Title:

“Fault Seal Breakdown Analysis in HP/HT Field – A Study of Egret Field in the North Sea”

By

Percy Paul Obeahon

A project carried out in Shell UK for the completion of M.Sc. in Petroleum Engineering at Imperial College

September 2012
DECLARATION OF OWN WORK

I declare that this thesis:

“Fault Seal Breakdown Analysis in HP/HT Field – A Study of Egret Field in the North Sea”

Is entirely my own work and that where any material could be construed as the work of others, it is fully cited and referenced, and/or with appropriate acknowledgement given.

Signature: ...........................................................................................................

Name of student: PERCY PAUL OBEAHON

Name of supervisors: MR. GERMEN YPMA (Shell U.K)
PROFESSOR ALAIN GRINGARTEN (Imperial College)
“Do not believe everything you read.”

Alain Gringarten
ACKNOWLEDGEMENTS

I would like to thank my Parents and Church family, the Centre for Global Evangelism for all the love and tremendously invaluable support they have shown me all my life. I would not be who I am today without that support.

This project would not have been completed without the help of my supervisors Prof. Alain Gringarten (Imperial College) and Germen Ypma (Shell). Special thanks to Jorrit Glastra, Kachi Onyeagoro, Mark Wood, Shankar Rao, Poornesh Govinda and Terence wells at Shell U.K. for providing guidance at crucial points of the project. Thank you all for sharing your knowledge with me. Special thanks also go to Anco Maan (Chief Reservoir Engineer – Shell Europe) and Osayande Igiehon (Chief Reservoir Engineer – Shell Sub-Saharan Africa) for giving me the opportunity to do my project with the company and for the study leave granted.

I thank my numerous friends and colleagues. Thank you for your unflinching support. Your indirect contribution to this work is deeply appreciated.
Table of Contents

TITLE PAGE ...................................................................................................................... i
DECLARATION OF OWN WORK ......................................................................................... ii
ACKNOWLEDGEMENTS ....................................................................................................... iv
LIST OF TABLES .................................................................................................................. vii
LIST OF FIGS ...................................................................................................................... viii

MAIN REPORT – Fault Seal Breakdown Analysis in HP/HT Field .......................................... 1
  Abstract ............................................................................................................................. 1
  Introduction ....................................................................................................................... 1
  Field History .................................................................................................................... 2
  Problem Statement/Justification ....................................................................................... 2
  Objectives of the Project .................................................................................................. 2
  Literature Review .......................................................................................................... 3
  Approach ......................................................................................................................... 4
  Pressure Transient Analysis (Appraisal well) ................................................................. 4
  Discussion of Result ........................................................................................................ 5
  Production Analysis (Producer well) ................................................................................ 6
  Discussion of Result ........................................................................................................ 7
  Scenario 1 ......................................................................................................................... 8
  Scenario 2 ......................................................................................................................... 8
  Deconvolution (Producer well) ....................................................................................... 9
  Dynamic Reservoir Simulation ....................................................................................... 10
  Modelling Strategy ......................................................................................................... 10
  Reservoir Model Construction ....................................................................................... 11
  History Matching Results ............................................................................................... 11
  Results and Discussion .................................................................................................. 14
  Conclusion ...................................................................................................................... 15
  Recommendation ........................................................................................................... 15
  Acknowledgments ........................................................................................................... 15
  Nomenclature .................................................................................................................. 15
  References ....................................................................................................................... 16

APPENDIX A ..................................................................................................................... 17
  A.1: Milestone in Fault Seal Breakdown Analysis and Critical Literature Review .................. 17
  A.2: Summary of Papers Reviewed ................................................................................... 19
LIST OF TABLES

MAIN REPORT – Fault Seal Breakdown Analysis in HP/HT Field.................................................................1
Table 1: Input Parameters used in PTA ........................................................................................................5

APPENDIX A
Table A.1: Milestone in Fault Seal Breakdown study................................................................................17

APPENDIX B
Table B.1: PTA results comparison ...........................................................................................................30

APPENDIX D
Table D.1: STOIIP estimate comparison for different Compartment ..........................................................35
LIST OF FIGS

Fig 1: Top structure map for Skagerrak reservoir showing reservoir compartment ........................................2
Fig 2: Field X-section .................................................................................................................................2
Fig 3: Variation in Fault throw, thickness and clay content ............................................................................3
Fig 4: Field pressure profile for 8 years of production ..................................................................................3
Fig 5: QA/QC on pressure gauges .............................................................................................................5
Fig 6: Analytic model on pressure and pressure derivative response for FP2 .............................................5
Fig 7: Analytic model on deconvolved pressure and pressure derivative response for FP1 and FP2 ........5
Fig 8: Numerical model on pressure and pressure derivative response for FP2 ........................................6
Fig 9: Numerical simulation using saphir .....................................................................................................6
Fig 10: Upper Skagerrak Facies distribution map .......................................................................................6
Fig 11: Boundaries captured in geological model .........................................................................................6
Fig 12: STOIIP estimate using normalized rate cumulative plot for pressure decline period ....................7
Fig 13: Fetkovich plot for pressure decline period .....................................................................................7
Fig 14: 4D seismic showing depletion area ..................................................................................................8
Fig 15: Skagerrak U3 formation showing boundaries ..................................................................................8
Fig 16: Scenerio 1 – Fault Seal analysis geometry using topaze ..............................................................9
Fig 17: Scenerio 2 – Fault Seal analysis geometry using topaze ..............................................................9
Fig 18: Scenerio 1 & 2 – History match on historical production and pressure using topaze ....................9
Fig 19: Deconvolved derivative for producer well using TLSI .................................................................10
Fig 20: Schematic showing host rock, Kf and distances used in computing seal factors ...............................11
Fig 21: Apprasial well Kh variation with depth ...........................................................................................11
Fig 22: Stage 1 – Pressure distribution profile after 3 years of production ..............................................12
Fig 23: Stage 1 - History match result when well depletes compartment A ............................................12
Fig 24: Wells and perforation intervals ......................................................................................................12
Fig 25: Fault Pc against Kf .......................................................................................................................12
Fig 26: History match result without the influence of B5 ...........................................................................13
Fig 27: Saturation distribution before waterthrough ..................................................................................13
Fig 28: Saturation distribution after waterthrough .....................................................................................13
Fig 29: Stage 2 – Pressure distribution profile in 2008 ............................................................................13
Fig 30: History match result .......................................................................................................................14
Fig 31: Initial pressure distribution across fault .........................................................................................14
Fig 32: Pressure distribution across fault in 2005 .....................................................................................14
Fig 33: Pressure distribution across fault in 2008 .....................................................................................14

APPENDIX B
Fig B.1: Semi-Log plot for FP2 .................................................................................................................29
Fig B.2: Semi-Log plot for FP1 and FP2 ..................................................................................................29
Fig B.3: History plot for numerical simulation ..........................................................................................29
Fig B.4: History plot for deconvolution ....................................................................................................29
Fig B.5: Full skagerrak U3 top structural map ..........................................................................................31

APPENDIX C
Fig C.1: Historical cumulative production allocated to Egret field ...........................................................32
Fig C.2: Scenario 3 – Fault Seal Analysis geometry using topaze ................................................................. 33
Fig C.3: Scenario 3 – History match on historical production and pressure using topaze ........................................... 33
Fig C.4: Early-late time match on deconvolved pressure and pressure derivative response using Saphir ..................... 34
Fig C.5: Late- late time match on deconvolved pressure and pressure derivative response using Saphir ..................... 34
Fig C.6: Fault breakdown analytical solution geometries as modelled using Saphir ................................................. 34

APPENDIX D
Fig D.1: Relative permeability curve for different porosity class generated from analog (Skua Field) .......................... 35
Fig D.2: Capillary pressure curve for different porosity class generated from analog (Skua Field) ............................ 36
Fig D.3: Match on Historical Rate (Model Constraint) ......................................................................................... 36

APPENDIX E
Fig E.1: Modeling reservoir compartment using MBal .......................................................................................... 37
Fig E.2: Schematic showing fault leakage scenario .............................................................................................. 37
Fig E.3: Phase 1 - Rapid decline in reservoir pressure .......................................................................................... 38
Fig E.4: Phase 2 - Reservoir pressure stabilization above bubble point ................................................................. 38
Fig E.5: History match result using MBal ............................................................................................................. 39
Fault Seal Breakdown Analysis in HP/HT Field – A study of Egret Field in the North Sea

Percy Paul Obeahon

Imperial College London Supervisors: Prof. Alain Gringarten
Industry Supervisor: Germen Ypma (Shell U.K)

Abstract
This work presents the results of a study conducted on a high pressure/high temperature (HP/HT) heavily faulted reservoir in the North Sea. The reservoir pressure declined by half the initial pressure for the first seven months of production then experienced pressure stabilization for the next eight years with pressure above bubble point pressure, thus suggesting recharge from another compartment. In recent times, fault seal breakdown are seen to have significant impact on recovery. The ability to predict these impacts of faults on well productivity is critical to optimal well placement, reservoir management and field development decisions, particularly for high pressure high temperature deep water developments.

