TGB4851 - Experts in Team
NTNU

Gullfaks - Group 3

Paul Gundersen Åsmund Våge Fannemel
Håvard Kamsvåg Nordahl Vivien Helen Vestre

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Abstract

In our project we are to evaluate prospect Zircon in the Gullfaks area. The prospect is located close to already proven oil reserves, but at a greater depth. This implies that we had to look for possible scenarios for the oil to be trapped and sealed from migrating further up. Even so, there is reason to believe that we have good oil carrying sandstones if some sort of trapping has occurred. In our approach we used seismic data already processed and interpreted by Statoil. We mostly agree with these interpretations, and have also tried to find alternatives and argue for some geological interpretations such as slumping. Some techniques we have used to check for hydrocarbons are the AVO analysis and V_p/V_s ratio. Our results indicate hydrocarbons and we think that our arguments for our geological interpretations are worth looking into.

Limitations

We chose a project which consisted of interpretation of seismic data and a geological evaluation based on slumping. In retrospect, this does not appear as the best of ideas. The group lacked a lot of the necessary experience and knowlegde to grasp the project at hand from day one. In spite of receiving introductory courses in both seismic and software, the group members did not acquire enough knowledge to efficiently interpret seismic data.

In retrospect we understand that we could not have know how to approach the task in order to solve it satisfactory, until we had acquired the much needed knowledge. The pieces fell into place gradually. It has slowly grown clearer and clearer to us what exactly the task was. The work that was done early in the semester has proved to be totally redundant, this because we just did not know what we were doing. In the final phase of our work, we have found out what we were supposed to do and have been working hard to get this work done. Still, we have wasted to much time so that we have not managed to reach all goals.

Contents

1 Introduction

1.1 Gullfaks field

The Gullfaks field is one of the largest field in the North Sea. It is located at a depth of around 135 meters in the north of the North Sea (block 34/10). It was discovered in 1978. It has been developed by three large concrete platforms, Gullfaks A, B and C. Gullfaks is very close to the Statfjord field. The license is currently held by Statoil and Hydro. It currently has around 60% recovery, and they are aiming to get this quite a bit higher, it's one of their main goals on this field. They started the field in 1986. More than 200 wells have been drilled, and three satellite fields have been developed as satellite tie-backs, remotely controlled from Gullfaks A and C platforms.

The field contains oil, gas and condensate. Oil and condensate are stabilized and stored on Platform A and C, before it is loaded directly into shuttle tankers on the field. The gas are brought through pipes to shore, and then to the European continent.

The Gullfaks field has been subjected to many detailed structural investigations leading to an enhanced understanding of reservoir characteristics. One of the by-products of the many analyses is a greater understanding of seismic data.

1.2 Zirkon area

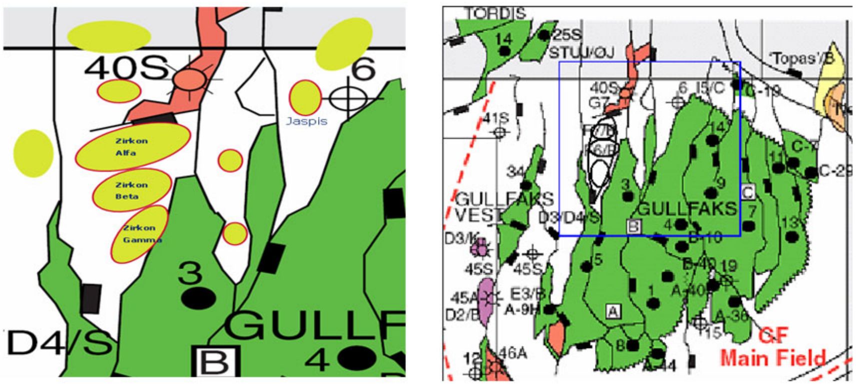

Figure 1: Show an simple image how the acquisition is done.

Zirkon is the term of three prospects, Alfa, Beta and Gamma northwest at Gullfaks. They represent a new search model, where slumping geometry is the main mechanism. Several potential lies in Tarbert and is independent with a seal floor and a seal at the side. The prospects have biggest probability to find gas in the north, since Alfa lies south for the gas area in segment G7. Probability for oil founds increases further south. Chance for making a discovery is insecure since the internal structure and structural settings may be negative influenced by the slumping process. The geometry is very complex, and the seismic images prove this.

Two or three of the prospects will be investigated with a side step from one of the Gullfaks B wells. If a possible discovery is there a possibility to produce from these structures. This has to be carefully planed from the results. Since this is a new search model in Gullfaks area it is important to examine this potential early as possible. With concern about the pressure, all Zirkon prospects will probably communicate with Tarbert in this segment series. A possible production from one of these prospects will probably get a limited production rate since the segment series is relatively thin. The pressure respond will be relatively low. Then it could be relevant to give pressure supply in segment G6, since the injection in G7 is heading north and west.

The seismic data from survey 85 was given to us. We divided the three prospects contained in the following lines and traces (x,y):

	LINE	TRACE
Gamma:	2711 to 2810	2600 to 2670
Beta:	2810 to 2870	2600 to 2650
Alfa:	2870 to 2920	2600 to 2660

2 Theory

2.1 Seismic

When a seismic wave arrives at a surface separating two media having different elastic properties, it gives rise to reflected, refracted and converted waves. Primary wave, P wave, is the wave generated from the source. When the wave hits an interface, the wave splits into pressure (primary) waves and shear (secondary) waves. These to waves are to different types of waves and travels with different properties like velocity and displacement.

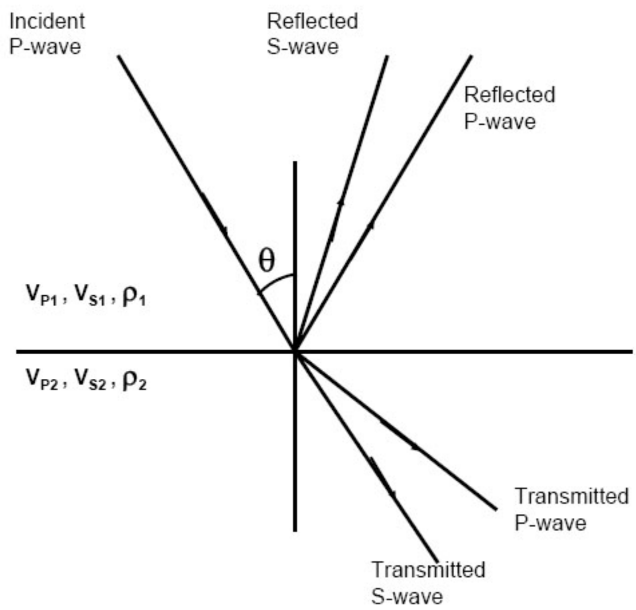

Figure 2: This figure show how the P wave hits an interface and the wave gets converted into P- and S waves.

The wave is generated usually (in marine circumstances) by an air gun, and recorded by hydrophones attached to several streamers. Air gun is a device that discharges air under very high pressure into the water. Then the wave will be like a "disturbance" that travels through the earth and carries energy.

All seismic data contains a mixture of signal and noise. In detailed reservoir characterization, it is commonly difficult to distinguish between real features and seismic artifacts. The term signal denotes any event we wish to obtain on our data, everything else is noise which we wish to remove to get a clearer image. This is especially a problem when interpreting seismic attribute maps. Such maps are widely used tools during reservoir description. Seismic interpretation will be based on an integrated use of seismic lines, cross lines and horizon attributes. To do this, the interpreter

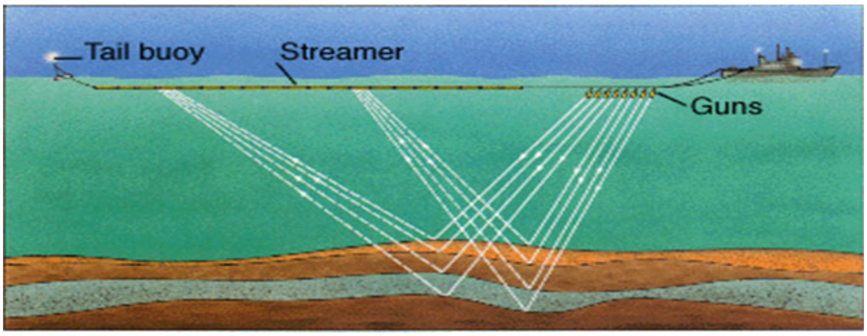

Figure 3: Show an simple image how the acquisition is done.

needs to combine knowledge with the complex disciplines of geology and geophysics. Misinterpretation may occur that can lead to fatal consequences for oil companies. The reliability of seismic mapping is strongly dependent upon the quality of the records. The quality of seismic data varies tremendously from areas where excellent reflections (or refractions) are obtained to areas in which the most modern equipment and sophisticated data processing do not yield usable data (NR areas). The noise can be random or systematic and have many different sources. The noise present in the seismic data will interfere with the real reflections and make it more difficult to interpret the real reflections from the noise.

The amplitude will give us valuable information and observing its behavior as it travel through the earth can better our understanding of the earth. We have always observed seismic amplitude in the seismic signal but, in the early days, we were concerned with its existence and not its magnitude because our objects were not structural. Digital processing today seeks to preserve "true" amplitude so that stratigraphic inferences can be made from it and more subsurface information extracted from our seismic data. But how true are these amplitudes and how much can we infer from them? Our ability to control and understand seismic amplitude is far from perfect. There is nevertheless much valuable information in seismic amplitude that we must use to the full in our interpretations and in our critical exploration and development decision making. So in our interpretation of the Zirkon area, we must be critical and consider carefully if there is a trapping geometry or any possible chance to discover hydrocarbons. The ability to see and distinguish features depends on the signal/noise ratio (which we want a high value of) and the knowledge and experience of the interpreter. Where a correct model is used for interpretation, it is possible to exceed conventional resolution limits, that is, if we know a priori exactly what we are looking for in very good data.

2.2 AVO anomalies

When amplitudes vary as a function of offset (or angle) the particular way the amplitude changes take place may be an indication of hydrocarbons. Normally we expect the amplitude to be more attenuated and absorbed further away from the source. When we have interfaces between cap rock and a reservoir we normally expect the amplitudes to increase with offset for the interfaces between the cap rock and the gas (or oil) filled reservoir. The same will occur for the gas/oil, gas/water or oil/water contact, but then with opposite polarity to the cap rock/gas interface. AVO is performed on prestack data, however it may be possible to do a partial stack (near stack, mid stack and far stack) to increase the signal to noise ratio. And at the same time preserve the amplitude characteristic for the various offsets.

2.3 AVO analysis

AVO analysis became popular, because it explains the direct impact of changes in the rock properties on the amplitude. It detects variation in the seismic reflection amplitude with offset, which indicates differences in lithology and fluid content in rocks at the reflector. AVO analysis is a technique by which it is possible (hopefully) to determine thickness, porosity, density, velocity, lithology and fluid content of rocks.

When applying AVO analysis, we have to be aware of many other factors influencing quality of the final result. For example it could be sensitive to the quality of pre-processing, signal to noise ratio, phase, multiple removal, anisotropy and absorption etc. Therefore the analysis could not be a stand-alone technique, but a useful tool in the interpretation. Our analysis is so simple that we could not take all this considerations seriously.

The most common and practical way to do AVO analysis of seismic data is to make cross plots of the zero-offset reflectivity(R0) versus AVO gradient (G). We did more simple analysis. We did(.) Due to the many cases where AVO has been applied without success, the technique has received a bad reputation of not being a reliable tool. However, part of the AVO analysis is to find out if the technique is appropriate in the first place. There are, like said before, many things that can influence on the seismic response with offset, for example are far offset response more attenuated and absorbed than for near offsets. Essentially there are two ways to attack this problem. One can try to correct systematically for the above mentioned effects, which is in a deterministic way. Another commonly used is to use well logs to calibrate the AVO response at a given interface.

AVO will only work if the rock physics and fluid characteristics of the target reservoir are expected to give a good AVO response. This must be clarified before the AVO analysis of real data. One can easily misinterpret AVO signatures in the real data, without doing proper feasibility study.

The feasibility study should be founded on a through understanding of local geology and petrophysical properties.

If we find that AVO analysis will work, and has the potential to detect hydrocarbons in the area of investigation, a new question arises: When should we do the analysis? Should it be done before, at the same time or after the interpretation?

AVO is done with pre-stack data, but it is becoming more common to interpret partial stacks, like we do in our interpretation. AVO techniques are integrated with geologic interpretations of seismic data during prospect evaluation. Defining a prospect based predominantly on an AVO anomaly would create an AVO drive project. Then we need a geological model that can explain the observed AVO anomaly. This have we done. We are thinking about a slumping geology, and a good possibility to find oil, that leaves us with a good reason for do a (simple) AVO analysis. [3], [8]

2.4 Flat spot

When a horizontal reflector crosses dipping stratigraphy we may have an instance of a horizontal fluid contact making an acoustic impedance contrast with the surrounding geology. A flat spot is normally associated with a gas/water or gas/oil interface. An oil/water contact will normally not show up on seismic data because the acoustic impedance for an oil filed reservoir and a water filled reservoir is normally not much different. The situation is very different for a gas filled reservoir. The velocity and density for a gas filled reservoir are normally much lower that for an oil or a water filled reservoir. Note that a flat spot may not be perfectly flat. A dipping flat spot can be caused either from a dipping fluid contact or it may come from velocity variations above the reservoir. A flat event can also be interpreted as a multiple. Multiple is a type of noise that looks like a primary signal. A flat spot is something the interpreter looks for.

2.5 The petroleum system

A Petroleum System links the source rock to a hydrocarbon deposit These are necessary conditions for a petroleum accumulation:

- Mature source rock. Source rock means when there is accumulation of organic matter which didn't get access to oxygen during the accumulation. Then under a lot of pressure and higher temperature the organic matter become kerogen after a maturing process, and then becoming a source rock.

- Migration path from source to trap. Most hydrocarbons probably are expelled from the source rock as liquids, called primary migration. The expulsion of the oil out of the source rock is a dynamic process driven by the maturing process, kerogen becomes oil. The fluid pressure of the oil within the black shale can become high enough to produce micro fractures in the rock. Once the micro fractures form, the oil is squeezed out and the source rock collapses.

Secondary migration is the movement of hydrocarbons along a "carrier bed" from the source area to the trap. Migration mostly takes place as one or more separate hydrocarbons phases. Gas or liquid, depending on pressure and temperature conditions. The force that acts on the migration is vertically and is proportional to the density difference between water and the hydrocarbon, so it is stronger for gas than heavier oil.

