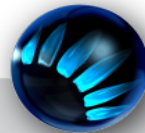


Open or closed, or something in-between?

Implementing low to high case behavior of threshold pressures
and fault transmissibilities in an uncertainty workflow



Ulf Læg Reid | Terje Rudshaug

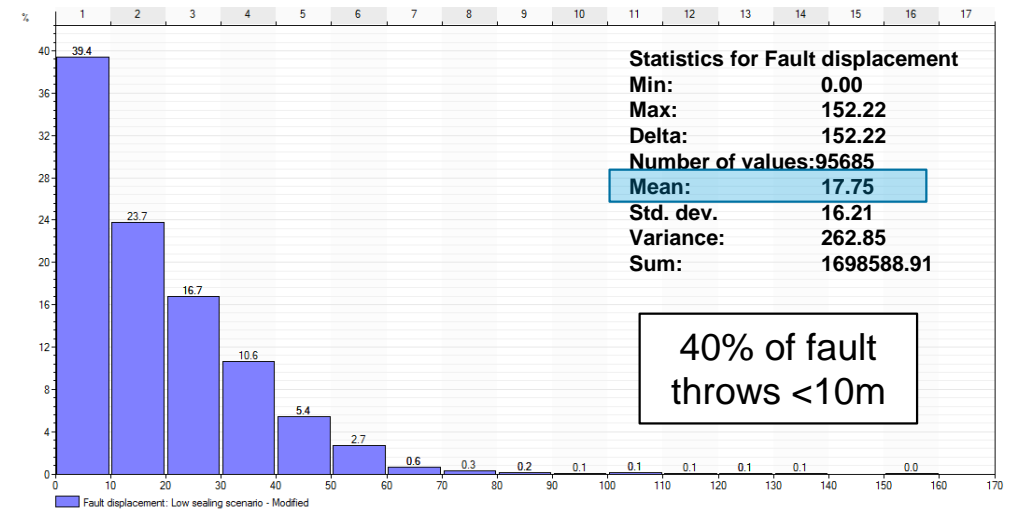
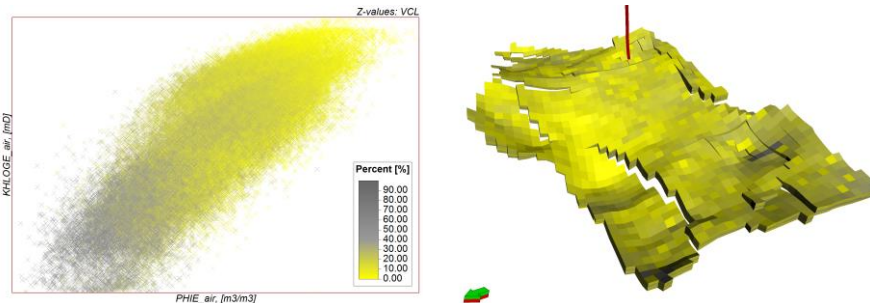
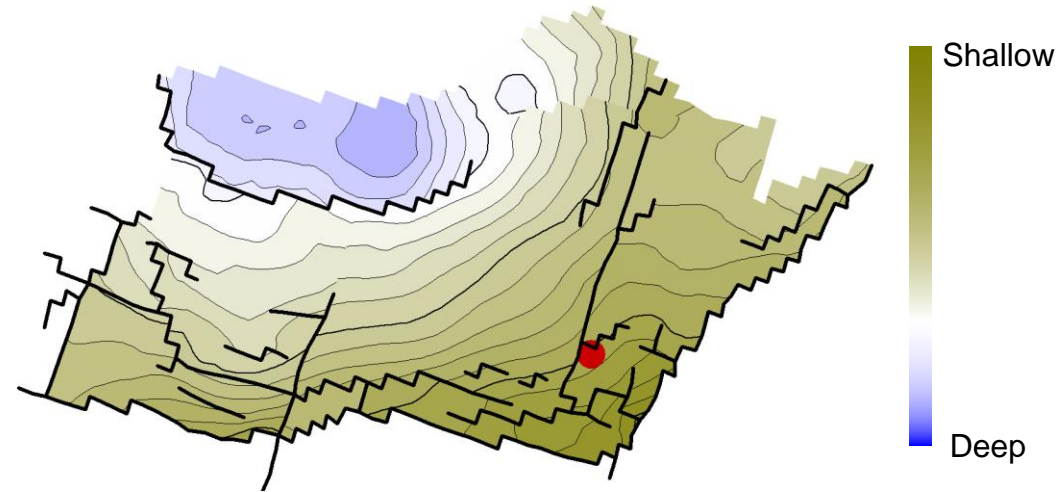
Agenda

- The dataset
- Why?
- Defining:
 - Fault threshold pressures
 - Fault transmissibility multipliers (and fault thickness)
- Implementation in Petrel
- Results
- Conclusions



The dataset

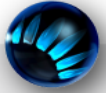
- Field:
 - Clastic oil reservoir.
 - Production by depletion.
- All mappable faults included as vertical in regular grid.
- Faults statistics:
 - 40% of fault throws < 10m.
 - Mean throw = 18m.
 - Most faults have sand to sand juxtaposed.
- Permeability and Vclay:
 - Input to threshold pressure and transmissibility calculations.
 - Stochastic simulation with proximal to distal facies classes.
 - Co-simulated with porosity.
 - Very low Vclay content, but spatial trends exist.



Why?

- Starting-point for modelling is often:
 - simplicity first
 - then add complexity.
- For Pth and TMs
 - RDR functionality not straight forward.
 - Cumbersome workflow.
 - Add-on (initially) to Petrel («different flavor»).
- Consequence
 - Constant min and max values are often used.
- Initial project
 - 3 scenarios defined the fault properties/compartmentalization.
 - Base and High case in principal open models.
 - Low-case very segmented with TM=0.
 - Low-case was weighted drastically in order to stretch the distribution.
 - Volume assessment (P90) very pessimistic.
- New concept
 - Use field data - MICP-measurements and Vcl.
 - Use literature and tie industry correlations to field data.
 - Calculate fault properties for export to simulator based on weighted scenarios:
 - Fault threshold pressures
 - Fault transmissibility multipliers





DEFINING FAULT THRESHOLD PRESSURE

Threshold pressure

Methodology

- Petrel needs
 - Relationship between V_{cl} and threshold pressure.

- Threshold pressures are obtained from:
 - Industry correlations
 - generally based on $P_{th} = f(K_{fault})$ or $f(SGR, \dots)$
 - Capillary pressure measurements
 - MICP

- Need to correlate P_{th} to mappable petrophysical property.
 - Permeability
 - Clay content

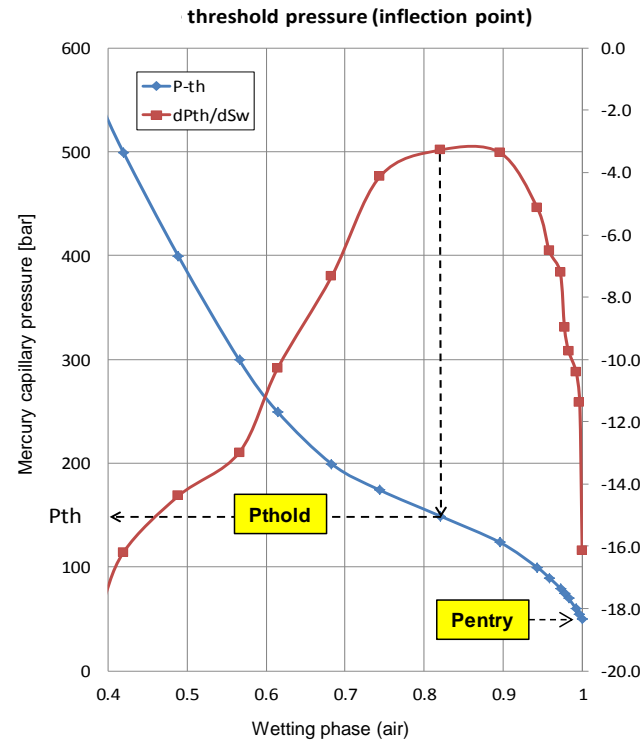
- Definition of *Range of uncertainty*.