Though history matches are invariably non-unique, there is a danger that fault transmissibility multipliers are used to compensate for other problems associated with reservoir models. This work fills the knowledge gaps in dynamic fault seal modeling by presenting a new concept on how to characterize sealing nature of reservoir boundaries and achieve history matches in reservoirs where seal factors changes dynamically. This was achieved using pressure transient analysis, production analysis and deconvolution method. The report demonstrates that using well test interpretation results and a systematic approach to fault seal breakdown, history matched-dynamic model that will explain fault seal breakdown can be constructed.

This project also reviews the evolution of fault seal breakdown analysis over the last century and shows improvements over the past decades.

Well test interpretation models can be reconciled with geological models. Result obtained from well test interpretation was incorporated and validated using dynamic model to improve history match results. Fault seal breakdown investigated using pressure transient analysis, production analysis, deconvolution and history matching identified the same fault as the leaky boundary. In particular, history matched model that incorporated all the analyses carried out revealed that in addition to absolute fault seal, when capillary threshold pressure of approximately 1000psi is exceeded, fault seal breaks down.

Introduction
This work evaluates fault seal breakdown in Triassic Skagerrak formation of the Egret field. This field is part of the HP/HT Central Graben area of the central North Sea. Egret structure is defined as a faulted footwall structure with dip closure to the east (Figure 1). The Triassic Skagerrak Formation forms the main reservoir and overlying Jurassic Pentland a secondary unit (Figure 2). Both formations are truncated over the crest of the structure by the Base cretaceous unconformity. The Upper Skagerrak comprises fluvial channel and sheet flood sandstones, inter-bedded with calcrite soils and lacustrine shale. Recent 4D seismic mapped at least 5 separate compartments separated by fault.

It is well known that faults can severely compartmentalize reservoirs resulting in reduced hydrocarbon recovery when they act as flow barriers or improve hydrocarbon recovery when they breakdown during production. In recent times the understanding of how faults may affect fluid flow within reservoirs and how to account for the presence of their seal capacity in dynamic simulation model has been improved by activities of many researchers. Historically this has been attempted by altering the fault transmissibility multipliers on the grid blocks adjacent to faults in a particular manner until a history match of the actual production data is obtained (Knai and Knipe, 1998). A problem with this approach is that it assigns a uniform seal factor over the fault plane and ignores the fact that the seal factor naturally varies over the fault plane due to variations in fault throw (Figure 3), fault rock permeability ($K_p$), thickness, shale content and host rock permeability ($K_h$). Another problem with such
an approach is that history matches are invariably non-unique and so there is a danger that fault transmissibility multipliers are used to compensate for other problems associated with the model. In this project, an attempt was made to fill the knowledge gaps in dynamic fault seal by presenting new concept on how to achieve history matches in reservoirs where seal factors change dynamically. Firstly, boundaries were characterized using well test interpretation methods from pressure transient analysis, production analysis and deconvolution method. Secondly, the results from well test interpretation are incorporated and validated using dynamic simulation model. This approach was to improve history matching results. Finally, validated well test Interpretation result and history matched model are used to demonstrate the impact of fault seal breakdown on production behavior.

Field History
The field was discovered in 1991 by an appraisal well. The reservoir contains highly over-pressured and under saturated volatile oil. Recent estimate of stock tank oil initially in place (STOIIP) is about 72.8MMstb oil (Skagerrak contains 64.5MMstb while pentland contains 8.3MMstb) with approximately 62Bscf of associated solution gas. The Skagerrak formation is made up of the upper and lower Skagerrak. The upper Skagerrak has two oil bearing sands (U1 and U2) and a water bearing formation (U3) all separated by shale. The lower Skagerrak also contains water. The formation is salt saturated at reservoir conditions with very high concentrations of barium and strontium ions. Production started in 1999 initially from the upper zones of the Upper Skagerrak formation and in late 2003 from the pentland formation. The main recovery mechanism is depletion drive and aquifer activity is uncertain. The field has one producer and one appraisal well. The producer well flowed naturally until 2006 after which it went into sporadic production for a few years and was finally closed-in in October 2008 due to produced water handling limitations at the CPF. To date, about 8.6MMstb of oil and 9.9Bscf of associated solution gas have been produced from the field.

Problem Statement/Justification
Few authors have written on dynamic fault seal breakdown and where this exists, few of them have made detailed analysis to account for the dynamic (changing) nature of the seal in fault rocks and likely impact on recovery process. Figure 3 shows how seal factors are not uniform and could change along fault zones. Figure 4 shows the observed reservoir pressure decline profile in Egret Field. During the first seven months of production the reservoir pressure declined by half the initial pressure after 1.1Mstb oil production and later stabilized at above the bubble point with significant production. Aquifer activity is uncertain. The key question is: where is the pressure support coming from?

Objectives of the project
The objectives of this project are:

- Reviews the evolution of fault seal breakdown analysis over the past decade.
Objectives

- Characterize fault seal failure in a number of successive faults in the Egret field using well test interpretation methods.
- Build a history matched model to assess connected pathways across faults and explain pressure behavior in the reservoir.
- Compare results with other examples from literature.

Literature Review

Field which are relatively deep (up to 4500m tvdss) with initial reservoir pressure and temperatures of up to 12900 psia (pore pressure of at least 0.8 psi/ft) and 350°F respectively are classified as HP/HT field. Fault breakdown is a challenging task because it involves many related factors. Knowledge of these factors is both non-uniform and subjective. Most faulting processes have been studied in isolation and the relationships among many of the processes are poorly understood (Sorkhabi et al. 2000).

In the classic paper of Bouvier et al. (1989) he mention how fault seal break down may occur along weak clay-smear seals as a result of increased pressure differentials from production on one side of a fault, but did not give examples or explain what they actually meant. Reservoir depletion can, in principle, induce stress paths capable of reactivating intra-reservoir faults and hence potentially cause breakdown of their sealing integrity. Fault seal breakdown may be invoked falsely where oil–water contacts change across a fault, i.e. the fault is a capillary seal, but the fault does not compartmentalize pressures in production. This apparent seal failure can arise since there is pressure communication in the water leg below the oil column. It is not at all clear why pressure depletion should cause capillary seal failure. Only three publications exist which attribute observed production behavior to fault seal breakdown in a production context due to pressure depletion on one side of a fault. The first example is reported as a case of fault seal breakdown in Niger Delta’s Cawthorne Channel Akaso field, yet the preferred interpretation of the pressure data by the authors of the paper (Jev et al. 1993) is that the behavior was caused by across fault flow in water-leg and there was little (if any) across fault hydrocarbon flow. Flow in the water-leg was possible because the fault is not a seal below the hydrocarbon column as evidenced by decreasing clay smear factors. Hence this example does not show fault seal breakdown, but merely a difference in fault seal integrity on the fault surface and effects of flow of water through the fault.

The second example from the Marsh Island 36 field, Gulf of Mexico (Davies et al. 2003) is a situation in which the hydrocarbon is in a low-pressure compartment and water pressure gradient within the fault rock in the high pressure compartment supports the column. As the low pressure compartment is depressurized, the pressure differential across the fault gradually increases until the capillary threshold pressure is exceeded and the fault becomes permeable to oil. Capillary fault seal failure with this pressure configuration is well understood (Underschultz 2007) but requires rather specific hydrodynamic conditions. However, no history match model was build for this field to support this theory.
The third reported case of fault seal breakdown is discussed by Gilham in 2005, and involves a fault in the Shearwater HP/HT reservoir in the Central North Sea. The gas water contact is the same across the fault, and evidence that the fault was a static seal at the onset of production was interpreted from different fluid compositions measured in samples acquired from wells drilled on each side of the fault. Dynamic evidence for initial fault sealing and later breakdown in Shearwater was derived from interpretation of a P/ZZ plot (Gilham et al. 2005). They interpreted a sharp change in linear slope in the Shearwater P/ZZ plot, but a close examination of the plot indicates that a curved trend may be equally likely. This would imply that a low transmissibility (but non-sealing) fault is present throughout the period considered, and does not require any changes in fault properties (Dake 2001; Zijlstra et al. 2007). In summary, therefore, the case for both static fault seal as well as for subsequent fault seal breakdown in the Shearwater field may not be unequivocal.