- Trap composed of structure, seal and reservoir. There are different types of traps. A trap means a cap rock which stops the hydrocarbons to migrate any further. This cap rock has to be very/no permeable so it can be a good seal for the hydrocarbons. A trap we are dealing with in the Zirkon area is a structural trap, which is formed by deformation of reservoir rock, such as by folding or faulting.
- Permeable reservoir rock. A good reservoir is a rock with good porosity and permeability, like sandstone, which we are looking for in Zirkon area. This reservoir rock which lays beneath the cap rock must be trapped with seal, which in our case caused by large blocks were tilted by faulting.
- Preservation The reservoir rock has to preserve the hydrocarbons and prevent further migration and keep the hydrocarbons and mature it the right way, not to little and not to much. This depends on pressure and temperature.
- Right timing of all these elements. This has to be right timing considering migration and maturing, [8], [9], [3].

2.6 Vp/Vs ratio

This is inverted data which can give us valuable information about the lithology. This is the ratio between the P wave's velocity and the S wave's velocity. The velocity depends on composition, porosity, fluid content and cracking for non porous rocks. *The shear wave does not propagate in fluids, but the pressure wave does. This is something the interpreter takes advantage of. When the waves hits a medium filled with fluids, the shear wave travels along the grains, and the pressure waves gets affected depending on type of fluid. If it hits gas, the velocity gets damped a lot and the seismic image gets scured.*

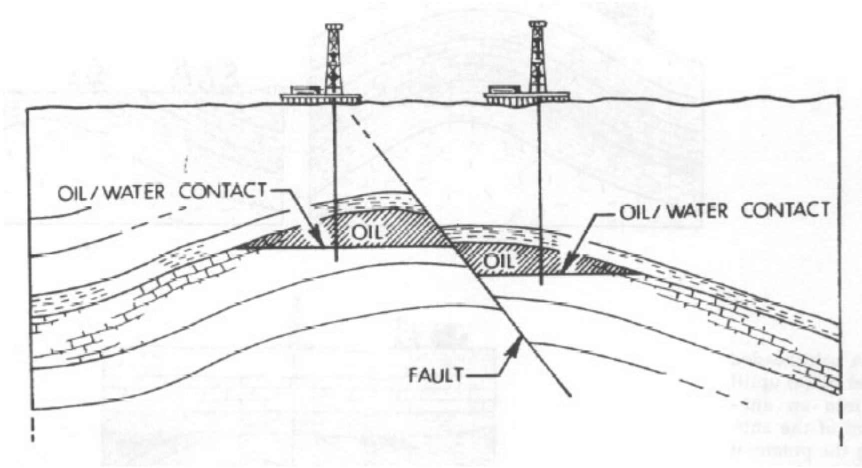

Figure 4: Shows how you can get a deeper oil/water contact with a sealed fault.

This image we get is in color, which each color can tell us what kind of rock is in our located area when we compare with another area where we know the formation. Like in our interpretation we will compare Zirkon area with segment G6 where we know the reservoir is sandstone. Is Zirkon area the same color, then we trust a bit more that there is possible sandstone reservoir in Zirkon. In our image we can see the same structure as we can see in seismic data. [8], [10]

3 Tools and data

3.1 Seisworks

Seisworks is a part of Landmark Software, you open Seisworks through Openworks. Seisworks is the industry's technology leader for 3D seismic interpretation and analysis. Because it supports seismic interpretation in either time or depth, Seisworks makes interpretation a convenient reality. Seisworks includes full multi-survey merge capabilities allowing you to easily combine 2D with 3D projects, and to merge multiple 3D projects without data reformatting or reloading. The seismic balance functions allow you to correct for differences in amplitude, phase and frequency across multiple surveys and within 2D projects, it is also possible to calculate the size of a reservoir. Faults and horizons can be interpreted and edited on vertical seismic sections and time slides. The work the interpreter do, like locate faults and horizons are stored in the Openworks database, so information from interpreters working on a single project or multiple projects is quickly updated and instantly accessible. [2]

3.2 Gullfaks data base

NTNU has access to Statoil's database where there is information about the Gullfaks field. The database gives us information about general info of the Gullfaks field, different reservoirs, geology, well data and political info. We have used this to get info about the nearby wells around Zirkon, we have tried to compare the well logs with what we observe in the seismic data. We also used the database to get general info of project Zirkon as a search model and about the different formations.

3.3 Well data

We have concentrated on the closest wells to Zirkon. That is B-12, C-36 and B-35. To calibrate the seismic response observed on the seismic data with response expected based on observations in wells. This will be done to take a slide show of seismic images from the well and through Zirkon to se the geologic development. [8]

3.4 Promax

Promax is a part of Landmark. This is a tool which you can do successful processing of seismic data and other services. This technology is designed to bring the geophysicist closer to the seismic data with visualization tools that allow rapid viewing of pre-stack and post-stack seismic data. Knowledge-based seismic data processing leverages your understanding of the geology to guide seismic data analysis and parameter selection in order to optimize seismic processing sequences. Promax workflows facilitate construction of the optimum seismic image of the geologic target. [1], [2]

4 Seismic interpretation

In our interpretation we have examined partial stacks. These have an improved signal to noise ratio, and provides the possibility to perform AVO analysis. We have also evaluated the at Vp/Vs ratio, which is a good lithology indicator. When doing interpretation of possible reservoirs and trying to discover hydrocarbons it is important to be critical and work with experienced people who can identify attributes and know what to look for.

4.1 Localization and discussion

Material provided to us from Statoil helped us localize prospect Zircon on the map. The first we did was transfer the prospect over to a map with the seismic linenumbers and tracnumbers as coordinates. The lines are numbered from south to north and the trace from east to west. Thereafter we started examining the lines in SeisWorks. It was not easy to define the difference between the top-reservoir of the oil reserves directly east of Zircon, which we will reference as ,(Oil_ref_1) see Figure 5. The Zircon prospect is also at a greater depth. As indicated in the localization beneath the depth is given in time (ms) and the traces in length (m).

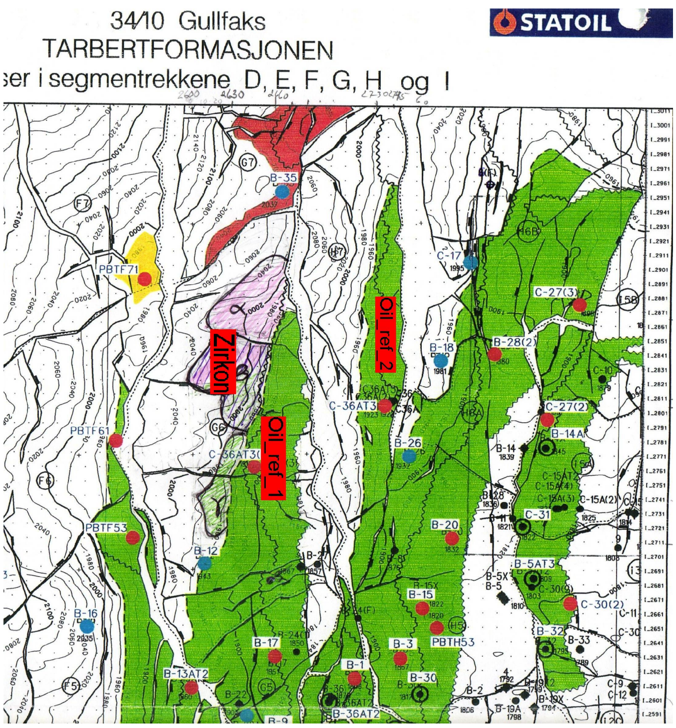

Figure 5: Map showing location of Zirkon, Oil_ref_1 and Oil_ref_2.

The seismic amplitudes shows good correlation from line to line, but varied much at larger steps in both the top-reservoirs. These kinds of variations could come from noise in the signal, noise from activity around and geometrical scattering. Another possible reason of importance is that the layer above the top reservoir could change. This is in fact thought to be the case in the Tarbert formation above top-Zircon. An interpretation of this kind can be seen in Figure 6. We support this interpretation because we in general find lower amplitude in prospect Zircon compared with Oil_ref_1 and Oil_ref_2. See the map for localization of the prospects and the oil references. Additionally it is of course not to exclude the case that we have no trapping formation and no hydrocarbons if we see low amplitudes.

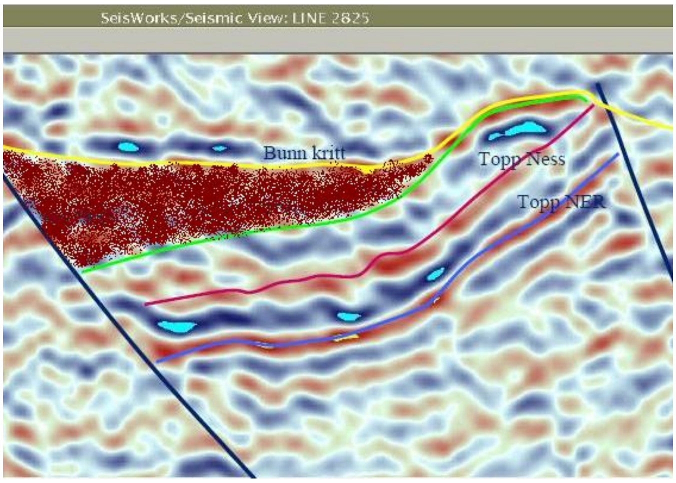

Figure 6: It is thought that we have a chock of clay sediment coming in from west.

4.2 AVO Analysis

4.2.1 Method

Our AVO-Analyzes is based on seismic data lf8516 (far stack) and ln8516 (near stack), shot in 1985. These data cover the Gullfaks field including prospect Zircon. We made use of the software SeisWorks. Our method of choice was to find the ratio between the far and near offset amplitudes in Zirkon, two known producing reservoirs and from sandstone containing water. Then we compared the ratios to see if Zircon has the same properties as the known reservoirs or the water filled sandstones. To achieve this we studied the seismic data and found what we interpret as the possible top reservoir of the Zirkon field. This top is seen in the seismic data as positive, or blue, amplitudes. The data needed was found by collecting readings of the amplitudes assumed to be the top of the reservoirs, for both near and far stacked data. The way we did this was to follow the positive amplitude and register local vertical maximums in small steps along the horizontal axis. These maxima were used to find the mean value and the variance. The mean and the variance were used to find the far versus near ratio and the uncertainty. We used the Oil_ref_1 and Oil_ref_2 segments which are in oil production today, and the G7 segment containing gas reserves as references. As a reference for sandstone containing water we used data from the same sandstone layer that contains oil and is in produduction by well C-36T3(2), but to the east of the fault that forms the trap. The far versus near ratio is found from:

$$Ratio = \frac{F}{N}$$

where N is the average maximum amplitude found in the near stack data, and F is the average maximum amplitude found in the far stack data. The standard deviation was approximated by:

$$f = \frac{F}{N}$$
$$\Delta(f) = \frac{\partial f}{\partial F}\delta F + \frac{\partial f}{\partial N}\delta N \approx \sqrt{\left(\frac{\delta F}{N}\right)^2 + \left(\frac{F\delta N}{N^2}\right)^2}$$

where the standard deviation δ is approximated by $\Delta(f)$, δF is the standard deviation of the avarage F values, and δN is the standard deviation of the avarage N values.

The top of the possible reservoir in prospect Zircon is continuous with the top of the reservoir in Oil_ref_1. Since it is known that there is oil in Oil_ref_1 and the oil-water-contact is known, we interpreted Zircon as the part of the continuous amplitude from the oil-water-contact on Oil_ref_1 and toward west.

The oil reservoir in the Oil_ref_2 segment is on the other hand a separate oil column east of Oil_ref_1. We registered several amplitude values for each area/segment and calculated the average and the standard deviation between them. Since the seismic data has a rather low resolution it was not trivial to determine which point to use or the precise area. Also, possible reasons for uncertainty can be random noise on the seismic signal and noise due to activity in the area around. Small scale geological structures are of course also a problem because of the low resolution in the seismic data. Anyhow, the fluctuations did of course result in a big standard deviation in our cluster of points which gave a considerable, in some cases perverse, uncertainty in the far over near offset amplitudes. The ratio values found on Zirkon varied between the extremes 0.63 and 2.3 while the uncertainty interval varied between plus or minus 0.36 to plus or minus 1.27. See attached Excel-sheet 36 for details of the statistics. The biggest standard deviation in percent is +-57%, which is quite high. The resulting ratios found on Zirkon are shown in three figures, one for each field, gamma, alpha and beta, see figures 7 - 9. The ratios found from the gas field in G7 is shown in figure 10 and the ratios found from the sandstone containing water is shown in figure 11.

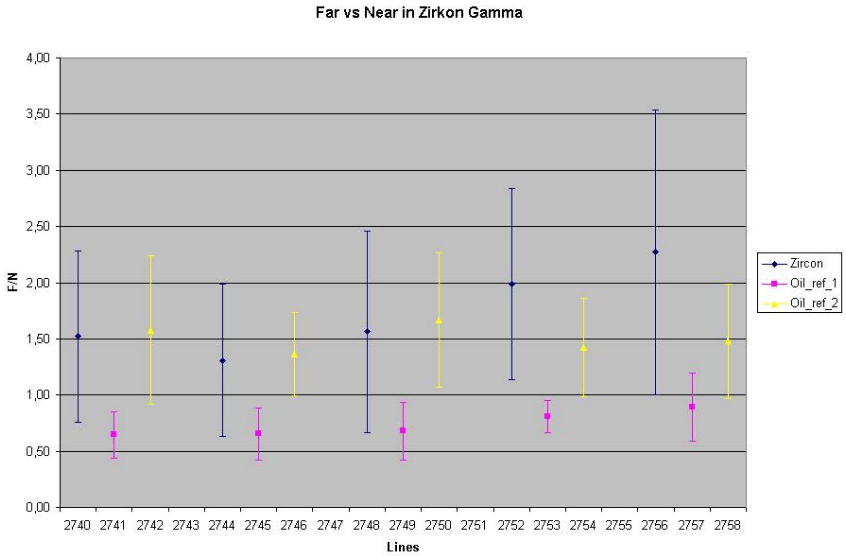

Figure 7: F/N ratio from Zirkon gamma, Oil_ref_1 and Oil_ref_2

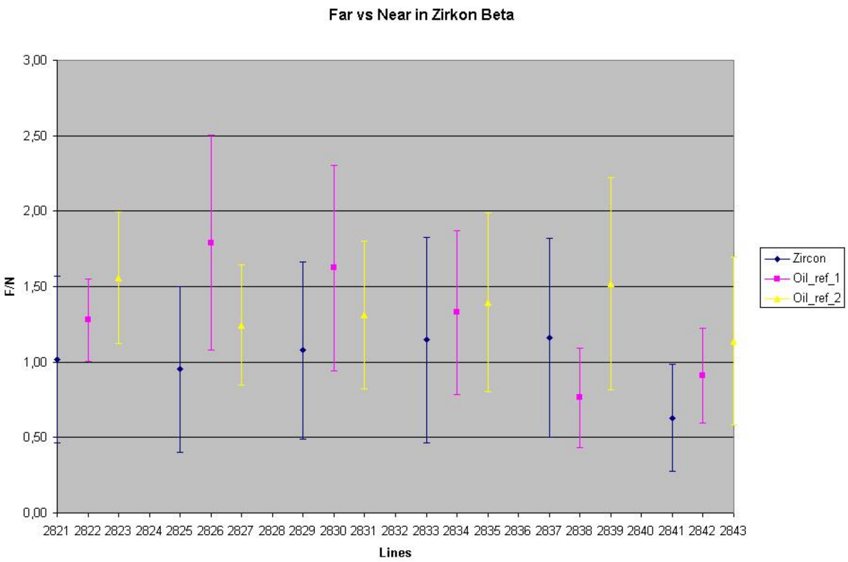

Figure 8: F/N ratio from Zirkon beta, Oil_ref_1 and Oil_ref_2.