Threshold pressure

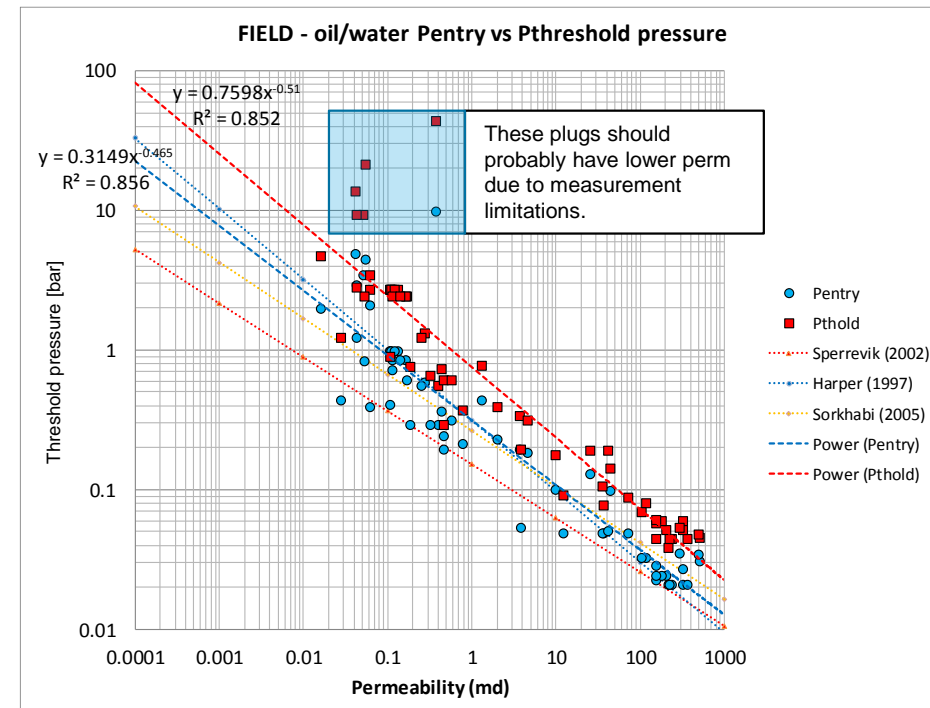
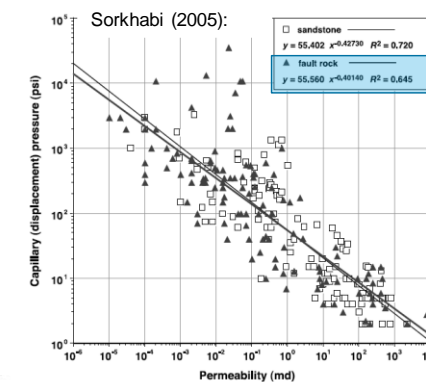
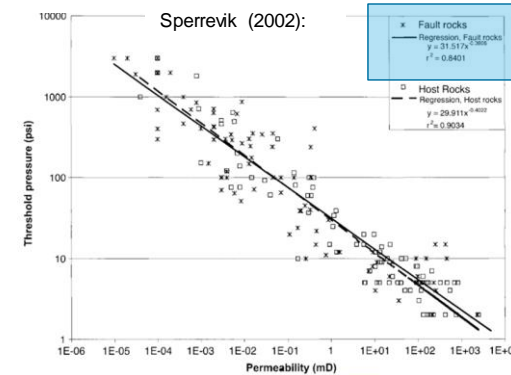
Definition

- Definition(s):
 - Entry pressure
 - first entry of non-wetting fluid into the largest pores.
 - Threshold pressure
 - inflection point where there as a continous phase of non-wetting fluid through the pores.



Threshold pressure vs permeability

- Industry correlations (Sperrevik, Sorkhabi, Harper) show *strong correlation* between *threshold pressure* and *permeability*.
- Host rock* permeabilities and *Fault rock* permeabilities show similar trends.
- This means that P_{th} vs Host rock data can be used to estimate P_{th} for Fault rock.
- FIELD measured MICP data
 - show an *Entry pressure* trend (blue dots/stippled line) that is very much in line with the industry correlations.
 - the FIELD *Threshold pressures* are on a higher trend (red dots/stippled line).



Threshold pressure

Literature gives different answers

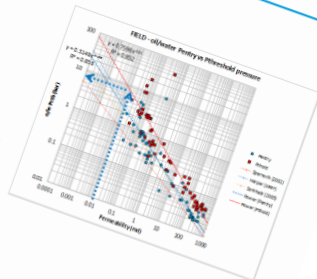
Manzocchi Fault rock permeability

Fault P_{th} for the main facies have been estimated based on the Manzocchi correlation for fault rock permeability:

$$\log k_f = -ASGR - \frac{1}{4} \log(D)(1 - SGR)^2$$

- K_f: Fault permeability (md)
 - SGR: Shale Gouge Ratio
 - D: Fault Displacement (m)

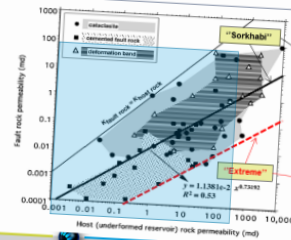
and FIELD P_{th}old vs perm data (right)



Sorkhabi Fault vs host rock permeability data

Sorkhabi et al (2005):

- Plot of a data set containing 66 pairs of host rock and fault rock permeability (from Antonides & Aydin (1994); Fowles & Burley (1994); Leville et al. (1997); Fisher & Krige (1998); Gibson (1998))
- All data pertain to normal faults in sandstone rocks. The fault rocks show reduced permeability by one to three orders of magnitude compared to the associated undeformed rocks. Cemented fault rocks have the lowest permeability, and deformation bands show the highest permeability.



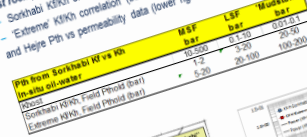
G. Baltas et al (2015):

- Graph showing permeability values for various types of cataclastic deformation bands as a function of related host-sandstone permeability
- These data come from 31 published studies and several new field examples.
- Each dot represents a value of permeability measured on cataclastic structures and the corresponding permeability value of host rock which could be an average value on the study site)

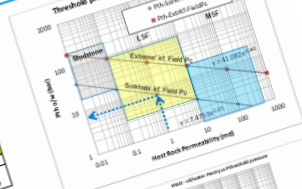
Sorkhabi Fault rock threshold pressures based on fault vs host rock permeability data

Fault P_{th} for the main facies have been estimated based on fault vs host rock permeability data from Sorkhabi (2005):

- Sorkhabi K_f/k_h correlation (if similar to Manzocchi)
- 'Extreme' K_f/k_h correlation (based on Sorkhabi/Baltas data) and Heyje P_{th} vs permeability data (lower right figure)



Threshold pressure vs Host Rock Permeability

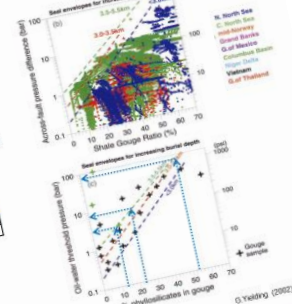
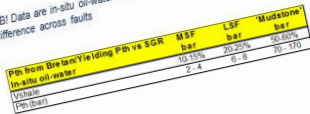


Bretan/Yielding Fault rock threshold pressures based on SGR

Bretan et al (2003) based on G. Yielding (2002):

$P_{th}(\text{bar}) = \text{power}(10, (SGR/27 - C))$
 C= 0.5 for burial < 3 km
 C= 0.25 for burial between 3-3.5 km
 C= 0 for burial > 3.5 km

NBI Data are in-situ oil-water threshold pressures (based on column height difference across faults)

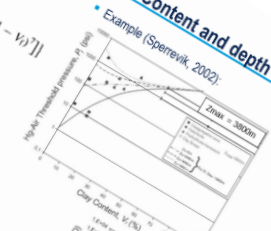
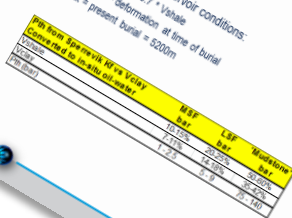


Sperreik Fault rock threshold pressures based on Clay Content and depth

Use Sperreik (2002) correlations:

$$P_t = 31.838 \times k_f^{0.3868}$$

Convert to FIELD oil-water reservoir conditions:
 - NBI W_f = V_{clay} = 0.7 V_{shale}
 - Z_f = 520m = detrimation at time of burial
 - Z_{max} = present burial = 5200m



