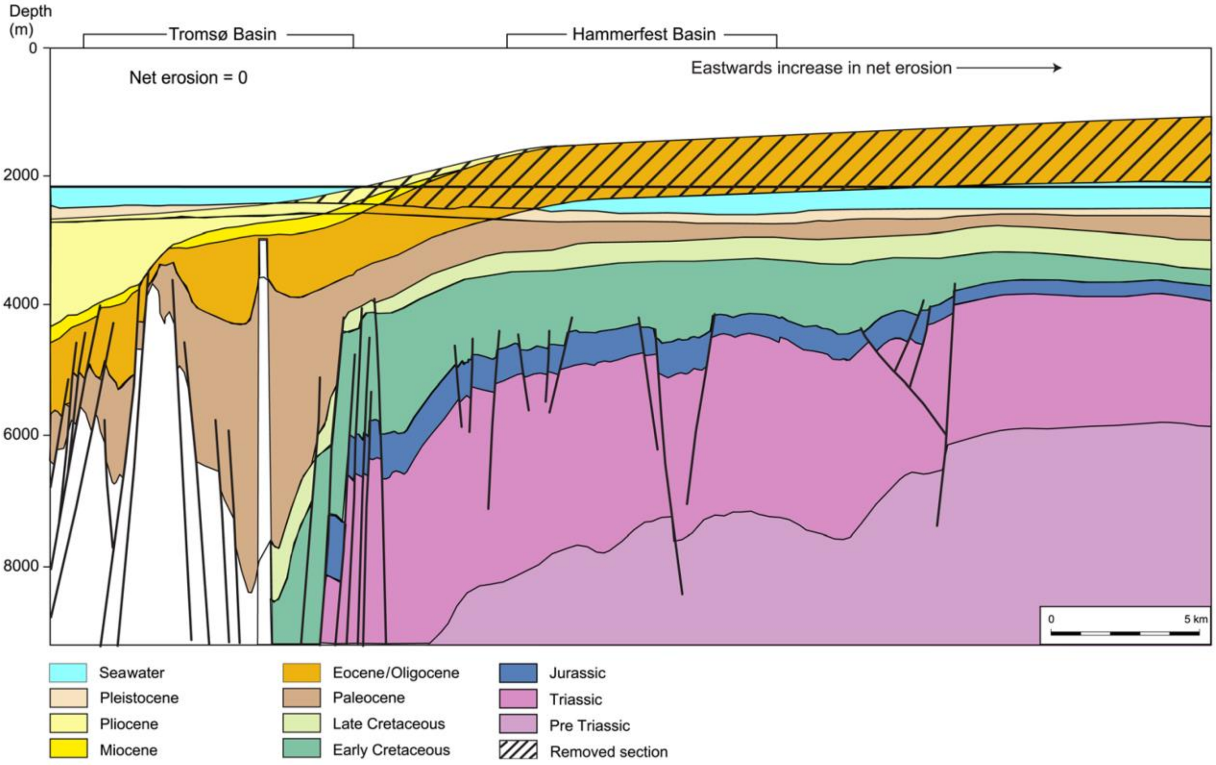


Figure 4.2: Regional profile with net exhumation (net erosion) in the Barents Sea from west to east. From Henriksen et al. (2011a).

4.2 North Sea

There exists a well-recognized uplift and erosion of mainland Norway and the basins close to the shoreline in the North Sea and the Norwegian Sea; This has traditionally been explained by isostatic uplift of Fennoscandia, or a relation to the Atlantic Ocean being opened and the peripherical bulge resulting from this (Hansen, 1996). This implies wells chosen for the reference area (no uplift) must be outside the area affected by uplift and erosion. It was based on iso-uplift lines from Hansen (1996) which show net exhumation lines along the coast (figure 4.4, a). There are much more wells in not uplifted regions of the North sea compared to the Barents Sea (e.g Baig et al., 2016), meaning that a representative reference could possibly be better represented from the North Sea. The reference wells selected from this area are shown in figure 4.4 b, being the wells 34/7-1 and 15/9-6. We wanted to test wells being geographically spread out. As mentioned we tested a reference well in the Barents Sea as well. How and where each of these reference wells were used will be explained when creating the reference trends.

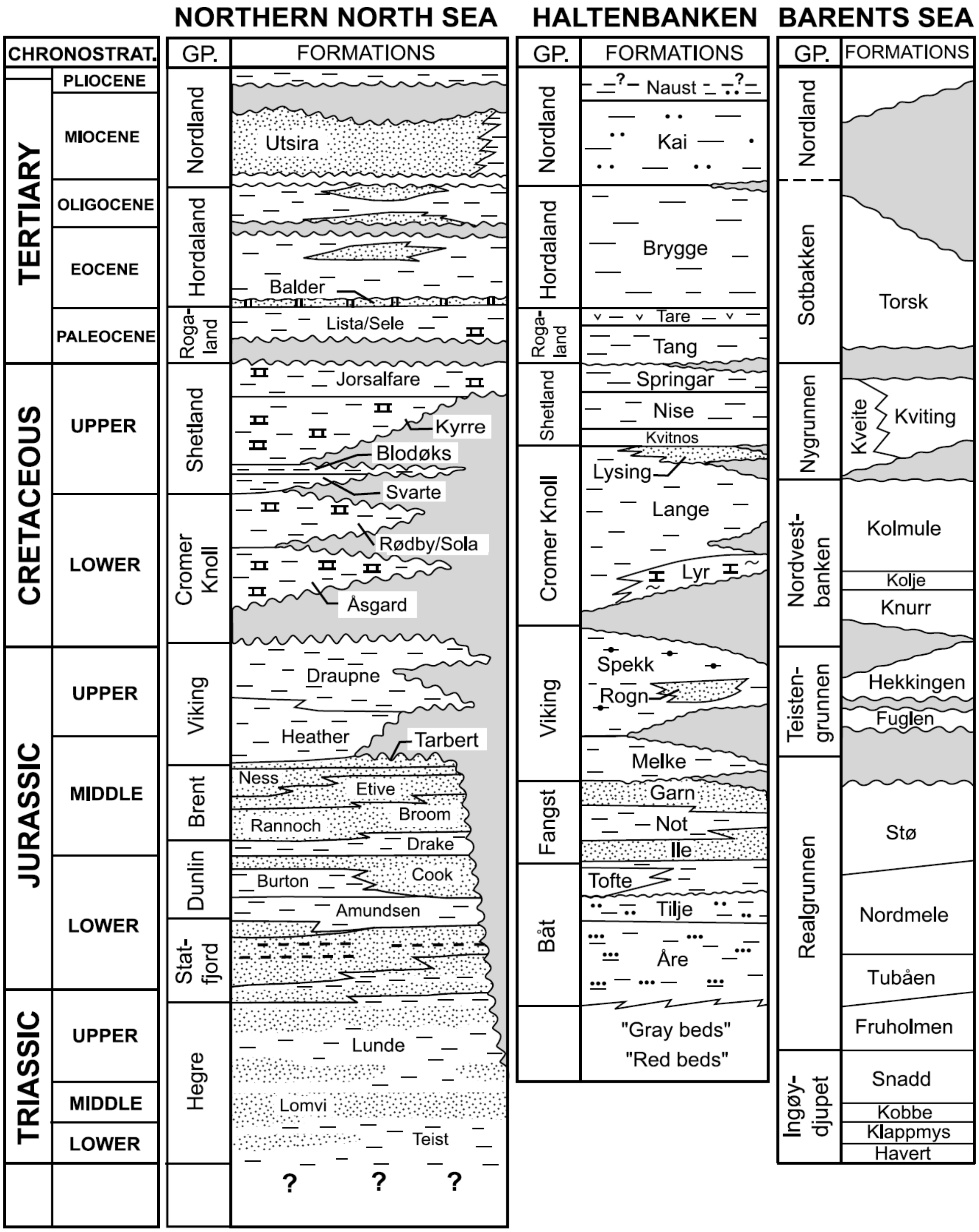


Figure 4.3: Main Groups, Formations and ages in the North Sea, the Norwegian Sea (Haltenbanken) and the Barents Sea. From Storvoll et al. (2005).

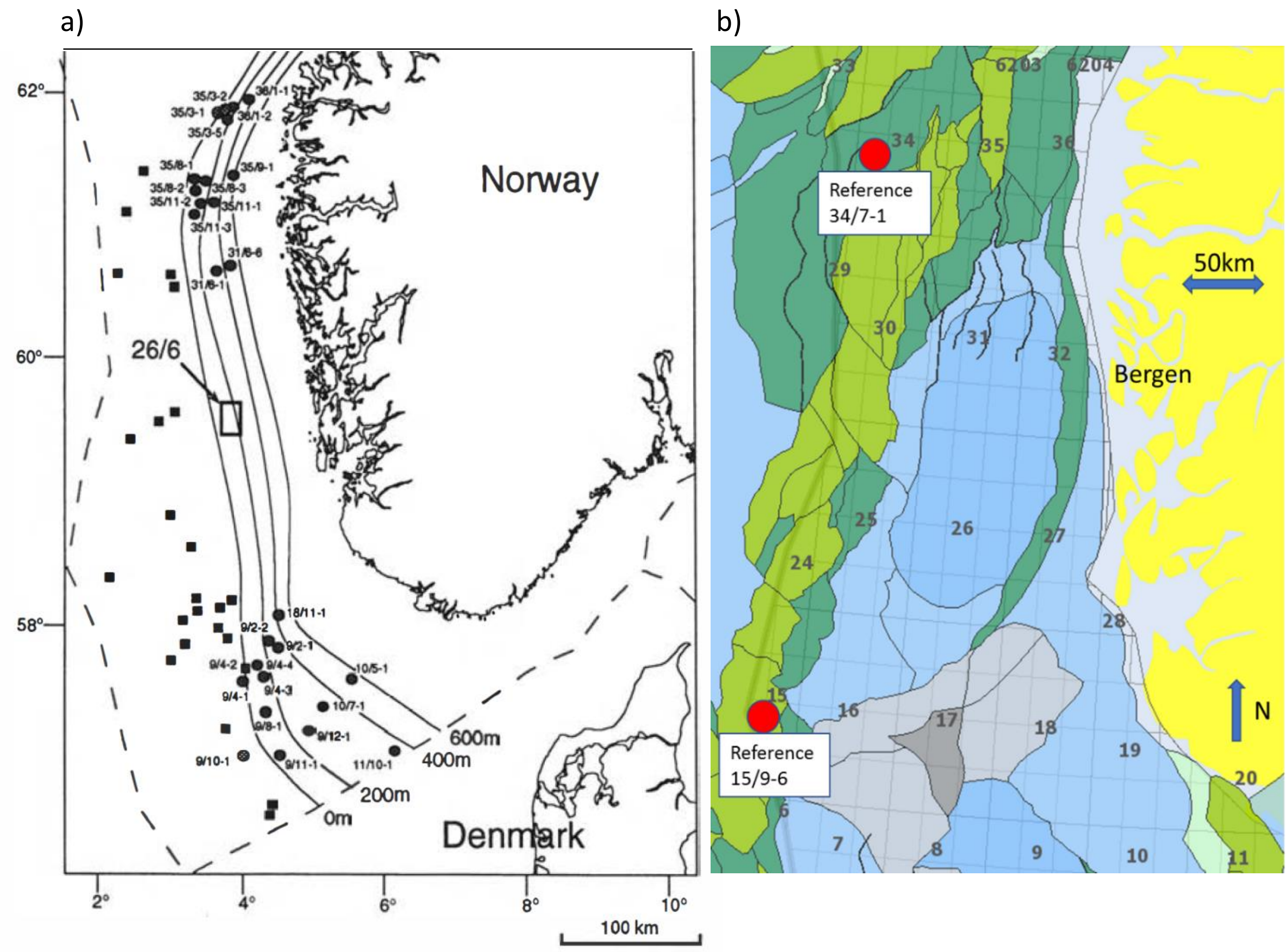


Figure 4.4: Reference North Sea. a) showing iso-net exhumation lines based upon shale velocity from Hansen (1996). Reference wells in the North Sea should be chosen outside these lines. b) showing the reference wells chosen in the North Sea with no net exhumation. Modified from NPD (2017).

