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Open or closed, or something in-between?

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

Ulf Lægreid | Terje Rudshaug

Agenda

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

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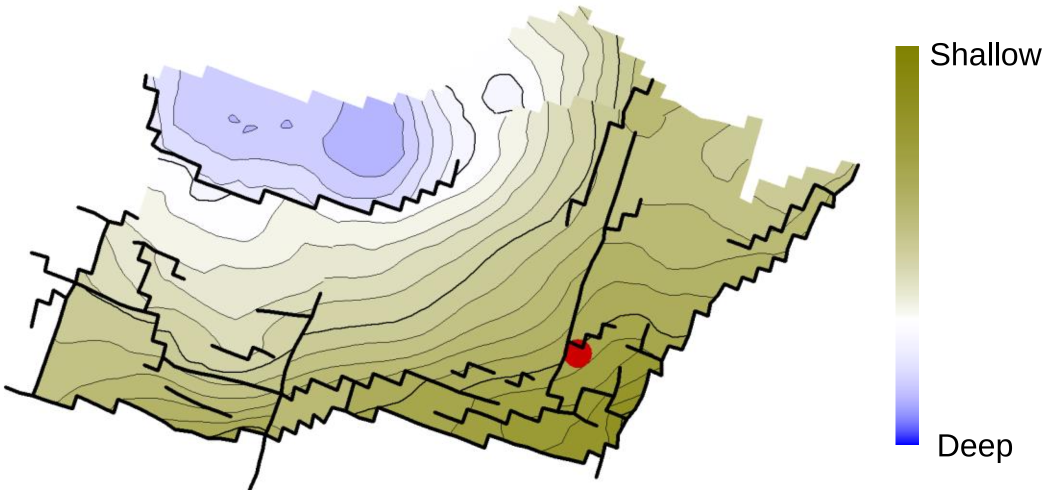
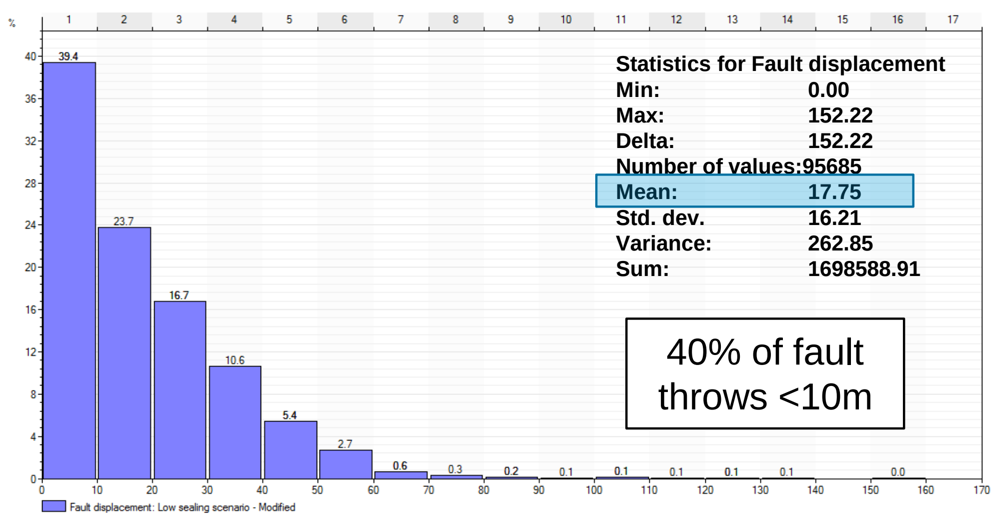
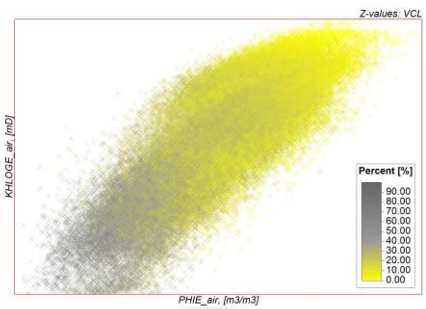
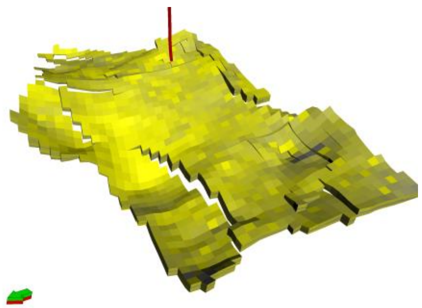
The dataset

- 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»).
- Concequence
  - 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 Vcl and threshold pressure.

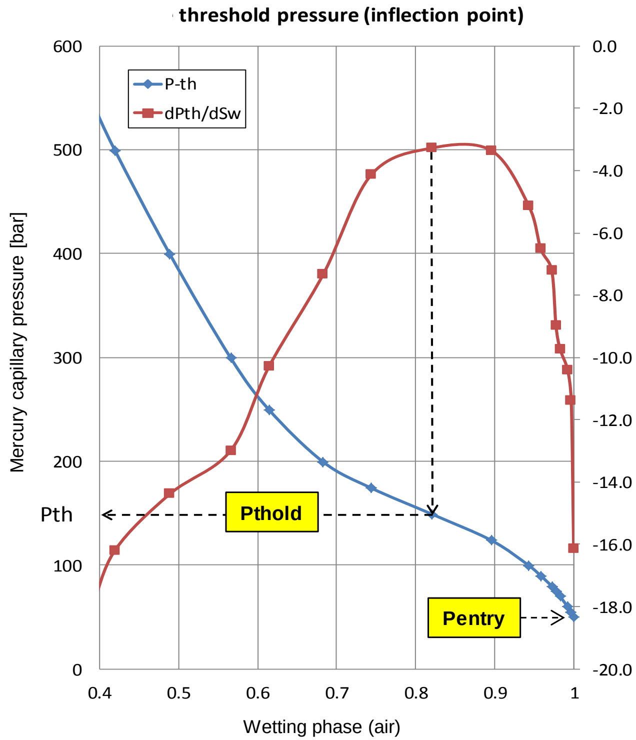
- Threshold pressures are obtained from:
  - Industry correlations
    - generally based on Pth = f(Kfault) or f(SGR,...)
  - Capillary pressure measurements
    - MICP

- Need to correlate Pth to mappable petrophysical property.
  - Permeability
  - Clay content