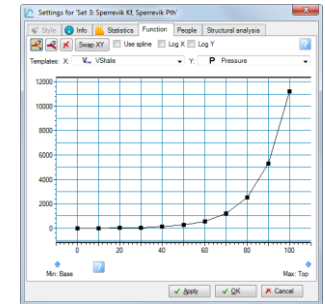
More and more pessimistic estimations

Threshold pressure

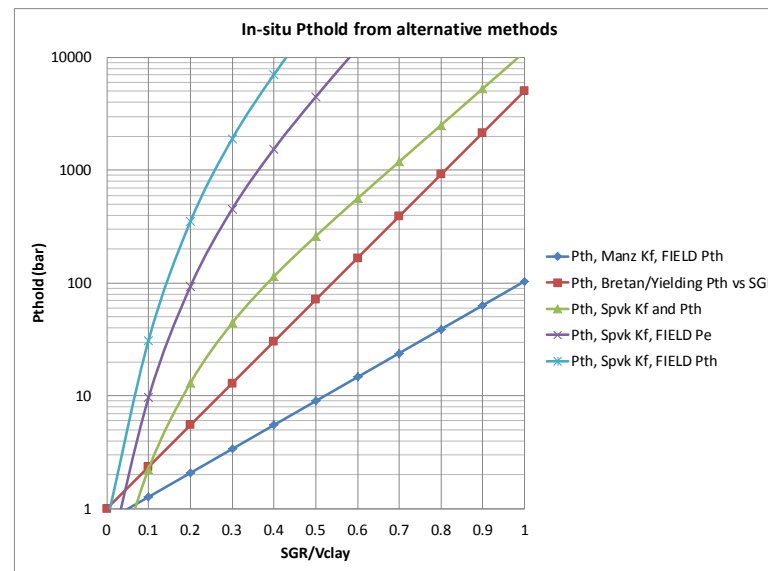
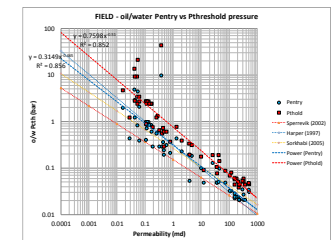
Defining the uncertainty range

- Based on the results from the previous slide *Mid to High case scenarios* are defined as:
 - A **HighHigh case** (P=10%) based on Manzocchi Kf and FIELD Pthold correlations
 - A **High case** (P=20%) based on Bretan (SGR, Zmax)
 - A **Base case** (P=40%) based on Sperrevik Kf and Pth correlations

- To cover the *Low case scenarios* the following cases are defined:
 - A **Low case** (P=20%) based on Kf from Sperrevik and **Pentry** from FIELD data
 - A **LowLow case** (P=10%) based on Kf from Sperrevik and **Pthold** from FIELD data

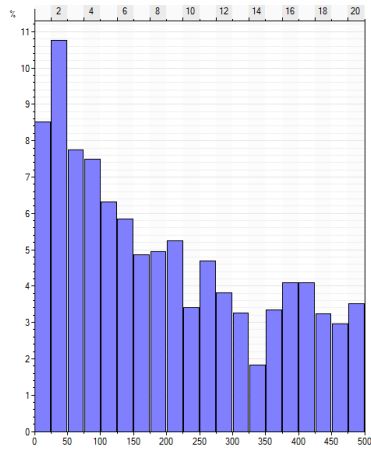


Cases defined as functions in Petrel (Vcl versus Pth)



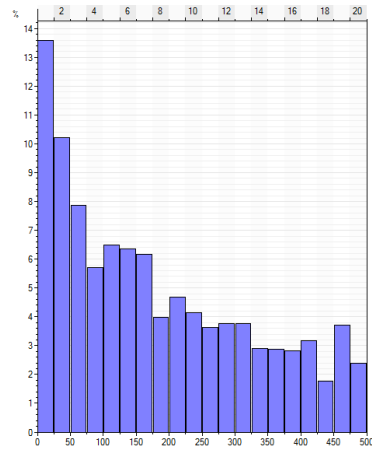
Threshold pressures Calculated on FIELD

Low Low case



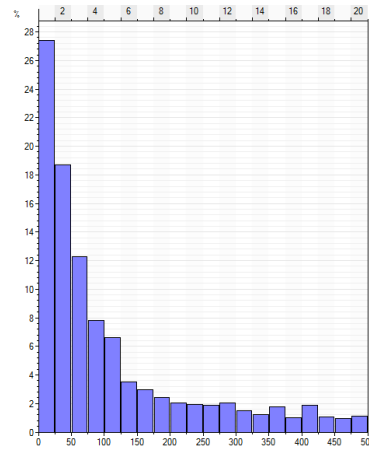
Sperrevik $k_f=f/SGR, Z_{maz}, Z_f$
FIELD Pth vs kf

Low case



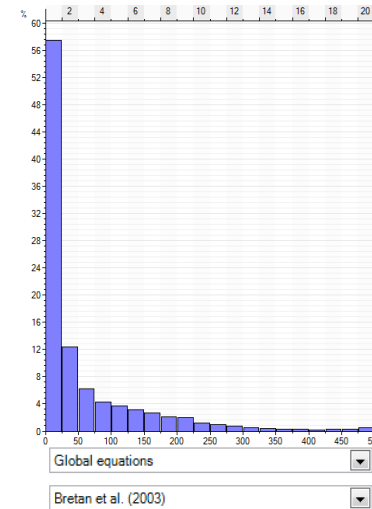
Sperrevik $k_f=f/SGR, Z_{maz}, Z_f$
FIELD Pe vs kf

Base case



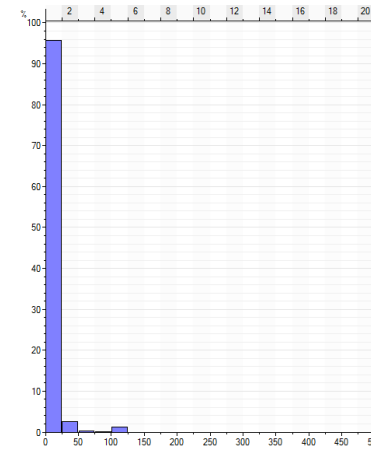
Sperrevik $k_f=f/SGR, Z_{maz}, Z_f$
Sperrevik Pe vs kf

High case



Bretan
Pth vs SGR

High High case



Manzocchi kf
FIELD Pth vs Kf

Decreasing Pth



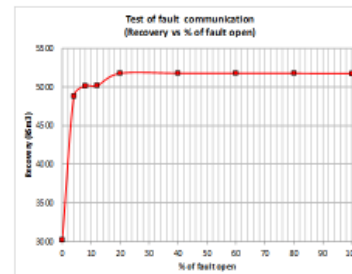
Threshold pressures

Eclipse limitation

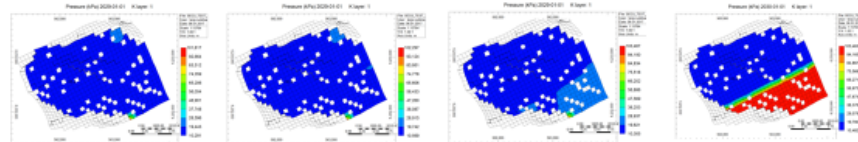
- Can only handle one Pth per fault.
- Need to find ONE representative Pth value per fault:
 - Estimated by simulating on element model, with one fault.
 - Varying the percentage of fault open.
 - Only 10% of the fault needs to be open to have an effective drainage from the other side (FIELD specific).

Fault threshold pressures Communication across faults = $f(\%open)$

- Eclipse does only handle one single threshold pressure per fault. The following procedure was devised to determine the values for each fault:
- Estimated how large fraction of a fault which needs to be open before there is effective communication across by simulating recovery vs %open in a segment model (see figures).
- Significant impact on communication only seen when less than 10% of fault is open!
- Calculated Pth for all fault connections (45,000), determined the 10%-percentile (where 10% of Pth is less than this value) for each fault and used that as threshold for each fault
- NB! This percentile is for a depletion process in this FIELD and may be different for other drive mechanisms and fields (e.g. 25% for a WI case).