4.3 Data

The estimates of net exhumation were based upon well logs and check-shot data. All the calculations were performed in MATLAB (MathWorks), R2016b and Microsoft excel. The well data was provided by Statoil, Schlumberger and NPD. The data was quality checked, and spikes in data (which were not relevant for overall trends) were taken care of. The depth datum is the seafloor unless stated otherwise. All the selected wells are more or less vertical. The selected wells in the Barents Sea are geographically spread out to ensure differences in the magnitude of net exhumation between the wells.

5. Results

5.1 Reference trends

5.1.1 Reference for standard compaction methods

Due to the large uncertainty associated with establishing a proper reference trend for the standard methods, a single properly chosen well (34/7-1) was used for the density/sonic methods (figure 5.1). The trend lines created from the density log and velocity log are highlighted on figure 5.1 and represent Shetland shales (Shetland group, figure 4.3). The well is located far west of the uplifted zone indicated by Hansen, 1996 (figure 4.4). The reference was chosen in the north since the south is dominated by more carbonate lithology. The Shetland group is considered to be a shale dominated lithology not influenced by the presence of smectite as the Hordaland Group (e.g Storvoll et al., 2005). This means it should be very comparable to similar shales in the uplifted Barents Sea. The well was chosen since both the density and velocity data plotted very linearly for the Shetland Group, and had reasonable seabed values (V_0). Also, as elaborated upon in the discussion, having an increasing number of wells as a reference is by no means an assurance that it would represent a proper reference. It is affected by the ratio of wells in different areas, and thus their different properties. The sonic reference trend is: V (z) = 1433m/s + 0.625*(1/s)*z (V = velocity (m/s), s in seconds and z = depth (m)); and the density reference trend is: RhoB (z) = 1.925g/cc + 0.0002172*(1/s)*z (RhoB = bulk density in grams/cubic centimeter). The velocity trend line is similar to the linear shale dominated trends of Storvoll et al. (2005) and Johansen (2016), being V(z) = 1477m/s + 0.57*(1/s)*z and V(z) = 1555m/s + 0.55*(1/s)*z, respectively. It was also attempted to create a reference trend with the Torsk Formation in well 7316/5-1, however the V_0 is around 1750m/s, which is relatively high compared to the well-established trends, thus it was not chosen. In addition, the Torsk Formation's bulk density shows relatively high values compared to the sonic, which we believe would not represent the uplifted Kolmule Formation.

As for the Groups/Formations in the uplifted parts of the Barents Sea, the Kolmule Formation was mainly selected. It is widespread and has equivalent properties as the Shetland shales (NPD, 2017, Baig et al., 2016, Storvoll et al., 2005). If it was thin, absent or if the log intervals were small, then other Formations/Groups were used or included (showed for each well later). The selected formations are although all clay dominated as described by NPD (2017).

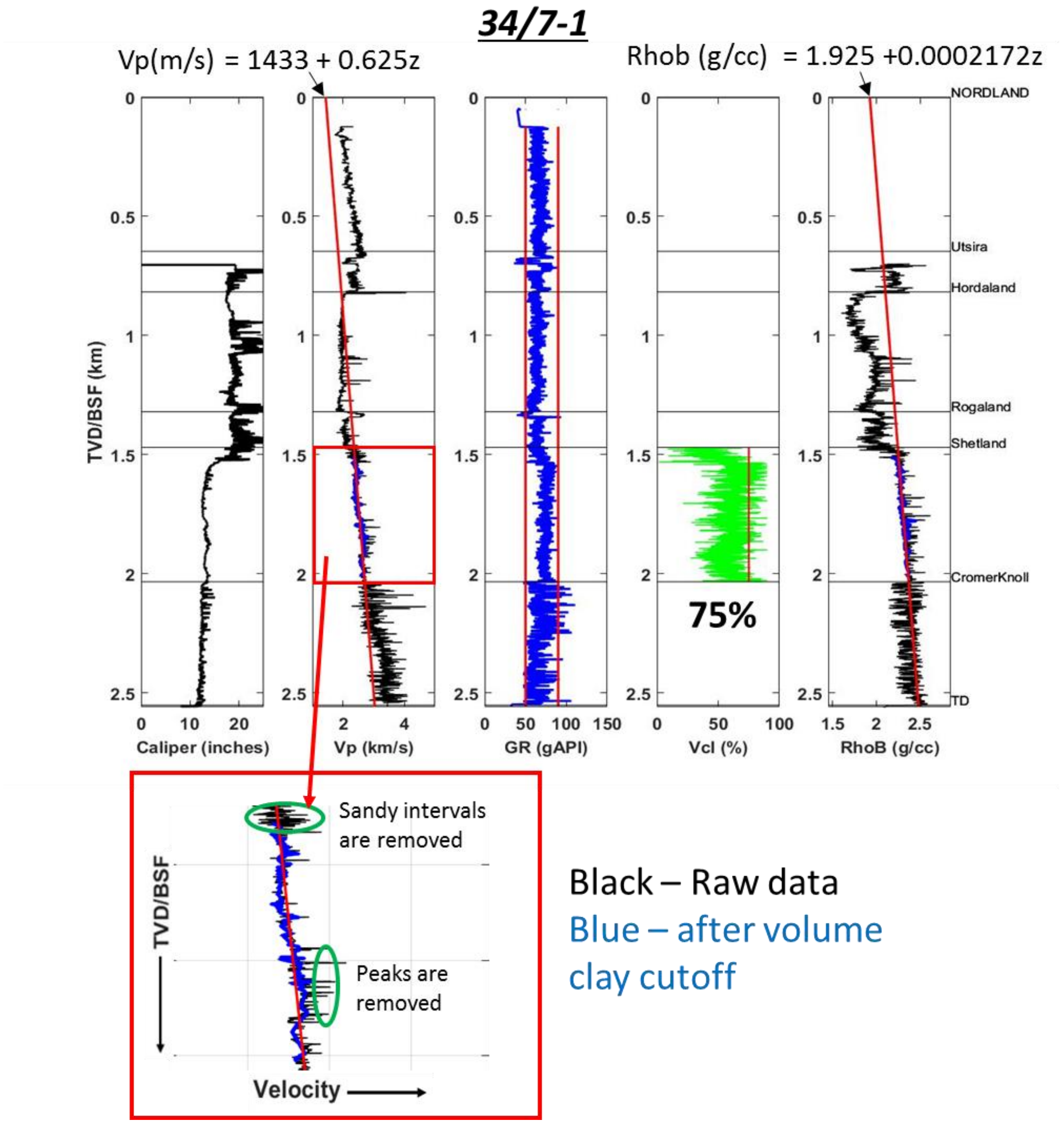
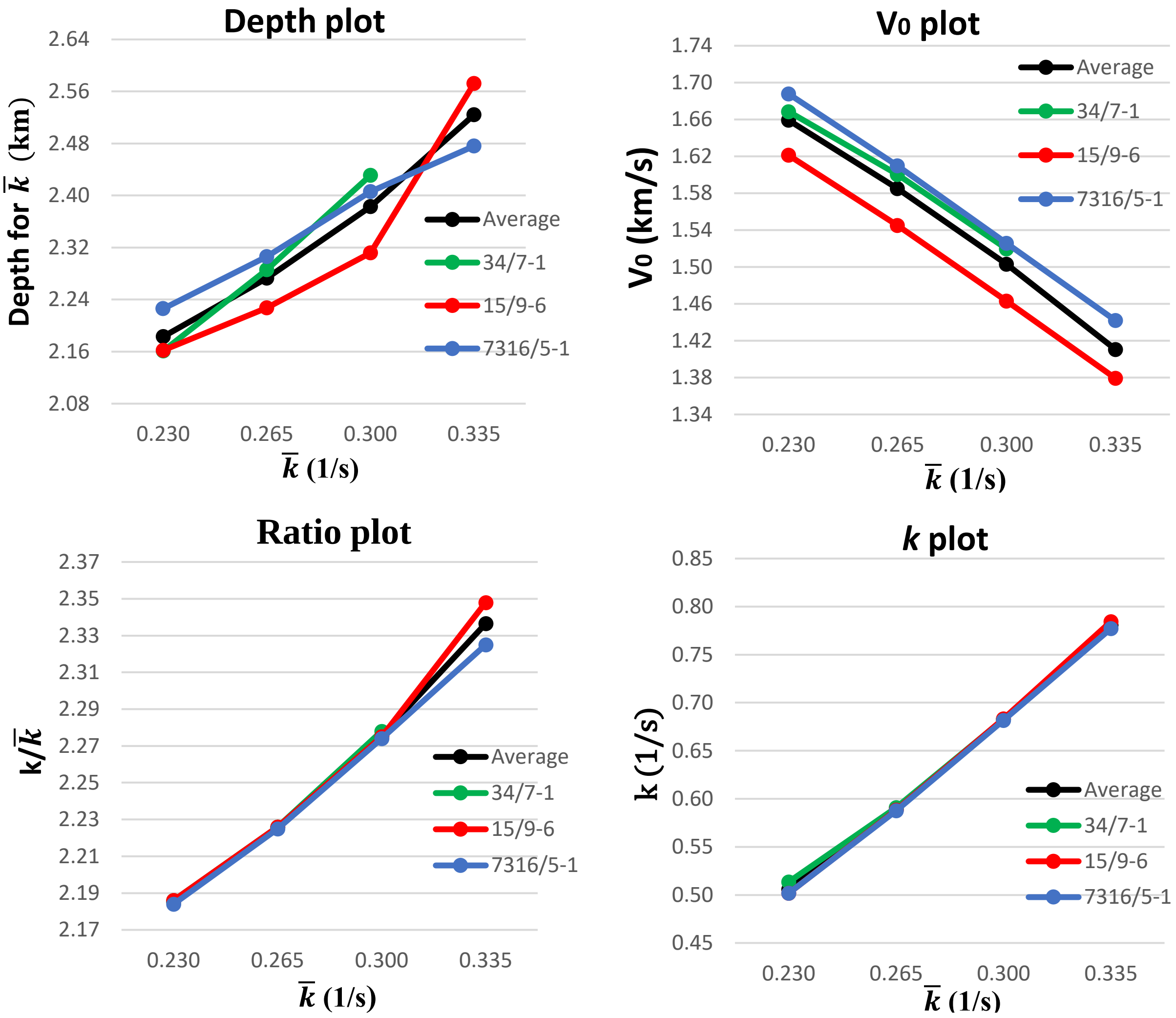


Figure 5.1: Well log 34/7-1. Both the trend lines for the sonic log (Vp - P wave velocity) and density log (RhoB) are showed on the Shetland group. Notice the volume clay cutoff (Vcl) at 75%. Points to the left of this line were excluded. It was based on gamma ray values (GR) being the red lines on the gamma ray log (left red line = sand line, right red line = 100% shale line). After cutoff, density and velocity are represented by the blue points, (black points are without cutoff). This difference is showed clearer on the sonic log zoomed in. Similar procedure was done on wells in the uplifted area.

