Introduction and Executive Summary

• A review was undertaken of the faults bounding fault block A in the Gullfaks field, in the North Sea.
• The fault block is bounded by an array of very segmented faults.
• The aim of the scoping study was to review the fault geometry and make relevant amendments and improvements.
• Changes involved splitting faults into sections based on anomalies in their displacement profiles.
• In this report you will find:
  1. Introduction in the Gullfaks field.
  2. Fault Geometry Theory.
  3. List of faults to be modeled.
  4. Fault displacement profile modeling:
     1. Geometry Analysis.
     2. Fault Editing.
  5. Conclusions and proposed fault growth model.
• A Top Ness depth map and a Z-map fault polygon was used for the analysis.
Theory: Gullfaks

- The Gullfaks field is located in the North Sea and occupies an area of approximately 50km$^2$.
- The Gullfaks fault block is divided into several smaller fault blocks.
- Fossen and Hesthammer (1998) divided the field into a westerly domino style fault array and an easterly horst complex that is separated by an accommodation zone.
  - The domino area has shallow easterly dipping faults.
  - The horst complex is comprised of steeper westerly dipping faults.
Theory: Fault Geometry & Displacement Profiles

• Faults grow by the coalescence of smaller faults.
  – This often results in the strong undulation of fault trace and displacement profiles.

• The lateral variation of displacement is a good indicator of the validity of a fault's interpretation, and should be consistently modeled.
  – Displacement profiles usually vary systematically along the fault plane.
  – Faults typically have a point of maximum displacement, with zero throw at the tips of the fault, the throw diminishes radially from the position of maximum displacement.

• If the profile is more complex it is likely that the fault is segmented or there is a problem with its interpretation.
Theory: Fault Geometry and Displacement Profiles

• Cross cutting faults can help generate complex displacement profiles.
• To accurately analyse a fault with such a displacement profile the structural geologist would ideally review the seismic data looking for fault linkages and branch lines.
• However, pragmatically in a fault seal analysis the fault can be split into two or three segments to look for leak points in the compartment.
• This style of analysis is quick and easy to do and will greatly improve the quality, and accuracy of your 3D models.
• When investigating the probability of fault leakage and/or across fault flow this analysis is a vital step in the workflow.
• This process is easily performed in FaultRisk™ by using the fault splitting tool.
Theory: Throw Length Ratios

- The relationship between maximum fault displacement and the fault trace length is still under discussion in the academic community.
- Pickering et al (1996), plotted fault throw/length ratio from faults in the North Sea, and found that the data showed considerable scatter, but if they added a length of 500m to make up for the fault tips that were below seismic resolution, the data more closely fitted a linear relationship (Fig. 1).
- Schultz and Fossen (2002) plotted published fault data and their deformation band data into a 2D diagram on Max Displacement/Length (Fig. 2).
Gullfaks Input Data
Data: Base Map and Z-map

- The Top Ness depth map was loaded into FaultRisk™.
- The faults were then loaded from the Z-map string selection window.
Data: Fault Block A

- Fault block A is bounded by two faults (Fault 18 and 19) that strike roughly North-South.
- Faults 16, 17 and 6 play a role in the development of the fault array imposed on fault block A.
- The faults are all Easterly dipping normal faults and form part of a domino style fault array.
Fault 18
Data: Fault 18

- The fault is approximately 7,500m long with a maximum vertical displacement of 203m.
- The displacement profile of this fault is composed of several undulating sections, each of which possessing varying amounts of throw and heave.
- This is most likely a result of fault segmentation and fault interference.
Results: Fault 18 - Geometry and Displacement Profile

- The fault was split into the three sections that are annotated on the profile.
- Dip azimuths of the sections vary significantly from 83 – 184 degrees.
- Maximum displacements ($D_{\text{max}}$) vary significantly (from 53 to-203m).
- Cross cutting faults are indicated by the use of arrows on the profile.
- The throw length ratio has been annotated onto the $D_{\text{max}}$ vs Length diagram of Schultz and Fossen (2002).
  - This can be seen to be just within the acceptable range, however it could be improved.
  - This is expected to arise once the fault is split into sections.
Results: Fault 18 - Geometry and Displacement Profile

- The $D_{\text{max}}$ and Length values were plotted onto Schultz and Fossen’s (2002) plot.
- Some of the faults still require additional work, as they continue to plot on the edge of the desired range.
- **18.1**: is most likely part of fault 6, this may have been misinterpreted.
  - This explains why it does not plot well on the $D_{\text{max}}$ Vs Length plot.
- **18.2**: This fault clearly has a lot of interference associated with it.
  - This is associated with fault 4 and 21.
  - Most of which can be removed from the model as it has no significant effect.
  - The fault string will be edited to improve the model (Next Slide).
- **18.3**: This small fault is the linkage point between faults 18 and 17.
  - The throw at the end of the fault, which when added to the throw of fault 17 at the point of linkage equals the maximum displacement of fault 17.
Results: Fault 18.2 - Geometry and Displacement Profile

- Both the length and geometry of fault 18.2 was changed.
  - In this model you will notice the fault is slightly shorter.
  - The tips of the fault that were below seismic resolution have been removed.
  - The effect of the cross cutting fault 21 was “ironed out” in order to make the profile look better and allow for a better interpretation.
  - This fault may create some compartmentalization within the fault block, and later would need to be taken into account.
Data: Fault 6e - Geometry and Displacement Profile