- Definition of *Range of uncertainty.*

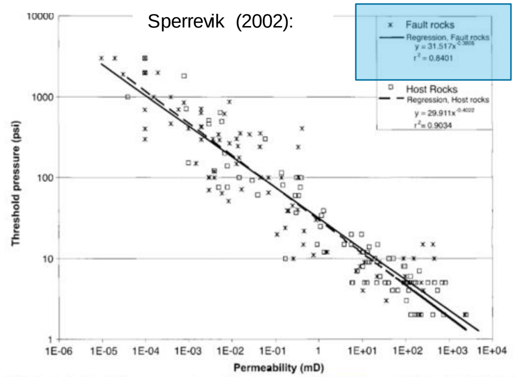
Threshold pressure
Definition

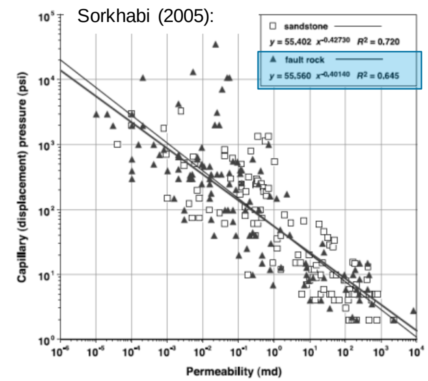
- Definition(s):
  - Entry pressure
    - first entry of non-wetting fluid into the largest pores.
  - Threshold pressure
    - inflection point where there as a continous phase of non-wetting fluid through the pores.



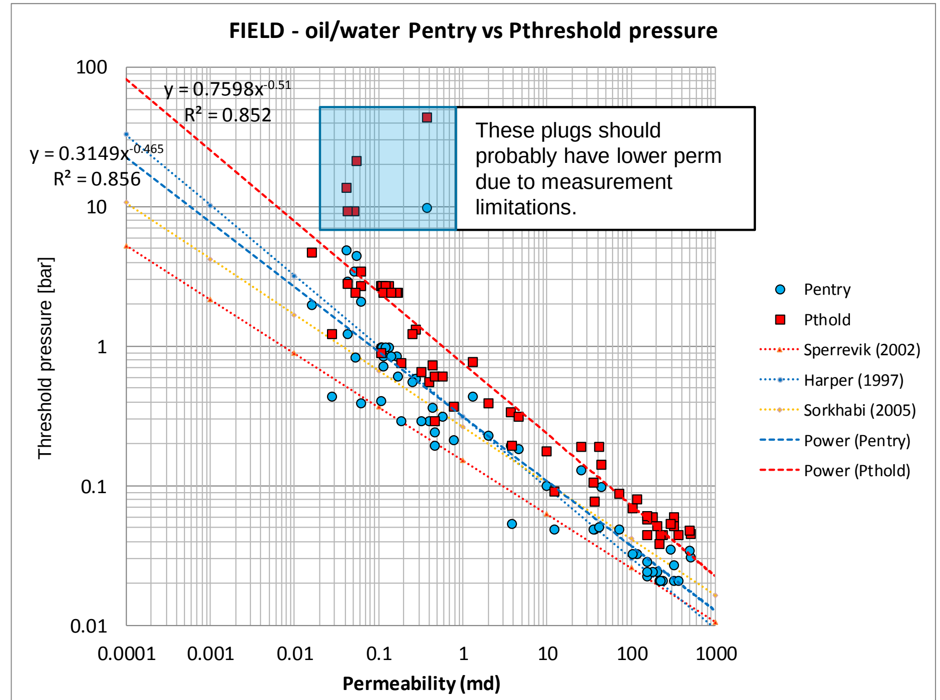
Threshold pressure vs permeability

- 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 Pth vs Host rock data can be used to estimate Pth for Fault rock.