The first attempts to incorporate geologically reasonable fault properties into production simulation models involved the calculation of transmissibility multiplier based on the absolute permeability and thickness of fault rocks (Knai and Knipe, 1998). These calculations do not capture the multiphase behaviours of fault rocks (Fisher and Knipe, 2001). A key problem with this approach is that a huge number of pseudo-functions are needed to be calculated to take into account the large variation in the properties (e.g. thickness, absolute permeability), flow rates and whether or not the faults is going through drainage or imbibitions during production (Christie, 1996). The second attempt (Manzocchi 1999) involves calculating transmissibility multiplier based on $K_F$. The key problem with this approach is that $K_F$ only depends on shale gouge ratio (SGR) and fault displacement. The calculation does not capture the impact of $K_H$ on $K_F$.

There is a greater consensus as to how faulted rock should be modelled in production simulation studies, largely because the controlling properties are inherently more predictable (sealing capacity of faults is controlled by the weakest point). Methods for calculating faults in flow simulation models have been reviewed recently by Onyeagoro, Fisher & Jolley in 2007. They concluded that the most important aspect is ensuring that the correct juxtapositions are contained in the model and that geologically reasonable $K_F$ and thickness values are used to calculate transmissibility multiplier. In some situations such as structures with high net to gross reservoirs and cataclastic fault rocks, two-phase fault rock properties should be considered as capillary properties may be significant.

**Approach**

This methodology involves characterizing reservoir boundary using an integrated approach. Results derived from pressure transient analysis (PTA), production analysis (PA), deconvolution and other information pertinent to this field were used to obtain history matched model. In calculating transmissibility multipliers, SGR, $K_H$, $K_F$ and fault thickness are considered. In this work the effect of clay smear potential (CSP) is not considered, this is because shale layers present in HP/HT fields, presents little or no ductility. Hence, CSP will have little effect on $K_F$.

At first, Interpretation models are presented from analyzing well test data available for the appraisal (tested) well and Fault seal analysis (Production analysis) as well as deconvolution on production data available for the producer well. This was done using the well test interpretation software package Ecrin 4.20 from Kappa engineering.

Information derived from well test interpretation is reconciled with the existing static model, and boundaries identified from well test interpretation are verified for existence within the available static geological model. In cases where they do not exist they are introduced. The dynamic model (history matching) was constructed using Dynamo a Shell reservoir modeling simulator package. The dynamic modelling is divided into 2 stages:

**Stage 1:** Rapid decline in reservoir pressure

**Stage 2:** Flattening of reservoir pressure.

**Pressure transient analysis (Appraisal well)**

The objective was to identify reservoir boundaries, connectivity and estimate reservoir permeability. The appraisal well is a vertical well drilled in 1991 into the eastern fault block of the upper and lower Skagerrak reservoir. The oil bearing Skagerrak interval 14324 - 14604 ft TVDSS was tested and found to produce 41⁰API oil at a stabilized rate of 4300 bbl/day (test GOR 1000 - 1100 scf/stb). Bottom-hole pressure (BHP) data is available for two Build ups and two drawdown tests conducted using two down-hole gauges positioned at different depths (Figure 5). The comparison of the two gauges suggests that they are slightly out of sync. The top gauge (brown line in Figure 5) was shifted by -0.0001 hr to synchronize it with the bottom gauge (reference gauge). In order to check the drift, the top gauge was depth shifted to the bottom gauge’s (green line in Figure 5) depth by adding 2.2 psi (difference of 3 ft), there is a good correlation between the two gauges and negligible drift. Both
gauges are suitable for interpretation. The bottom gauge was used as the reference gauge for the analysis presented in this work.

The pressure difference plot with bottom gauge as the reference gauge is shown in Figure 5, ideally in a build-up period; the pressure difference should be zero after correcting for depth. During the flow period (FP), the difference is non-zero on account of frictional pressure drop between the gauges. During shut-in period, there is after flow occurring in the wellbore due to wellbore storage which should be detected in the difference plot. The difference plot in this case suggests that there is after flow for a very short period (<0.2 hrs) and hence a very short wellbore storage period can be expected in the diagnostic plots. The data has a frequency of 5 minutes with a 1 psi resolution (poor resolution). The input parameters and sources for information used for PTA are summarized in Table 1.

### Table 1: Input Parameters used in PTA

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Input Values</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness, ft</td>
<td>210</td>
<td>Completion Report</td>
</tr>
<tr>
<td>Well Radius, ft</td>
<td>0.291</td>
<td>Well status diagram</td>
</tr>
<tr>
<td>Porosity, %</td>
<td>0.21</td>
<td>Log Data</td>
</tr>
<tr>
<td>Oil FVF, bbl/day</td>
<td>1.68</td>
<td>PVT</td>
</tr>
<tr>
<td>Viscosity, cp</td>
<td>0.33</td>
<td>PVT</td>
</tr>
<tr>
<td>Total compressibility, sip</td>
<td>1.5E-06</td>
<td>Skua Field (Analogue)</td>
</tr>
</tbody>
</table>

**Discussion of Result**

Figure 6 shows the log-log plot for the second build up (main flow period). It lasted for 50hrs. When trying to obtain a match we applied a low degree of smoothing. This was done to capture the boundary effect because the data had a high frequency (5 minutes). The most suitable interpretation model obtained analytically from pressure and pressure derivative match was an open rectangle model.

![Figure 5: QA/QC on pressure gauges](image)

![Figure 6: Analytic model on Pressure and pressure derivative response for FP2](image)

![Figure 7: Analytic model on Deconvolved Pressure and pressure derivative for FP1 and FP2](image)

We deconvolved the two available flow periods, to validate the open rectangle geometry. This same geometry seems to match the deconvolved pressure and pressure derivative response for the two flow periods. Figure 7 shows the match on deconvolution response. The difference between the results obtained by different interpretation methods is within the
confidence interval (Azi et al). The wellbore storage seems to be discontinued before 0.1 hrs. This is in line with the observation in the difference plot.

The open rectangle interpretation model was also verified using numerical simulation method. Figure 8 shows the result obtained by superimposing the Skagerrak U3 (mid-perforation Interval) structural map on the voronoi grid in Saphir (Figure 9). The red box in Figure 9 shows the additional boundary introduced during numerical simulation. This additional boundary was not captured on the Skagerrak structural map.

Investigation of the stratigraphic model across the perforation interval reveals the presence of a shale barrier between the tested and producer well (See Figure 10). This shale layer gradually thins out deeper into the U2 formation. Barriers captured in stratigraphic model might not actually exit since they are based on stochastic population. However, boundary captured from well test interpretation is validated by the stratigraphic model.

![Figure 8: Numerical model on Pressure and pressure derivative response for FP2](image)

![Figure 9: Numerical simulation using Saphir](image)

Figure 11 shows the reservoir boundaries captured on geological model. The white circle in Figure 11 shows a gap between Boundary 5 (B5) and boundary 3 (B3) contrary to numerical simulation result that show that these boundaries intersect (Figure 9). Identical pressure and pressure derivative behavior similar to PTA interpretation results for the tested well can only be obtained if B5 is extended to reach B3 in the geological model. The true existence and extent of this barrier was considered during history matching.

![Figure 10: Upper Skagerrak Facies distribution map](image)

![Figure 11: Boundaries captured in geological model](image)

Production Analysis (Producer well)

Production from this field started January 1999 with an initial takeoff rate of 7.5Mstb/day. The well has been shut in since October 2008 due to well lift and high salinity water production (350000ppm). Prior to being shut in, total oil production was
8.6MMstb, total water production 1.6MMstb and total associated gas production: 9.9Bscf (Appendix C.2). Water production started July 2001 with a very suspicious high rate (allocated rate based on monthly well test). Permanent down-hole gauge was initially installed but stopped working after the first 3 months of production, so most of the pressure data available for the field are tubing head pressures (THP). The BHP data used for analysis was generated from historical THP using Hagedorn and brown correlation. For quality control check, the calculated BHP was compared with results obtained using two extreme correlations: Fancer Brown’s correlation and Duns & Ros modified correlation. Fancer Brown correlation assumes no slippage as a result over predicts BHP while Duns & Ros modified correlation under predicts BHP because it considers pressure losses. The comparison shows that the result obtained is within acceptable limit. The top of perforation was used as the depth reference point with an uncertainty of about ± 1500 psi (maximum difference between Hagedorn and brown correlation and the two extreme correlations). This was done using the production and system performance analysis software (PROSPER).