5.1.2 Reference for average velocity.

We tested all the three not uplifted wells as potential references in the average velocity method. This is because the assumptions in the method dictates this should be possible if the wells are not uplifted. All the parameters associated with different $\bar{k}$ values are showed in figure 5.2 and table 1. The wells are from different areas with different lithology and properties (figure 5.3), however they yield very similar V_0 for a given $\bar{k}$. In general, not all wells have the $\bar{k}$ values which could be investigated, for instance well 34/7-1 have its highest $\bar{k}$ value at 0.3. The parameters vary with increasing $\bar{k}$ as showed in figure 5.2 and table 1. For all wells V_0 decreases with increasing $\bar{k}$,


Depth plot

V0 plot

Ratio plot

k plot

Figure 5.2: Showing graphical demonstration of table 1. Top left showing the depth extraction for a particular $\bar{k}$ value. Top right showing how the V_0 is close to 1500m/s for $\bar{k}$ equal to 0.3. Bottom left show how the $k/\bar{k}$ ratio varies as a function of $\bar{k}$. Bottom right showing the value of k as a function of $\bar{k}$. Note that well 34/7-1 did not have any $\bar{k}$ being 0.335, thus the lack of data. Note that the *k* and V_0 patterns would also be present when varying the $\bar{k}$ for the uplifted areas, the main difference is simply a higher V_0.

whereas $k/\bar{k}$ and k increase with increasing $\bar{k}$ “Depth $\bar{k}$» in table 1 is the average depth for $\bar{k}$. Although there is a pattern for the average depth for $\bar{k}$ in these wells, it is not a general pattern as will be showed on the uplifted wells later. The volume clay (V-clay) in table 1 is the average volume clay (from gamma ray) down to the average depth for $\bar{k}$**.** No clear volume clay pattern is observed between the wells, indicating that the velocity is relatively unrelated to the volume clay derived from the gamma ray log. The wells show very similar parameter values for a given $\bar{k}$ despite coming from very different areas. Net exhumation was calculated with each reference for each uplifted well with $\bar{k}$ = 0.3, the average net exhumation from these three per uplifted well are presented with standard methods later.

Reference wells	$\bar{k}$ (1/s)	Depth $\bar{k}$ (m)	V_0 (m/s)	$k/\bar{k}$	k (1/s)	V-clay (fr)
34/7-1	*0.23*	*2161*	*1669*	*2.19*	*0.51*	*0.44*
15/9-6	*0.23*	*2162*	*1621*	*2.19*	*0.50*	*0.55*
7316/5-1	*0.23*	*2226*	*1688*	*2.18*	*0.50*	*0.79*
Average	*0.23*	*2183*	*1659*	*2.19*	*0.51*	*0.60*
34/7-1	*0.265*	*2286*	*1600*	*2.23*	*0.59*	*0.44*
15/9-6	*0.265*	*2227*	*1545*	*2.23*	*0.59*	*0.55*
7316/5-1	*0.265*	*2306*	*1610*	*2.23*	*0.59*	*0.80*
Average	*0.265*	*2273*	*1585*	*2.23*	*0.59*	*0.59*
34/7-1	*0.30*	*2431*	*1520*	*2.28*	*0.68*	*0.44*
15/9-6	*0.30*	*2312*	*1463*	*2.28*	*0.68*	*0.54*
7316/5-1	*0.30*	*2406*	*1526*	*2.27*	*0.68*	*0.80*
Average	*0.30*	*2383*	*1503*	*2.28*	*0.68*	*0.59*
15/9-6	*0.335*	*2572*	*1379*	*2.35*	*0.78*	*0.52*
7316/5-1	*0.335*	*2476*	*1442*	*2.33*	*0.78*	*0.79*
Average	*0.335*	*2524*	*1411*	*2.34*	*0.78*	*0.66*

Table 1: Detailed parameters when testing different reference wells in the average velocity method. $\bar{k}$ = 0.3 was decided as the general reference. Well 34/7-1 did not have $\bar{k}$ higher than 0.3.

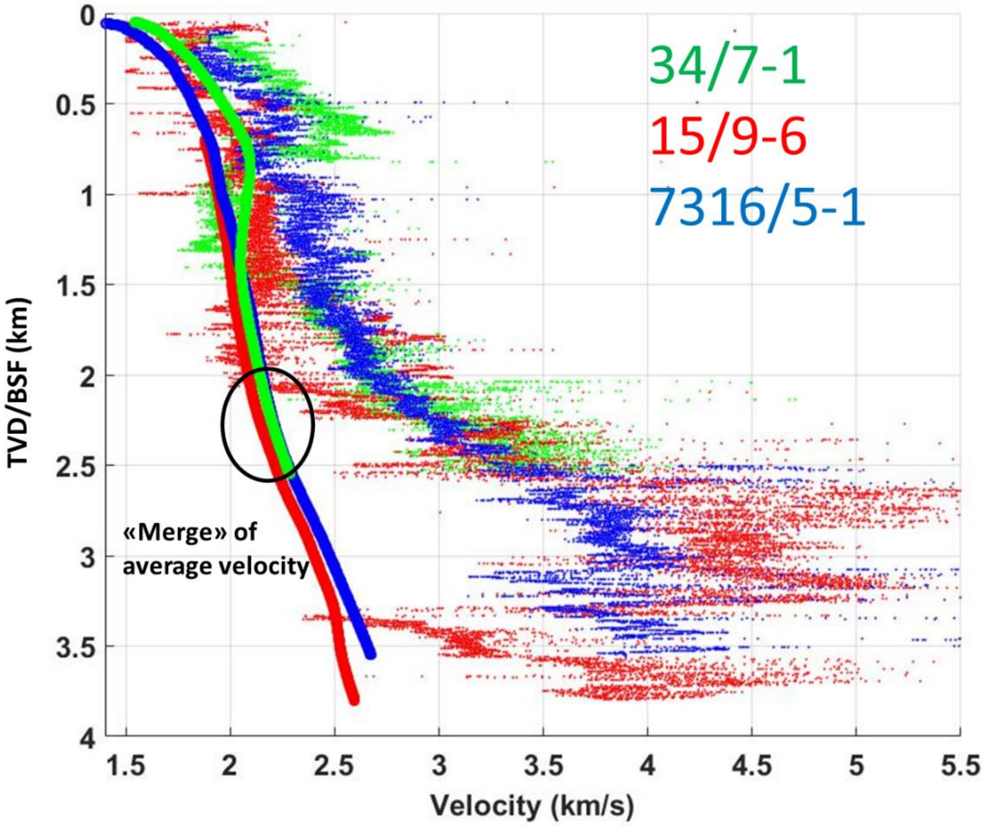


Figure 5.3: Velocity for the three reference wells. Small points indicate well log sonic interval velocity points whereas the solid lines show average velocity from check-shots. All the wells show around the same $\bar{k}$ and average velocity at the circle marked in black. These were around the depths for the different $\bar{k}$ values in table 1. The wells show similar parameter values despite being from very different areas; it relates possibly to the average lithology/acoustic properties being somewhat similar since the wells are not exposed to net exhumation.

5.2 Net exhumation on well data from all methods:

This section shows the net exhumation from all the wells in figure 4.1 for all the methods. The net exhumation for density (RhoB), P wave velocity (Vp), and the check-shot method are first exemplified in more detail on well 7121/4-1 with reference well 34/7-1 (figure 5.4 and 5.5). All the same methods were applied on the other wells as well.

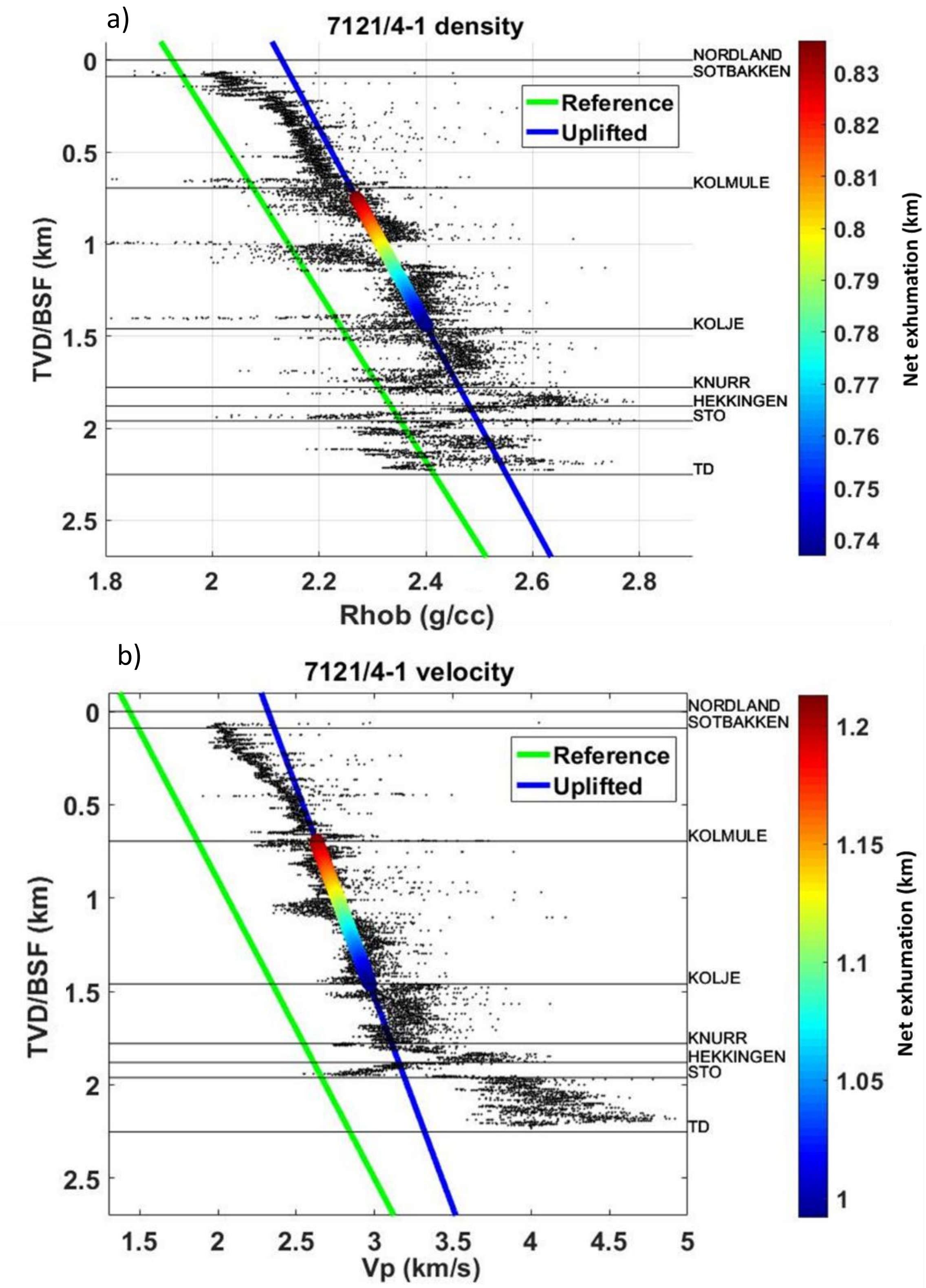


Figure 5.4: Example of net exhumation using standard methods on well 7121/4-1 – a) showing density log yielding average net exhumation 785m, b) showing velocity yielding average net exhumation 1100m. In this well the density/velocity gradients for the uplifted area and not uplifted area are fairly similar.