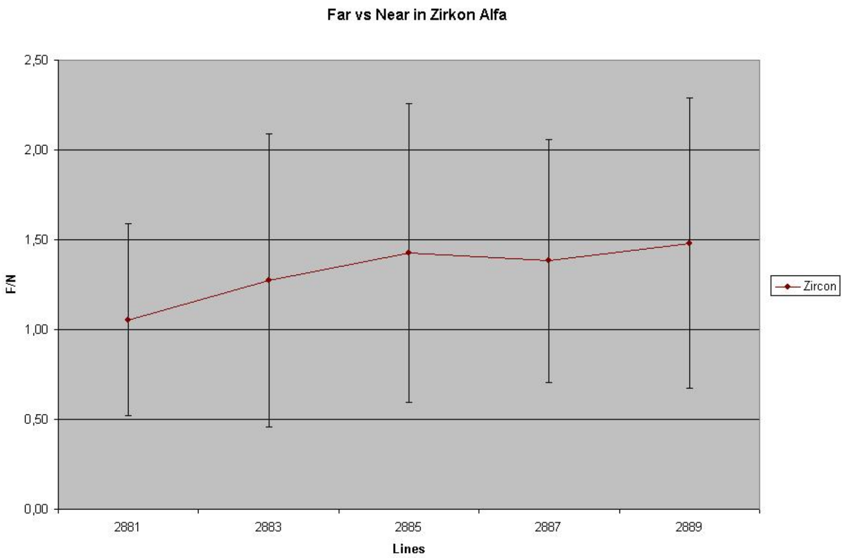

Figure 9: F/N ratios from Zirkon alpha

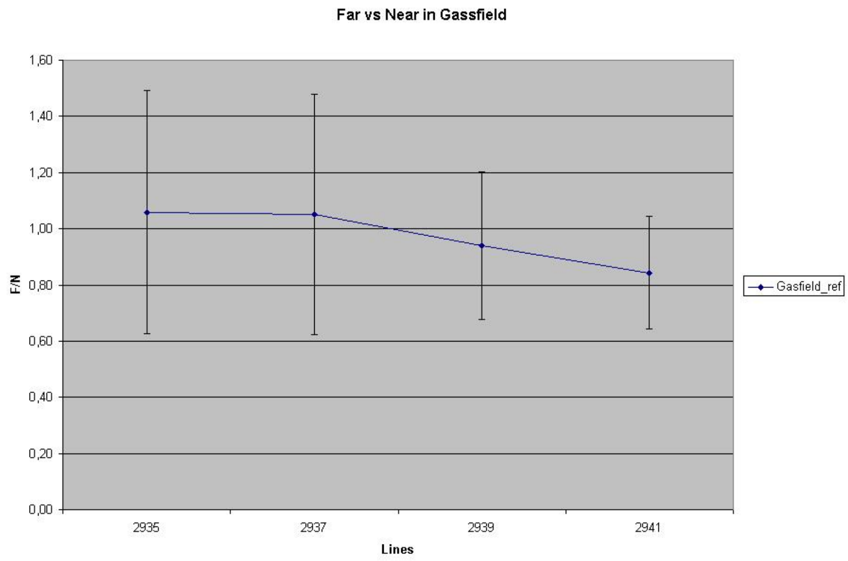

Figure 10: F/N ratios from the gas field in G7

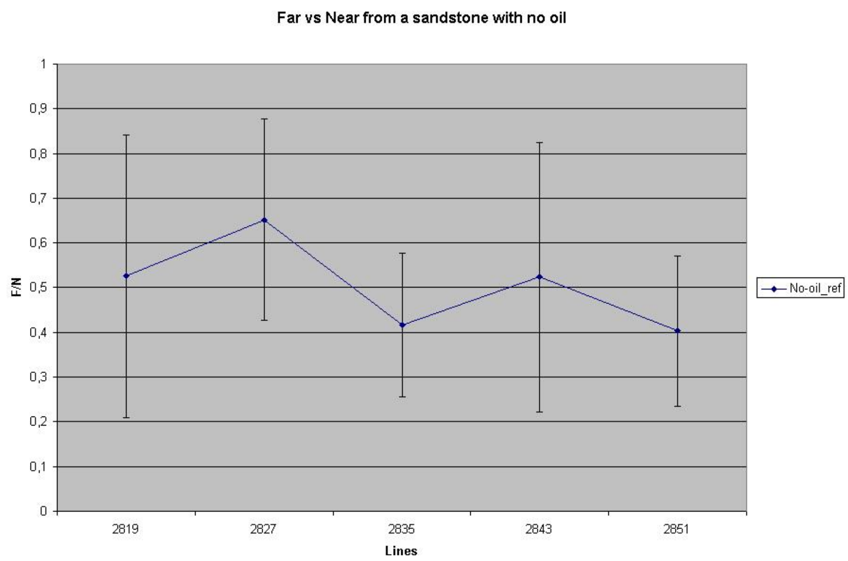

Figure 11: F/N ratios from sandstone that does not contain hydrocarbons

4.2.2 Results and interpretation of the AVO analysis

The ratios from Zirkon gamma is shown in figure 7 together with the reservoirs used as references. The two references shown on the left of each ratio from gamma is found from the same line as the ratio found from gamma. That is, three and three ratios are found from the same line. The references have been moved to the left to better see them. From figure 7 we can see that the ratio for Zircon gamma has somewhat greater uncertainty than the reference ratios. We can also see that the oil_ref_2 ratios are mostly within the range found on gamma, while the oil_ref_1 ratios are partly within the range of the gamma ratios, but only the lower part of the gamma range and the upper part of the oil_ref_1 range overlaps. The ratios from the field contianing gas is in the area of 1 with a standard deviation of approximately 0.3-0.4, see figure 10. This is within the lower range of the ratios found from gamma. From figure 11 it is seen that the ratio from the water filled sandstone has approximately an average of 0.5 and a standard deviation of about +-0.2-0.3. This means that some of the ratios found on gamma is slightly within the range of the range of the ratios from the water filed sandstone. By comparing the figures 7 and 11 one can see that gamma has an approximate average of 1.75, while the hydrocarbon references have an approximate average of 1-1.2, and the water filled sandstone reference has an approximate average of 0.5.

The ratios from Zirkon beta is shown in figure 8, again the references are shown in the same figure, and again they are displaced to better be seen. The uncertainty in the ratios gathered on beta are smaller than for gamma. This is seen in figure 8 as a smaller range around each ratio. From the figure, it can also be seen that the ratio gathered on beta overlaps much of the ranges of the hydrocarbon references. The leftmost ratio from beta is almost not seen since it is on the very edge of the figure, the same goes for the rightmost ratio of oil reference 2. If one compares figures 8 and 11 it is seen that the lower range of the ratios from beta contains the upper range of the ratios found from the sandstone containing water. The beta values has an approximate average of 1, while the hydrocarbon references have an approximate average of 1-1.5 and the water filled sandstone 0.5.

The ratios from Zirkon alpha is shown in figure 9. Since we had limited time, we chose to not gather more data for references than we already had. This was maybe not to smart, since we then can not plot the references in the same figure as the ratios from alpha. But one can still see from figure 9 that the ratios with uncertainties are in the same range as the references in figures 7 and 8. From figure 11 it is seen that the lower part of the ratio ranges from alpha overlap the upper ratio ranges of the water filled sandstone ratios. The uncertainties for the ratio from alpha are slightly greater than for beta, and smaller than for gamma. The approximate average of the ratios from alpha is 1.3 while, as before mentioned, the hydrocarbon references have an average somewhere around 1-1.5 and the water filled sandstone 0.5.

If one looks at the trend in the gathered data, it is seen that the ratios found on the different prospects on Zirkon has similarities with the ratios from the oil and gas fields. That is, the ratio is greater than one. At the same time the gathered data also have similarities with the ratios found from the water filled sandstones, though these ratio ranges never exceeds one. It seems that the actual values of the ratios from prospect Zirkon is somewhere around the ratio from the hydrocarbon references and above the water filled sandstone. The ratios from the water filled sandstone has the biggest standard deviations out of the calculated ratios. It is approximately +-60%. The bigges standard deviations from the hydrocarbon refernces is found in figure 8 and is appromimately +-50%, while the biggest standard deviation found on Zirkon gamma is found in figure 7 and is approximately +-57%.

It should be notetd that all ratios have been calculated based on readings from far stacked data scaled differently than the near stacked data. This results in lower ratios than excpected. But since all the samples have been taken without changing the scales, the information from the raios is still valid. The deviations, however, might be effected by the skew scalings. Since the far stacked data was sceled to low, the amplitdues were weeker than they should have been. This has made the detecion of the excect boundries of a given amplitude harder to detect, and thus the data gathered has greater uncertainty.

As the theory says, in the case of hydrocarbons we should see a larger amplitude with furter offset. Our results for prospect Zircon indicate a trend like this, and are therefore a hydrocarbon indicator. But, as discussed above, there is a lot of uncertainty in these analyzes. We can easily see the large deviation in the far over near plots. Especially the lines at same height as Zircon Beta from the G5 segment, where there is known oil reserves, shows a ratio less than one and weakens the AVO-Analyzes. But looking at the big picture we get in general a ratio larger than one in the known oil columns and in prospect Zircon, while the water filled sandstone gives a ratio of 0.5. This was a motivating result for us, knowing from the start that this is already an interesting prospect from Statoil's point of view. We also registered a statistic from the field above Zircon Alfa. This field contains known gas reserves which we used to compare with our far over near ratio from Zircon. The ratio came pretty close to one over the lines we analyzed. This fitted good with our results from the Zircon Beta area indicating gas reserves there. However, the individual amplitudes were both much higher in the gas field compared with the Zircon Beta prospect. The high amplitude is intuitively understood because of the large difference in mass density going from rocks to gas. This therefore weakens our statistical hint there being gas in this prospect. This argument is also strengthen by the fact that the B-35 well lies pretty close to the Zircon area and we can easily trace the upper formation of the gas-field going south to Zircon. However our statistic has shown that the amplitudes can vary much from two different known oil segments and is therefore, of course, not to be trusted completely. For example we have seen very high amplitudes in oil segments too, not only in the gas-field penetrated by the B-35 well.

Another thing to comment is that the amplitudes collected in prospect Zircon is in general lower compared to the G5 and H7 segments. It is, for us, not easy to conclude with anything concerning this trend, but that fact that the prospect is at a greater depth may have something to do with it. However, the shape of the reflecting layer on prospect Zirkon has a almost parabolic shape and should therefore consentrate the reflections and make them stronger. May it be that this is why the amplitude is somewhat stronger on prospect Zirkon than from the surrounding non hydrocarbon filled structures? Might it be that it is not the presens of hydrocarbons that has caused tha AVO anomaly? We don not know. But we do need to do some further analysis to see if we can find out.

4.3 Further interpretation of the Zirkon areas

Crossplots of different variables are an efficient way to do a discovery, here you take advantage of elastic parameters like acoustic impedance and Poisson's ratio. This data is extracted from seismic data using AVO behaviour. These two terms can be used together in cross plotting to identify hydrocarbon accumulations - something that is displayed in the final map, which is a DHI (direct hydrocarbon Indicator. The acoustic impedance describes the properties of the rocks at zero-offset reflectivity, something that is quite close to the near offset. The Poisson's ratio term determines the change in amplitude from near to far. This is a mathematical operation that uses angle of incidence and not offset. This is similar to Vp/Vs ratio. Other parameters useful in interpretation, together with AVO, are velocities and densities.

We have performed a simple AVO analysis, examined Vp/Vs data and tried to find supporting results from crossplots. In practise this is far from enough to make a proper conclusion, but we have received a crossplot from Statoil to help us to improve our understanding and hopefully a better conclusion.

We used Landmarks Seisworks to view our data. We had to locate Zirkon and the producing area with inlines, crosslines and depth in time. Zircon is located deeper and has a more complex structure than the surrounding producing areas. Interpretation of horizons where already done by Statoil. The datasets where locked for other interpreters to do something about it. We have used both partial stacks data from 85 and 96, but thea data from 85 is better processed and provides as clearer view. This has lead us to mostly examine the 85 data. We just looked at the data and the amplitudes. The structure is difficult to see, but we can see the degree of complexity and how strong and continuous the reflections are. Then we looked at time slices. We map the area in different depth (ms), and tried to interpret the amplitudes from above.

We used Promax to interpret the inverted data. The image we get appears similar to the seismic image. To find our location, we needed some coordinates and the time delay, which is 1200 ms. The image Promax produces is multi-coloured, where each colour represents different values. The values lithologies. We will look for shale and sandstone, where sandstone shows a as lower value. The colourbar will tell us how the Vp/Vs values are distributed in the colour range. We will take images where the AVO analyses have been done. That is inline number;

- 2741 and 2795 in the Gamma area
- 2821 and 2841 in the Beta area
- 2871 and 2891 in the Alfa area
- 2991 in the gas area in segment G7

Zircon is divided into three zones, we have interpreted them separately. We begin with Gamma.