The objectives of performing production analysis are as follows:

1. Estimation connected oil volume during rapid pressure depletion
2. Verify influx of fluid from another compartment into the producing block using numerical interpretation method. This is achieved by changing the fault transmissibility multiplier (FTM) on the fault until a satisfactory match on Skagerrak historical data is obtained.
3. Identify the broken down fault using deconvolution and estimate distance travelled by pressure transient after fault seal failure. We shall also attempt to predict the origin of fault seal failure based on distance obtained

Since the fault leak occurred before the perforation of the Pentland formation (October 2003) Production analysis was restricted to the Skagerrak historical production data. Moreover, it is difficult to get a match on changing KH using the available well test interpretation software package.

The information used for this analysis includes: historical production data, completion data, 2005 4D seismic interpretation results and PTA interpretation result. To capture the uncertainty associated with areal and vertical continuity of the boundary identified from PTA (B5), Sensitivity on the area extent and leakage factor associated with B5 was investigated when trying to obtain a match on Skagerrak historical data.

**Discussion of Result**

The first part of this analysis was to perform reservoir diagnostics to estimate the connected volume during pressure decline. This was done using normalized rate cumulative plot (See Equation 1). This method gives best STOIIP estimate for oil reservoir under depletion (boundary dominated flow). The intercept on the x-axis indicates the initial connected volume. Figure 12 shows normalized rate cumulative plot for the pressure decline period. The result shows that the reservoir was initially connected to about 36mmbbl before receiving additional pressure support. Also, Simple Material balance calculations using Dake’s equation for under-saturated oil reservoir suggests that the well was initially connected to 34mmsctb.

![Figure 12: STOIIP estimate using normalized rate cumulative plot for pressure decline period](image)

![Figure 13: Fetkovich plot for pressure decline period](image)
Fault seal breakdown analysis in HP/HT field

\[
\frac{Q}{P_t - P_w(t)} = \frac{Q_{ST}}{C(t)}
\]

Figure 13 shows the Fetkovich plot during pressure decline. The Fetkovich plot is used to identify transient flow and boundary dominated flow condition (See Equation 2). From the match on the Fetkovich generated response we see that pseudo steady state (PSS) was reached during pressure decline. This indicates that the well is initially depleted by a compartment.

Fault seal was investigated using Topaze. Here we superimposed the Skagerrak map on the voronoi grid in Topaze, boundaries identified from 2005 4D seismic interpretation (Figure 14) as sealing was used as our external boundaries (B1, B4 and B5). Here we made sure the volume of the constructed reservoir was the same with the Skagerrak volume estimate (64 mmstb), history matching was based on changing fault transmissibility multiplier (FTM) also known as seal factor for different boundaries and extending the area length of B5 (boundary identified from PTA). A number of different solutions gave a satisfactory history match on the Skagerrak historical data. The two most feasible scenarios based on other supporting evidence such as 4D seismic interpretation result (Figure 14) are presented in this work.

**Scenario 1:** Field geology has it that the left side of B3 has a small throw (ST) while the right side has a large throw (LT). See Figure 15. The expectation is that the weakest point on the fault is the region with smallest fault throw, to represent this behavior B3 was subdivided into two. History match result was obtained by assigning ST an FTM of 0.05 and LT an FTM of 0.005 for B3, all other boundaries were closed (FTM=0). Figure 16 shows the reservoir boundaries and FTM for this scenario. The boundary identified from PTA (B5) was captured in the model. However, B5 was not extended to reach B1. This was done to allow flow from the left compartment into the producer well. The direction of movement is shown by the blue arrow.

**Scenario 2:** In this case, history match was obtained by assigning FTM of 0.005 to ST of B3 and 0.01 FTM to B5. All other boundaries were closed (FTM =0). Figure 17 shows the reservoir boundaries and FTM for this scenario. The work presented here suggests that there is most likely fault seal failure across side ST of B3 (the side with the lower throw) and that B5 is most likely leaky to some extent as observed in the two cases.

Figure 18 shows the history match on Skagerrak historical data obtained for both scenarios. The red continuous line in Figure 18 shows the match on liquid rate, the red dotted line a match on cumulative liquid production while the green line shows the match on flowing BHP. Similar match on historical production were obtained for both scenarios. The blue circle in figure 18 highlights deviation from historical data because of re-perforating the pentland formation and U3 water bearing Skagerrak (increasing the value of KH).
Deconvolution (Producer Well)

Gringarten (2010) gave an intuitive description on practical use of deconvolution and showed how we can use the method to show compartmentalization and pressure recharge from other layers which could not be observed from conventional analysis. A similar approach was applied to this work.

The deconvolved derivative response for the Skagerrak production data prior to increasing perforated interval is shown in Figure 19. This was done using TLSD (Imperial college software). The deconvolved pressure derivative response is boundary dominated. For boundary dominated flow conditions, the response is not sensitive to initial pressure so it was easy to estimate the initial reservoir pressure. The brown and green lines in Figure 19 yields identical response with an initial pressure \( (P_i) \) of 12382 psi compared to the black line with incorrect \( P_i \). (RFT gives a \( P_i \) of 12380psi at a datum of 14013ft tvdss).

Note that early and middle time deconvolved derivative responses are not seen most likely because the production data for the first two months were not included in the analysis, due to unavailability. Moreover early time response in deconvolved derivative is an average. In describing the deconvolved derivative behavior, the late times response is broken down into early-late, middle-late and late-late times.

The red line in Figure 19 shows the deconvolved derivative response for the Skagerrak historical production data. At early-late times, when the pressure transient encounters B1 and B3 (Figure 15), the deconvolved response is that of a half unit slope shown in yellow line (before recharge). The early-late time half unit slope here suggest that B1 and B3 were initially sealing, at middle-late times, the pressure derivative follows a transition. The transition here occurs around 5000hrs (in the 7th month) with duration of about 6 months (8 months period) and suggests that B3 becomes a leaky fault and production is supported by
Fault Seal Breakdown Analysis in HP/HT Field

fluid pressure and volume from the North block. This is supported by the observed pressure behavior in the field. The deconvolved derivatives eventually stabilized at another half unit slope at late-late times shown in blue line which corresponds to B1 and B4. This means its takes 8 months for the pressure transient to move from B3 to B4.

As a final step, two open rectangular models were applied to the deconvolved response obtained using Saphir (Appendix C.2). This was done to compute the distance between B3 and B4. A distance of approximately 400ft was travelled by the pressure transient before hitting B4. A possible location for this distance is suggested by the blue arrow in Figure 15. It highlight possible location of this distance gotten by inspecting the distance between B3 and B4, but it could be anywhere around that region. This interpretation is consistent with results from Fault leakage investigation (PA) performed using Topaze. Both method identified the same fault to be leaky (B3) and also suggests that seal failure starts from the side with the smallest throw.

Dynamic Reservoir Simulation

Modeling Strategy

The objective of the dynamic simulation is to gain understanding of the pressure behavior and produce a history matched model that will identify the leaky fault among a number of successive faults in this field. Result obtained from dynamic simulation will be validated for consistency with well test interpretation result and 4D seismic interpretation result. The model $K_h$ will be generated from porosity-permeability relationship established for the field. This is represented in equation 3 below

$$K_h = 1.449 \times 10^{(14\times0.2-1.1)}$$

In the first stage, the focus is on identifying initial producing compartment; the $K_F$ at various points within the fault is computed using the Shell $K_F$ model. The $K_F$ relationship is derived as a function of host rock permeability, SGR and fault throws. The static fault seal factors (FTM) will be generated for various values of $K_F$ using equation 4.

$$\text{static seal} = \frac{\text{Transmissibility with fault}}{\text{Transmissibility without fault}} = \frac{L_1}{2K_1} + \frac{L_2}{2K_2}$$

In the second stage approach, the effect of fault capillary pressure ($P_C$) on flow across fault by introducing a dynamic seal factor is considered. The dynamic seal factor is a function of 2 phase relative permeability and capillary threshold pressure in
the fault. The two phase relative permeability threshold was set to a constant value because of lack of data; it is not expected to affect the results because the effect of two phase relative permeability on fault rock is more significant in gas fields (Ziljstra 2007). This value is based on a global data set and it means that at water saturation below 10 % in the fault rock, the non wetting phase becomes mobile. Using the Shell fault Pc model for this rock type: phyllosilicate framework fault rocks (mechanical mixing of sand and shale), fault Pc for different $K_f$ was generated. During the history matching the focus is on sensitizing aquifer strength, aquifer permeability, $K_H$, parameters affecting $K_f$, the vertical and area extent of the B5.