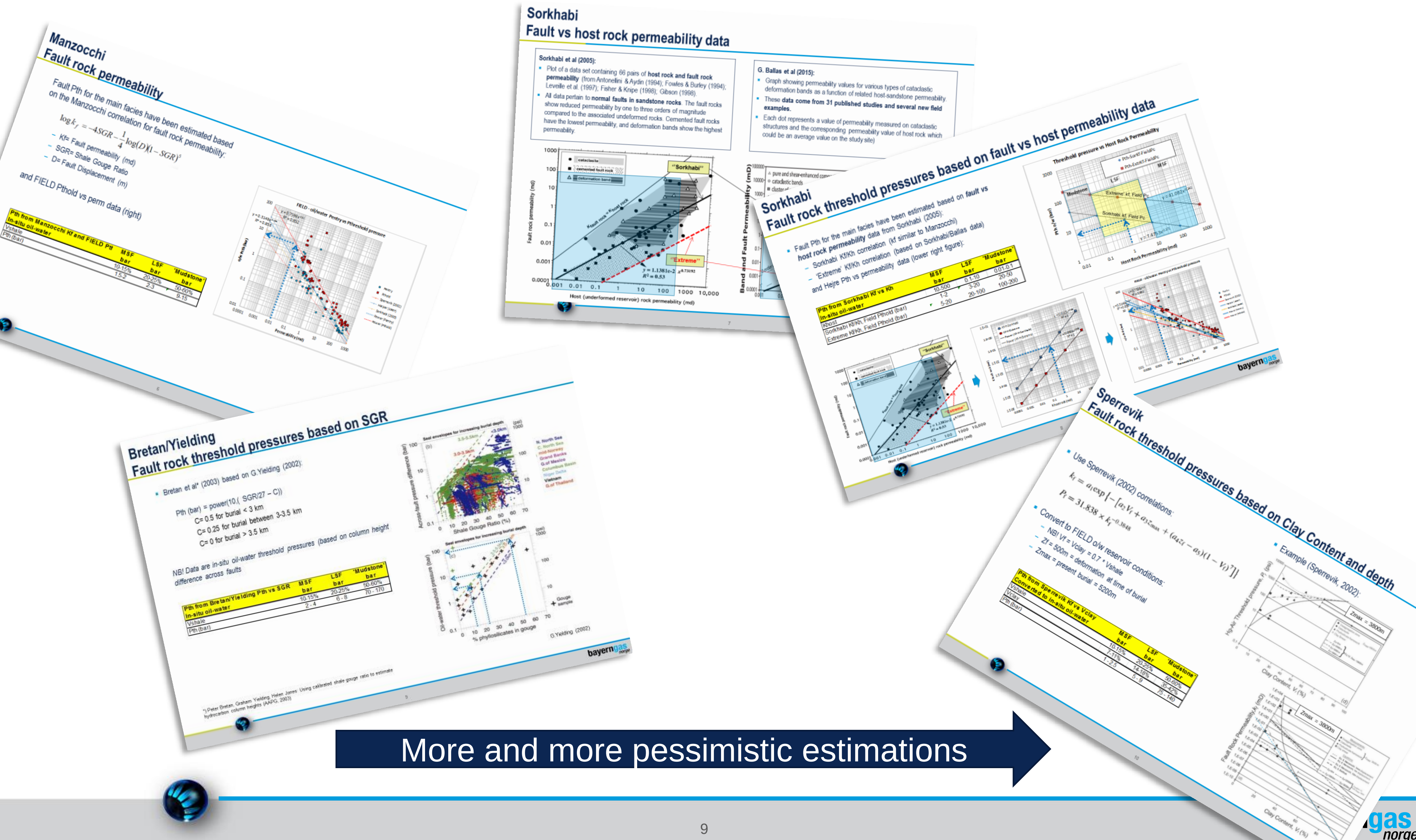




- FIELD measured MICP data
  - show an *Entry pressure* trend (blue dots/stippled line) that is very much in line with the industry correlations.
  - the FIELD *Threshold pressures* are on a higher trend (red dots/stippled line).



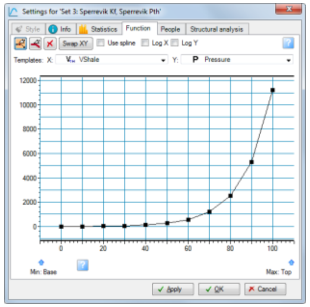
Threshold pressure
Literature gives different answers



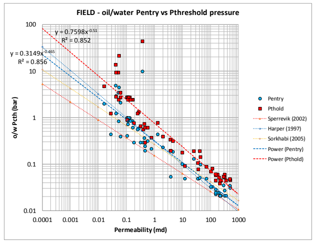
More and more pessimistic estimations

Threshold pressure
Defining the uncertainty range

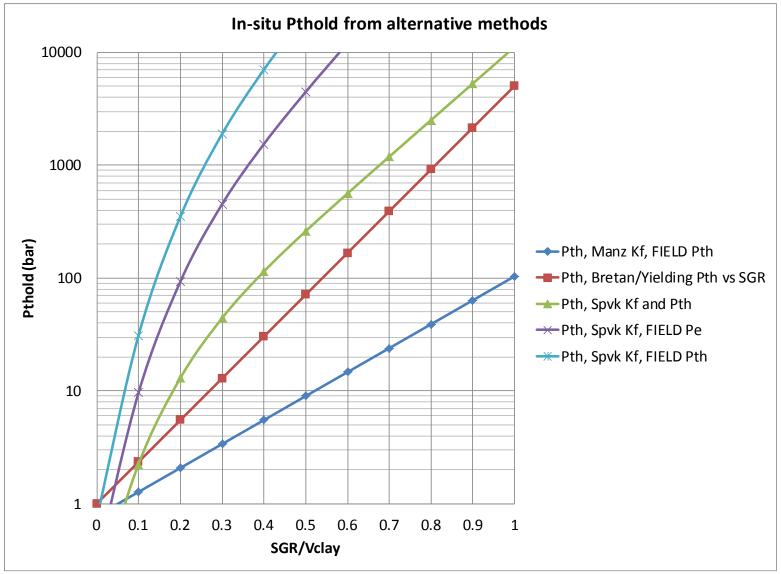
- Based on the results from the previous slide *Mid to High case scenarios* are defined as:
  - A **HighHigh case** (P=10%) based on Manzocchi Kf and FIELD Pthold correlations
  - A **High case** (P=20%) based on Bretan (SGR, Zmax)
  - A **Base case** (P=40%) based on Sperrevik Kf and Pth correlations



Cases defined as functions in Petrel (Vcl versus Pth)

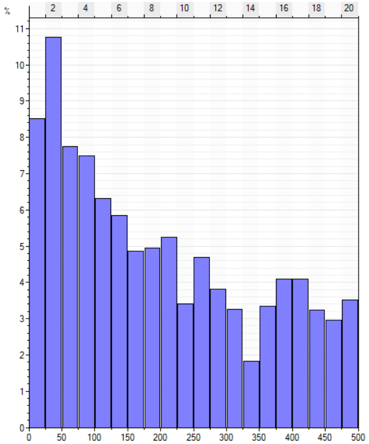


- To cover the *Low case scenarios* the following cases are defined:
  - A **Low case** (P=20%) based on Kf from Sperrevik and **Pentry** from FIELD data
  - A **LowLow case** (P=10%) based on Kf from Sperrevik and **Pthold** from FIELD data



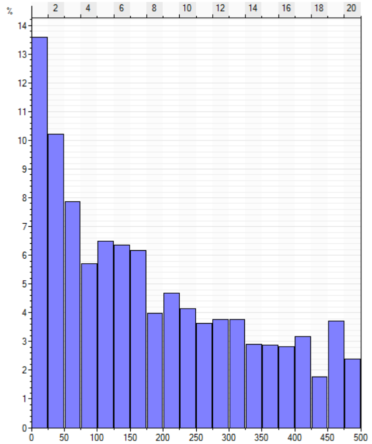
Threshold pressures
Calculated on FIELD

Low Low case



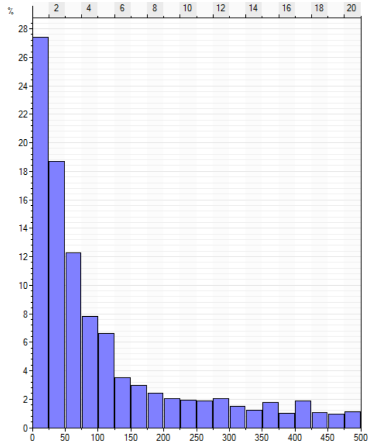
Sperrevik kf=f/SGR,Zmaz,Zf
FIELD Pth vs kf

Low case



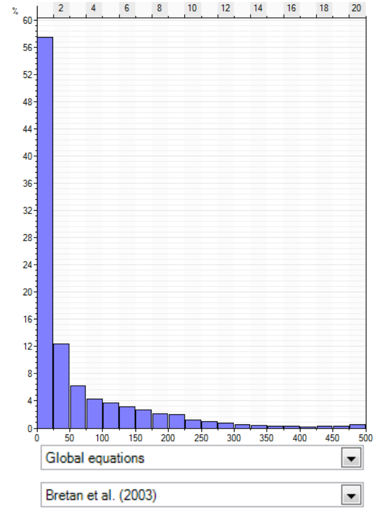
Sperrevik kf=f/SGR,Zmaz,Zf
FIELD Pe vs kf