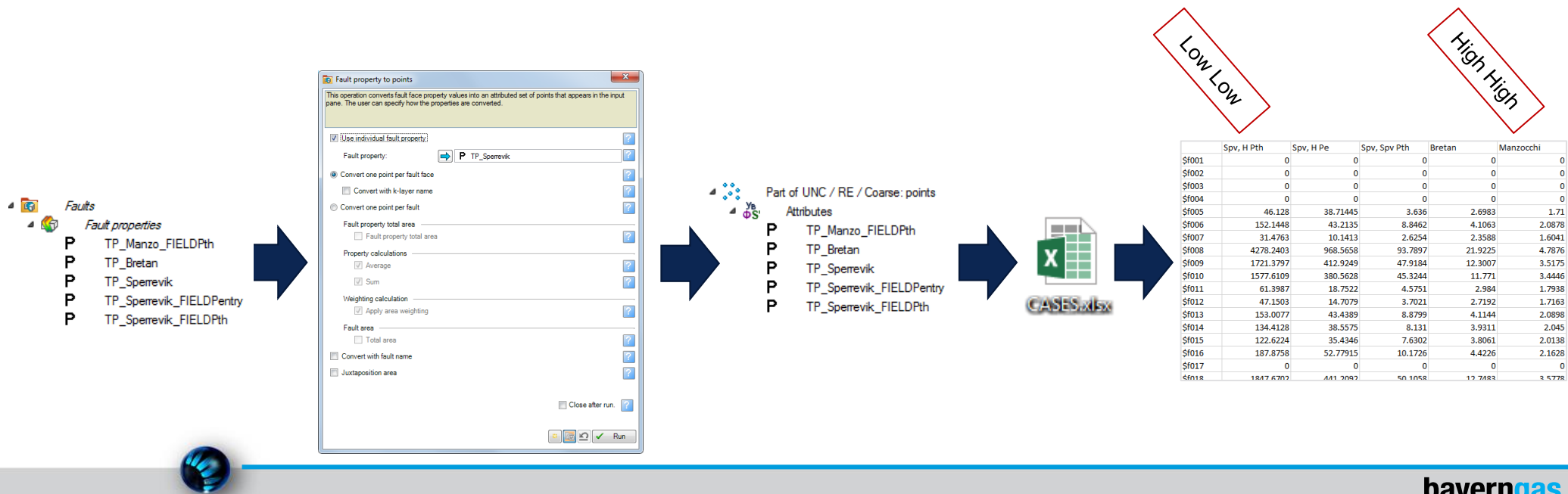
- 100% open: 5173 kSm³
- 40% open: 5177 kSm³
- 100% open: 5173 kSm³
- 20% open: 5176 kSm³
- 100% open: 5173 kSm³
- 4% open: 4882 kSm³
- 100% open: 5173 kSm³
- Closed: 3018 kSm³



Threshold pressure

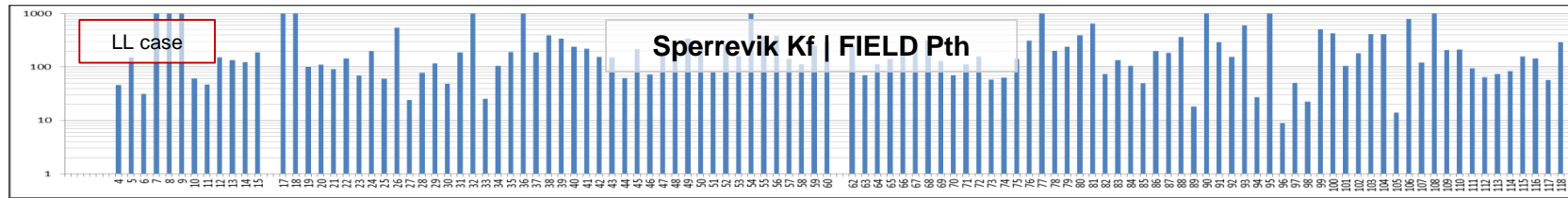
Estimation of the 10-percentile (from FIELD data)

- The 10-percentile is found by statistical analysis in Excel.
 - Threshold pressures are calculated for each case.
 - Then the calculated fault threshold property is resampled as points.
 - The point set is exported to Excel, where the 10-percentile for each fault is calculated (*manual work*).
 - Data is tabulated for import into Petrel uncertainty workflow (*Load/Read output sheet per fault and column*).

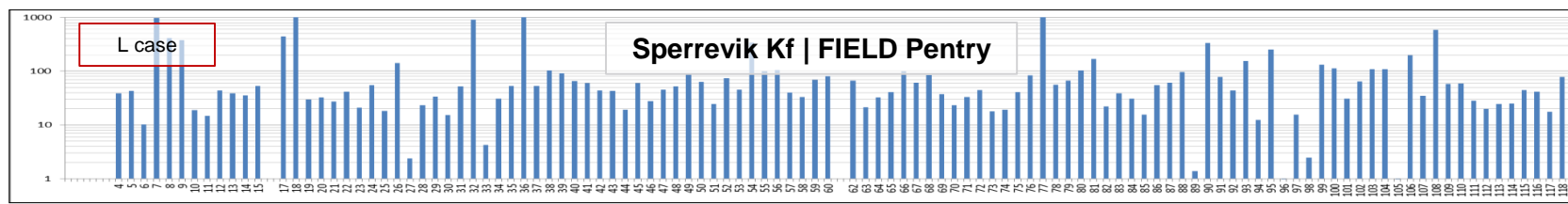


Input to Eclipse

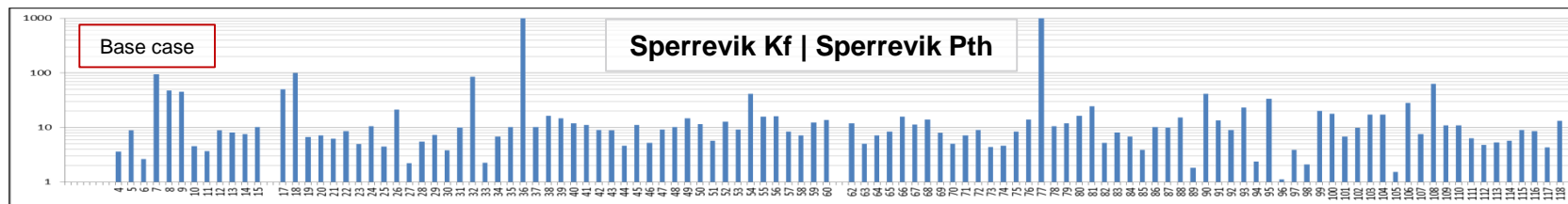
Threshold pressures



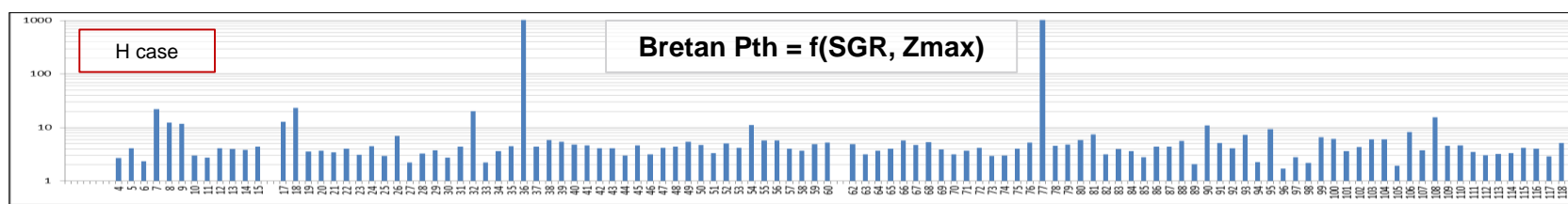
P= 10%



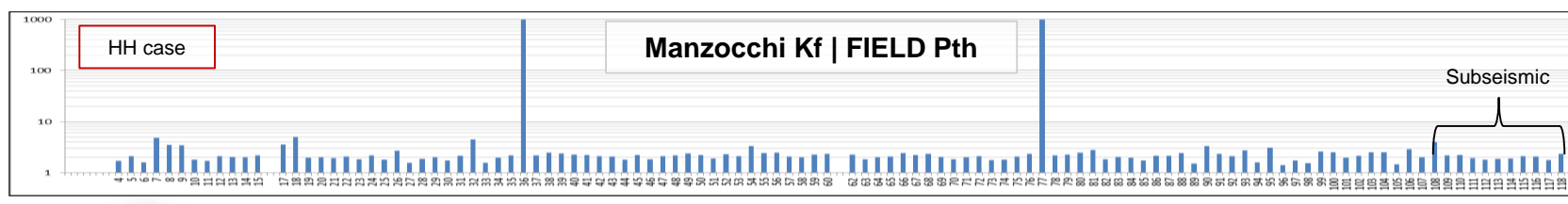
P= 20%



P= 40%



P= 20%



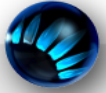
P= 10%

Tph

Fault #

■ 10% < TP





DEFINING FAULT TRANSMISSIBILITY MULTIPLIERS

Transmissibility multipliers

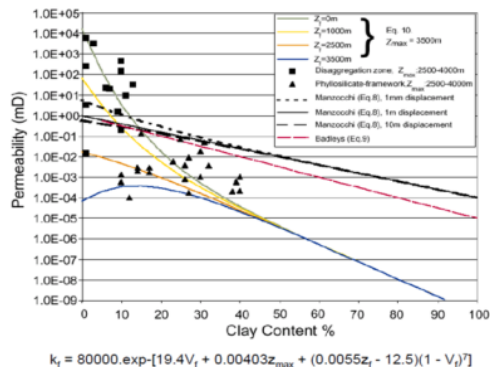
Methodology

- Petrel needs:

- Fault thicknesses
 - Industry correlations
 - Throw (3D grid)
- SGR
 - Vcl parameter
 - Throw (3D grid)
- Fault rock permeabilities
 - Industry correlations
 - Calibration to FIELD data
- Definition of *Range of uncertainty*.



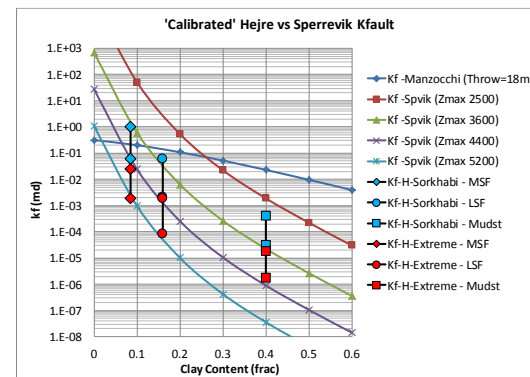
Fault thickness



Comparison of permeability measurements on core samples (symbols) and predicted permeability (solid lines).

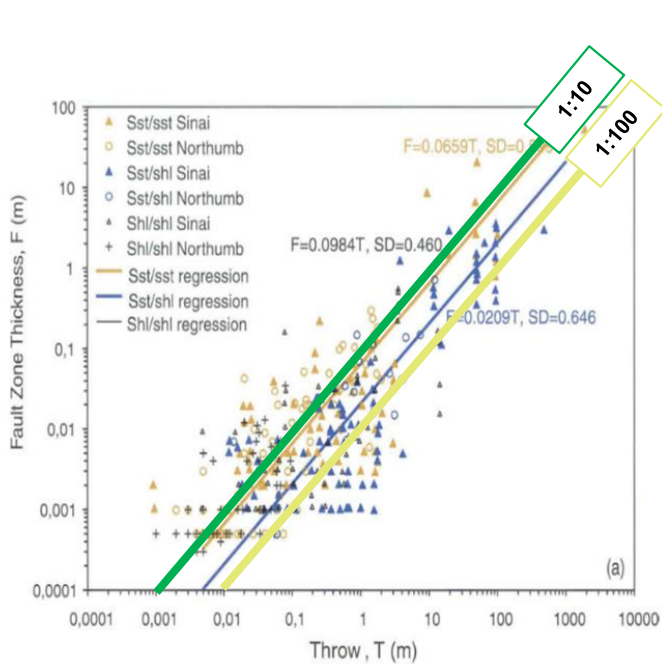
Z_i = Initial burial depth (during faulting)
 Z_{max} = Maximum burial depth
 V_f = Clay fraction of fault rock

From Sperrevik et al 2002

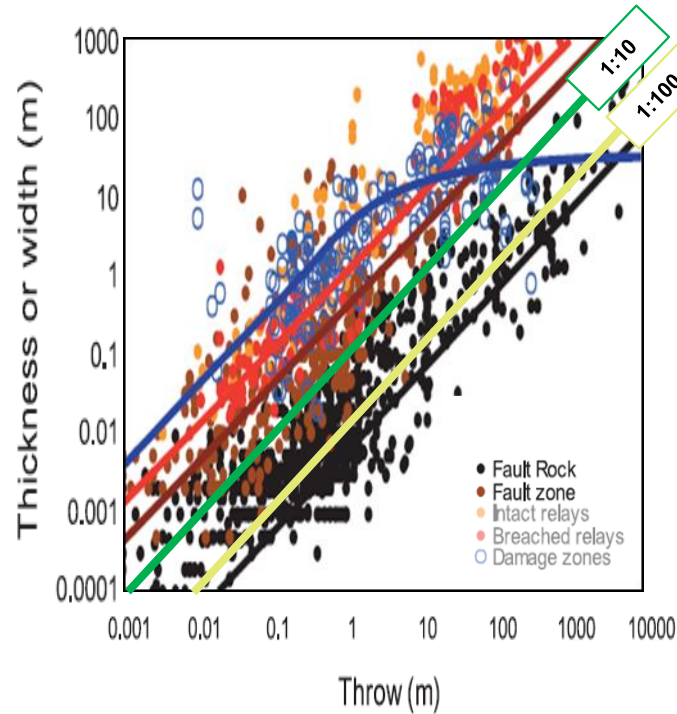


Fault thickness

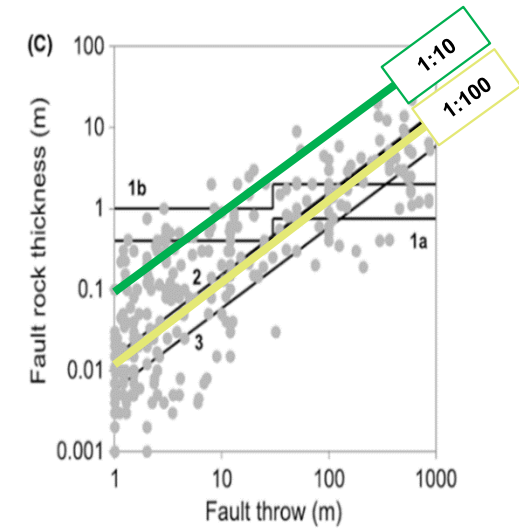
From published data



Sperrevik et al (2002)



Manzocchi et al (2008)



Manzocchi et al (2011)



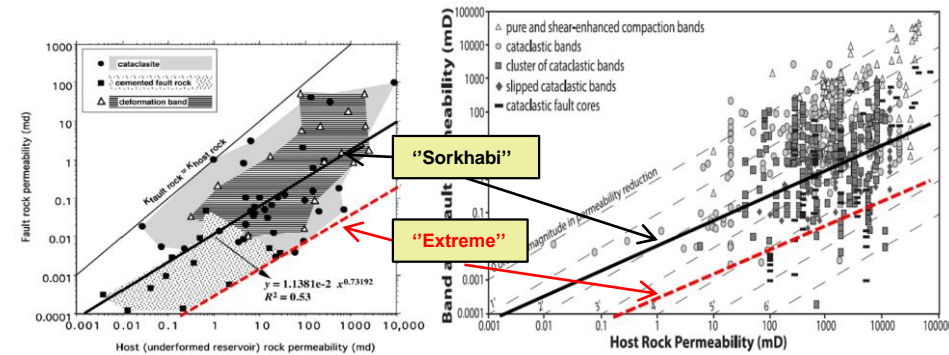
Transmissibility multipliers

'Calibration' of K_{fault} vs V_{clay} functions

- Used properties in MSF, LSF and mudstone to calibrate:
 - Average V_{clay}
 - Range of K_{host} permeabilities
- Estimate range of K_{fault} permeabilities for individual facies using:
 - Sorkhabi K_f/K_h correlation (High value)
 - Extreme K_f/K_h correlation (Low value)