4.3.1 Gamma

Gamma is stretched from L2721 - 2801, T2620 - 2635, depth 1930 - 2000 ms. Gamma changes a bit as we move through it. It gets more complex, smaller and shallower in the south. Gamma which is furthest south in the Zirkon area is the area that has less probability for a discovery. This area is very complex and there is probably not one large reservoir, but many smaller reservoirs in a complex geometry structure. Comparing the near, mid and far stack from the 96 survey is interesting. The amplitude increases with offset. This is a typical AVO feature. Gamma is located very close to a producing area, and here is expected less chance of discovery, but if there is one there will probably be oil present.

The image in figure 12 below is from inline 2741. The three horizons from the top are, Cretaceous, Brent and Ness. Our target lies in Brent formation, which is between the yellow and the lowest red horizon. The green line that crosses is B - 35 which is in the gas field to the north.

Inline 2741, south gamma, denoted with a circle in the image in figure 12, have a small area. It's from T2620-2635, depth: 1948 ms. Here we don't see a strong reflector as the producing area (T2635-2680), which is shallower, 1916 ms.

Figure: Show Vp/Vs ratio for inline 2741. The black line shows where Gamma is located.

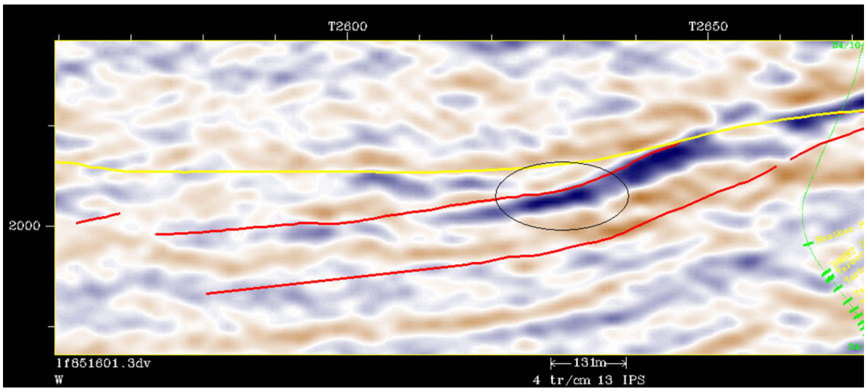

Figure 12: Inline 2741, where the horizons from Kritt, Brent and Ness is displayed. Gamma is denoted with a circle. This is mid 85 data.

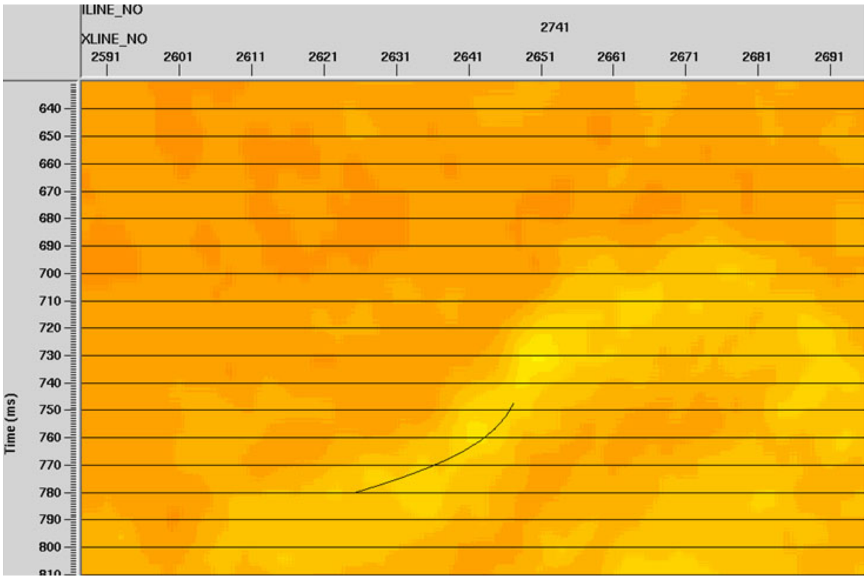

Figure 13: Vp/Vs ratio for inline 2741. The black line shows where Gamma is located.

Vp/Vs ratio for inline 2741, look at Figure 13 below, shows that the colours overlap a little bit. The producing area has different values. The colour is different from the producing area which contains both bright and darker yellow. The ratio here is a lot higher. The Vp/Vs ratio at Gamma has ratio at 2.2, the producing area, from T2535 - 2680, has a ratio at 1.7 - 2.0. Here there is a variety in bright colours. The darkest here is the one we see in Gamma. Vp gets smaller when it travels through gas, Vs don't get effected. More red colour represent higher ratio. Vp travels faster in oil and water than gas, but usually slower than in grains. This may be an indication of little gas since the ratio is higher.

In seismic interpretation one way to look at the data is from above, where you get an overview of the amplitudes from above in different times. This is an efficient way to look for amplitude behaviour. Zirkon is located deeper than the producing area, it is from 1948 ms south, to 2060 ms in north. The first time slide represented here is from depth 2000 ms. Gamma is located at the strong blue reflector, see 14. The time slices are an efficient way to look for AVO anomalies. In figure 14 below, far 85 is to the left, near 85 to the right. You can see how the reflections vary. The reflectors that gets weaker and thinner to the left are an AVO anomaly.

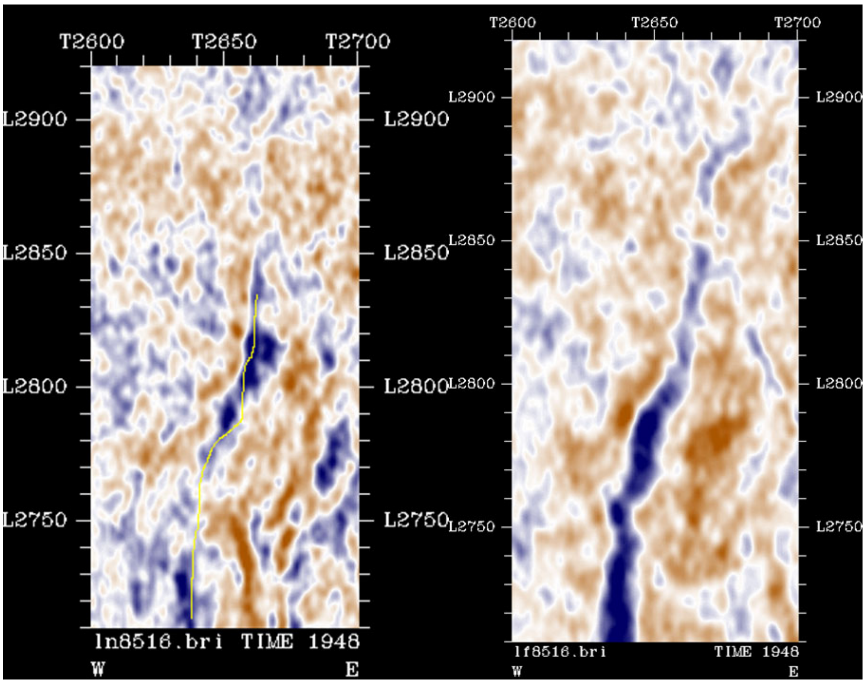

Figure 14: These two images show the near and far 85 data at depth 1948 ms. Far is to the right, you can see the amplitudes area stronger here. Gamma is the strong blue vertical reflector up to inline 2800.

If we move further north, to inline 2795, Gamma gets deeper, at 2000 ms, and is located at T2625 - 2650. We're going to look for slumping geometry in our task. This is difficult to see in our data, especially for an untrained interpreter. What we can see in our image is how the reflections behave from the producing area and Gamma, and compare this with near and far data. North Gamma is deeper and wider, but the basic seismic image looks much the same, see figure 12 of inline 2741.

We tried to flatten this seismic data. That means we command the data to make the reflections flat. Then we can hopefully see how the different layers was distributed before blocks got rotated. Then we saw this continuous reflector between Gamma nd the producing area. But why is Gamma deeper and more complex then? This can be explained by geology.

In the Vp/Vs ratio in inline 2795 we get about the same result as the previous inline, 2741. In figure 15 Gamma is located at the circle. The producing area is the other flat circle with a possible fault in between.

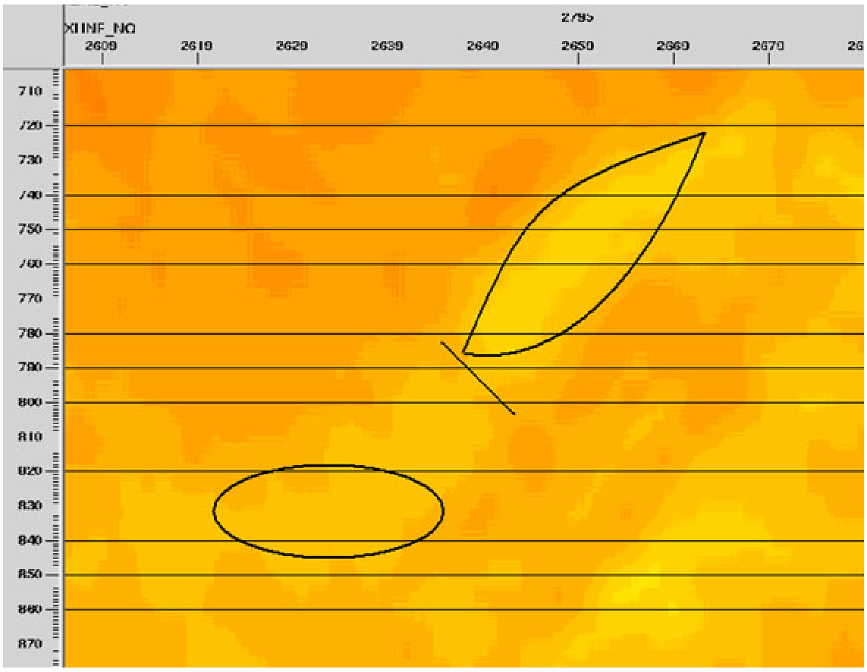

Figure 15: Vp/Vs ratio of inline 2795

Gamma gets a ratio at 2.0 and the producing area 1.9. We can see that the colours overlap a bit. In this kind of interpretation it does overlap, for example there are no distinct difference between shale and sandstone. That makes it a bit inaccurate. It could be the same lithology, but nothing to be sure about. But maybe the flatten seismic support that it is the same lithology, that it was one time a continuous bedding; Gamma and the producing area. What we are looking for is a reason why the reflector has been separated and why there is a possible discovery.

The time slice in figure 16 is about the same as for inline 2741. Here we can see an indication of a strong reflector denoted by a circle. The producing area you can't see on this depth, the image 16 shows the producing area at 1916 ms. This shows strong reflections compared to Gamma, and is a lot bigger. What we observe in Gamma is a tiny spot of strong reflection. We know this area is small, but is this strong little spot enough to conclude something?

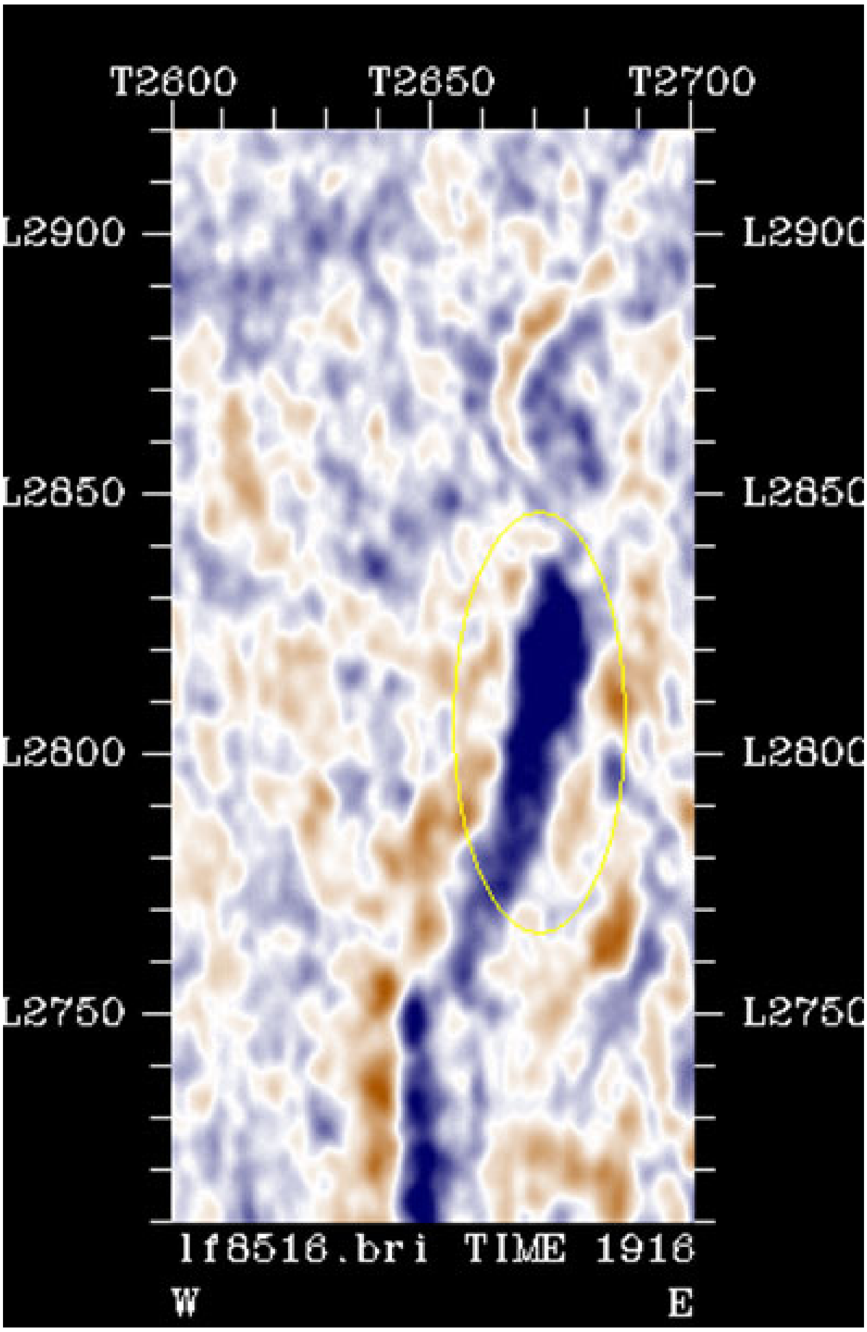

Figure 16: The image is just to show how the producing area looks like in depth 1916 ms. This is a strong reflector.