![Figure 20: Schematic showing host rock, $K_f$ and distances used in computing seal factors](image)

**Reservoir Model Construction**

A 3D full field simulation model was applied, with 587,250 grid blocks and full corner point gridding. Twelve (12) faults exist in this model with fault throws between 25ft and 175ft. One to one upsampling was applied on reservoir sand in order to preserve flow. At the early stage of reservoir model construction, sensitivities were run on $K_H$ generated from porosity permeability relationship by changing multipliers. A multiplier of 5 gave the best permeability estimate. Figure 21 shows the comparison of model $K_H$ and actual $K_H$ for appraisal well at different depths. Also, the model permeability-thickness ($K_H$) was compared with result from PTA. The results are comparable. PTA gave a $K_H$ of 10800md while the model gave a $K_H$ of 9300md. The last quality control step was to compare STOIIP estimates for each compartment; this was done after initializing the model (Appendix D). The result was also comparable.

**History Matching Result**

Since no SCAL data was available for this field, capillary pressure and relative permeability curves for nine different porosity estimate were generated from neighboring Skua field and summarized into three classes (Appendix D)

In the first stage (EHM031), sensitivity on $K_f$ was done using the shell model until a match for the pressure decline period is obtained. Figure 22 indicates that the producer well is depleting compartment A. Pressure at other compartments are still at initial condition. Figure 23 shows the history match on pressure decline periods. The thick lines represent reservoir model behavior while the dotted lines represent actual reservoir performance. The blue circle captures when model flowing BHP begins to deviate from the actual flowing BHP. This occurs after 7 months of production (consistent with deconvolution interpretation). The reservoir needs additional pressure and volume support to completely match historical production. Since the tested well was only perforated at the U1 and U2 interval, B5 was adjusted to penetrate these intervals. Figure 24 shows the wells and the perforated layers. Stage one process identified B5 and compartment A as principal factors influencing the pressure decline behavior. Compartment A has a STOIIP estimate of 36MMstb. This is consistent with information from Normalized rate cumulative plot (Figure 12) that suggests that the reservoir was initially connected to 36MMstb.
In stage two (EHM027), the effect of fault Pc was considered. Fault Pc was estimated for the range of $K_F$ generated from stage one. This will be converted to water/oil system in the numerical simulator. It is expected that when the pressure difference ($\Delta P$) across B3 exceed the capillary threshold pressure the fault seal should break.

Figure 25 shows Log-log plot of Fault capillary threshold pressure against $K_F$ for egret field compared to that proposed by different authors. The generated trend for the field was compared to that obtained from laboratory estimates by Gibson, Fisher, Knipe and Sperrevik. This field variation is similar to that proposed by Sperrevik. Gibson, Fisher and Knipe observed a straight line relationship between fault Pc and SGR while Sperrevik observed an exponential relationship between fault Pc and SGR. In addition to clay content, Sperrevik considered the influence of burial depth at the time the faults were formed and the maximum burial depth. These correlations are based on laboratory result for core samples taken from the North Sea, Gulf of Mexico and Niger Delta. The slope of the Fault Pc line will serve as input into the numerical simulation. In our model the seal factor was computed monthly (dynamic seal factor) and where the threshold pressure is exceeded at any point on the fault plane, the fault will become leaky (Seal factor becomes greater than zero).

Figure 26 shows the match on historical data when B5 is not included in the model. The history match result shows that the well is connected to a larger volume based on indications that the model pressure behavior is higher than the actual reservoir performance. This is also observed in scenario 3 from PA (Appendix C.1)
This confirms the presence of a barrier, but the true nature of this barrier still remains uncertain. This barrier could be structural or stratigraphic. Figure 27 and 28 shows a cross section of fluid saturation distribution across the producing well before and after water production indicating the direction of water production. During history matching it was discovered that water production is moving from the eastern flank, down the U3 layer into the producer well. This was achieved by attaching a weak aquifer to the eastern flank of the reservoir and increasing the permeability of shale layer present between U2 and U3 layer by a multiple of 10 (Figure 27). This shale layer could be smaller in reality than captured in geologic model. B5 was extended to reach B1 across U1 and U2 reservoir layers to allow water movement from U3 into the producing well (Figure 28).

Figure 29 shows the depleted compartment from the history match result obtained in Figure 30. Result indicates that production was initially from compartment A, then latter from other blocks when capillary threshold pressure across compartment is exceeded. The blue oval shape in Figure 30 highlights a poor match on initial water production. The water allocation for this well is suspicious due to the following reasons:

- Perforation on the water bearing U3 layer in October 2003 does not contributes to water production from allocated rate
- Initial water breakthrough allocated rate to this well is too high, water rate was 0.7 before increasing perforation in 2003 then 0.1 after increasing perforation (Appendix D)
Figure 31 shows the initial pressure distribution for various compartments while Figure 32 shows the pressure distribution across the compartments after 6 years of depletion. In 2005 production was from the North and N1 block with a little bit of depletion in the N2 block. Investigation shows that when fault threshold \( P_c \) of approximately 1000psi was exceeded B3, B4 and B7 breaks down. This occurs at around 2005. This pressure behavior across the compartment is similar to the pressure depletion across the field as suggested by 2005 seismic interpretation result (Figure 14).

Figure 33 shows the pressure depletion across the field in 2008 just before shut in. This indicates that the well is depleting the four compartments. B6 and B1 were made sealing and excluded from the dynamic fault seal calculations because seismic interpretation result shows that they are sealing. Fault seal do not fail across the pentland formation. The history matched model developed in this work will be validated for use based on the 4D seismic interpretation latter in the year.

Results and Discussion
The primary aim of this study was to show how well test interpretation could be useful and validated in history matching process where fault seal breakdown affects production and also identify fault breakdown using dynamic seal factors. PTA captured the presence of a barrier between wells, with an uncertainty around nature of the barrier. Fetkovich plot for the first year of production indicates early boundary effect. Fault seal analysis on Skagerrak historical data using topaze identifies B3 and B5 to be the leaky boundary. Deconvolution not only identified B3 to be the leaky fault but also identified region where seal failure started. This was evident from the distance travelled by the pressure transient during the transition period.

Incorporating B3 and Fault \( P_c \) computed from different \( K_f \) in a dynamic model, it was possible to obtain a match on historical production. Fault seal analysis using topaze and history matched model confirms the existence of B5 (Boundary introduced as a result of pressure transient interpretation result). Well test interpretation result and history matched model suggest B1 as a no
flow boundary whereas the structural model indicates discontinuity along the extent of the fault. Results obtained from matching history are consistent with that from PA and deconvolution (Figure 24 and 25). Additionally, history matched results identified fault capillary seal failures to be responsible for flow across all faults. The dynamic model also suggests that we are currently depleting the N2 block. This can all be validated from new 4D Seismic data acquisition or reprocessing. Result obtained from History matching is consistent with that from scenario 2 in production analysis and 4D seismic interpretation. Uncertainties are expected in our results based on flow rate allocation error (monthly well test) and THP measurement error. However, the range in error is not expected to greatly affect the conclusions. The fault rock two phase relative permeability threshold was set to a constant value due to lack of relative permeability measurement. These are not also expected to affect our result because this effect in fault rock is more significant in gas field (Ziljstra 2007).

**Conclusion**

The following conclusions arise from the work. They are:

1. This report have discussed and demonstrated some well test analysis techniques for investigating fault seal breakdown in hydrocarbon-bearing reservoirs. Results obtained from well test interpretation techniques are consistent with that obtained from history matched simulation model
2. Connected volumes were controlled by Fault Seal, intra shale layers and capillary threshold pressure
3. Fault B1, B3 and B7 breaks down when \( \Delta P \) of approximately 1000psi across fault is exceeded.
4. Fault seal breakdown do not occur across the pentland formation
5. The history matched dynamic model can be validated from the New 4D Seismic data interpretation.
6. Fault seal breakdown investigation should be an integrated approach between all subsurface disciplines with input from a structural geology expert
7. An oil field in the North Sea was used as case study and has been presented to demonstrate the usefulness of the procedure

**Further work Recommended**

I hereby recommend the following.

1. New vintage 4D Seismic data acquisition or reprocessing of the existing data to confirm the sealing nature of B1 and to also validate the reliability of the model, if we see depletion across the N2 compartment.
2. Acquisition of core data for capillary pressure and relative permeability measurement.
3. The interpretation method presented in this work should be applied to neighboring field or other HP/HT fields to validate presented concepts.

**Acknowledgments**

The author thanks the staff of Shell U.K. for the access to the software used in this work. My appreciation also goes to Petroleum Technology Development Fund Abuja, Nigeria for the scholarship to study at Imperial College.