Base case



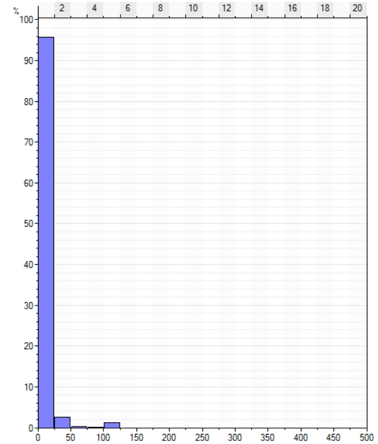
Sperrevik kf=f/SGR,Zmaz,Zf
Sperrevik Pe vs kf

High case



Bretan
Pth vs SGR

High High case

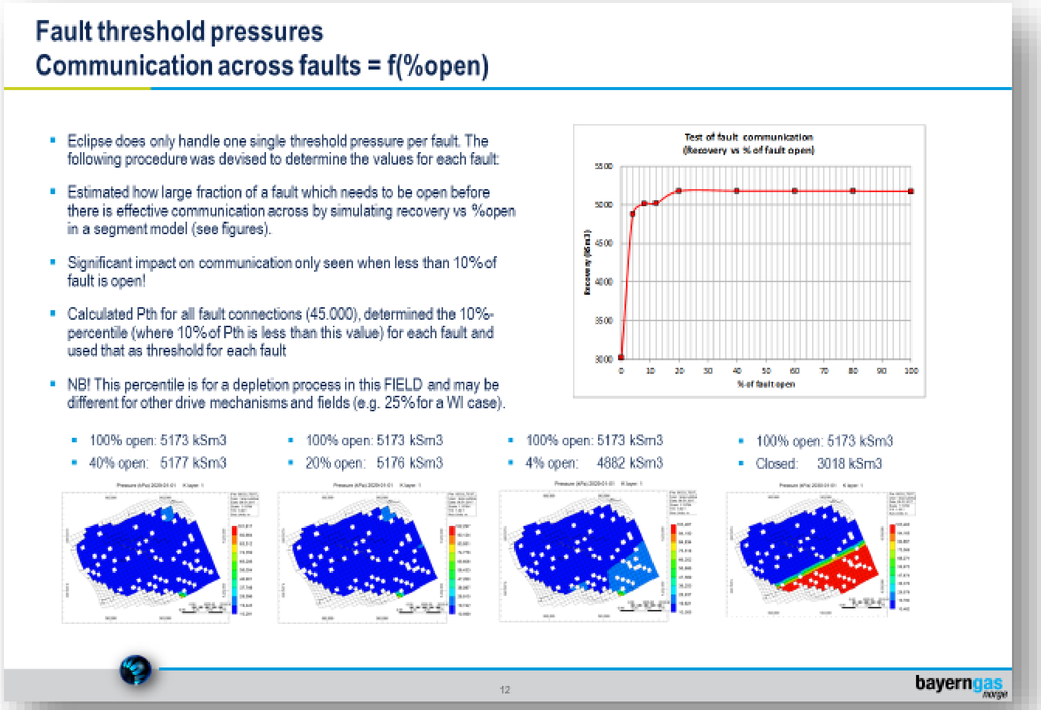


Manzocchi kf
FIELD Pth vs Kf

Decreasing Pth

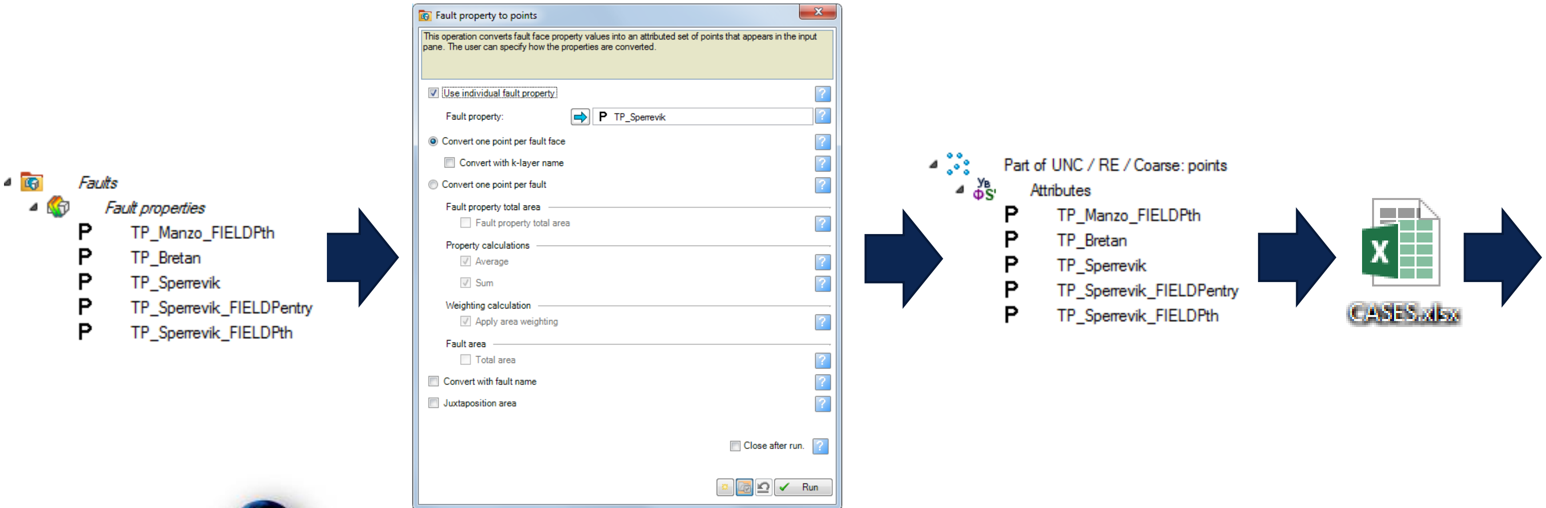
Threshold pressures
Eclipse limitation

- 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).



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*).