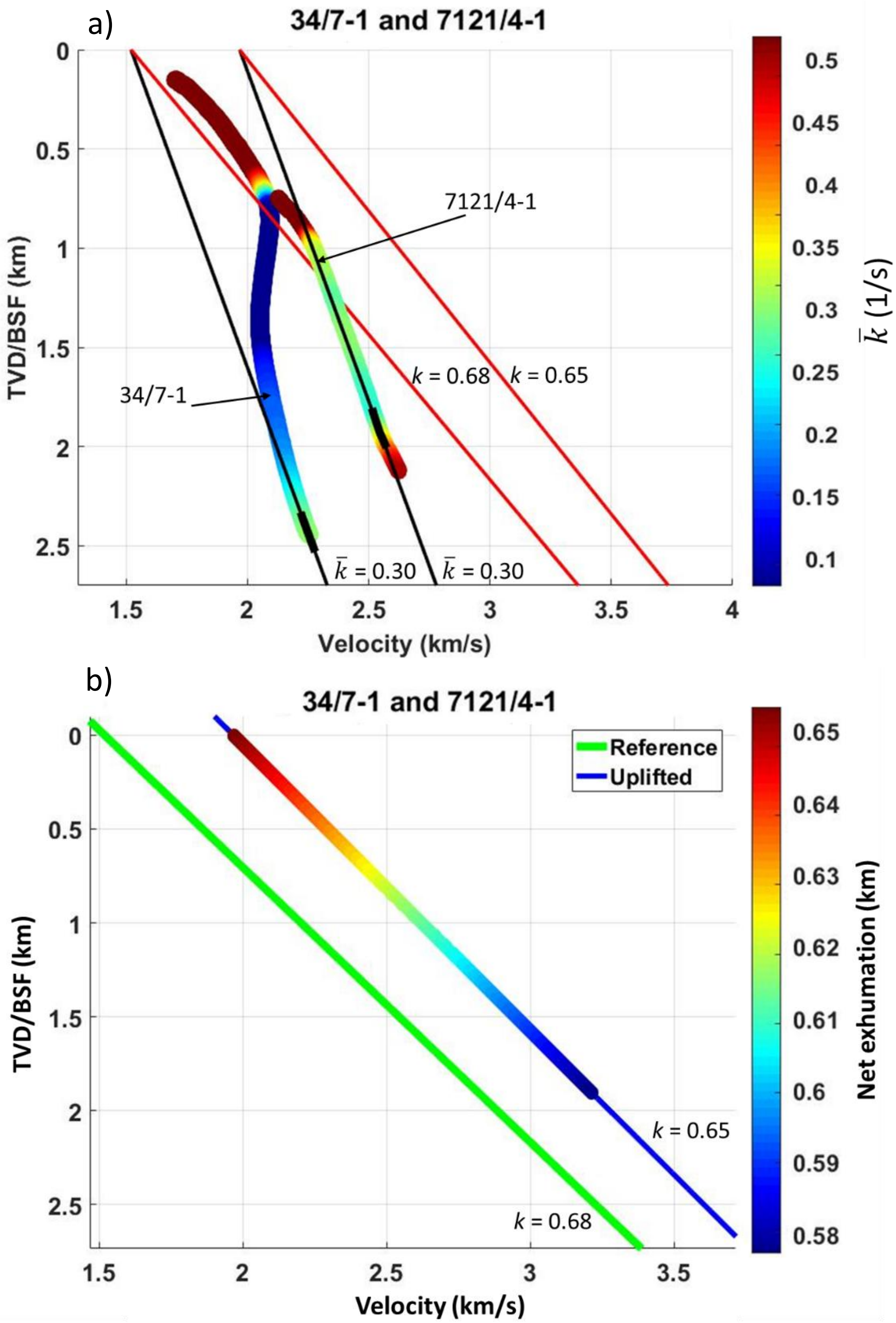


Figure 5.5: Example of net exhumation using the average velocity method ($\bar{k} = 0.3$), using wells 34/7-1 (reference) and 7121/4-1 (uplifted). a) showing the black lines resulting from regression based on $\bar{k} = 0.3$. The two red lines are the corresponding interval velocity lines after finding $k/\bar{k}$. In this example the $k/\bar{k}$ = 2.28 for k = 0.68 (reference 34/7-1), and $k/\bar{k}$ = 2.18 for k = 0.65 (7121/4-1). b) showing net exhumation as it varies with velocity because of the difference in *k*. The difference in net exhumation between top/base is not very large because the k gradients are only slightly different. Its plotted down to the average depth for $\bar{k}$ in the uplifted well.

Note how the $\bar{k}$ values in figure 5.5 are extracted from different depths in well 34/7-1 and 7121/4-1. These are the depth values corresponding to $\bar{k} = 0.3$ (showed in black). The depths are around 2.4km in well 34/7-1 and 1.9km in well 7121/4-1. Well 34/7-1 has velocity inversion giving low average velocity at depths 0.8-1.5km (due to the smectite rich Hordaland Group, see figure 3.3) (e.g Storvoll et al., 2005). We think it is necessary to go deeper in well 34/7-1 (2.4km) to get the same average lithology as well 7121/4-1 (1.9km). This is by entering the Cromer Knoll group. It is possibly necessary to add 500m (2.4km-1.9km) to 34/7-1 to make up for the "abnormal properties" associated with the Hordaland Group. The slightly different k values being k = 0.68 and k = 0.65 are related to different $k/\bar{k}$ ratios, it is also related to the $\bar{k}$ being from different depths.

Figure 5.6 show how net exhumation for the check-shot method vary based on the which reference well being used. They all show increase in net exhumation from SW to NE. An average net exhumation was then created for each uplifted well by taken the mean of these three net exhumation estimates. This is the one which is compared with standard methods later. Well 15/9-6 gives slightly higher net exhumation than the other wells, simply because of the lower V_0 for $\bar{k}$ = 0.3 (table 1). It's interesting to see how well 34/7-1 and 7316/5-1 yield almost the same net exhumation for a given uplifted well. This indicates a robustness where a reference well could come from completely different areas, given that you find the depth for the proper $\bar{k}$.

When finding the $\bar{k}$ values all the wells use $\bar{k}$ = 0.3, except 7117/9-1 and 7119/7-1 which use $\bar{k}$ = 0.25 and $\bar{k}$ = 0.33, respectively. 7117/9-1 does not have any $\bar{k}$ above 0.25, and 7119/7-1 does not have any below 0.33. This also meant these estimates of net exhumation correspond to references with similar $\bar{k}$ values (0.25 and 0.33), and from the same reference wells as the other estimates (table 2). 34/7-1 does not have a $\bar{k}$ above 0.3, thus the two other reference wells are used for net exhumation in 7119/7-1. All of this and additional parameters are showed in table 2. Despite using other $\bar{k}$ values, the net exhumation estimates from these two wells are included to have a more comprehensive database. The values (0.25 and 0.33) are considered relatively close to $\bar{k}$ = 0.3, thus any difference in net exhumation due to this is expected to be minimal. Well 7120/5-1 have its $\bar{k}$ = 0.3 at the shallow depth of 1231m as it is not present deeper down. A general pattern is also the increasing $k/\bar{k}$ with increasing depth. Again, no volume clay pattern is detected.

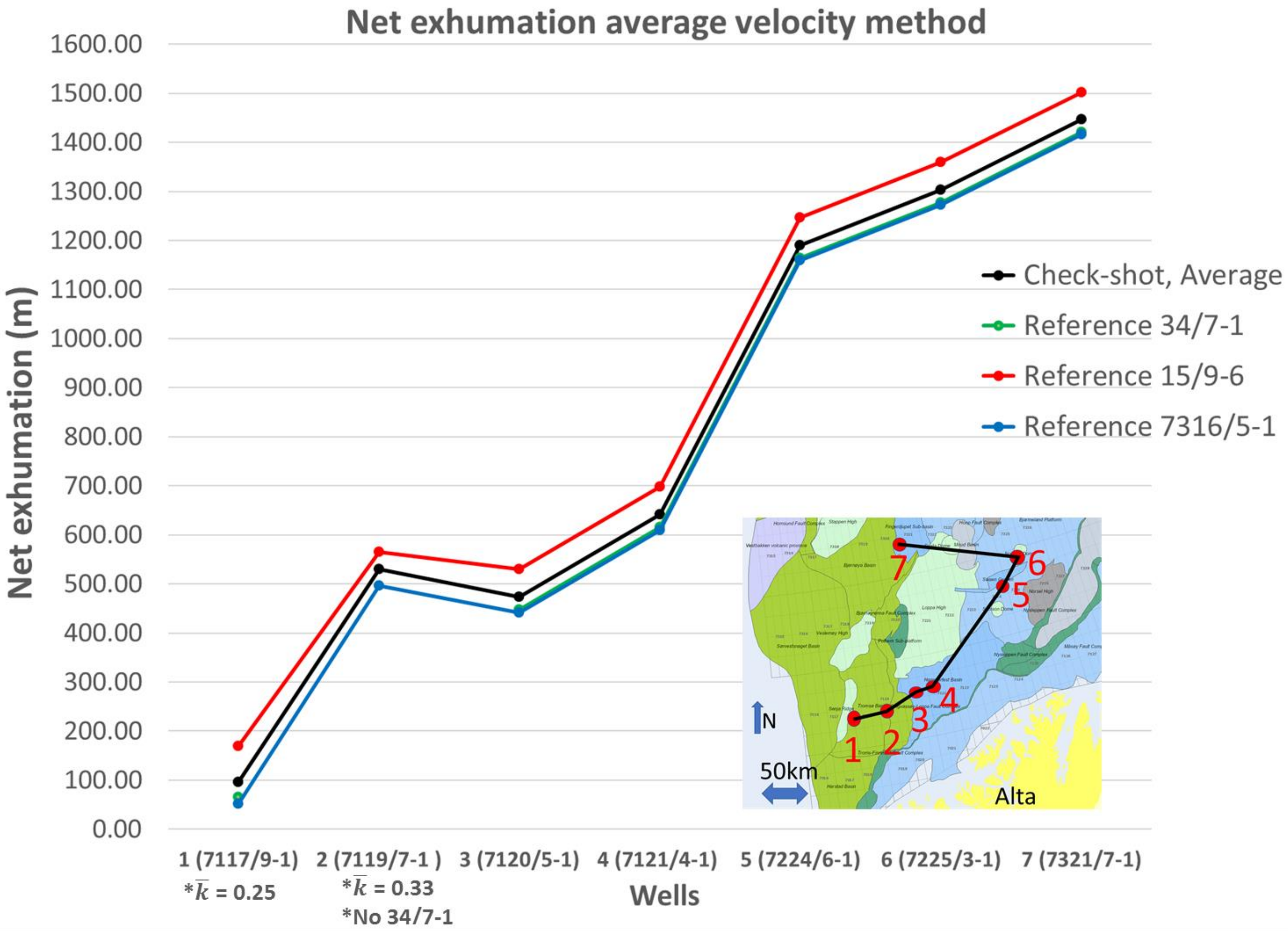


Figure 5.6: Net exhumation for each uplifted well using check-shot, based on the 3 different references and then the average net exhumation estimates from these three. Notice how $\bar{k}$ is 0.3 for every well except well 7119/7-1 and 7117/9-1 which used other values due to lack of data.

Uplifted wells - parameters						
Wells	**$\bar{k}$ (1/s)**	**Depth $\bar{k}$ (m)**	**V_0 (m/s)**	**$k/\bar{k}$**	**k (1/s)**	**V-clay (fr)**
7117/9-1	0.25	2350	1670	2.21	0.55	0.57
7119/7-1	0.33	2681	1854	2.28	0.75	0.43
7120/5-1	0.3	1231	1853	2.13	0.64	0.41
7121/4-1	0.3	1907	1967	2.18	0.65	0.62
7224/6-1	0.3	1710	2350	2.14	0.64	0.60
7225/3-1	0.3	1594	2428	2.12	0.64	0.49
7321/7-1	0.3	2817	2521	2.20	0.66	0.62
Other reference wells - parameters						
34/7-1	0.250	2236	1634	2.21	0.55	0.44
15/9-6	0.250	2202	1574	2.21	0.55	0.55
15/9-6	0.330	2562	1392	2.34	0.77	0.52
7316/5-1	0.250	2276	1642	2.21	0.55	0.79
7316/5-1	0.330	2471	1449	2.32	0.77	0.79

Table 2: Various parameters for the uplifted wells and extra references in the check-shot method. These were used to create net exhumation estimates. The parameters for reference wells with $\bar{k}$ = 0.3 are shown in table 1, whereas the other $\bar{k}$ reference values are shown here.