**Nomenclature**

- CSP = Clay Smear Potential
- HP/HT = High pressure/High temperature
- \( K_f \) = Fault Permeability in mD
- \( K_h \) = Host rock Permeability in mD
- \( K_v \) = Host rock vertical Permeability in mD
- \( K_H \) = Permeability thickness in mD-ft
- TVDSS = True vertical depth subsea
- GOR = Gas oil Ratio in scf/stb
- BHP = Bottom hole pressure
- ST = Short throw
- LT = Large throw
- FTM = Fault transmissibility multiplier
- PA = Production Analysis
- \( P_c \) = Capillary entry pressure in psi
- PTA = Pressure Transient Analysis
- SGR = Shale Gouge Ratio
- \( L_f \) = Fault thickness
- \( L_i \) = Length of grid block
- \( P_i \) = Initial pressure in Psi
- \( B_o \) = Oil formation volume factor in bbl/stb
- \( Q \) = cumulative production in MMstb
- \( Q_n \) = Normalized cumulative production in MMstb
- \( C_t \) = Total compressibility in sip
- \( \psi \) = Porosity in %
- \( B_{scf} \) = Billion standard cubic feet
References


## Appendix A

### A.1: Milestones in Fault Seal Breakdown Analysis and Critical Literature Review

**Table A.1: Milestones in Fault Seal Breakdown Analysis**

<table>
<thead>
<tr>
<th>Author</th>
<th>Paper No.</th>
<th>Year</th>
<th>Paper Title</th>
<th>Major Contribution</th>
</tr>
</thead>
</table>
| J. J. Barry             | SPE 22667 | 1991 | Representation of Fault sealing in a Reservoir Simulation: Cormorant Block IV, UK. North Sea. | 1. First to provide a semi-quantitative modeling procedure of fault sealing assuming clay smear and shale juxtaposition to be the primary sealing mechanisms.  
2. Showed that combination of fault seal and reservoir simulation model effectively enhances final reservoir model. |
| M. R. Bentley           |           |      |                                                                            |                                                                                      |
| Arild Selvig            | SPE 25010 | 1992 | A Stochastic Fault Modeling Procedure Applied to a North Sea Reservoir      | Provided a methodology for relating the uncertainty in fault characteristics (fault geometry and transmissibility) to uncertainty in time-dependent production characteristics. |
| Torbjorn Fristad        |           |      |                                                                            |                                                                                      |
| J. K. Silseth           |           |      |                                                                            |                                                                                      |
| William A.              | SPE 49023 | 1998 | The Effects of Faulting on Production from a Shallow Marine Reservoir – A study of the Relative Importance of Fault Parameters | 1. Showed that Fault plane seal and cross faults are the most important factors affecting recovery.  
2. Showed that Fault displacement and several sedimentary parameter had no significant influence on recovery. |
<p>| Chris Townsend          |           |      |                                                                            |                                                                                      |
| R. Sorkhabi             | SPE 59405 | 2000 | Structural Evaluation of Petroleum Sealing Capacity of Faults               | Presented a conceptual model for evaluating Individual faults as petroleum seals or pathways |
| U. Sukuki               |           |      |                                                                            |                                                                                      |
| D. Sato                 |           |      |                                                                            |                                                                                      |
| Q. J. Fisher            | SPE 94460 | 2005 | Recent Advances in Fault Seal Analysis as an Aid to Reservoir Characterization and Production Simulation Modeling | First to document the impact of multiphase flow across fault by including effects of capillary pressure and relative permeability characteristics of faults in reservoir simulation |</p>
<table>
<thead>
<tr>
<th>Authors</th>
<th>Conference/Journal</th>
<th>Year</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>B. Al-Busafi, Q. J. Fisher, S. D. Harris M. Kendall</td>
<td>SPE 93429</td>
<td>2005</td>
<td>The Impact of Faults Representation on History Match and Future Generated seismic Impedance Response in Reservoir Models – Case Study for Pierce Field, North Sea</td>
</tr>
<tr>
<td>F. Cuisiat, E. Skurtveit, R. Cleave</td>
<td>11CISRM</td>
<td>2007</td>
<td>Fault seal prediction in unconsolidated sediments with a novel experimental apparatus</td>
</tr>
<tr>
<td>N. R. Edris, K. D. Stephen, A. Shams, C. MacBeth</td>
<td>SPE 113557</td>
<td>2008</td>
<td>Updating Fault Transmissibilities in Simulations by Successively Adding Data to an Automated Seismic History Matching Processes: A Case Study</td>
</tr>
<tr>
<td>L.G. Rodriguez, L.B. Cunha, R. Chalaturnyk</td>
<td>CIPC 017</td>
<td>2009</td>
<td>Coupled Flow simulation in a Deepwater Reservoir: Fault Leakage Analysis</td>
</tr>
<tr>
<td>T. Manzocchi, C. Childs, J. J. Walsh</td>
<td>Geofluids</td>
<td>2010</td>
<td>Fault and Faults properties in Hydrocarbon flow models</td>
</tr>
</tbody>
</table>

1. They showed that traditional methods for calculating transmissibility multiplier uses values that are two orders of magnitude higher than that obtained when multiphase flow properties are considered.
2. Above the FWL transmissibility multiplier should take two phase flow properties into account.

Developed a ring shear apparatus to investigate clay smear processes and shear band formation under large strains and stresses.

Updating fault transmissibility in reservoir simulator in a step by step workflow is more useful in matching fluid saturations and pressure to 4D or production history observations.

They developed a new iterative computational program that can predict pressure and allowed to safety operate a water injection project with oil leakage via faults.

Reviewed existing work flows used to predict and model capillary threshold pressure for exploration fault seal analysis and transmissibility multipliers for production simulation.
A.2: This section presents a one page summary of each of the papers presented in Table A.1

SPE 22667 (1991)
Representation of Fault sealing in a Reservoir Simulation: Cormorant Block IV, UK. North Sea.

Authors: M. R. Bentley and J. J. Barry.
Contribution to the understanding of Fault Seal & Breakdown Analysis
They both presented a procedure for combining the reservoir simulation and fault seal models

Objective of the paper:
The paper objective was to demonstrate how to effectively represent sealing potential of reservoir rocks in numerical simulators

Methodology used:
Fault seal in Cormorant Block IV was modeled using a reservoir simulator assuming Clay smear and sand shale juxtaposition to be the primary sealing mechanism

Conclusion reached:
- Fault sealing was semi-quantitatively modeled using an empirical relationship describing the potential for clay smear development during extensional faulting
- Results from clay smear modeling were built into a numerical reservoir simulation to help define cross flow paths over major in-field faults
- Iterative introduction of ranked leak paths into the simulation model should be done during history match, and an effective calibration of the clay smear model against production data
- Numerical simulation using a curvilinear grid successfully reproduced the material balance behavior of a strongly compartmentalized field
- The fault seal model provides an effective enhancement to the reservoir simulation, illustrating the benefit of an integrated geological/reservoir engineering approach to reservoir modeling

Comments:
Multiphase flow properties such as relative permeability and capillary pressure across the faults were not considered in the simulation model.
A Stochastic Fault Modeling Procedure Applied to a North Sea Reservoir

Authors: Arild Selvig, Torbjorn Fristad and J. K. Silseth

Contribution to the understanding of Fault Seal & Breakdown Analysis
They developed a procedure to compare uncertainty in fault characteristics (fault geometry and transmissibility) to uncertainty in time-dependent production characteristics.

Objective of the paper:
The paper discusses the impact of undetectable, small faults on the field production performance compare

Methodology used:
Stochastic fault modeling approach was used. The useful of this method relies on the precision of the statistical input data. The problem was split into two parts;

- The fault pattern generation
- The generation of fault zone transmissibilities

Conclusion reached:

- Incomplete knowledge about infield faulting is more the rule than the exception for many North Sea reservoirs
- Stochastic modeling of highly faulted reservoirs can help capture different outcome range which is useful prior to deciding on the field development plan
- The procedure proposed in this work is very useful when information about the infield fault pattern is sparse

Comments:
Conclusion based on application of methods to only one Reservoir in the North Sea
SPE 49023 (1998)
The Effects of Faulting on Production from a Shallow Marine Reservoir – A study of the Relative Importance of Fault Parameters

Authors: A. Williams and Chris Townsend

Contribution to the understanding of Fault Seal & Breakdown Analysis
They identified Fault seal as the most important parameter affecting recovery in a faulted Reservoir from a number of sensitivities

Objective of the paper:
The paper describes a sensitivity study in which a variety of fault patterns was superimposed on a set of realistic heterogeneous sedimentary models of a near-shore marine environment

Methodology used:
An experimental design technique was used to analyze 32 faulted reservoir models. Statistical analysis was used to study the relative effects of the various fault pattern parameters

Conclusion reached:
- Fault plane seal and cross faults are the most important factors affecting recovery
- Fault displacement and several sedimentary parameter had no significant influence on recovery
- In reservoirs with impermeable layers, faulting can improve vertical communication by juxtaposing previously unconnected layers.