- The fault traces from fault 18.1 and fault 6 have been stitched together to create a single fault.
- This fault is much more plausible given the new displacement profile.
  - This is further supported when the $D_{\text{max}}$ and Length values are plotted upon Schultz and Fossen’s (2002) plot.
Data: Fault 19

- Fault 19 is approximately 6,500m long with a maximum displacement of 288m.
- The displacement profile of this fault is composed of several undulating sections, each of which possessing varying amounts of throw and heave.
- This is most likely a result of a combination of fault segmentation, linkage and interference from other faults.
  - The fault has interference is from faults 1, 7, 8, 10, 20.
Results: Fault 19 - Geometry and Displacement Profile

- The fault was split into the five sections that are annotated on the profile.
- Dip azimuths vary from 78 – 89 degrees.
- Maximum displacements ($D_{max}$) vary from 105 – 144m.
- Cross cutting faults are indicated by the use of arrows on the profile.
- The throw length ratio has been annotated onto the $D_{max}$ Vs L diagram of Schultz and Fossen (2002).
  - This can be seen to be just within the acceptable range, however it could be improved. This is expected to arise once the fault is split into sections.
Results: Fault 19 - Geometry and Displacement Profile

- **19.1:** It is likely that this fault is actually a southern limb of fault 10.
- **19.2:** There is a large amount of interference from faults 8, 7, 1 and 20, this has been annotated on the trace profiles using red arrows.
  - The interference is not caused by cross cutting faults rather there has been some small amount of fault linkage.
  - The fault most likely initiated between faults 1 and 7, then propagated north and south until linkage occurred with faults 18 and faults (19.1 and 10).
  - The displacement profile was improved once the effect of the smaller faults was “ironed out”.
- The faults plot very well on the $D_{\text{max}}$ Vs Length plot of Schultz and Fossen (2002).
  - Fault 19.1 plots on the edge of the desired range, however as suggested this may be a southern limb of fault 10.
  - Joining these to faults together would improve this, the length of the fault would be increased resulting in a much better plot.
Fault 16
Results: Fault 16 - Geometry and Displacement Profile

- The displacement profile appears somewhat skewed and requires work.
- As a result the fault was edited to remove its northern section.
  - The northern end of the fault appears to have very little throw.
  - The throw is less than the seismic resolution.
- The $D_{\text{max}}$ Vs L have been plotted onto Schultz and Fossen’s (2002) plot.
  - The red lines represent the original fault.
  - The yellow lines represent the new edited fault.
- The original fault appears to plot better than the new edited fault.
  - This indicates that more work is required on the maps and fault interpretation.
  - Many uncertainties arise when features are mapped that are below seismic resolution.
  - It is also quite likely that this fault continues further south beyond the extent of the map.
- The fault needs to be more accurately interpreted before an assessment on sealing capacity can be undertaken.
  - However the small amount of throw is less than the reservoir thickness and would most likely result in the communication of reservoirs either side of the northern section of fault 16.
- Pragmatically in a fault seal analysis the fault can be split into a northern and southern section, with the northern section discarded.
  - The southern section would most likely create no compartmentalization as fluids would travel up and around the tip of the fault.
- This fault will have no affect on fluid movement within the fault block A.
Data: Fault 17

- Fault 17 is approximately 4,500m long with a maximum displacement of 202m.
- The displacement profile of this fault is fairly good, there are two undulating sections.
  - This is most likely a result of a combination of fault segmentation, linkage and interference from other faults.
- Although it does not appear to have a direct influence on the fault block, fault 17 has influenced the development of fault 18.
- It forms a possible relay ramp with fault 18, if the ramp has not been breached fault 17 could now be a boundary for fault block A.
Results: Fault 17 - Geometry and Displacement Profile

- The footwall and hangingwall depth (z) values were edited slightly to soften the effect of faults 18 and 20.
- This cleaned the fault up substantially.
  - As a result the throw of the fault was reduced slightly, the fault now plots better upon Schultz and Fossen's plot.
- There is still some throw on the northern end of the fault.
  - This is as if the all of the fault has not been traced completely.
  - It would be expected that the throw to diminish the further North it progresses.
Conclusions: Summary of Fault Block A

• Editing the faults improves the model.
• It is likely that some of the faults in the initial interpretation were pushed through too far and are not actually linked.
• This resulted in a hard linked fault system, which is actually most unlikely.
• There is still some uncertainty given that there may be some faulting below seismic resolution, however the effect of this may be negligible.
• Next Steps:
  – Track the fluid flow and leak points
  – In particular across fault 16 as there may be some fault compartmentalisation.
Conclusions: Proposed Fault Growth Model

- The growth model below was created by plotting the position of maximum displacement of the faults. The model then assumes that faults nucleate over time, eventually forming the hard linked Gullfaks fault system.
- Stage 5 of the fault growth model displays the faults that have been “pushed through” in grey.
  - These faults have displacements that are close to or below seismic resolution.
- Fault 18 has grown by segmentation until the fault has linked with fault 17, creating a structure that looks like a relay ramp.
Conclusions

• The process of analysing and editing faults provides geoscientists with an improved learning in relation to the fault growth history of the area, and subsequently a developing a fault growth model.
• The refinement of the model has a first order effect on the ability of the system to hold hydrocarbons.
• A robust fault model is vital for further fault framework development, and fault seal analyses.
• This kind of study is easy to do and can be done with limited data.
• It is highly recommended that you download a copy of the FaultRisk™ software and perform your own analysis.