4.3.2 Beta

Beta is located further north and deeper. From inline 2800 - 2860, T2610 - 2660, depth is from 1970 - 2040 ms. Beta looks more flat and is a bigger area than Gamma. The seismic image show us the depth in time and how continuous the reflections are. This tells us something about the complexity and if it's a dipping interface. If there should be a possibility for a slumping geometry there might be an advantage that it is dipping, like Gamma does a little bit.

Gamma from south to north gets less complicated, and deeper. We took two inlines to show if there is any big difference from north to south. Figure below show inline 2821. Beta is located at depth 1970 - 2035 ms. The producing area is from T2660 - 2680.

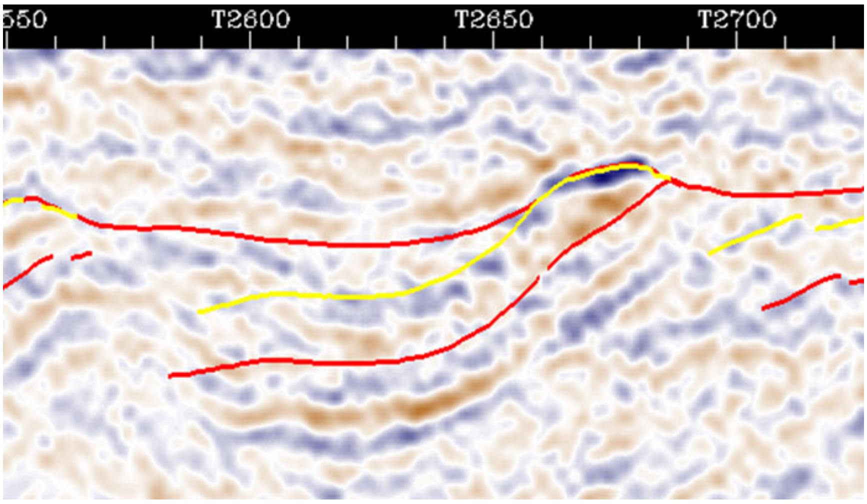

Figure 17: Inline 2821 in Beta south. Beta is located between the yellow and lower red horizon, T2610 - 2660, at depth 1970-2035 ms.

We can see that Beta is complex and not a strong continuous reflector, from figure 17. Maybe that is an indication of a complex slumping geometry?

This inline, 2821 of figure 18, is the beginning of the Beta area. The Vp/Vs ratio is similar to the producing area, T2660 - 2680. This got an amplitude equal to 2.0, and 1.95 in the light spots. But in the darker layer above it gets lighter in Beta. Is this the same seal as the producing area has got, and is it a good seal further down?

In the image below, figure 19, you see how the structure has changed a bit, and becomes wider and deeper. Beta is located between the two arrows.

We see that there is a flat event, but it is most likely not a flat spot since there is a flat reflections above and under Beta. But since it is not dipping, but a flat continuous event, will that tell us there is no slumping? That does not have to be an answer. This depends on several things, for example erosional surfaces and the depth of the slumping, if the seismic waves will see it, or pass through the slumping as one layer.

The Vp/Vs ratio in Beta, see figure 20 below, the yellow area is Beta,

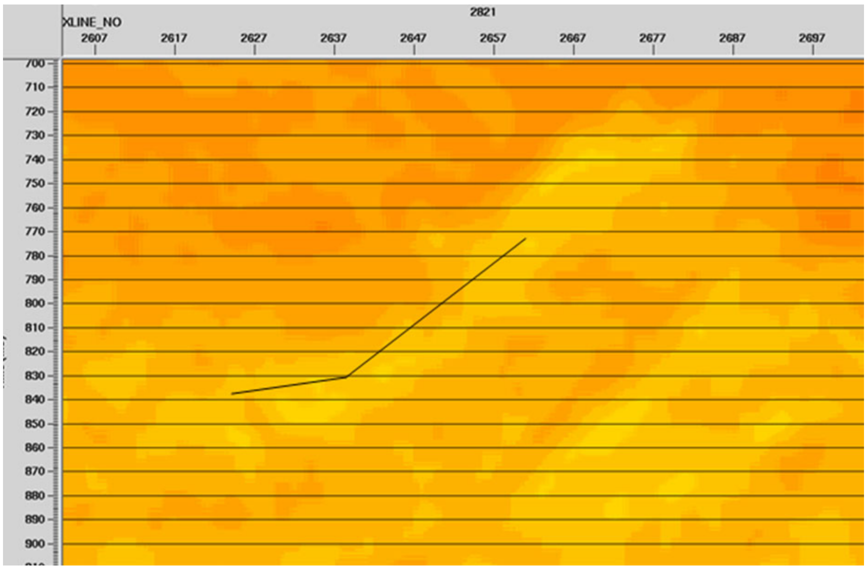

Figure 18: Inline 2821. Here follows the yellow producing area Beta area further down to 2035 ms, from trace 2610-2660.

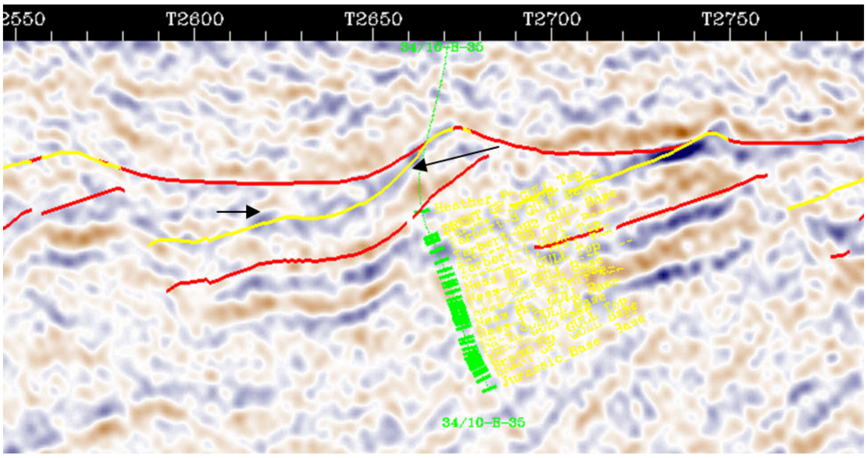

Figure 19: Here we can see beta north, L2841, T2620-2660, depth: 1960-2040 ms.

from T2610 till 2660, with a ratio at 2.0. The producing area, T2660 - 2680, is the same colour as Beta, which is located at deeper depth and a ratio at 2.0-2.1

We expect more gas in Beta, since it is deeper. How will this influence the ratio? Vp will drop dramatically in gas zones, and then the ratio will drop and we get a lighter colour. General at Gullfaks area, especially in Tarbert, there is usually no free gas, but there is light oil. But since Beta is so deep, it might be gas there if a discovery has been done. The colours

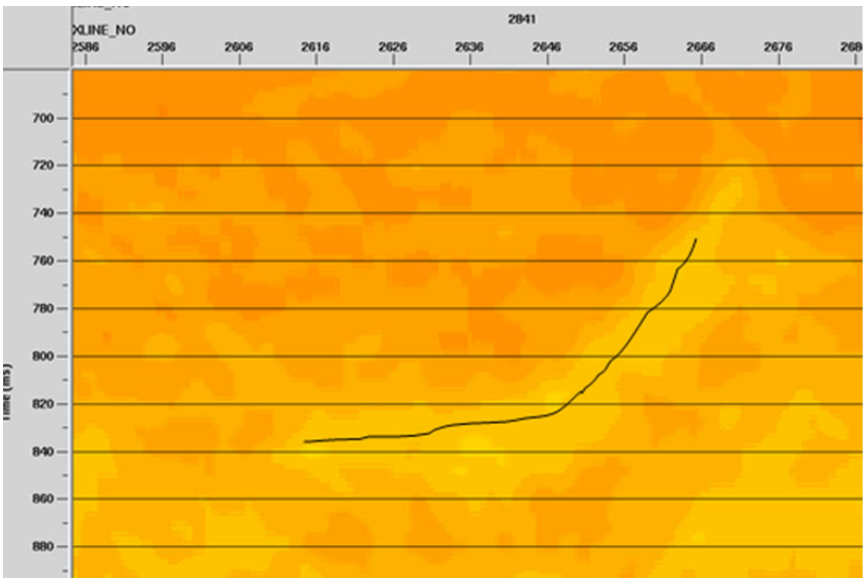

Figure 20: Vp/Vs ratio of inline 2841 in Beta north. The yellow continuous colour represents Beta, T2610 - 2660, the producing area to the far right (T2660 - 2680).

overlap a bit. The producing area is a bit darker to the far right. The ratio lies about 2.0 - 2.1, Beta lies on 2.0. But the ratios above the located areas are different. It is higher at the producing area than above Beta.

Beta has stronger indication of a bigger area with oil and gas when we see it with the same colour as the reservoir to the upper right. The difference between these two inlines, such as area, complexity, dipping is not too high. But the small difference can be caused of more gas in inline 2841.

In the time slices Beta goes from 1970-2040 ms. If we compare near and far data, we might see the amplitude behaviour. In the near data we see around 2000 ms a strong reflection in a small area close to the producing area. This trend can also be seen in the far data form 2030 - 2048 ms. When we go deeper in the near data the image get very complex and we don't see a clear structure through all Beta. In the far data we begin with a clear image at 2000 ms and the reflections change a lot. Until you get to 2060 ms. From here to 2084 you have a clear big area.

Below we see time slides from depth 2032 ms for near and far data see Figure 21. These looks very different from each other. The circle denotes the Beta area.

The near data is more complex and this was expected. But we don't see any AVO anomaly. In the far data we recognize the upper part of Beta which is located shallower.

As we go further north, we get deeper down. In time 2048 we see in the

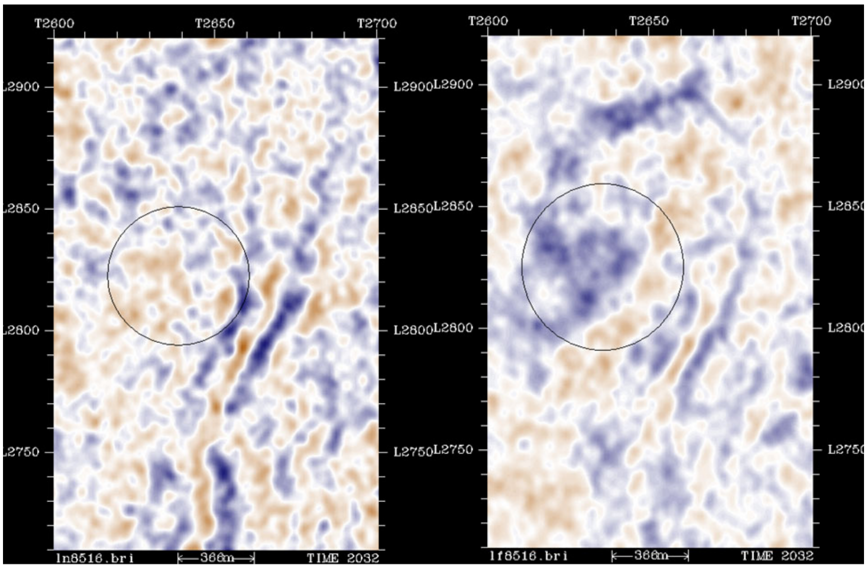

Figure 21: At 2032 ms we see different images for near and far data. Near to the left and far

Figure 22, the near is to the left, far to the right.

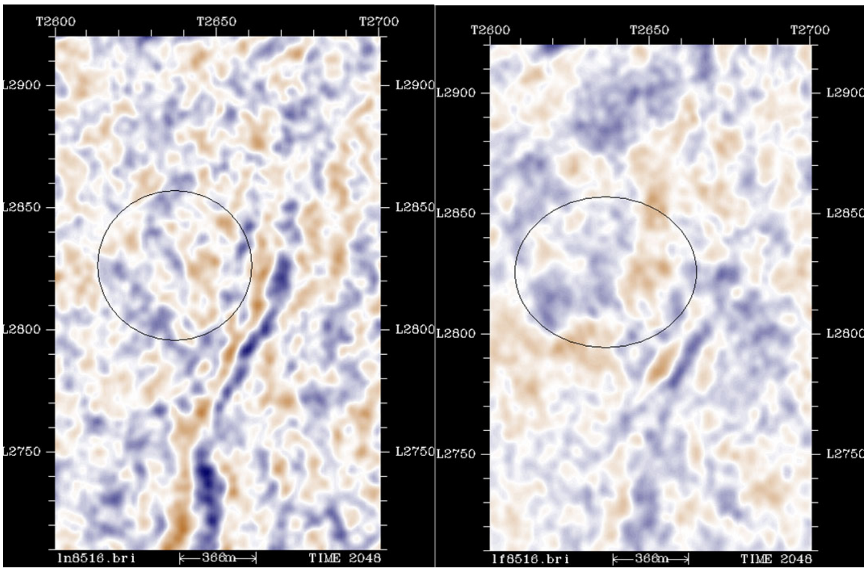

Figure 22: This is the middle of Beta, depth: 2048 ms. The near data is to the left, far to the right.

Why are the images, near and far, so different? What does it tell us?

As we go deeper Beta fade away, this happens when we pass 2052 ms. This is a little to deep if we compare the depth with the seismic image. See image below 23.

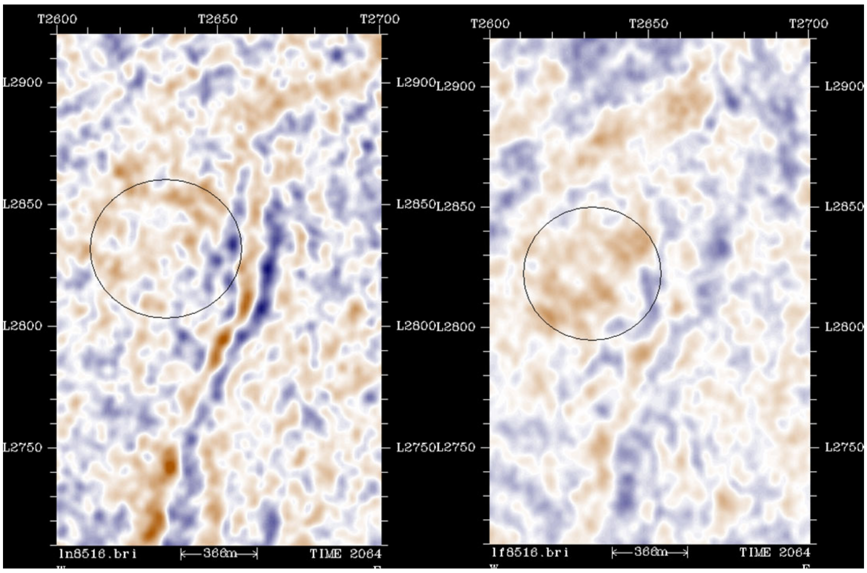

Figure 23: The near data is to the left, far to the right at depth 2064 ms.