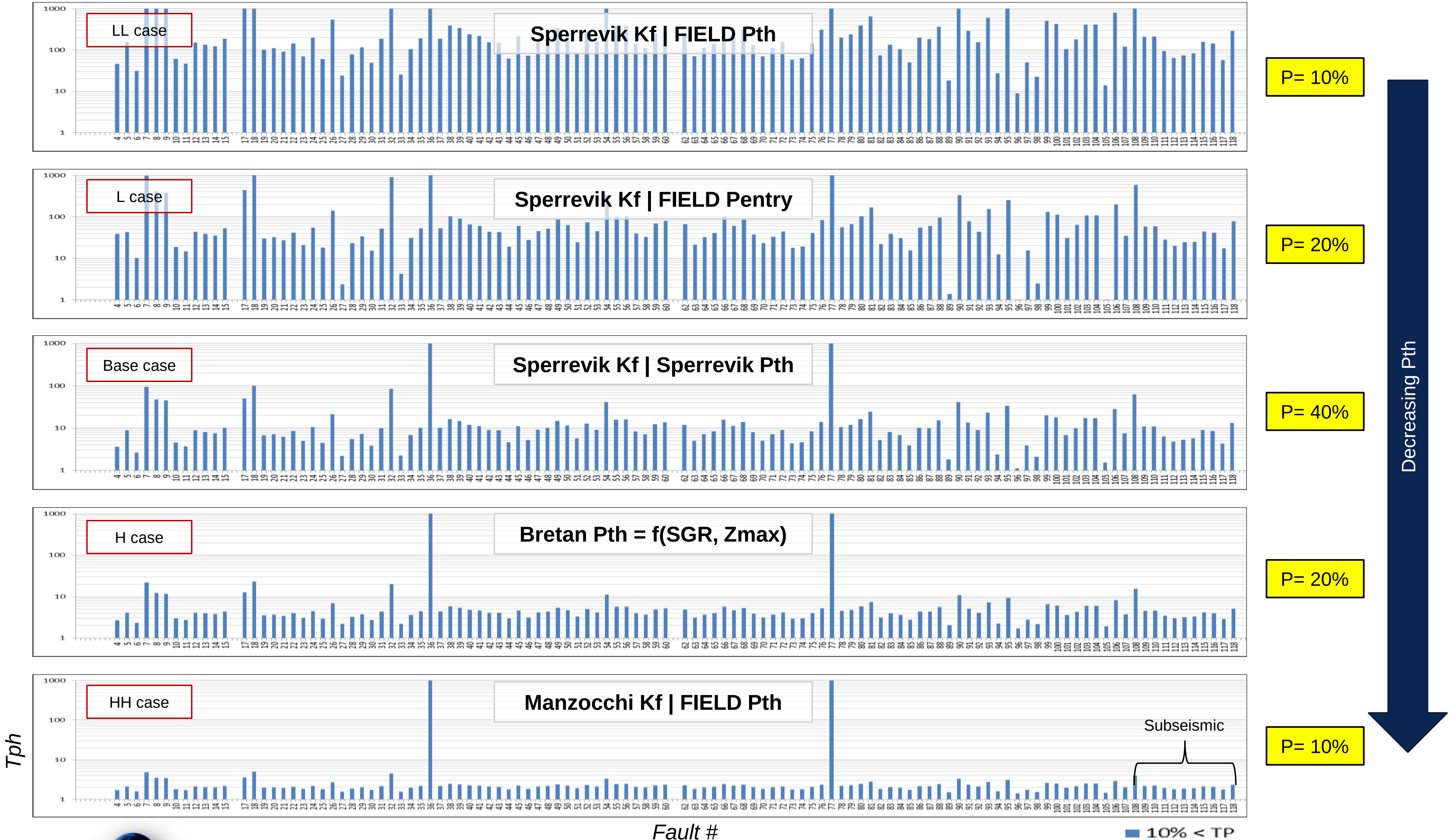


Low Low

High High

	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	46.128	38.71445	3.636	2.6983	1.71
$f006	152.1448	43.2135	8.8462	4.1063	2.0878
$f007	31.4763	10.1413	2.6254	2.3588	1.6041
$f008	4278.2403	968.5658	93.7897	21.9225	4.7876
$f009	1721.3797	412.9249	47.9184	12.3007	3.5175
$f010	1577.6109	380.5628	45.3244	11.771	3.4446
$f011	61.3987	18.7522	4.5751	2.984	1.7938
$f012	47.1503	14.7079	3.7021	2.7192	1.7163
$f013	153.0077	43.4389	8.8799	4.1144	2.0898
$f014	134.4128	38.5575	8.131	3.9311	2.045
$f015	122.6224	35.4346	7.6302	3.8061	2.0138
$f016	187.8758	52.77915	10.1726	4.4226	2.1628
$f017	0	0	0	0	0
$f018	1847.6702	441.2092	50.1058	12.7483	3.5778

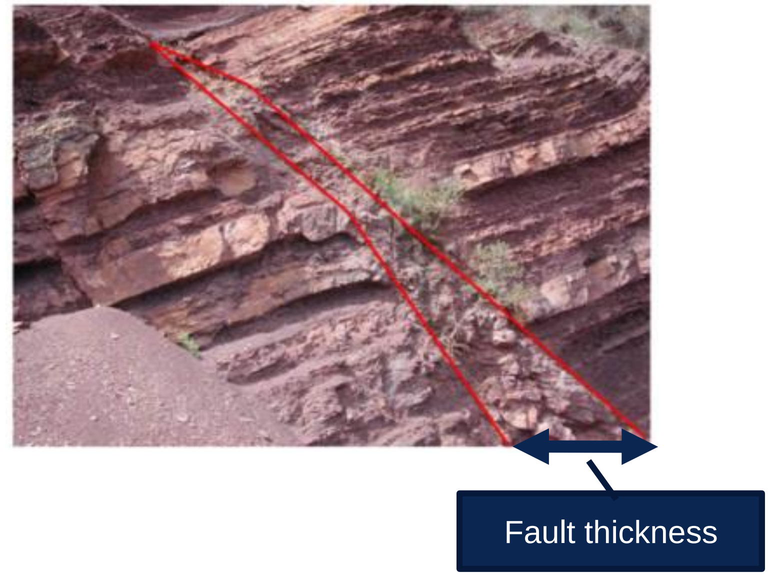
Input to Eclipse
Threshold pressures

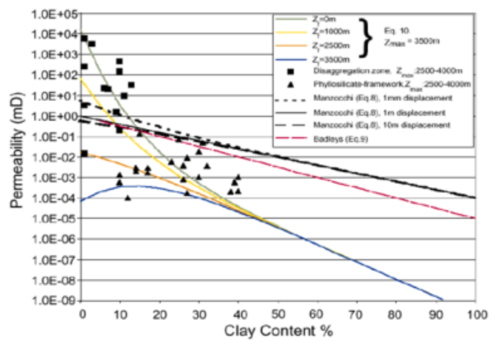


DEFINING
FAULT TRANSMISSIBILITY MULTIPLIERS

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.*



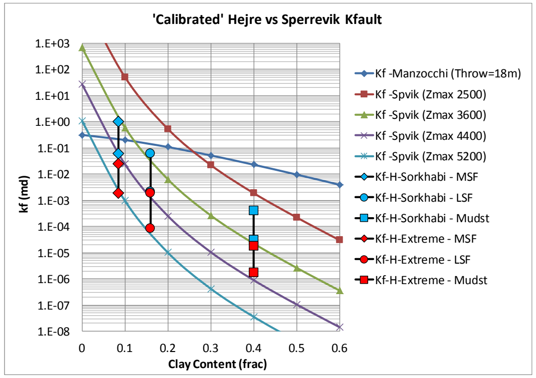


Comparison of permeability measurements on core samples (symbols) and predicted permeability (solid lines).