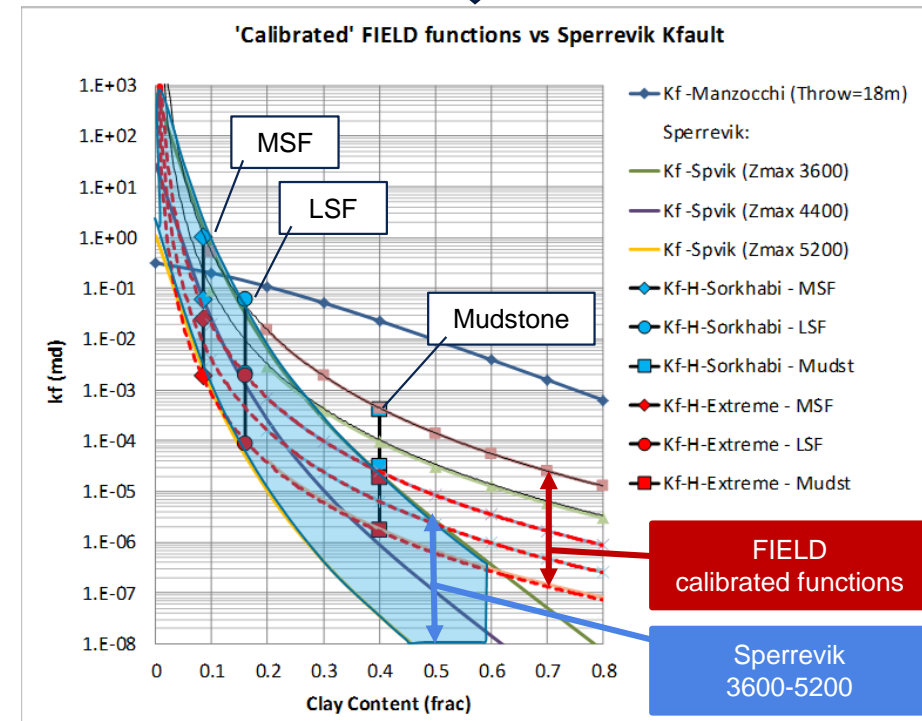
Fault permeability calibration				
	Range	MSF	LSF	'Mudstone'
V _{clay}		7-10%	14-18%	35-45%
K _{host}	Low	10	0.1	0.0003
	High	500	10	0.01
K _f -H-Sorkhabi	Low	6.0E-02	2.1E-03	3.1E-05
	High	1.0E+00	6.0E-02	4.0E-04
K _f -H-Extreme	Low	1.9E-03	8.6E-05	1.7E-06
	High	2.6E-02	1.9E-03	1.8E-05

- Tune Sperrevik correlations to FIELD data (blue shade) by Z_{max}:
 - Z_{max}= 3600-5200m match the K_{fault} range for MSF/LSF
- Defined a set of new FIELD specific functions based on the calibrated facies data for MSF, LSF and mudstone (see right).



Sorkhabi et al (2005)

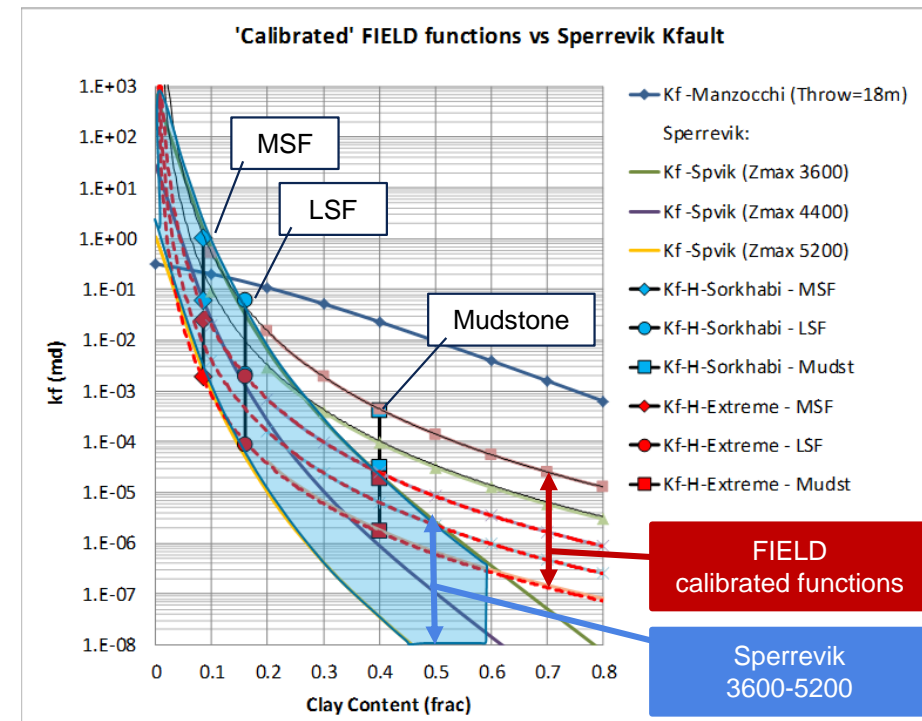
G. Ballas et al (2015)



Transmissibility multipliers

Defining the uncertainty range

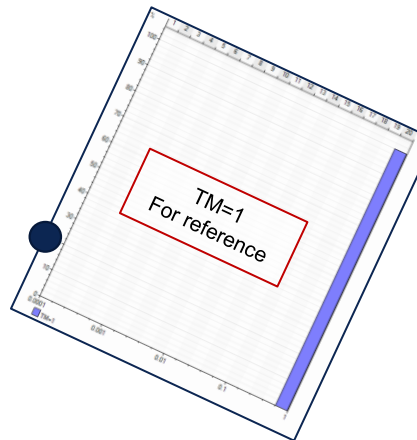
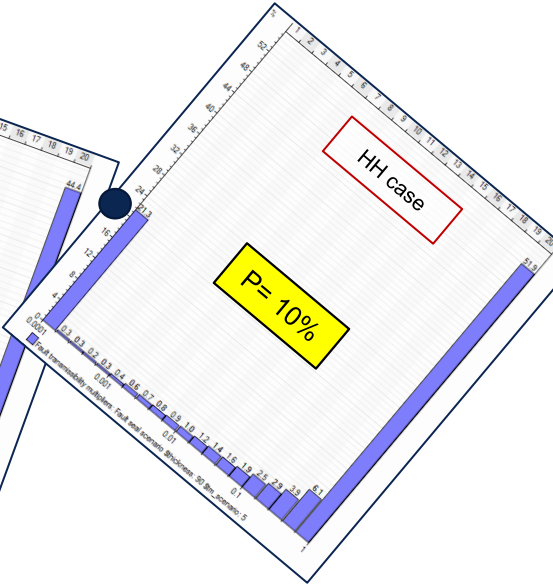
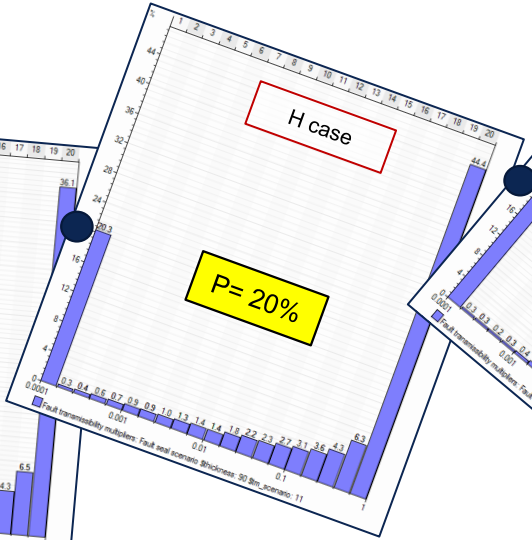
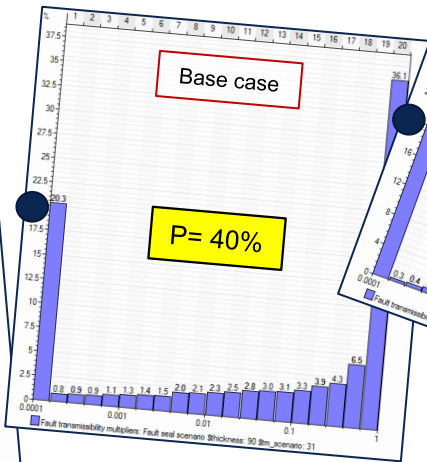
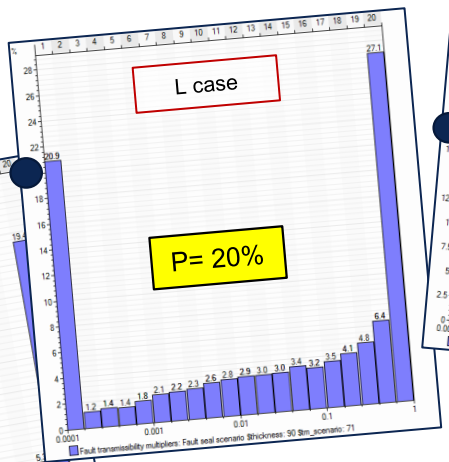
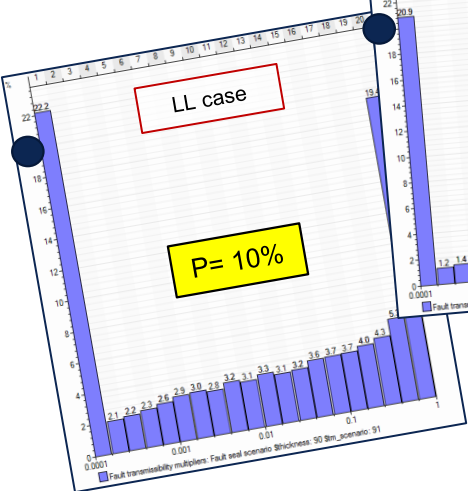
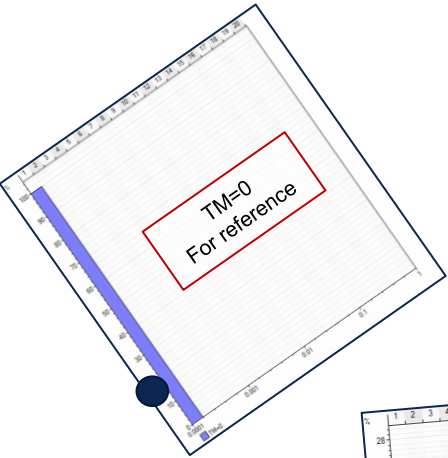
- Sperrevik considered pessimistic at $V_{clay} > 30\%$ compared to FIELD calibrated functions.
- Conservative approach if used.
- Project decision : use 'calibrated' Sperrevik Kf functions to represent the TM uncertainty range ($Z_f=500m$).
 - Use Sperrevik $Z_{max}=5200$ as **LOWLOW** case with $P=10\%$.
 - Use Sperrevik $Z_{max}=4800$ as **LOW** case with $P=20\%$
 - Use Sperrevik $Z_{max}=4400$ as **BASE** case with $P=40\%$
 - Use Sperrevik $Z_{max}=4000$ as **HIGH** case with $P=20\%$
 - Use Sperrevik $Z_{max}=3600$ as **HIGHHIGH** case with $P=10\%$