We see from the images 23 , that the reflections change a lot. But we have strong reflections in the far data, which is favourable.

4.3.3 Alfa

This area is the area which lay close to the gas field in the north of Gullfaks. Here it is expected to discover more gas than oil, if there is a discovery. Alfa is located from inline 2860 to 2901, T2620 - 2665, at depth 1980-2060 ms.

The seismic image of Alfa is very complex, see Figure 24.

The part of Alfa located at inline 2871, and between traces T2620 - 2660, and at the depth: 1990-2020 ms, looks very complex, there is no continuous reflection. The image in Figure 24 was the most continuous image we could find. Since it is expected more gas here we would maybe expect a bright spot. Since gas has very different acoustic impedance from grains or liquids. This we don't observe in this data.

The image 25, show Vp/Vs ratio of inline 2871 and T2620 - 2660.

Here we don't see any connection between a producing area and Alfa. The ratios, represented with different colours vary a lot through the traces. We don't see a concrete good sand indicator, or a possible reservoir. We see a low ratio 1.9 - 2.0 from T2600 - 2640, and a higher ratio 2.1 - 2.2 from T2640 - 2660.

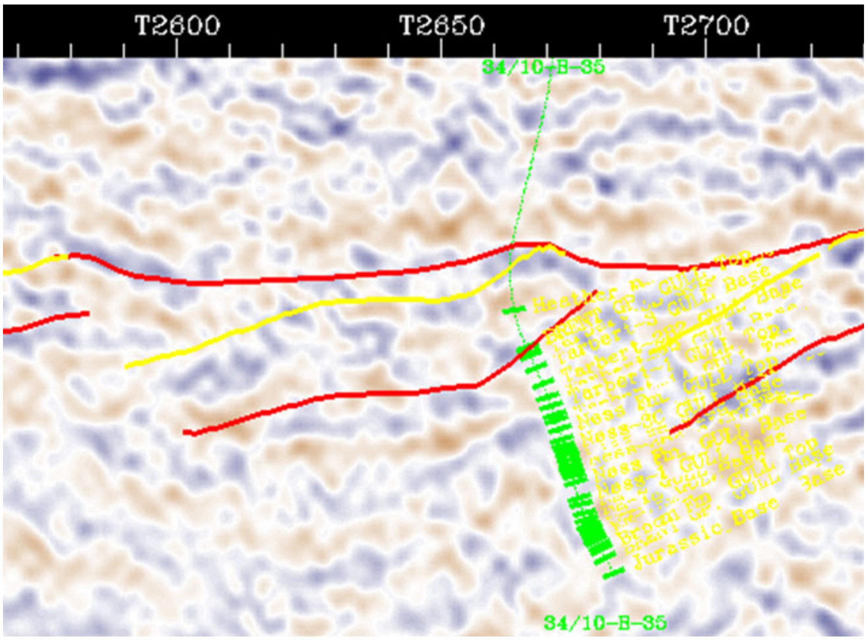

Figure 24: A seismic image of inline 2871.

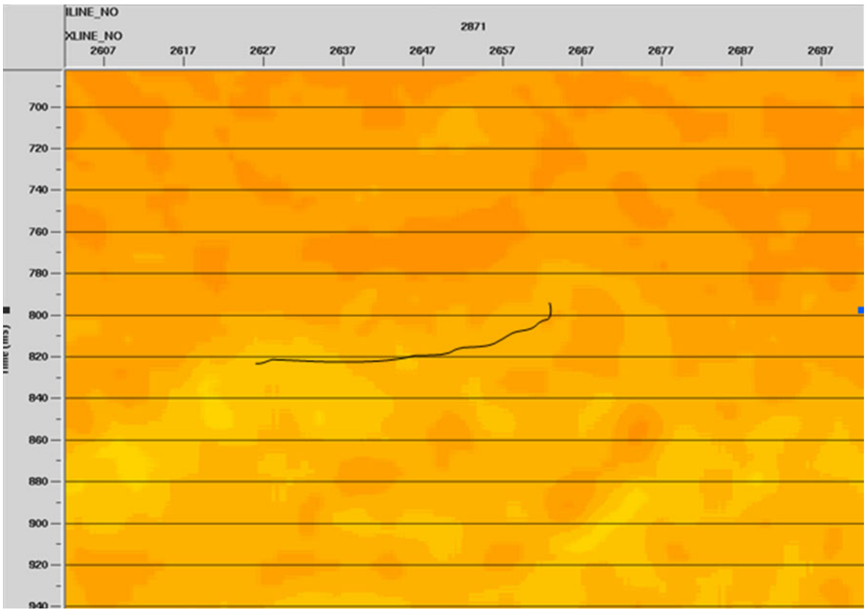

Figure 25: Vp/Vs ratio of inline 2871 in Alfa south, where Alfa is the bright area to the left and the producing area to the right.

The image of Figure 25 looks very complex. With regard to the cross lines we don't see any determined reservoir, or any particular roof. If there are hydrocarbons present, there has to be trapping system. It looks very complex and very unlike the gas field in G7. This was probably expected since the geometry is different from Alfa and the gas field. If there should be hydrocarbons in Zirkon there has to be a trapping geometry, which prevents the hydrocarbons from migrating any further. If we compare Vp/Vs with the seismic images, what we have concluded is a fault around cross line 2645.

When we compare Alfa, cross line 2620-2660, with the producing area in H7, cross line 2730 - 2750, we don't see too much similar colours in a reasonable geometry, see Figure 25. In the producing area we see a clearer reservoir with a seal over it. This could be because of different bedding. In the Alfa area we don't see this. Here is expected more gas, and that means bigger contrast in reflections. This is not what we observe here on the image 26 which show inline 2891, north Alfa.

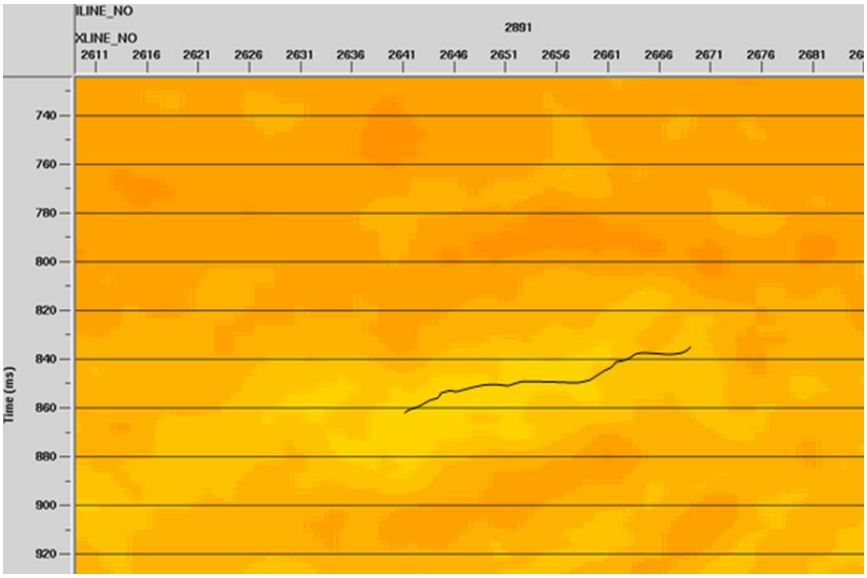

Figure 26: Vp/Vs ratio from inline 2891 Alfa north. The black line represents Alfa.

In Alfa what we have observed here is a better amplitude respond north in Alfa. The respond we see begins in depth 2000 ms. This continue till 2052, see Figure 27. The Vp/Vs value support this. Alfa south is to complex and we don't see any reasonable structure or values in the seismic. But if we move further north, we get deeper we get reasonable image on the seismic, values in Vp/Vs and amplitudes on the time slice.

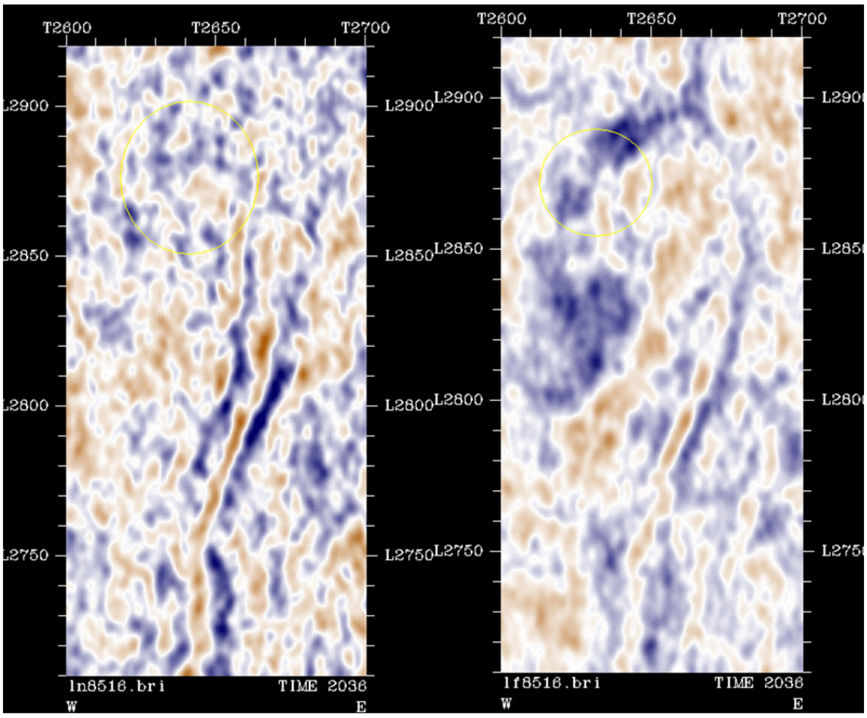

Figure 27: Time slice from Alfa at depth 2036 ms. The circle represents Alfa area. Near to the left, far to the right.

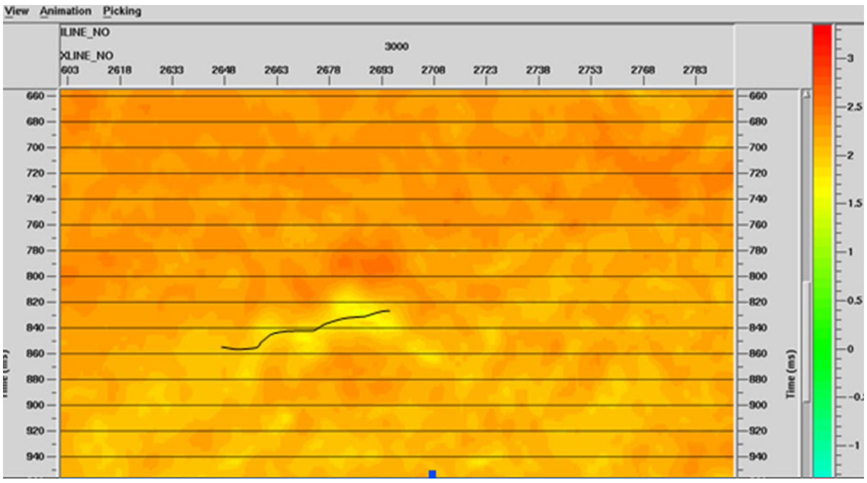

Figure 28: This image show Vp/Vs ratio of the gas field in the north. The bright spot is the gas reservoir, the dark colour the seal above it

4.4 Gas field

Figure 28 of the gas field, compared to the Alfa field which lay longer south of this gas field, doesn't look much the same. This field has a ratio at 1.6

- 1.9, and the seal has a ratio at 2.3 - 2.4. This is other values then we get in Zirkon. This doesn't have to mean that there is no gas in Alfa, but maybe there are heavier hydrocarbons present. The contrasts on reflection are bigger in the gas field. This indicates presence of gas. We can recognize the same area on the regular seismic data.

The crossplot received from Statoil was useful indeed. In Figure 29 you can see the crossplot of Poisson's ratio and acoustic impedance. Points with a high probability of hydrocarbon occurrence are warm coloured (yellow) and are characterised by low Poisson Ratios and low Acoustic Impedance values. Zirkon, Alfa, Beta and Gamma are denoted by circles, the rest of the warm colours to the right (east) are the producing area and the gas field up in the north, that is a good definition of known H-C areas.

The crossplot in Figure 29 is extracted between Poisson's ratio and acoustic impedance. Poisson's ratio is a mathemathical operation and can be expressed by the formula:

$$PR = (\frac{1}{2} - \frac{(\frac{V_s}{V_p}^2))}{1 - \frac{V_s}{V_p}^2}$$

Where Vs and Vp are shear velocity and pressure velocity respectively. This you can map in a way that illustrates how hydrocarbon areas are characterized. The map show PR values get affected by fluid fill. Vp get a reduction in fluid fill and will get more reduced by gas fill than an oil fill. Vs are relatively insensitive to fluid type, and will be unchanged. Within the water layer higher Vp values result in higher PR values.

Acoustic impedance, AI, is the product of density and velocity. This you can map in a way that the volume shows where hydrocarbon accumulations are located. HC fill has a lower density and velocity which will give a reduced effect in AI. This is typically characterised by low impedance values (warm colours). Places where the pore fluid is water, the higher fluid density and P-wave velocity result in a higher AI (cool colours).

These two elastic parameters result in a crossplot which we can see from the figure above where the warm colours are located, in Alfa, Beta and Gamma area which is denoted with three black circles. Here we can clearly see compared to the producing area that there is a high possibility that there is HC present.