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

$k_f = 80000.\exp\text{-}[19.4V_f + 0.00403z_{max} + (0.0055z_i - 12.5)(1 - V_f)^7]$

From Sperrevik et al 2002



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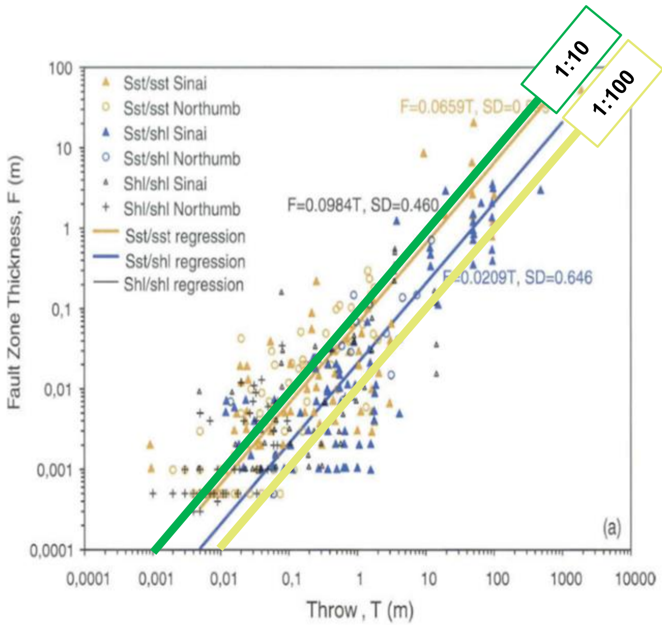
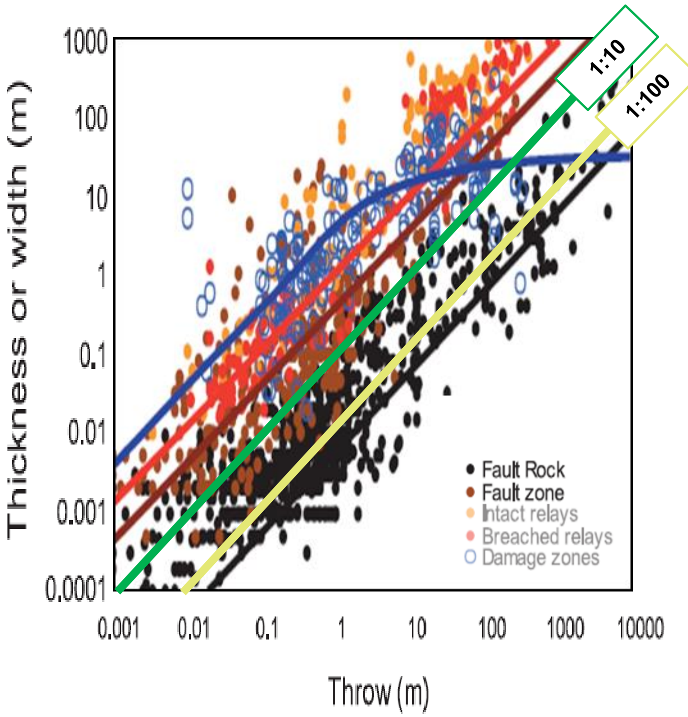
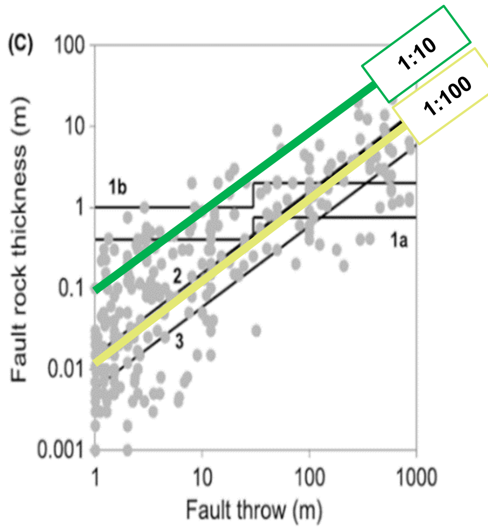
Fault thickness
From published data



Sperrevik et al (2002)



Manzocchi et al (2008)



Manzocchi et al (2011)

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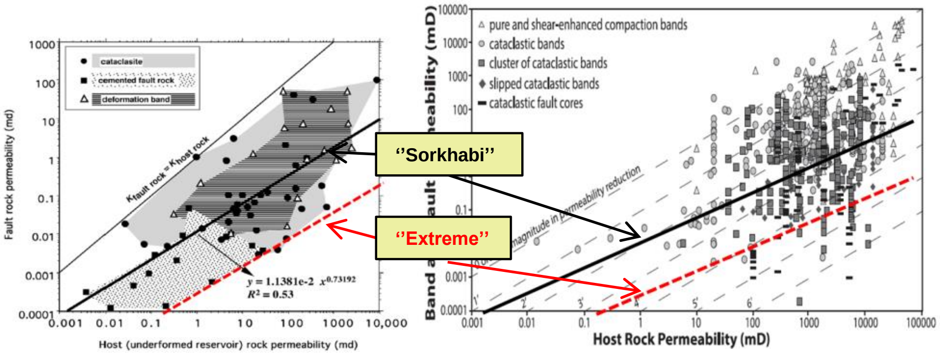
Transmissibility multipliers
'Calibration' of Kfault vs Vclay functions

- Used properties in MSF, LSF and mudstone to calibrate:
  - Average Vclay
  - Range of Khost permeabilities
- Estimate range of Kfault permeabilities for individual facies using:
  - Sorkhabi Kf/Kh correlation (High value)
  - Extreme Kf/Kh correlation (Low value)