Input to Eclipse

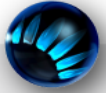
Transmissibility multipliers (varies per realization | fault throw & Vcl)

Increasing TMs 



NOTE: Y-axis min to max vary - Blue dot for reference = 20





IMPLEMENTATION

Petrel

FAULT scenarios

Summary

- Combine fault threshold pressures and transmissibility modifiers in 5 scenarios:
 - from LowLow to HighHigh
- Assign fault thicknesses
 - from uniform distribution:
 - independent of scenario
- Assign probabilities as shown below.

Case	Prob	Pth	TM	F-thickness
HH	10	Manz	Spv-3600	R(10-100)
H	20	Bretan	Spv-4000	R(10-100)
M	40	Spv	Spv-4400	R(10-100)
L	20	FIELD Pe	Spv-4800	R(10-100)
LL	10	FIELD Pth	Spv-5200	R(10-100)



Petrel

The workflow

With 3D grid For FORCE | P50-H / RE / Co Use: Specified grid

HH - Sperrevik | 3600 & Pth_Manzocchi

stm_scenario < 10

Create seal scenario Seal scenario: Scenario [global]

Numeric expression \$pth_col = 6

Run 14b_Fault_ReadPth Nested variables

H - Sperrevik | 4000 & Pth_Bretan

Else If stm_scenario < 30

Create seal scenario Seal scenario: Scenario [global]

Numeric expression \$pth_col = 5

Run 14b_Fault_ReadPth Nested variables

B - Sperrevik | 4400 & Pth_Sperrevik

Else If stm_scenario < 70

Create seal scenario Seal scenario: Scenario [global]

Numeric expression \$pth_col = 4

Run 14b_Fault_ReadPth Nested variables

L - Sperrevik | 4800 & Pth_Sperrevik_HejrePe

Else If stm_scenario < 90

Create seal scenario Seal scenario: Scenario [global]

Numeric expression \$pth_col = 3

Run 14b_Fault_ReadPth Nested variables

LL - Sperrevik | 5200 & Pth_Sperrevik_HejrePth

Else

Create seal scenario Seal scenario: Scenario [global]

Numeric expression \$pth_col = 2

Run 14b_Fault_ReadPth Nested variables

Endif

Structural and fault analysis Effective cross-fault transmissibility: Effective cross-fault perm

Load output sheet ..\Fault_ThresholdPressures_INPUT_UNC.bt

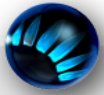
Read output sheet		Row:	Column:	\$pth_col
\$f001		2	\$pth_col	\$pth_col
\$f002		3	\$pth_col	\$pth_col
\$f003		4	\$pth_col	\$pth_col
\$f004		5	\$pth_col	\$pth_col
\$f005		6	\$pth_col	\$pth_col
\$f006		7	\$pth_col	\$pth_col

	LL case	L case	Base case	H case	HH case
	Spv, H Pth	Spv, H Pe	Spv, Spv Pth	Bretan	Manzocchi
\$f001	0	0	0	0	0
\$f002	0	0	0	0	0
\$f003	0	0	0	0	0
\$f004	0	0	0	0	0
\$f005	4612800	3871445	363600	269830	171000
\$f006	15214480	4321350	884620	410630	208780
\$f007	3147630	1014130	262540	235880	160410
\$f008	427824030	96856580	9378970	2192250	478760
\$f009	172137970	41292490	4791840	1230070	351750
\$f010	157761090	38056280	4532440	1177100	344460
\$f011	6139870	1875220	457510	298400	179380
\$f012	4715030	1470790	370210	271920	171630
\$f013	15300770	4343890	887990	411440	208980
\$f014	13441280	3855750	813100	393110	204500
\$f015	12262240	3543460	763020	380610	201380
\$f016	18787580	5277915	1017260	442260	216280