4.5 Discussion

With regard to the interpretation done by Statoil there are relatively good chances to discover hydrocarbons in Zirkon area. Zirkon is divided into three zones, Alfa, Beta and Gamma. These three zones are representing different chances of discovering oil and gas. Alfa is located near the big gas field north of Gullfaks. Chance of making a discovery is higher in Alfa, but here there is

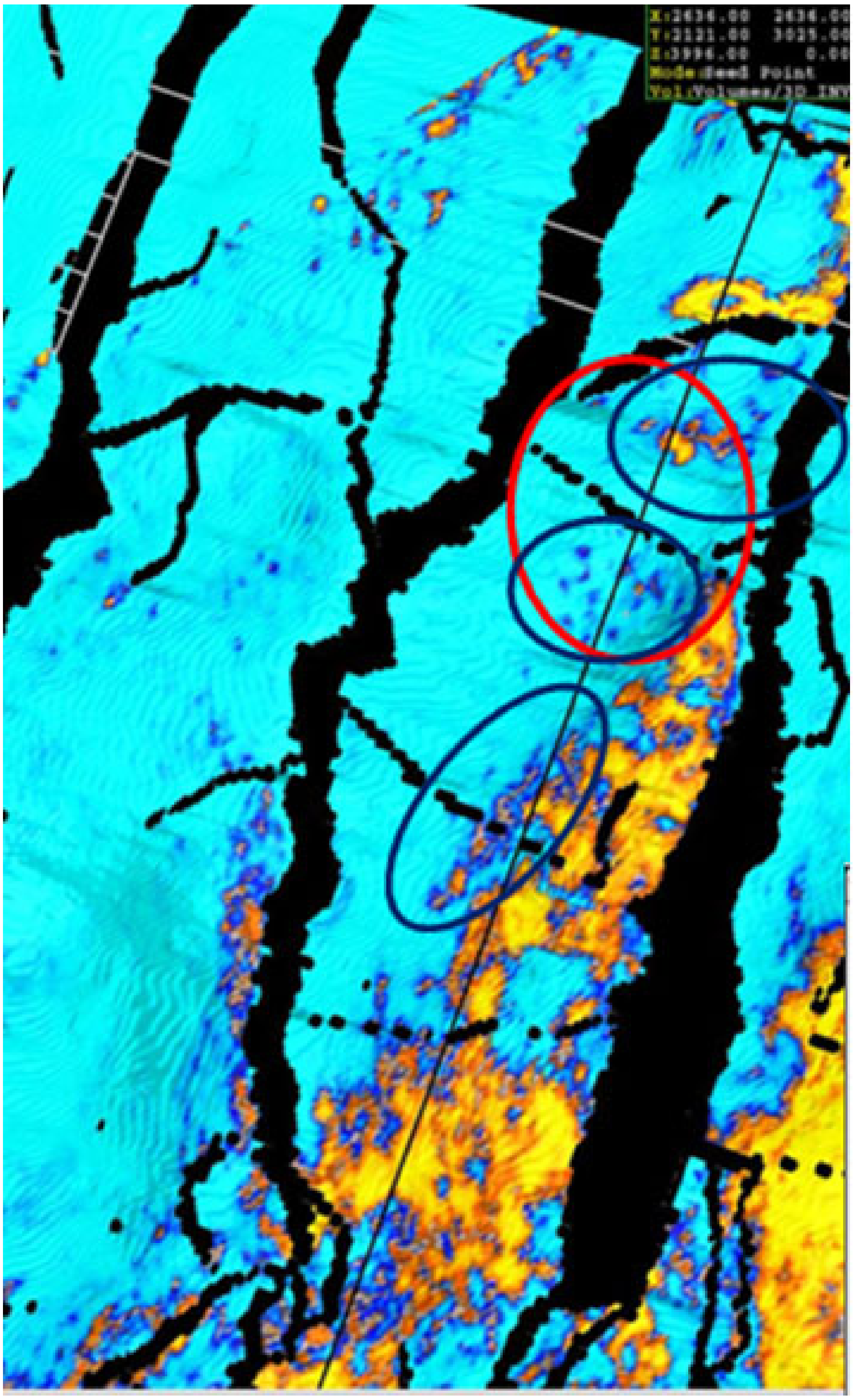

Figure 29: The crossplot between Poisson's ratio and acoustic impedance. The warm colours represent HC.F

probably much more gas than oil. Beta is located between Alfa and Gamma and the chance of making a discovery in Beta is a bit lower than Alfa. Statoils interpretation says there is in Beta equal chance of discovering oil as gas. Then there is Gamma, which is located most south in Zirkon area. Chance of discovery is lower here, but if there is a discovery, the chance for oil present is higher than gas present. The task was to explore Zirkon prospect to see if the is possible slumping geometry and possible discovery of hydrocarbons. We took basis of Statoils interpretation to locate and explore Zirkon to see if we get a similar conclusion or not.

To interpret the seismic data we used Landmarks Seisworks, mostly from the base survey 85. If the interpretation should be good and reliable, the interpreter needs experience and work next to a geologist to get a good interpretation. This we don't have. Still we think we got some answers from the seismic data through an AVO analyses, Vp/Vs ratio and geology knowledge. What makes Zirkon a little unusual is the geology geometry. Statoil have interpreted a possible slumping geometry in Zirkon area. This was something we looked for.

Gamma have a god AVO feature, but the Vp/Vs ratio is different from Gamma south to the producing area to the east. The colours area similar, and the ratios can overlap a bit. In regard to AVO analysis, Vp/Vs ratio and time slice we see that Gamma north is an area to look closer to. If we take the Vp/Vs ratio, which is a good lithology indicator, we compared our located area with a producing area to see if there were any similar colours. Gamma south, inline 2741, we get a different Vp/Vs ratio than the producing area. But this difference gets smaller as we move north and we get deeper. On the seismic data we saw an AVO feature, both on traditionally and on the time slices. This was confirmed with the analysis we did. The seismic reflection increases with offset. This is much clearer in Gamma than Alfa or Beta. The crossplot confirmed what we observed in our interpretation.

When it comes to Beta, this is a much bigger area than Gamma. The image changes a bit from north to south. This might not be a good sign since we want clear good reflections and a favourable AVO feature. This we don't see in the vertical seismic image, but we see in the time slice a clear big area with strong reflections, but only for a little depth interval. The Vp/Vs ratio shows that there are similar colours as the producing area, especially in the north. To see a slumping geometry is difficult on the inverted data or any data for that matter. The AVO analyses support the fact of less chance for discover. In the analyses Beta showed lowest amplitude, which we think is the area where there is less chance of discover. The crossplot show in the Beta area is not much warm colour, which we predicted.

Alfa is a more complex area regard to the seismic and Vp/Vs ratio. Comparing the near and far imapges, both on vertical and time slices we see a stronger amplitude with far offset, or wider angle if preferred. Alfa we expect more gas than Gamma, because it is more north, closer to gas field and deeper. But reflection on these both images, seismic and the ratio, don't show a typical high change in impedance, like there should the crossing over to top reservoir, from (probably) shale to gas. The AVO analyses show a bit high amplitude, but nothing compared to the gas field which lay next to Alfa.

We have to be careful to spit out conclusions of discovering hydrocarbons. Because that type of conclusion need a lot of work, many different analysis and interpretations to look into. We are a group of student who tried the best to look into this type of data, and with our knowledge to come with conclusions. All together we will try to conclude that our interpretation support some of Statoils interpretation. We believe that there is higher chance for discovery in Gamma, and then Alfa comes as number two. Beta we think are less chance of discovery. Unfortunately we could not manage to calculate a curtain percent of how much the discovery chance were.

5 Geological Introduction

5.1 Zirkon

Prospect Zirkon is located in the north-western corner of Gullfaks, in the area defined by North-South directing faults known as the Domino System.

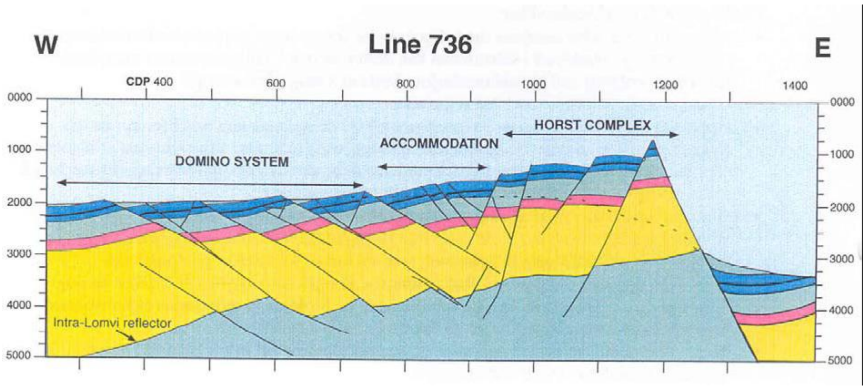

Figure 30: Structural view of Gullfaks

The area of interest consists of the Tarbert formation residing in upper Brent. Above the Tarbert formation lies Heather, a marine deposited layer of siltstone; a good ceiling for an oil-trap. Above Heather we find the clearly defined base Cretaceous which also is known for its ceiling qualities.

As seen in Figure 31 the Tarbert formation consists of two separated layers of sandstone with high permeability values. They also have a weak sand strength and very good lateral continuity. These qualities makes for a very good reservoir. An impermeable siltstone layer drapes the bottom of the formation. The formation consists of material deposited as a delta covering most of Gullfaks was retracting.

The main curiosity of Zirkon is the findings which imply that the OWC lies approximately 30-40 metres below the OWC of the surrounding producing reservoirs. If this is correct, and for the prospect to be viable, there has to be an impermeable layer working as a seal. As Figure 32 shows, the top of Tarbert is not as clearly defined in the seismic data as the layers below and no such faults are seen.

5.2 Slumping

Mass wasting is a phenomen where soil move downslope due to the forces of gravity. Slumping is a type of mass wasting where (loosely) consolidated materials slide downwards a typically listric-shaped slip-plane while rotating backwards. It was first defined by Coates in 1977 as "rotational motion on a concave upwards shear plane". Figure 33 illustrates slumping.

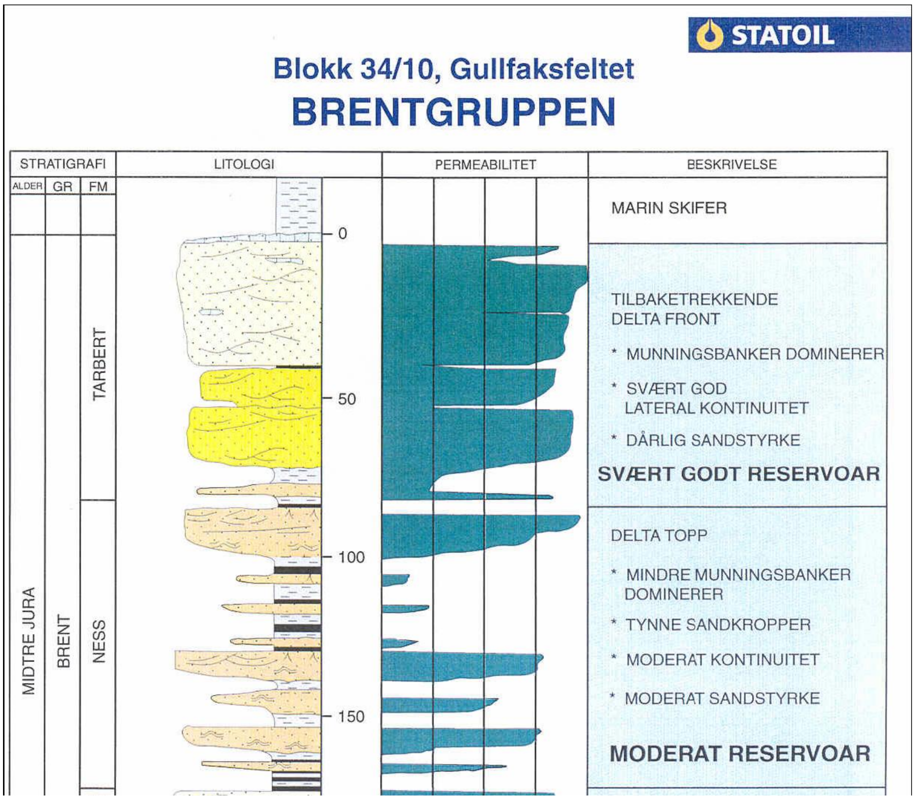

Figure 31: Stratigraphic view of top Brent containing Tarbert

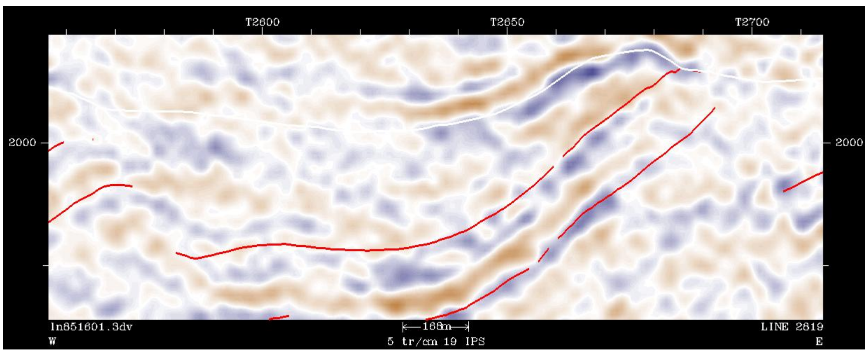

Figure 32: Seismic view of the Zirkon area. Tarbert not clearly defined

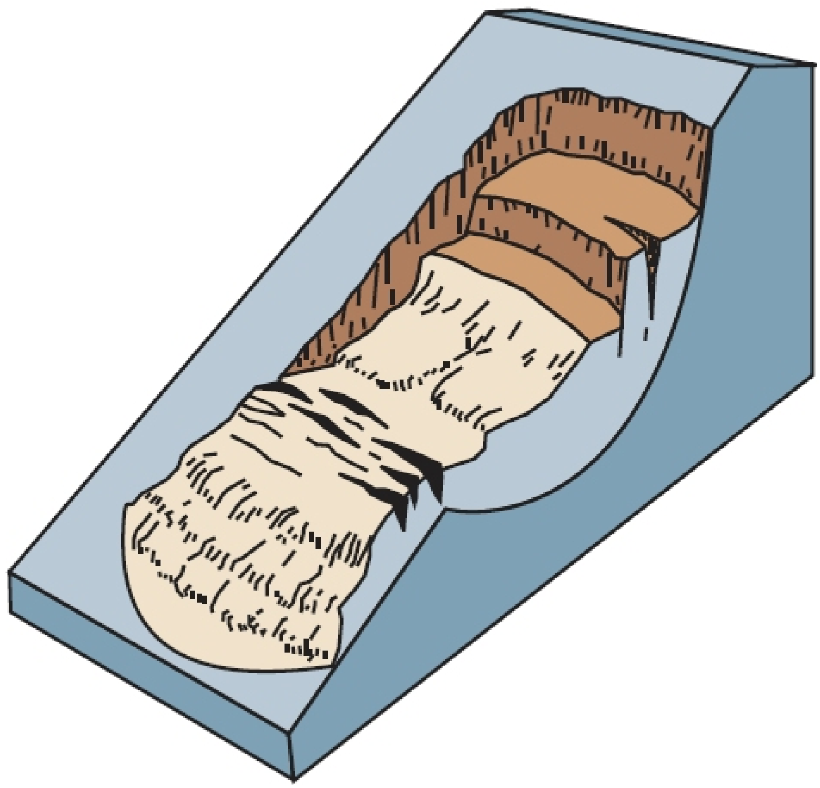

Figure 33: Illustration showing slump block

Both the size and sliding speed of slumping are varying. They range in size from centimetres, see [13] to kilometres and the speed can be as high as metres per second and as low as centimetres per year. If there is material at the toe of the slide, the slumping mass will be deformed due to compaction. Also if the sliding speed is sufficiently high the allocthonous units will be internally deformed and not just rotated. The internal deformation is typically increasing towards the toe. The consolidation of the sliding material effects the the amount of deformation as well. Ideally, a slow sliding slump block can be discovered after the slide below the scarp and only having been subjected to rotation.