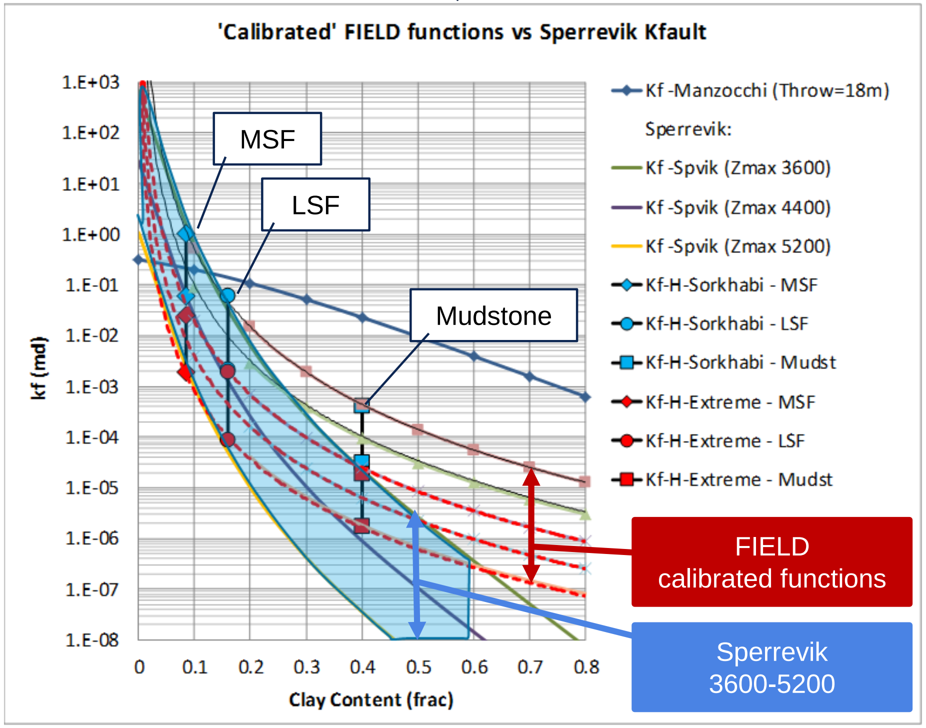
Fault permeability calibration				
	Range	MSF	LSF	'Mudstone'
Vclay		7-10%	14-18%	35-45%
Khost	Low	10	0.1	0.0003
	High	500	10	0.01
Kf-H-Sorkhabi	Low	6.0E-02	2.1E-03	3.1E-05
	High	1.0E+00	6.0E-02	4.0E-04
Kf-H-Extreme	Low	1.9E-03	8.6E-05	1.7E-06
	High	2.6E-02	1.9E-03	1.8E-05

- Tune Sperrevik correlations to FIELD data (blue shade) by Zmax:
  - Zmax= 3600-5200m match the Kfault 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).



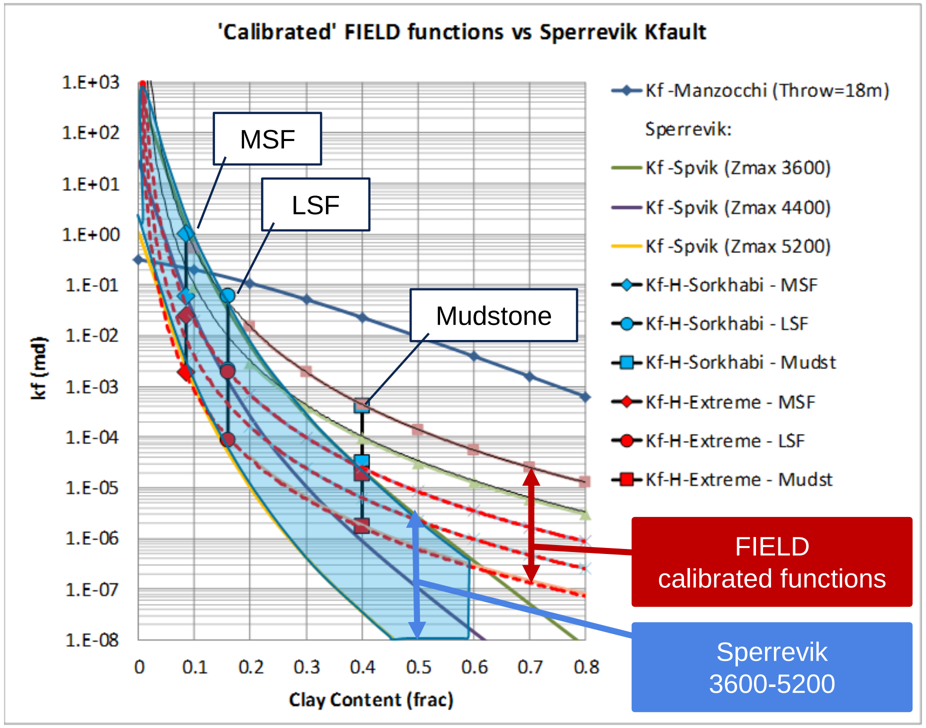
Sorkhabi et al (2005)