Figure 5.7 shows the average net exhumation from check-shots compared with standard methods. A general pattern is that the sonic log shows the highest amount of net exhumation, followed by the density log, and then the check-shot method. The net exhumation estimates derived from average velocity are considerably lower than those derived from sonic (100m - 750m lower, average ~450m lower), and slightly lower than those from density (-150m - 650m lower, average ~200m lower). The net exhumation for each method generally increases from well 1 to 7 (SW to NE). The average velocity method shows the steadiest increase in net exhumation from well to well; whereas the variation for the sonic and density derived net exhumation estimates are more significant. The net exhumation estimates from check-shot data are more similar to the density results when compared to the sonic results.

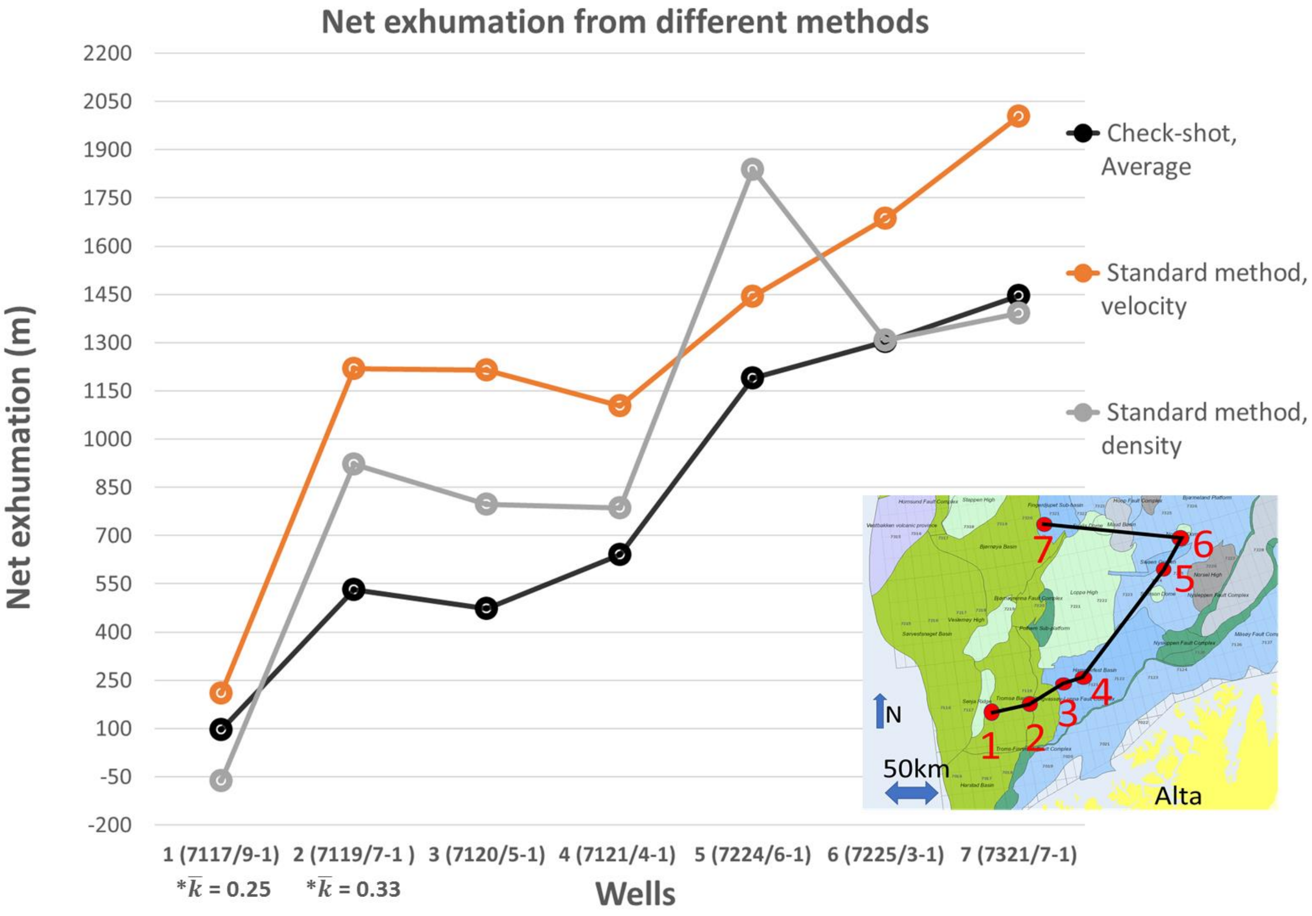


Figure 5.7: Net exhumation for all the methods. The net exhumation from the average velocity method use the average from figure 5.6, whereas standard methods use reference well 34/7-1. Sonic data shows generally the highest amount of net exhumation, followed by those from density and then check-shot.

6. Discussion

All the results, further testing, uncertainty and comparison with other studies are discussed in this section.

6.1 Comparison of net exhumation from different methods

According to Storvoll. et al (2005), over-pressured Jurassic sediments from Haltenbanken do not show significantly higher porosity/bulk density than its hydrostatically pressured equivalent, however it shows lower velocity. They suggest the lower velocity could be a result of less elastic compaction (not higher porosity). Therefore, proxies for compaction (e.g velocity) do not necessarily always provide a good estimate of compaction. The Shetland shales are known to be dominated by overpressure in certain regions (looking at various well reports, NPD, 2017), possibly meaning the reference shows too low velocity. If there is more overpressure in the Shetland Group than the compared Barents Sea Formations, then net exhumation could be overestimated by sonic logs. This might explain the difference in net exhumation between density and sonic. However, quantifying the contribution of overpressure is difficult as separating mineralogy and overpressure from compactions trends is challenging (Marcussen et al., 2009).

The lower and less varied net exhumation estimates from check-shots might be explained by its ability to be less affected by abnormal lithology/velocity. Firstly, since it investigates a larger interval compared to sonic/density, overpressure effects are less dominant because of the large interval (~2km). Secondly and more importantly, since the $\bar{k}$ values are found at different depths thought to resample similar average lithology/acoustic properties, then the overpressure might not be as relevant as its indirectly corrected for. This could explain why the net exhumation estimates are closer to the those derived from the density log, as these estimates might also be less affected by overpressure. Therefore, the net exhumation from check-shot and density could be more correct than those from sonic. The consistency in net exhumation estimates from check-shots (e.g. figure 5.6) could be explained by the large interval (2~km), it does not matter if a certain formation is missing/small.

Another reason for lower net exhumation from average velocity is related to the k values in uplifted areas, they are generally slightly lower than those in the reference. The example in figure

5.5 had k = 0.65 for 7121/4-1 and k = 0.68 for the reference. This means the uplifted trend line goes towards the reference trend line. This yields lower net exhumation when taking the average. However, it is only 35m lower net exhumation than if we were to use k = 0.68 for 7121/4-1. This means it does not generally explain the major differences between the methods.

Below are some additional explanations for individual wells when it comes to standard methods, which might explain why those methods show varied results. The uncertainty for the check-shot method is possibly more of a general uncertainty as opposed to the individual wells.

- **Well 7119/7-1** uses the Nygrunnen Group for sonic/density regression because the Kolmule Formation is not reliable (too deep, thin and inverse velocity trend). The Nygrunnen Group is chosen because of the similar gradients as the reference in well 34/7-1.
- **Well 7120/5-1** has very different gradients for the Kolmule Formation (density/sonic) compared to the 34/7-1 reference. This might yield a too high net exhumation for density/sonic. This general gradient issue is also present with other wells.
- **Well 7224/6-1** has a very thin Kolmule Formation with considerably different gradients for density/sonic when compared to the Shetland reference. Also, the density log in the Kolmule Formation shows very high values on average (2.45g/cc), whereas the sonic log shows around 2.5km/s. These are possibly unlikely density/velocity pairs. This make net exhumation from density relatively high. It could be due to some logging error in either the density log or the sonic log. It was attempted to use the Snadd Formation, but then net exhumation would be almost 2500m from the sonic log. This is unlikely when compared to other authors. There is simply too much uncertainty in having reliable data and a proper representative regression from this well. This well clearly demonstrates this type of difficulty when using standard methods to estimate net exhumation.
- **Well 7225/3-1** uses the Snadd Formation and down to the top of the Tempelfjorden Group when doing linear regression. This is because the Kolmule Formation has no data and is too thin, and these other intervals seem to plot with a somewhat matching gradient as the reference.
- **Well 7321/7-1** has no density log in the Kolmule Formation, but only in the Kolje Formation. Therefore, both the Kolmule and Kolje Formations are used for net exhumation from sonic/density logs. This was done to have consistency for the well.

6.2 Comparison with other studies:

The results in this study were also compared to the results of other authors (table 3). Most of their results are close to the sonic estimates of this study, but relatively varied. Again, the check-shot method shows lower net exhumation when compared to the estimates of these authors. Johansen (2016) used several methods, but the sonic derived net exhumation is showed here. The net exhumation from Baig et al. (2016) were based on the average from sonic, shot gathers and vitrinite reflectance; and from Henriksen et al. (2011a) the average from thermal methods, compaction methods and apatite fission track analysis. Net exhumation is also showed from Storvoll et al. (2005), which he based on shale interval velocities from Liu et al. (1992).

Net exhumation (m)

Methods **Wells**	**interval shale velocity**	**interval shale density**	**Check-shot**	**Johansen, (2016), interval shale velocity**	**Baig et al. (2016) (average, several methods)**	**Henriksen et al. (2011) (average, several methods)**	**Storvoll et al. (2005), as modified from Liu et al. (1992) interval shale velocity**
1 (7117/9-1)	211	-64	96	287	200*	100*	x
2 (7119/7-1)	1219	923	531	x	750*	700*	750.00
3 (7120/5-1)	1215	798	473	x	800*	1400*	1015
4 (7121/4-1)	1103	787	641	1150	900*	1050**	x
5 (7224/6-1)	1443	1839	1190	1434	1500*	1750*	x
6 (7225/3-1)	1685	1307	1303	1600**	1600*	1800*	x
7 (7321/7-1)	2004	1392	1446	1981	1850*	1800*	x

Table 3: Net exhumation estimates of this study (green) compared with Johansen (2016), Baig et al. (2016), Henriksen et al. (2011a) and Storvoll et al. (2005). Note that ** (7225/3-1) from Johansen (2016) was based on sandstone diagenesis, whereas ** (7121/4-1) from Henriksen et al. (2011a) was based on core porosity in sandstones. * Denotes being from retrieved from net exhumation maps as opposed to a specific well.

If the magnitude of net exhumation from the check-shot method is more correct than other studies/methods, an implication is possibly that prospectivity until now has been underestimated. The Barents Sea might not have been subject to as much uplift and erosion as indicated by others. This means good reservoir properties might be preserved in areas earlier thought to be completely non-favorable, this is with respect to properties such as porosity, net to gross and so on. Whether a lower net exhumation would be favorable/not favorable for a particular area would of course have to be investigated further. However, properties such as porosity would be generally higher if exposed to less net exhumation.

6.3 Uncertainty in standard methods

A major issue when only using a single reference trend is the difference in gradient (*k*) between the reference and uplifted trend. If the gradient is different, the average is used as the net exhumation (as demonstrated in the standard compaction method section). However, it becomes arbitrary because the net exhumation is now a function of the thickness of the rocks in the uplifted area (figure 6.1). This is irrelevant to uplift as the whole formation must have been uplifted equally. Authors do explain why there are different velocity/depth gradients (Marcussen et al., 2009, Storvoll et al., 2005), but few imply how to handle net exhumation if the gradient is different. For now, it has probably implicit been labeled as “acceptable” uncertainty (since you assume that similar lithologies/properties are chosen). A similar *k* is thus ignored as a criterion for net exhumation estimates. Even when using the well accepted Kolmule Formation, the gradients could be very different from the reference as demonstrated on well 7120/5-1 (figure 6.1). This is different from the example in figure 5.4 where the gradients are more similar. Clearly, net exhumation would depend on the selected thickness or the depositional thickness of the unit. The top yields 0.8km net exhumation whereas the bottom 1.6km. This factor might explain “spikes” in net exhumation when using standard methods. A solution might be to use several different reference trends depending on the trend in the uplifted area, or to use trends with more terms. The goal could also be to have matching gradients. However, we believe no trend line is the general solution for all uplifted areas. The gradient problem is probably even greater when the desired formation is missing, since then you are freer to choose formations/groups. Another method would be to use physical models as most existing methodologies utilize statistical manipulations (Corcoran and Doré, 2005).