Comments:
The conclusion only applies to shallow marine reservoirs, the effect of fault parameters on HPHT reservoir (deeply buried) is an area yet to be investigated.
SPE 59405 (2000)

**Structural Evaluation of Petroleum Sealing Capacity of Faults**

**Authors:** R. Sorkhabi, U. Sukuki and D. Sato

**Contribution to the understanding of Fault Seal & Breakdown Analysis**
They highlighted the fact that to completely understand the behavior of fault we need to understand the tectonic setting (remote stress), fault style (type and shape), fault geometric parameters (throw and length), fault rock characteristics (clay smearing, cataclasis, cementation), fault damage zone (fault zone width, fracture density, orientation and connectivity and mineral vein and deformation band), host rock characteristics and chronology of fault activities.

**Objective of the paper:**
The paper objective was to provide a conceptual model based on quantitative information and an integration of various parameters necessary for evaluation of individual faults as petroleum seals or pathways.

**Methodology used:**
They built a conceptual model to summarize various issues related to fault sealing evaluation

**Conclusion reached:**
- The study from available data indicate that CSP of >15, SSF of <7, and SGR of >18% are threshold values for fault sealing in normal faults.
- Analysis of fracture density, aperture, orientation and connectivity, as well as fault-zone diagenesis are therefore important in fault-sealing evaluation

**Comments:**
The paper did not attempt to quantify the sealing capacity or leaking conditions of faults.
SPE 94460 (2005)

**Recent Advances in Fault Seal Analysis as an Aid to Reservoir Characterization and Production Simulation Modeling**

**Authors:** Q. J. Fisher

**Contribution to the understanding of Fault Seal & Breakdown Analysis**

Fisher was the first to document the impact of multiphase flow across fault by including effects of capillary pressure and relative permeability characteristics of faults in reservoir simulation model.

**Objective of the paper:**

The paper shows results obtained from comparing fault transmissibility obtained from Reservoir Simulator to that obtained from Cores.

**Methodology used:**

The approach was to conduct a forward seal analysis

- Analyzed permeability and pressure threshold of numerous (>2000) faults rocks from cores
- Calculate transmissibility multipliers based on the fault offset and clay distribution within the reservoir
- Assess whether or not this could help explain the production data.

**Conclusion reached:**

- Multiphase flow properties of fault should be incorporated during reservoir simulation to better simulate real reservoir processes

**Comments:**

Fisher’s work did not say much about how the Multiphase flow properties of fault rock were measured.
SPE 93429 (2005)

The Impact of Faults Representation on History Match and Future Generated seismic Impedance Response in Reservoir Models – Case Study for Pierce Field, North Sea

Authors: B. Al-Busafi, Q. J. Fisher, S. D. Harris and M. Kendall

Contribution to the understanding of Fault Seal & Breakdown Analysis
They provided an approach for accounting for fault sealing capacities to petroleum cross flows based on their positions relative to the free water level.

Objective of the paper:
The paper objective was to investigate the effect of fault on History Match and future generated seismic impedance.

Methodology used:
Two similar models with different fault properties were used.
- First case, Adjusting fault transmissibilities and extending fault geometry in a trial and error manner to improve the match to fluid contacts and production history.
- In the second case, A step by step derivation of the fault transmissibilities in the Pierce field based on integration of collected and upscaled properties of the deformed and undeformed reservoir as well as empirical relationships between fault offset and thickness (using the methodology proposed by Manzocchi et al).
- Fault transmissibility was derived using Manzocchi’s equation;
  \[ \log k_f = A1 \times SGR - A2 \times \log(d_f) \times (1 - SGR)^{A3} \]
  Where \( K_f \) is the fault transmissibility (in mD) and \( d_f \) is fault displacement (in meters). A1, A2 and A3 are empirical constants fit to observed data, typically derived from outcrop and observed data.

Conclusion reached:
- Fault rock laboratory data improved fault representations in simulation models at early stage of reservoir life to gain early and reliable history matches.
- Predicted seismic generated from simulation models was used to plan the best timing for forthcoming seismic acquisition.
- New method for accounting for fault sealing capacities to petroleum cross flows based on their positions relative to the free water level was presented and applied. The method uses some empirical relationships along with micro structural and petro physical fault properties calculations. The method demonstrated the ability to improve history match when applied to real and highly faulted reservoirs.
- Fault representations plays an important role in creating seismic residuals that can be influential for geophysicists and reservoir engineers in planning their forthcoming seismic acquisition.

Comments:
The method uses some empirical relationships to predict fault permeability which might not be very represented of the reservoir geology.
Fault Seal Breakdown Analysis in HP/HT Field

SPE 105375 (2007)

Recent Advances in the Understanding and Incorporation of the Multiphase Fluid Flow Properties of Fault Rocks into Production Simulation Models

Authors: Suleiman M. Al-Hinai, Quentin J. Fisher, Carlos A. Grattoni and Simon D. Harris

Contribution to the understanding of Fault Seal & Breakdown Analysis
They presented a technique for measuring relative permeability and capillary pressure measurements for fault rocks and also presented an approach for incorporating them into a production simulation model.

Objective of the paper:
The paper objective was to review different existing methods for incorporating multiphase flow properties into simulation models and recommend some possible approaches for treating faults in simulators

Methodology used:
- Fault specimen were taken from extensional lossiemouth fault zone in the Clashach quarry near Burghead in north-east Scotland
- Microstructural properties were then examined using an X-ray computed tomography (CT) system
- Porosity was measured using a helium expansion porosimeter
- Gas and water relative permeability measurements were made de saturation technique
- Capillary pressures are obtained from J-functions
- Methods for Incorporating them into Simulation models are then presented

Conclusion reached:
- In zone below the FWL the transmissibility multiplier should be calculated using the formula below

\[ T_{abs} = \left[ 1 + L f \left( \frac{2/k_f - 1/k_1 - 1/k_2}{L_1/k_1 + L_2/k_2} \right) \right]^{-1} \]

- In the transition zone directly above the FWL, TM should be set initially at zero until the threshold pressure is exceeded
- At height above the FWL where the threshold pressure is exceeded, the transmissibility multiplier should be calculated using the formula below

\[ T_{abs} = \left[ 1 + L f \left( \frac{2{k_f}^2 - k_1 - k_2}{L_1/k_1 + L_2/k_2} \right) \right]^{-1} \]

Comments:
The models presented in the paper was only tested for a gas field, it was not tested for oil reservoirs where we might have effects of three phase relative permeability
SPE 113557 (2008)

**Updating Fault Transmissibilities in Simulations by Successively Adding Data to an Automated Seismic History Matching Processes: A Case Study**

Authors: N. R. Edris, K.D. Stephen, A. Shams, and C. MacBeth

**Contribution to the understanding of Fault Seal & Breakdown Analysis**
They demonstrated the fact that updating fault transmissibility in reservoir simulator in a step by step workflow is extremely useful in matching fluid saturations and pressure to 4D or production history observations

**Objective of the paper:**
This paper present the result of investigating the impact of successively updating faults by adding new data to observed dataset and comparing the results to that obtained from a single history match where all data is used

**Methodology used:**
Optimized history data by using a multi-dimensional inversion technique based on calculated misfit between observed and predicted data (UKCS Schiehallion reservoir using six years of production data and six seismic surveys). The steps involved include:
- Matching the first year of seismic history using short simulations
- Using the best Model from above, improving uncertainty measures of the parameter space
- Repeat the process by including a second year of Data
- Repeat the process by including four year of Data
- Perform a second inclusive run using all the data and compare results obtained using the two methods

**Conclusion reached:**
- Compared to the traditional method the step by step workflow of history match used in this work provides a good history match leading to improved confidence and higher quality of field development and management process
- Slightly better models were obtained when we explore the parameter space first with short simulations. It is possible to avoid unnecessarily long history matching runs
- We can improve our estimate of uncertainty and can identify parameters that are relatively unimportant

**Comments:**
Conclusion based on application of methods to one Reservoir: Schiehallion Reservoir
Coupled Flow simulation in a Deepwater Reservoir: Fault Leakage Analysis

Authors: L.G. Rodriguez, L.B. Cunha and R. J. Chalaturnyk

Contribution to the understanding of Fault Seal & Breakdown Analysis
They developed a new iterative computational program that can predict allowed to safety operate a water injection project with oil leakage via faults.

Objective of the paper:
Explore the production uncertainties in an undeveloped oil reservoir, under water injection project, with a major internal fault and the role of geomechanics in the fault reactivation

Methodology used:
- Use an Iterative algorithm for coupling multiphase reservoir flow simulation and geomechanics to investigate fault reactivation.
- Used two numerical simulators, one that emphasizes flow through porous media aspects and the other on the geomechanical behavior.