* The tabulated Pth needs to be multiplied by 100000 due to a bug in Petrel

Output : Pth – one value per fault
TM – variable values per fault/realization



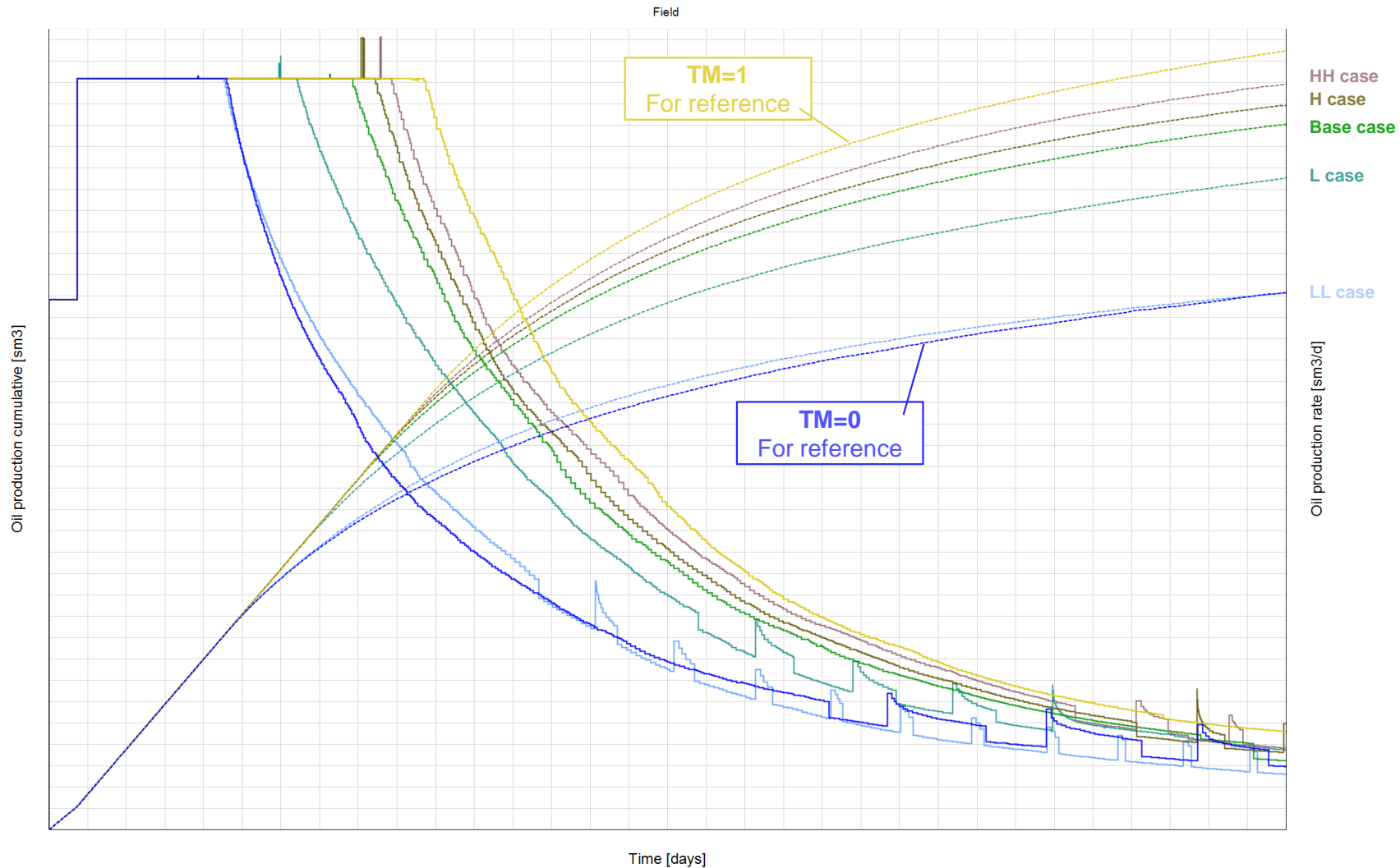


RESULT

Production profiles | Depletion through time

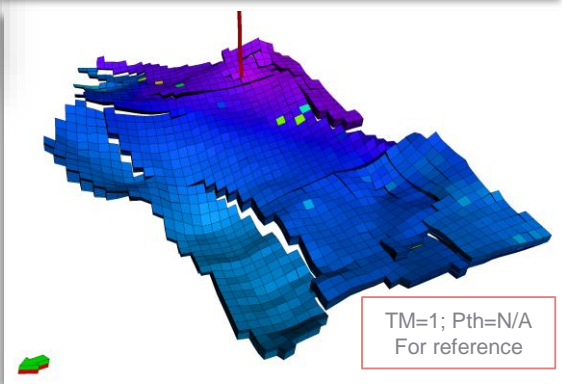
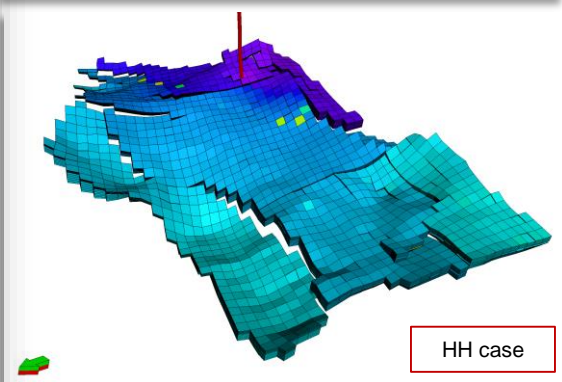
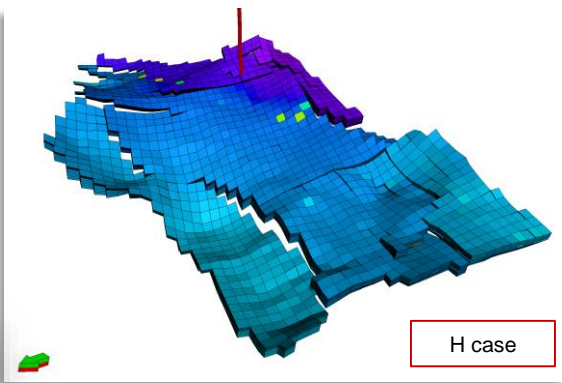
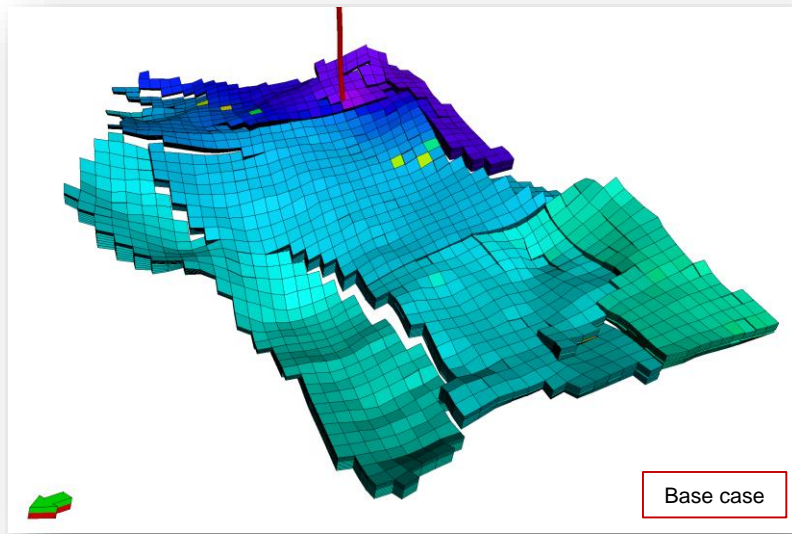
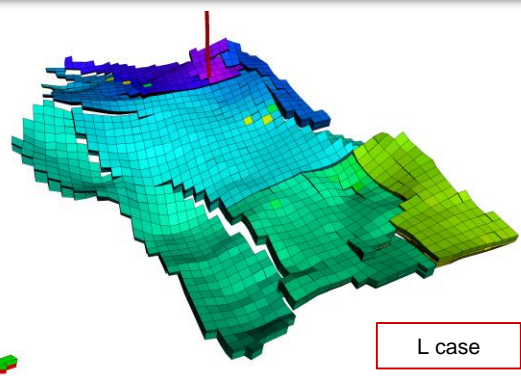
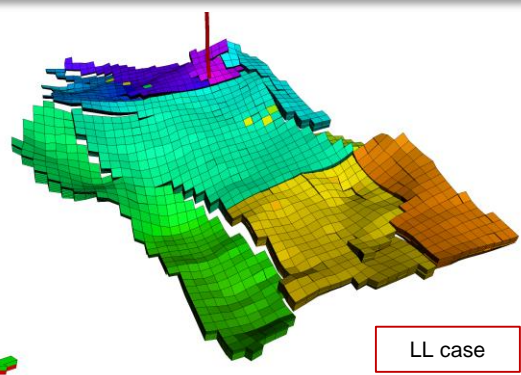
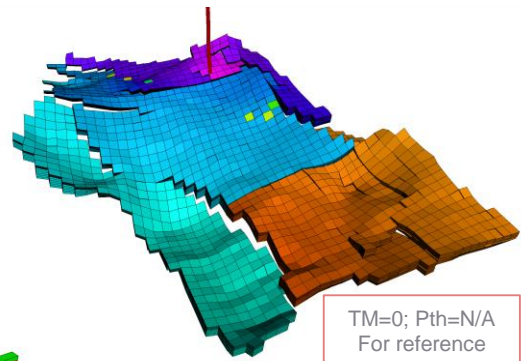
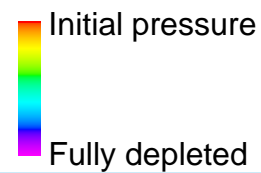
Result

Production profiles [FIELD] | One realization (P50)



Result

Pressure @ Field End | One realization (P50)



Conclusions

- Based on a combination of FIELD data and industry correlations a methodology was developed which provided justifiable ranges of threshold pressures and transmissibility modifiers to be used in dynamic simulation of fault behaviour.
- By assessing alternative fault threshold pressures and fault rock permeability methods the team have:
 - obtained larger understanding of the dynamics in the FIELD.
 - obtained confidence that the likelihood for small, isolated segments is less.



Thank you

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- ...and YOU for listening!