It’s as mentioned common practice to apply a volume clay cutoff for shale compaction trends in the standard methods. After a lot of internal testing we could see that the application of this filter sometimes changed the trend lines significantly, other times not. Thus an increase in gamma ray values (volume clay) isn’t necessary related to a decrease in for example velocity. It is as mentioned much more sensitive to for example smectite content, which seems to a certain extent to be unrelated to significant changes in the gamma ray log (Bjørlykke, 2014, Thyberg et al., 2009). In the wells used in this study, sometimes the velocity data continued in the same pattern despite fluctuations in the gamma ray, and sometimes the other way around. Furthermore, the volume clay cutoffs should possibly be based upon some criteria. For instance, Baig et al. (2016) chose 80% for shale net exhumation estimates, but has no explanation behind this number. Marcussen et al. (2009) choose 40% as a criterion for a creating mudstone velocity depth trends. The difference could be considered insignificant, and where any cutoff ranging from 40-80% gives the same net exhumation (and trend lines), but this should be elaborated upon and not inferred implicit by the reader. However, some internal testing shows that when approaching high volume-clay cutoffs (figure 6.2), regression could become unreliable and net exhumation will vary with tens to hundreds of meters depending on the volume clay cutoff. This is exemplified on well 7120/5-1 (figure 6.2). The cutoffs were applied on both the reference well and the uplifted well. Obviously, the data points which are included for a certain volume clay cutoff would depend on the chosen gr value corresponding to the max shale line and minimum sand line (e.g in figure 5.1). Thus, there is an uncertainty related to choosing these values. In this well the different volume clay cutoffs mainly changed the density/velocity-depth gradients in the uplifted well, this is due to the stability in data point spread in the reference well 34/7-1. When varying the volume clay cutoffs, it mainly affected the net exhumation derived from the density log compared to those derived from the sonic log. Volume-clay cutoffs near 0.8 would not yield reliable regression for the density log (the density/depth gradient became almost vertical), thus the volume clay cutoffs near 0.8 are only shown as an extreme unrealistic scenario. However, the net exhumation from density is for example 200m lower when using a volume clay cutoff at 0.7 compared to 0.55 (figure 6.2). Both could be realistic, and they result from different gradient/V_o pairs. Net exhumation for the sonic reaches around 150m uncertainty depending on cutoff. This emphasizes the need for a more deterministic way to choose volume clay cutoffs as opposed to just selecting a number.

It almost seems like it is a belief that a good reference trend is proportional to the number of wells giving input data. The issue arises mainly when using generalized trend lines from several areas (e.g Storvoll et al., 2005, Japsen, 1999) to estimate net exhumation. When the reference wells are from many different areas (North Sea + Norwegian Sea), it is difficult to argue that such data would fit a specific uplifted area with specific properties. It would more likely represent an average of the input. The number of wells in what locations would obviously influence the resulting trend lines. More wells with smectite rich shales and overpressure dominate different regions (Storvoll et al., 2005), and the ratio of such wells to other wells will thus affect the reference trend line; and is not necessarily representing a proper reference for a specific composition with specific pressure in the Barents Sea. Another example could be how the Nordland Group shows increasing velocity-depth gradient in the northern North Sea compared to the southern part, partly due to different provenance (Marcussen et al., 2009). If the Nordland Group is to be used as a reference unit for a particular study; should one thus represent "all the variation equally" when creating the reference, or is it necessary to look at what reference is the most relevant for a particular uplifted formation/group. And then it implies the sufficiency of a single properly chosen reference well/formation, assuming it is found. Maybe it is widespread practice to use multiple wells because it is hard to determine the relevant reference, and where people are limited to general and simple well log descriptions; thus the "average" is presented with the idea of it being robust. It's of course not realistic to know all the properties of a large lithological interval. However, it's again possible the physical properties are highly connected to the gradient *k*, which means very different gradients between the reference and uplifted area should be explained whenever possible, since it clearly affects net exhumation estimates as seen in figure 6.1.

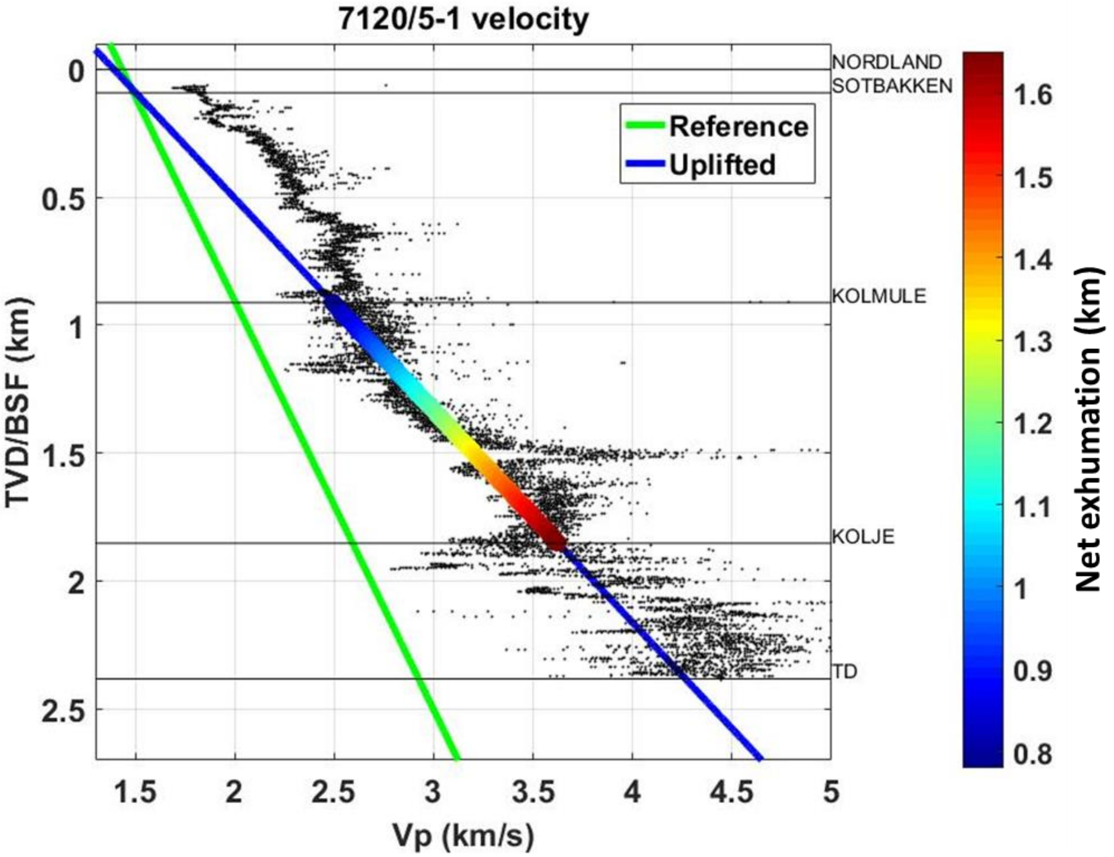


Figure 6.1: Example of variation in net exhumation on well 7120/5-1 versus reference well 34/7-1. Notice the big difference in gradient (*k*) between the reference and the uplifted area. Because of this the net exhumation varies across Kolmule from 0.8km (blue color) to 1.6km (red color). Clearly, the net exhumation would vary a lot depending on the depositional thickness of the Kolmule Formation and/or the included formations/groups.

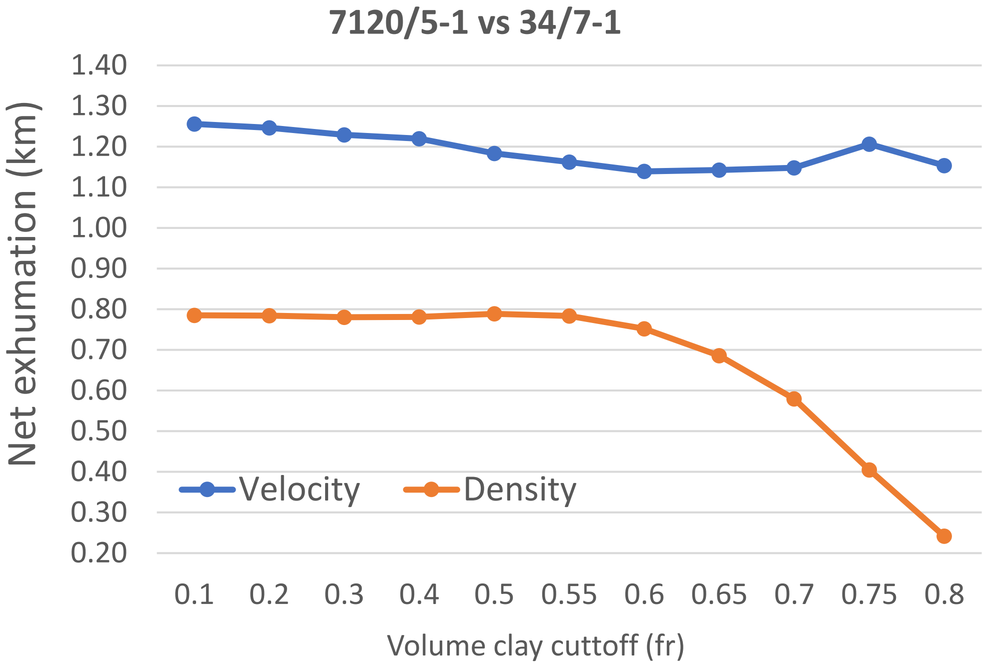


Figure 6.2: Showing how net exhumation varies as a function of volume clay cutoff in well 7120/5-1 versus the reference well 34/7-1. It's based on the Shetland Group (reference) and the Kolmule Formation in the uplifted area. The cutoffs were applied in both the uplifted well and the reference well. The average net exhumation does not vary significantly for the velocity log, but it does for the density log due to the trend lines becoming unstable/changed for high cutoffs. This demonstrates how volume clay is a critical issue to address. One cannot just "choose" a number.

6.4 Uncertainty by using average velocity

6.4.1 Net exhumation from varying the gradients

As mentioned earlier it is very important to look how the net exhumation estimates vary when changing $\overline{k}$ in the check-shot method. Two examples are shown below. They are conducted for single wells for both the uplifted area and the reference to ensure the k and $\overline{k}$ values are present for each case. In addition, as already shown, only subtle differences in parameters are present for each reference well for a given $\overline{k}$. The tests are conducted between well 7316/5-1 (reference) and 7121/4-1 + 7321/7-1 (figure 6.3). Notice how a higher $\overline{k}$ yields lower net exhumation. As showed in table 1 for the reference wells, the general pattern is that V_0 gets lower with increasing $\overline{k}$ and k

gets higher with increasing $\overline{k}$. This is also the case for the uplifted wells. This is a result of simply geometry; the depths where the different $\overline{k}$ values are extracted from (within a well) does not commonly vary with more than a few hundred meters, meaning that a slight increase in $\overline{k}$ gives a lower V_0. k then gets higher when using equation 10 because of the lower V_0. The difference between the uplifted V_0 and the not uplifted V_0 yields a ΔV_0 (for a given $\overline{k}$). This value is relatively constant no matter the $\overline{k}$. The net exhumation is decreasing with increasing $\overline{k}$ simply because it relates to higher k values. Thus, since the ΔV_0 is almost fixed, the net exhumation is a function of k and geometry. This concept is demonstrated graphically in figure 6.4 with these two wells.