Conclusion reached:
1. Oil and gas production in stress-sensitive reservoirs may be simulated by coupled numerical modeling. The relationship of stress with permeability, and fault strain with transmissibility can be set-up based on sufficient laboratory tests.
2. Parameters influencing fault leakage include reservoir temperature, injection pressure, reservoir pressure, fault permeability and well location with respect to fault position

Comments:
Conclusion based on application of methods to an offshore unconsolidated sandstone reservoir field located in Campos Basin of Brazil
A.3: Summary of advances in Fault seal breakdown analysis

- Fault seal breakdown analysis
- Empirical constant fit to observed data
- Fault permeability
- Fault throw
- Shale gouge ratio
- Fault capillary pressure

A.4: Program/Simulation Workflow

- Pressure Transient Interpretation
- Fault Leakage Analysis
- Deconvolution
- Geological model
- Fault rock Permeability model
- Fault rock Capillary pressure model
- Fault Rock relative permeability Model
- Well test Analysis
- History Matching
- Dynamic Model
- Dynamic Transmissibility Multiplier
- END
- Yes
- No
Appendix B

B.1: Further details on Pressure Transient Analysis and Interpretation Result (Appraisal well)

Pressure Transient Analysis and Interpretation Result

Figure B.1: Semi-Log Plot for FP2

Figure B.2: Semi-Log Plot for FP1 and FP2

Figure B.3: History plot for numerical simulation

Figure B.4: History plot for deconvolution
### Table B.1- PTA results comparison (Azi et al)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Analytical Model</th>
<th>Deconvolution</th>
<th>Numerical Model</th>
<th>Difference (Analytic versus Deconvolution)</th>
<th>Difference (Analytic versus Numeric Method)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kh, md-ft</td>
<td>11900</td>
<td>10800</td>
<td>11200</td>
<td>9%</td>
<td>6%</td>
</tr>
<tr>
<td>Initial Reservoir pressure, Psi</td>
<td>12408</td>
<td>12405</td>
<td>12400</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>K, md</td>
<td>56.6</td>
<td>51.5</td>
<td>53.2</td>
<td>9%</td>
<td>6%</td>
</tr>
<tr>
<td>C, bbl/psi</td>
<td>0.1</td>
<td>0.09</td>
<td>0.13</td>
<td>10%</td>
<td>30%</td>
</tr>
<tr>
<td>South, ft</td>
<td>130</td>
<td>157</td>
<td>130</td>
<td>20%</td>
<td>0%</td>
</tr>
<tr>
<td>North, ft</td>
<td>477</td>
<td>517</td>
<td>510</td>
<td>8%</td>
<td>7%</td>
</tr>
<tr>
<td>West, ft</td>
<td>509</td>
<td>577</td>
<td>480</td>
<td>13%</td>
<td>6%</td>
</tr>
<tr>
<td>Skin</td>
<td>-0.9</td>
<td>-0.5</td>
<td>-0.9</td>
<td>0.4</td>
<td>0</td>
</tr>
</tbody>
</table>
Figure B.5: Full Skagerrak U3 top structural map
Appendix C

C.1: Further details on Production Analysis and Interpretation Result (Producer well)

Production Analysis and Interpretation Result

![Graph of rates and cumulative production](image)

**Figure C.1: Historical cumulative production allocated to Egret field**

**Scenario 3:** In this case, we sealed off all boundaries (FTM = 0) but restrict the extent of B5 as captured from PTA interpretation. Figure C.2 shows the reservoir geometry as modeled using voronoi grid in Topaze. The match on historical data is shown in Figure C.3. The red line shows the match on liquid rate and cumulative liquid production while the green line shows the match on pressure. Figure C.3 shows a poor match on liquid rate and production indicating that the well is connected to too much volume. This is also observed during history matching (Figure 26) in dynamic model. History match here using topaze shows a poor match on Skagerrak historical data when we do not introduce B5. In Figure 26 we see a poor match on pressure (low drawdown) when well is constraint against cumulative production. This confirms the fact B5 has to be extended to reach B1. Thus, validating no flow boundary captured in stratigraphic model.
Figure C.2: Scenario 3 - Fault seal analysis geometry using topaze

Figure C.3: Scenario 3 – History match on historical production and pressure using Topaze
C.2: Further details on Deconvolution Result (Producer well)

Deconvolution using Saphir

The Saphir response shows a very high wellbore storage that was not visible from the response obtained using TLSD. This is not feasible since production was ongoing at the time. However our focus was the boundary effect. Both methods exhibit the end of initial half unit slope (B1 and B3) and start of latter half unit slope (B1 and B4). The transition is exactly the same and lasted for about 6000hr (8 months).

The match on the early-late time response in Figure C.4 corresponds to an open rectangular geometry. The transition lasted for about 6000hrs (8 months). The match on the late-late time response in Figure C.5 also corresponds to an open rectangular geometry. The difference in distance between the two geometries corresponds to the distance travelled by the pressure transient during the transition and it is approximately 400ft. See Figure C.6 for the geometry configuration for this response.

![Figure C.4: Early-late time match on deconvolved pressure and pressure derivative response using Saphir](image)

Beginning of transitions = 5500hrs

End of transitions = 11000hrs

![Figure C.5: Late-late time match on deconvolved pressure and pressure derivative response using Saphir](image)

![Figure C.6: Fault Breakdown analytical solution geometry as modeled using Saphir](image)
Appendix D

D.1: Further details on dynamic reservoir simulation

Dynamic Reservoir Simulation

Table D1 - STOIIP Estimates comparison for different compartment

<table>
<thead>
<tr>
<th>Static volume</th>
<th>Dynamic volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skagerrak &amp; Pentland</td>
<td>Skagerrak &amp; Pentland</td>
</tr>
<tr>
<td>Compartment A</td>
<td>STOIIP (mmstb)</td>
</tr>
<tr>
<td>North</td>
<td>6.3</td>
</tr>
<tr>
<td>N1</td>
<td>11.3</td>
</tr>
<tr>
<td>N2</td>
<td>8</td>
</tr>
<tr>
<td>N Graben</td>
<td>2.1</td>
</tr>
<tr>
<td>Fault Slither</td>
<td>6.2</td>
</tr>
<tr>
<td>Total</td>
<td>72.8</td>
</tr>
</tbody>
</table>

Figure D.1: Relative permeability curve for different porosity class generated from analog (Skua field)
12 different porosity estimates for both relative permeability and capillary pressure were analyzed from the neighboring Skua field. The curves shown in Figure E.1 and E.2 above summarize the 12 different porosity estimate into three classes. For porosity less than 0.164 the black curve shown in Figure E.1 and E.2 is used to define the relative permeability or capillary pressure, similarly for porosity between 0.164 and 0.207, the red curve is used and finally for rock with porosity greater than 0.271 the blue curve is used.

Figure D.2: Capillary pressure curve for different porosity class generated from analog (Skua field)

Figure D.3: Match on Historical Rate (Model Constraint)
Appendix E

E.1: Summary of Fault Breakdown Analysis on Egret field investigated using MBal (Analytic Method)

Objective of study:
The objective of this study was to use material balance to gain understanding of the field production performance by history matching historical production and pressure data

Methodology used:
The modeling was divided into three phase:

- Phase 1: Rapid decline in reservoir pressure
- Phase 1: Flattening of reservoir pressure decline and period covering up to 2003 add perf intervention
- Phase 1: Post intervention covering period up to the well shut in

Figure E.1: Modeling reservoir compartment using MBal

Figure E.2: Schematics showing fault leakage scenario
Phase 1 Results and Observation:

Observations
1. Rapid and linear pressure drop
2. No sign of pressure support
3. 6000 psi decline after 1.1mstb production
4. Appraisal well test shows small connected volume

![Figure E.3: Phase 1 - Rapid decline in reservoir pressure](image)

Phase 2 Results and Observation:

Observations
1. Flattening of decline observed after 1.1mstb and 6000psi depletion
2. Flattening not expected until below bubble point in reservoir if no change in connected STOIIP
3. Recharging during shut down
4. Pressure profile cannot be explained if connected to only small volume
5. Pressure support most likely from a leaky fault

![Figure E.4: Phase 2 - Reservoir pressure stabilization above bubble point](image)
Phase 3 Results and Observation:

**Observations**

1. Increase in pressure because of U3 reservoir unit
2. Communication is via the well and not the reservoir

**Conclusion reached:**

1. Good illustration of sub-surface integration to gain understanding of the field
2. MBal modelling effectively used to model the dynamic behaviour of the field
3. Faults with significant throw do not seal, although they do provide baffles to flow (small faults will maintain the vertical shale barrier)
4. No significant aquifer support

**Comments:**

Initial reservoir pressure used in this work for the all reservoirs layer is the same (lower layers should have higher initial reservoir pressure).