The slip-plane is typically listric shaped and amphi-teatre like when viewed from above and the bedding plane will dip upwards after sliding, see 34. It will typically form along a weakened line.

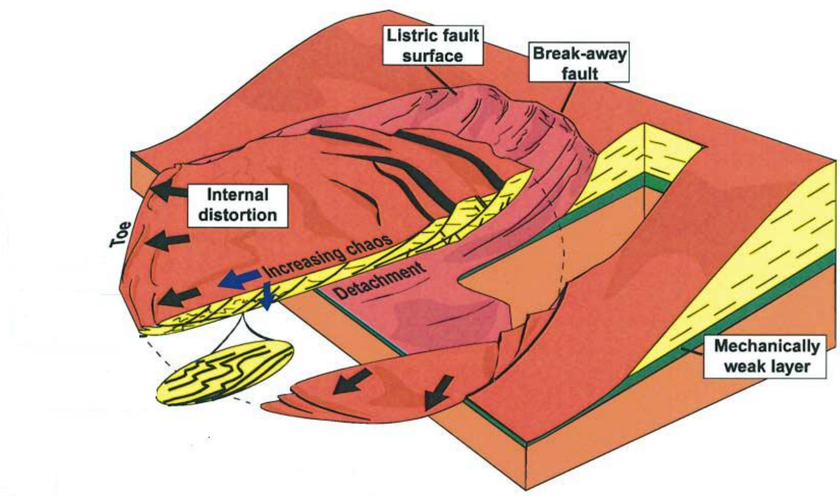

Figure 34: The slip-plane is listric and amphi-teatre like when viewed from above

Generally slope failures occurs as a result of increasing shear stress and/or decreasing shear strength followed by a triggering event. Where the shear-stress is greater than the shear-strength a rupture point will follow. The decreased shear-strength due to the initial rupture points may then lead to the development of an continuing detachment surface called the slip-plane or fault-plane (slip-line, fault-line in the two dimensional case) which the mass slides on. The slip-line can be permeable or impermeable.

The site [18] gives us the following reasons for slope-failure:

Processes that increase shear stress:

- increasing the resting weight
- oversteepening

- sub-surface collapses
- earthquake shaking

Processes that decrease shear-strength:

- increased pore-pressure
- dissolution of cements in sedimentary rocks
- fissuring
- removal of vegetation and roots that hold the soil

Another reason for slope-failure is liquefication. Liquefaction occurs in saturated soils, that is, soils in which the space between individual particles is completely filled with water. This water exerts a pressure on the soil particles that influences how tightly the particles themselves are pressed together. Prior to an earthquake, the water pressure is relatively low. However, earthquake shaking can cause the water pressure to increase to the point where the soil particles can readily move with respect to each other.

When slumping occurs, all overlying layers are affected and move as well, but the underlying layers are mostly unaffected. At most they are influenced afterwards due to change in the overlying weights. [16] discusses that the listric shape of the slip-plane can be formed by a gradual change in pore-pressure. Also, "there is abundant seismic and well evidence for 'listric' fault shapes associated with overpressured slopes."

In this report we talk of several slumps in the same area, as in Figure 35, as slumping structures.

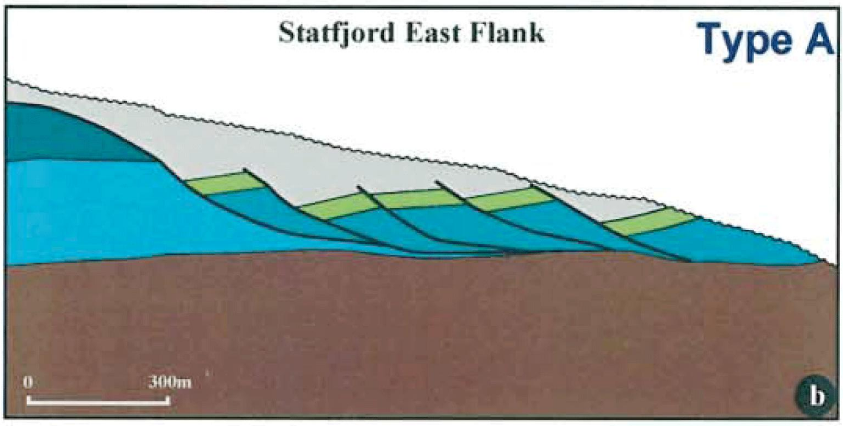

Figure 35: Illustration of slump structures from the East flank of Statfjord

Slumping structures form a very complex geological structure. Combine this with small size of the separate slump blocks, and you have a structure which is difficult to identify using the conventional methods and tools for analysis in hydrocarbon searching. This is also mentioned in [13].

6 Geological Discussion

6.1 Preliminary

One of our goals in this assignment was to identify if slumping is a probable geological explanation to the other findings. We have not considered other geological methods besides general mass wasting. This geological discussion can not be valued as more than indicial, but we do provide feasible geological explanations to the issue at hand. With more knowlegde of the area, including seismic interpretation, gathering and analysis of well data and general geological knowlegde of the area would make the geological assesment more conclusive. Our seismic analysis does not reach far as to provide evidence or conclusions towards slumping. The results gathered merely imply hydrocarbon findings.

Slumping is known to be the dominating trap geometry of the East Flank of Statfjord. Considerable amounts of well data and seismic interpretation have made an extensive geological interpretation possible and the findings there are to some extent applicable to this prospect. The main difference between the two areas being that the slumping in Statfjord has propagated downwards through several formations, from the Brent Group, Denlin Group and the Statfjord formation.

6.2 Causes of slumping

When examining the seismic, see Figure 32, we see that the underlying layers are unaffected by what has happened in Tarbert and base Cretaceous showing no signs as well. This implies that the slumping have occured prior to base Cretaceous, probably in mid to late Jurassic. Since it occured while the layer was on top or buried very shallow, diagenetic processes have not been contributing to weakening the fault-line. When examining the geometry of Zirkon, we find that the general slope angle is not steep enough to be an important factor.

This leaves excess pore-pressure as the probable reason for weakening the formation and leading to a fault plane. [13] provides a summary from several articles about pore pressure and dispatch planes.

When there is excess pore pressure the shear-strength gradient gets steeper, i.e. the shear strength increase slower than it would if the pressure was hydrostatic. This leads to rupture points developing more easily. The mass wasting event will typically detach within or immediately below an impermeable layer which acts as a decollement. In Zirkon we have layers which formed as result of cyclid loading of deposits with Heather, an impermeable clay formation, on top and a draping of silt stones in bottom. This bodes well with the findings from Statfjord and the effects mentioned in the article by Hesthammer. Detachment in stratigraphically homogenous formations are thought to have occured, but are to be viewed as an exception rather than the rule.

Excess pore pressure can develop in a number of ways, including rapid sedimentation, land-elevation relatively to water, and several forms of diagenesis. As previously mentioned, Zirkon consists of mass deposited from a retracting delta-front. This makes the rapid sedimentation explanation highly probable.

Rapid sedimentation can lead to excess pore pressure. Intuitively it can be understood as if the sedimentation clogs the pores such that "incomplete drainage prevents normal compaction and allows excess pressure to build up". Areas with excess pore pressure will typically lead to a listric normal fault, which is supported by the following excerpts from [16].

- "In the overpressured layers the normal fault steepens up-dip"
- "The listric shape on an overpressured slope may be attributed to the action of the abnormally high pore pressures which may drastically change the direction of ρ'_{max}"
- "a gradual change in pore pressure will produce a continous change in dip angle (listric)"
- "There is abundent seismic and well evidence for 'listric' fault shapes associated with over pressured slopes (...) only when shear-stress has a non-vanishing value."
- "Price interprets the listric shape (...) essentially as the result of a gradient in overpressure"

Pore pressure can also develop from diagenetic processes leading to a change in fluid volume, or cementation. A "closed system" may develop from cementation, i.e. one that has low outer permeability. A volume change in a closed system will also lead to changes in pore pressure. Typical diagenetic processes are smectite-to-ilite and gypsum-to-anhydrite transformation. Diagenetic processes require sufficiently pressure and temperature to develop so they are not probable causes in this setting.

6.3 Impermeable seals

The fault-lines can be both impermeable or permeable. This is a problem which poses difficult questions. The Zirkon prospect dependens upon an impermeable seal between itself and the adjacent OIL_REF1. If this seal is missing, any eventual oil would simply migrate into the higher lying reservoir. But these predictions are a bit nonsensical or at least not necessary, since our basis for evaluating slumping are the indications that show the hydrocarbons already being there, and thus the impermeable seal must be present. The geological evaluation will never provide more than a likelihood that something is there anyhow. It will be of great use of it could provide an overview of the reservoir-structure and migration routes so the drilling operation could be performed optimally.

[14] discusses clay smearing and the effects of diagenesis on the creation of impermeable fault lines. Clay smearing is a process which can greatly reduce permeability. In sedimentary successions where clay or shale layers are present, dragging or ductile flow of these layers along the fault plane between the up- and down-thrown source beds can result in a clay smear along the fault plane. The problem clay smearing as an explanation is that we are unsure as to the clay/shale content in Tarbert. We do know that Heather which lies on top consists of clay, but are unsure as to wether it was deposited prior to the slumping occured. Diagenetic processes occuring after the area had slumped and later on being subjected to high pressure from the weight on top could also be a possible explanation to impermeability. Citing [14] ”precipitation of minerals composed of, for example, iron (Fe) or manganese (Mn) oxides, or calcite ($CaCO_3$), can cement an originally permeable fault plane until porosity is partially or almost removed.” Mobilization and redistribution of the minerals could have occured due to the slumping or fluid flow along the fault.

6.4 Conclusions

Slumping is a probable geological phenomen in Zirkon. Slumping is known to be the geological structure containing hydrocarbons on the East Flank of Statfjord. If the internal deformation of the slump blocks are low then there are very good possibilities of having good quality reservoirs in the reservoirs and with impermeable fault-planes combined with the Heather clay on top there also is a proper trap geometry. The slumping has occured the Tarbert formation in upper Brent in middle to late Jurassic time but prior to Cretaceus, this can be seen due to the clearly defined base Cretaceous. The important weakening mechanism were probably excess pore pressure developed from rapid sedimentation. Diagenetic processes are unlikely to have contributing to the dispatch of slumping. As well as slumping being uncertain, the impermeability of the seals, and the viability of the prospect with them, are uncertain. We have not been able to conclude about a probable sealing effect, but clay smear and diagenetic processes as precipitationa of minerals has been mentioned.

A Referanseliste

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B AVO analysis in Excel

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
1			FAR						NEAR													
2			2615-2635		2645-2680		2725-2745		2615-2635		2645-2680		2725-2745		FAR / NEAR							
3	Line		zircon	STDEV	G5	STDEV	H7	STDEV	zircon	STDEV	G5	STDEV	H7	STDEV	Zircon F/N	Awik (+/-)	Oil_ref _1 F/N	Awik (+/-)	Oil_ref _2 F/N	Awik(+/-)	Gass-felt	Awik (+-)
4																						
5			Zircon gamma																			
6	2740		40	10,3	44,6	12,7	79,4	6,9	26,3	7,4	69,1	9,7	50,3	20,5	1,52	0,76	0,65	0,20	1,58	0,66		
7	2744		41,1	14,1	41,1	10,76	73,1	16,1	31,4	6,3	62,9	15,3	53,7	8,6	1,31	0,68	0,65	0,23	1,36	0,37		
8	2748		42,9	10,3	46,3	13	78,9	16,9	27,4	11,6	68	17,3	47,4	13,7	1,57	0,90	0,68	0,26	1,66	0,60		
9	2752		73,7	9,2	73,1	9,2	76,6	20,6	37,1	12,4	90,3	11	53,7	8	1,99	0,85	0,81	0,14	1,43	0,44		
10	2756		52	16,2	59,4	15,4	58,3	6	22,9	11,2	66,3	14,4	39,4	12,9	2,27	1,27	0,90	0,30	1,48	0,51		
11																						
12																						
13			Zircon beta																			
14	2821		59,4	14,7	107,4	14,9	103,4	20,2	58,3	13,8	84	13,7	66,3	13,4	1,02	0,55	1,28	0,27	1,56	0,44		
15	2825		57,1	9,7	107,4	16,9	78,3	22,1	60	17,3	60	21,9	62,9	9,5	0,95	0,55	1,79	0,71	1,24	0,40		
16	2829		63,4	8,50	102,9	27	76,5	24,3	58,9	17,7	63,4	20,7	58,3	11,3	1,08	0,59	1,62	0,68	1,31	0,49		
17	2833		62,9	13,6	76	18,5	90,86	22	54,9	19,3	57,15	18,72	65,14	22,71	1,15	0,68	1,33	0,54	1,39	0,59		
18	2837		61,71	14,8	51,43	17,96	102,3	27,31	53,14	16,3	67,43	17,2	67,43	25,6	1,16	0,66	0,76	0,33	1,52	0,70		
19	2841		50,86	9,72	44,29	9,83	98,9	29,3	80,86	14,37	48,57	12,74	86,9	33,84	0,63	0,36	0,91	0,31	1,14	0,56		
20																						
21																						
22			Zircon alfa																			
23	2881		38,6	10,8					36,6	7,5					1,05	0,53						
24	2883		43,7	12,9					34,3	10					1,27	0,82						
25	2885		42,3	13,6					29,7	6,87					1,42	0,83						
26	2887		47,4	9,4					34,3	8,9					1,38	0,68						
27	2889		44	9,8					29,7	8,3					1,48	0,81						
28																						
29			Gassfelt ved B-35																			
30	2935		91,4	22,8					86,3	28											1,06	0,43
31	2937		94,9	25,7					90,3	27,6											1,05	0,43
32	2939		88	15,7					93,7	20,2											0,94	0,26
33	2941		76,6	9,1					90,85	18,7											0,84	0,20

Figure 36: F/N ratios