Even though the net exhumation for well 7321/7-1 varies from around 2km to 1km, when using $\overline{k} = 0.23$ and $\overline{k} = 0.37$, respectively (Figure 6.4), these two extreme values are not considered realistic. This is because the corresponding V_0 values in the reference well are not considered probable, these are around 1.7km/s ($\overline{k} = 0.23$) and 1.35km/s ($\overline{k} = 0.23$), respectively. The assumption here is that V_0 in the reference must represent a physical value and cannot be a statistical artifact. It might be the velocity the average lithology being investigated would have at seabed. Coarse Sand can have velocities up to 1.8km/s right under the seabed, whereas pure clay around 1.5km/s (Hamilton et al., 1971). Due to the main lithology in the investigated basins being clay dominated (e.g Storvoll et al., 2005), the V_0 for a such a large composite lithology should probably be closer to the V_0 of clay rather than sand. Therefore, I argue the reference V_0 should probably lie between 1.5km/s to 1.6km/s. This means realistic net exhumation estimates are most likely constrained to $\overline{k}$ values yielding V_0 values around 1.5-1.6km/s in the reference wells. For well 7321/7-1 this would indicate around +- 150m net exhumation. This is by looking at the variation of net exhumation corresponding to the V_0 reference range of 1.5-1.6km/s. Well 7121/4-1 would yield around +- 50m net exhumation when using the same principle. Uncertainty thus increase with increasing exhumation, but it is relatively low for lower net exhumation estimates. It was attempted to see a correlation of V_0 to the volume clay and gamma ray, but due to the velocity not being very strongly related to gamma ray (for example Smectite), it was hard to see any pattern.

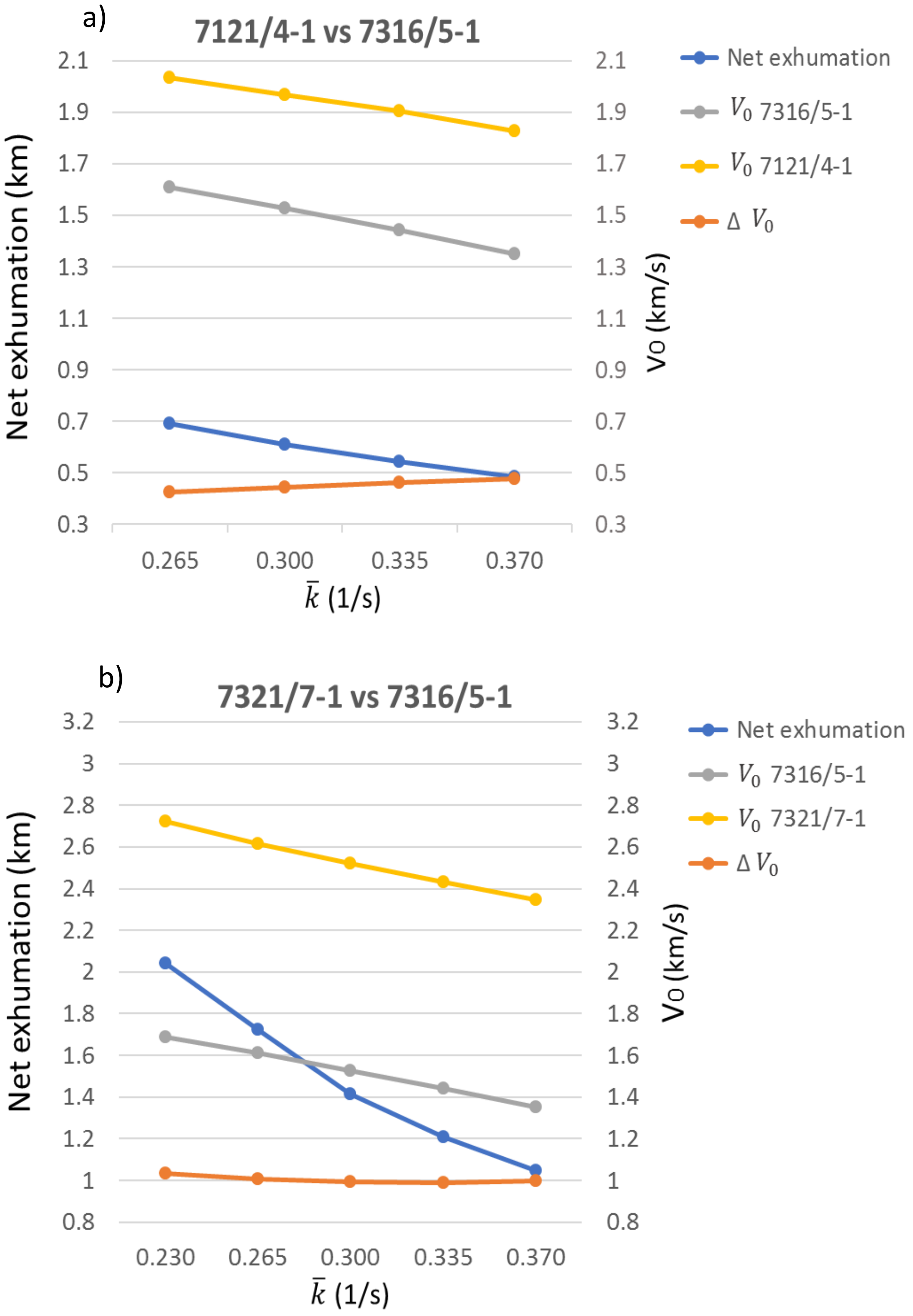


Figure 6.3: Net exhumation, Δ V_0, and V_0 for scenario 7121/4-1 (a) and 7321/7-1 (b). It is shown as function of varying $\bar{k}$ and using the reference well 7316/5-1. Since Δ V_0 is more or less constant for any $\bar{k}$, then net exhumation varies as a function of the change in $\bar{k}$ and thus k.

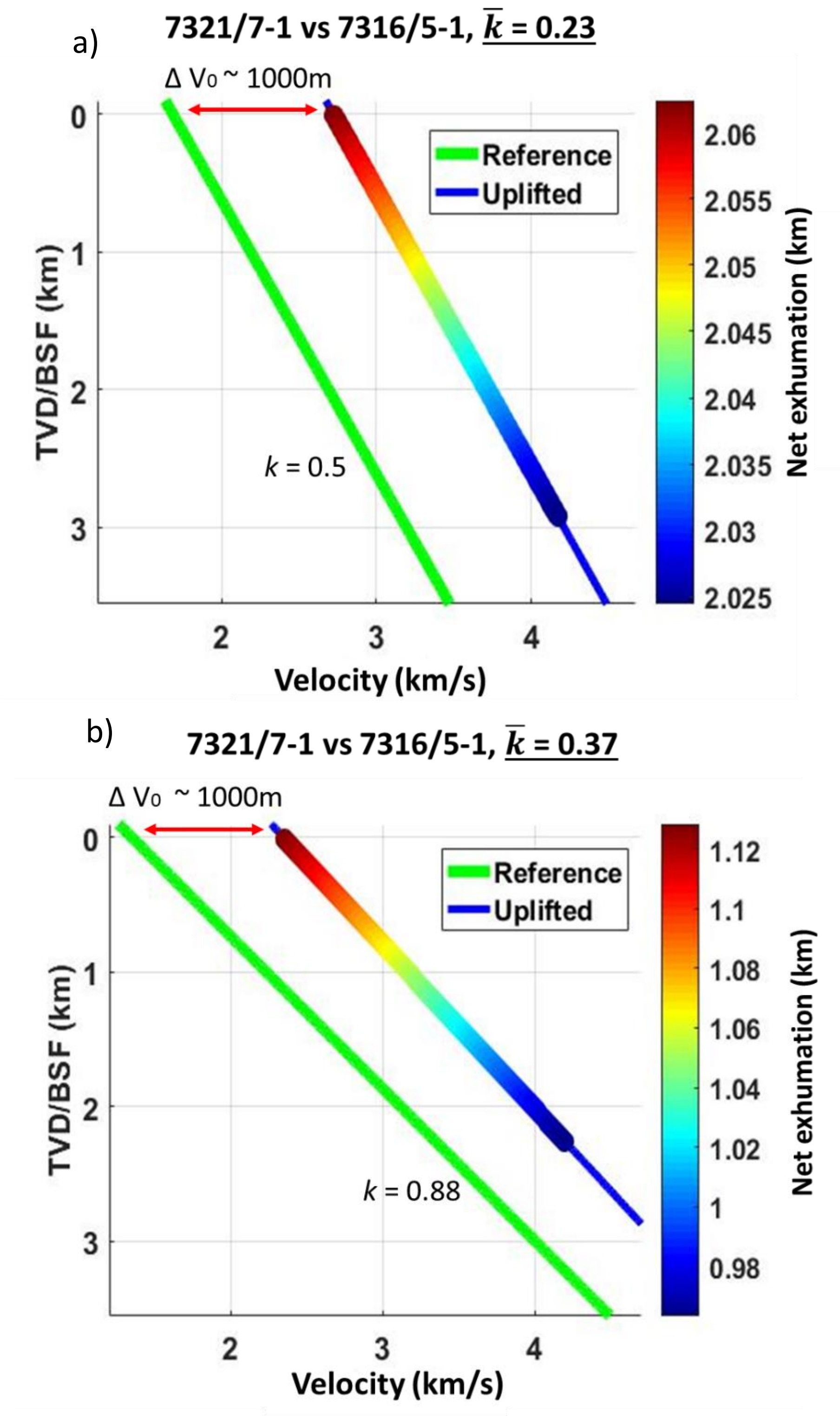


Figure 6.4: Net exhumation for wells 7321/7-1 (uplifted) and 7316/5-1 (reference) using the check-shot method. $\overline{k} = 0.23$ (a) and $\overline{k} = 0.37$ (b). This serve as a graphical demonstration of the end points ($\overline{k} = 0.23$ and $\overline{k} = 0.37$) in figure 6.3. The ΔV_0 is almost constant in both cases, meaning the net exhumation is a function of the variation in gradients *k*. A lower *k* (a) yields much higher net exhumation compared to a higher k (b).

6.4.2 Multiple depths for a gradient

It was also necessary to test the non-uniqueness of a particular $\overline{k}$, meaning that in some cases a given $\overline{k}$ could be present at various depths in a well, giving rise to different V_0 and net exhumation estimates. This is demonstrated on well 7225/3-1 (figure 6.5). Two scenarios use $\overline{k}$ = 0.3, but at very different depths. The net exhumation estimates corresponding to the deep $\overline{k}$ = 0.3 yields net exhumation of 1133m, whereas the shallow one give 1277m of net exhumation (using the reference well 34/7-1 from table 1, $\overline{k}$ = 0.3). The reason the average velocity is not increasing linearly and has the very low $\overline{k}$ around 2km is related to the interval velocity being relatively low over a large interval around that depth, before increasing again. It's similar to the effect of the Hordaland Group in well 34/7-1 where it's also possible to see the same $\overline{k}$ = 0.3 at shallower depths. $\overline{k}$ = 0.3 can be seen in well 34/7-1 and 7121/4-1 at just below 1km depth (figure 5.5 as showed earlier). However, these depths were considered being located too shallow to have representative data.

At great depths (for example >2km), the change in V_0 for a particular $\overline{k}$ resulting from different depths is not significantly large. The example above is probably a bit extreme, as most wells had more subtle changes, but it demonstrates the point. V_0 is not changing with 500m/s for instance, but only around 150m/s (figure 6.5). The likelihood for having the same average lithology would probably increase at greater depths, which means the compared rock columns are more reliable. This means the same $\overline{k}$ at various depths will not affect the net exhumation estimates to a considerable extent assuming you use a relatively large depth in both cases. It also makes sense intuitively as the average velocity is a function of the whole overburden, and therefore cannot change significantly at greater depths. Being practical, the $\overline{k}$ would always have a high value at very shallow depths (as indicated by the red gradient colors), and then it would decrease to 0 at infinite depth (theoretically). Local variations in between give rise to variation of $\overline{k}$. Thus, the practical ranges to extract the value could for example be between 1.5-4km. Or one could choose the $\overline{k}$ closest to a particular depth. However, this was also difficult to accomplish as the different wells sometimes had $\overline{k} = 0.3$ only at very different depths. For well 7120/5-1, $\overline{k} = 0.3$ was only found at less than 1500m depth whereas for well 7321/7-1 it was only found at more than 2500m depth (table 2).

A consequence of the potential different depths for a given $\overline{k}$ value, could mean that $\overline{k}$ is nothing more than an arbitrary parameter showing how the interval velocity changes relative to the average velocity at that depth. If this is the case then $\overline{k}$ says little very about the "average lithology". However, although not understanding all the aspects with the method, it's interesting to see how we get the stable net exhumation estimates close to those derived from density logs.

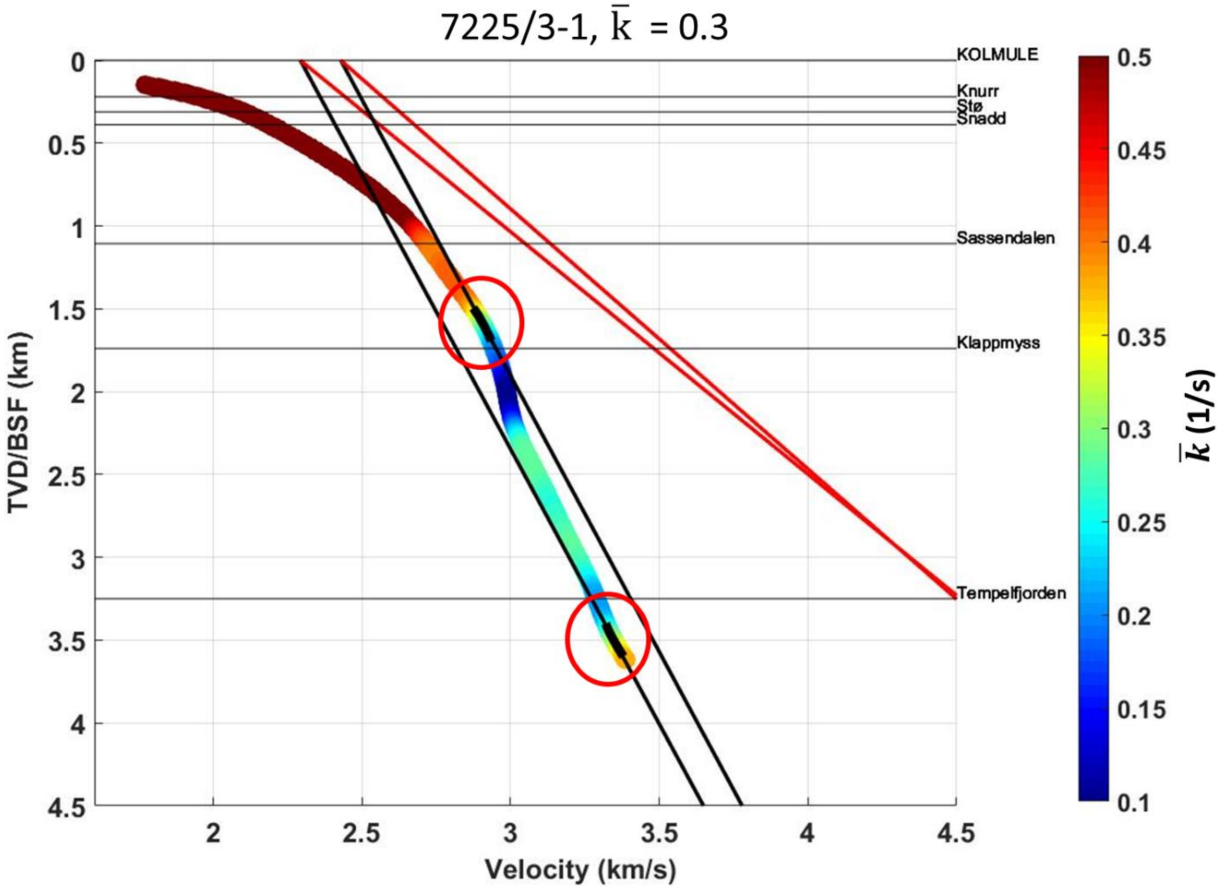


Figure 6.5: Average velocity for well 7225/3-1. V_0 and k varies for two scenarios as a function of having a particular $\overline{k}$ (0.3) at two different depths highlighted with the two red rings. These depths are separated with almost 2 kilometers. The V_0 is differing with more than hundred meters. The net exhumation difference is around 150m between them when comparing to the 34/7-1 reference, 1277m net exhumation for the shallow $\overline{k}$ and 1133m for the deep $\overline{k}$.

6.5 Significance of parameters

Al-Chalabi (1997) argues for the lack of a physical meaning of V_0 and k, as many combinations of them can be valid when performing regression on a given dataset. The uncertainty is thus very large on spiky data sets as when using the sonic/density logs. He further argues that k has often been mentioned in the literature as describing the compaction factor of a lithological unit, but because of uncertainty the parameter is not physically significant. He uses the same argumentation for V_0, where it cannot be used as information about sand/shale ratio. We believe the arguments of Al-Chalabi (1997) are mainly relevant for sonic/density intervals which are very influenced by spikes in the data, and if the lithological column of interest is very thin. However, since average velocity from check-shots have significantly less spikes, we argue that the non-uniqueness is significantly less when performing regression ($\overline{k}$) on average velocity. It's also represents a greater lithological column reducing uncertainty. This means V_0 could possibly be inferred as a physical property of the lithological column above the depth of $\overline{k}$.

Even when using sonic/density data, there are obvious reasons for the change in V_0 and *k*. For instance, a general pattern is that an uplifted area shows a higher V_0 than not uplifted areas. This is especially the case if the gradient is the same. Typical observations indicate V_0 ranging from 1500-1750 m/s in the not uplifted areas, and going over 2500m/s where there is almost 2000m uplift (well 7321/7-1). When looking at other groups and formations, in the case of a low *k* (or even negative); it could be related to for example smectite presence/overpressure (for example in the Hordaland Group, figure 2.2). A high *k* could on the other hand indicate the presence of easily compacted sand (for example in the Nordland Group) (Marcussen et al., 2009, Storvoll et al., 2005). The *k* would in these cases clearly represent a physical indication. Whether a minor change in V_0 and *k* is significant should be investigated further. The cause for a given *k* and V_0 could of course arise from many different scenarios, however in many cases it seems very explainable.

Data relatively deep in the subsurface gives more uncertainty in V_0 when compared to it being shallower in the subsurface. This is equivalent to moving a stick; the outer parts of the stick move more than the inner part (in actual meters). This has nothing to do with the regression of the data itself, but when extrapolating the value up to the seabed. Thus, the longer the stick (deeper burial of a certain formation) the more the outer part (seabed-V_0) moves. This would be the distance from the dataset and up to the sea-floor. A tiny difference in smoothing/regression on data at greater depth would then give a significant impact on the V_0, this emphasizes especially how V_0 is a factor with possibly greater uncertainty than *k*, and it is not necessary a physical value. As an example, on the Shetland shales in well 34/7-1 there will be uncertainty relating to V_0 depending on volume clay cutoff. When creating the sonic reference trend for the Shetland Group in this well, V_0 could vary around 200m/s depending on different reasonable volume clay cutoffs, thus it has the "long stick" phenomenon. By adding more wells this could possibly could reduce this type of uncertainty.

7. Conclusion

Estimating net exhumation using check-shot data and average velocity data has its main benefit of using larger lithological intervals compared to standard shale compaction trends. There is no need to choose a specific shale lithology. Since the whole rock column and thus "average lithology" is being uplifted, it indicates the viability of using average velocity if a similar average lithology can be found in the reference well. We postulate that similar average lithology can approximately be found at depths below seafloor corresponding to similar values of certain gradients ($\overline{k}$) of how the average velocity changes with depth. This is because the $\overline{k}$ ranges are more or less preserved when subject to net exhumation. A given $\overline{k}$ for an uplifted and a reference area would then yield two V_0 values, which can be used to create linear velocity trend lines, which gives net exhumation.

In general, net exhumation for the 7 studied wells in the Barents Sea show less magnitude from check-shot data when compared to estimates from density logs (100m-750m less ~ average 450m less), and sonic logs (-150m-650m less ~ average 200m less). The high net exhumation estimates from sonic compared to density might be explained by the Shetland Group having more overpressure than similar formations in the Barents Sea. The large variation and difference in gradients (*k)* for uplifted shales compared to the Shetland shale reference give large uncertainty in net exhumation estimates from standard methods. There is also uncertainty for standard methods when the desired formation is missing, along with handling different volume clay cutoffs.

The lower magnitude of net exhumation by using average velocity can possibly be explained by its ability to be less affected by effects such as overpressure. It's possibly related to the similar $\overline{k}$ values, which might yield equivalent average properties in the uplifted /not uplifted areas. Its stability/lack of "spiky net exhumation estimates" between wells is probably related to the large depth interval of investigation. Uncertainty for the check-method is mainly related to the validity of the primary assumptions, knowing which V_0 and $\overline{k}$ to use, along with handling multiple depths for a given $\overline{k}$. Additional work should be done to test the validity of the method, along with using more wells/seismic data. The hydrocarbon potential and properties such as porosity might have been underestimated in the past if the new net exhumation estimates by using average velocity are accurate. Using average velocity is for now an exciting front for further research.

8. Further work for the check-shot method:

1) We assume that a particular $\overline{k}$ and depth/TWT translates into an interval velocity that can be used to measure net exhumation. Sometimes we have multiple depths for a particular $\overline{k}$, along with the difficulty in knowing the proper $\overline{k}$ and V_0 for the reference. Additional work could be done to understand more about the $\overline{k}/V_0$ relationship and the underlying assumptions in the method.
2) Instead of using an arbitrary selected $\overline{k}$ and the corresponding V_0 in the reference, a particular $\overline{k}$ can be found to yield a more deterministically selected V_0 in the reference. Then this corresponding $\overline{k}$ can be used in both the reference and the uplifted area. The V_0 could maybe be found by performing more accurate volume clay studies for the wells investigated.
3) Instead of using the same $\overline{k}$, another criterion could be to use the exact same interval velocity gradient *k*. Right now, it is slightly different between the reference and uplifted regions because of the different $k/\overline{k}$ ratios (despite having the same $\overline{k}$). The V_0 and $\overline{k}$ would still need to be selected in the reference, but this would maybe be a better way of finding V_0 in the uplifted regions. However, it would be necessary to have a time/depth in the uplifted area to find *k*, otherwise you have three unknows. This could maybe be solved by simply using the depth for $\overline{k}$ from the reference and finding the time corresponding to this same depth in the uplifted area. In this case you would need both depths to be present in each check-shot. However, since the *k* parameters already are relatively similar between uplifted/not uplifted areas, the impact on net exhumation would probably be minimal.
4) It took several months of trial and error to figure out the methodology (current theory finalized late April 2016), so it was only tested on 7 wells. In addition, it is possible to test it on even more wells along with velocity cubes. This would yield a better spatial coverage along with a better understanding of the various implications and robustness. The velocity cubes have average velocity, which when corrected for anisotropy could be used to yield the magnitude of net exhumation. $\overline{k}$ and net exhumation could thus possibly become an attractive attribute for velocity cubes.

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