G. Ballas et al (2015)

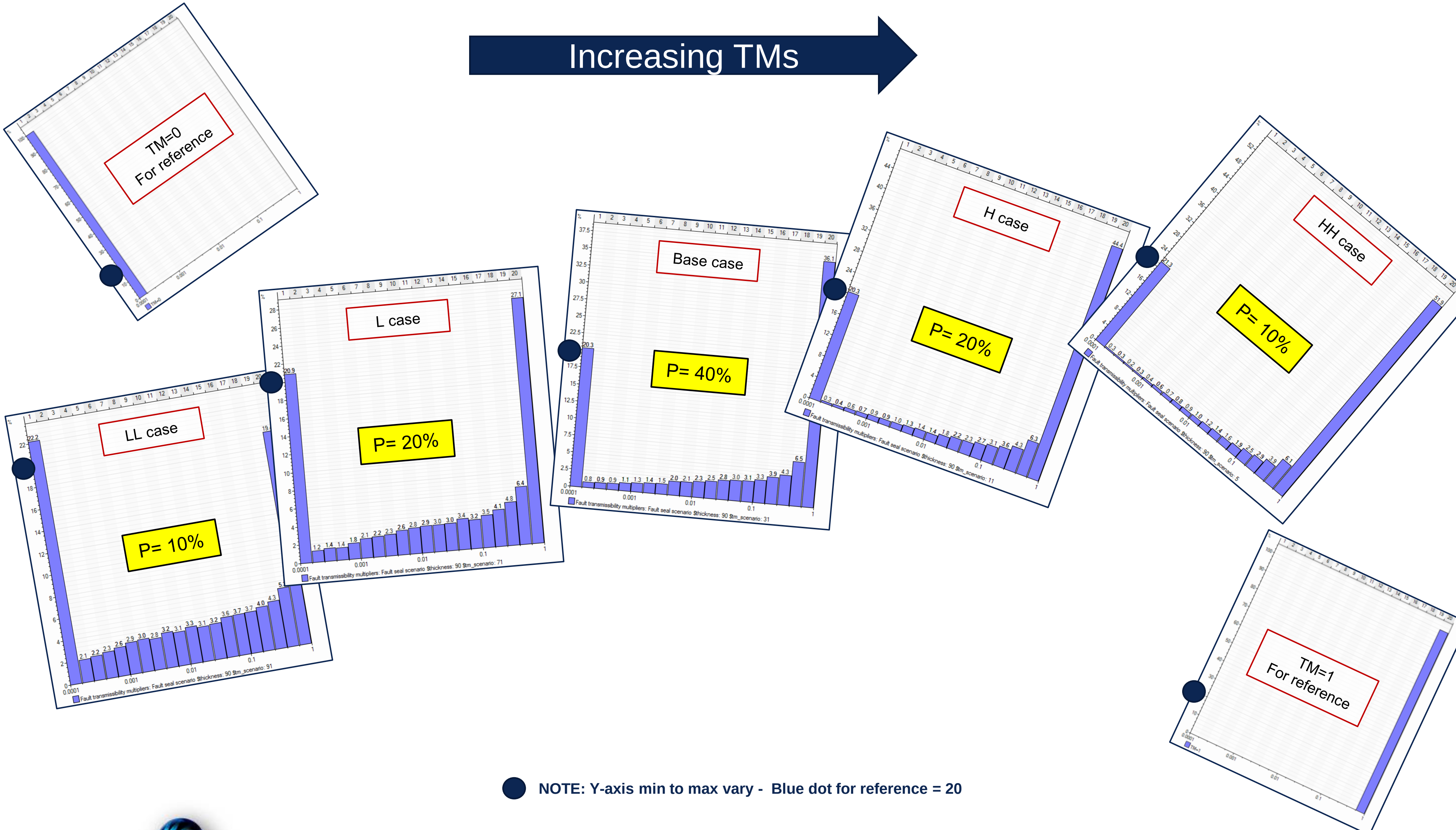


Transmissibility multipliers
Defining the uncertainty range

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



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



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

IMPLEMENTATION

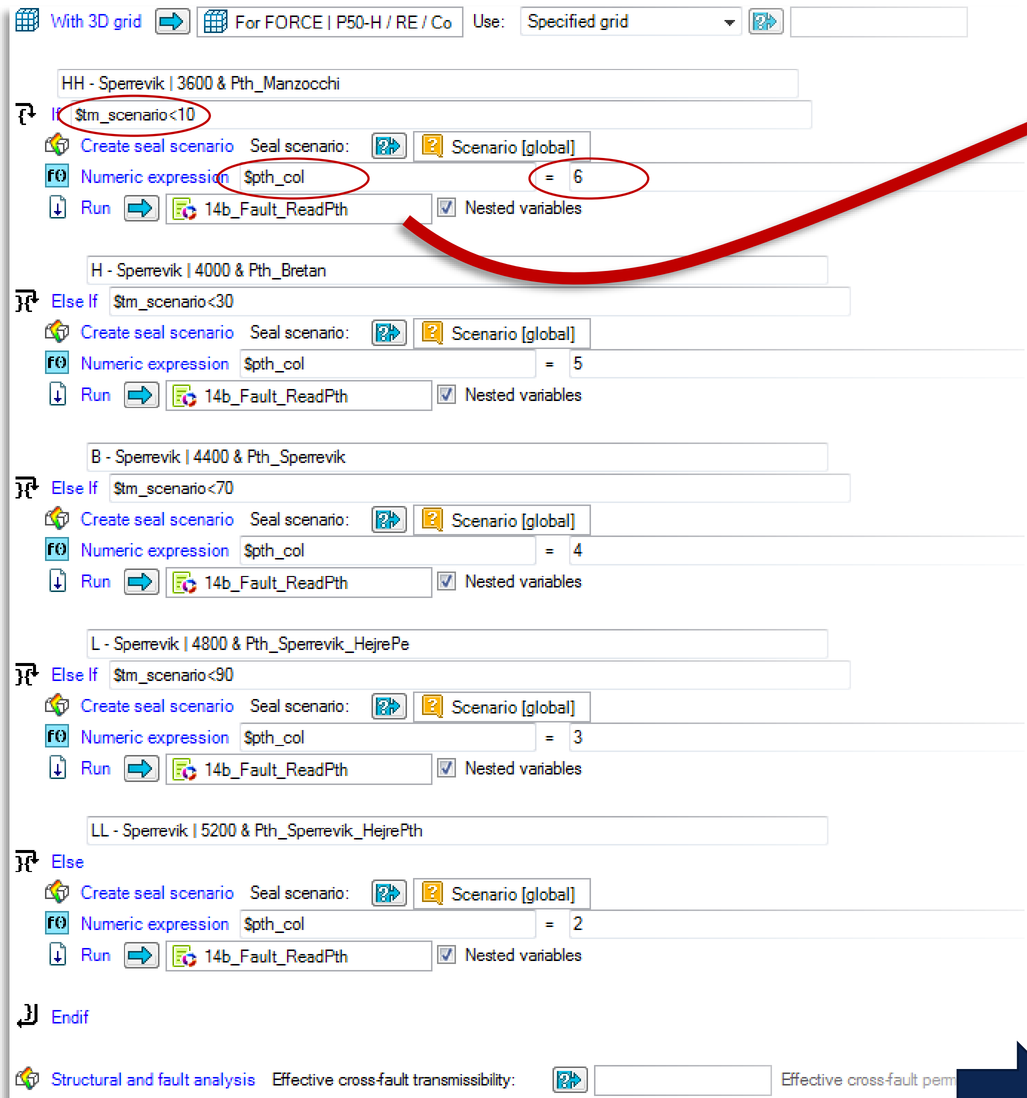
Petrel

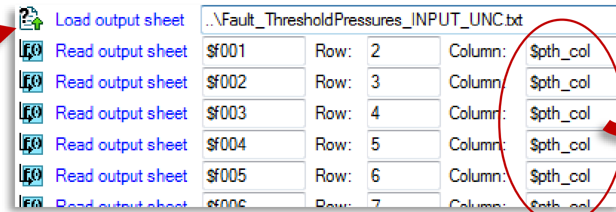
FAULT scenarios
Summary

- 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





	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

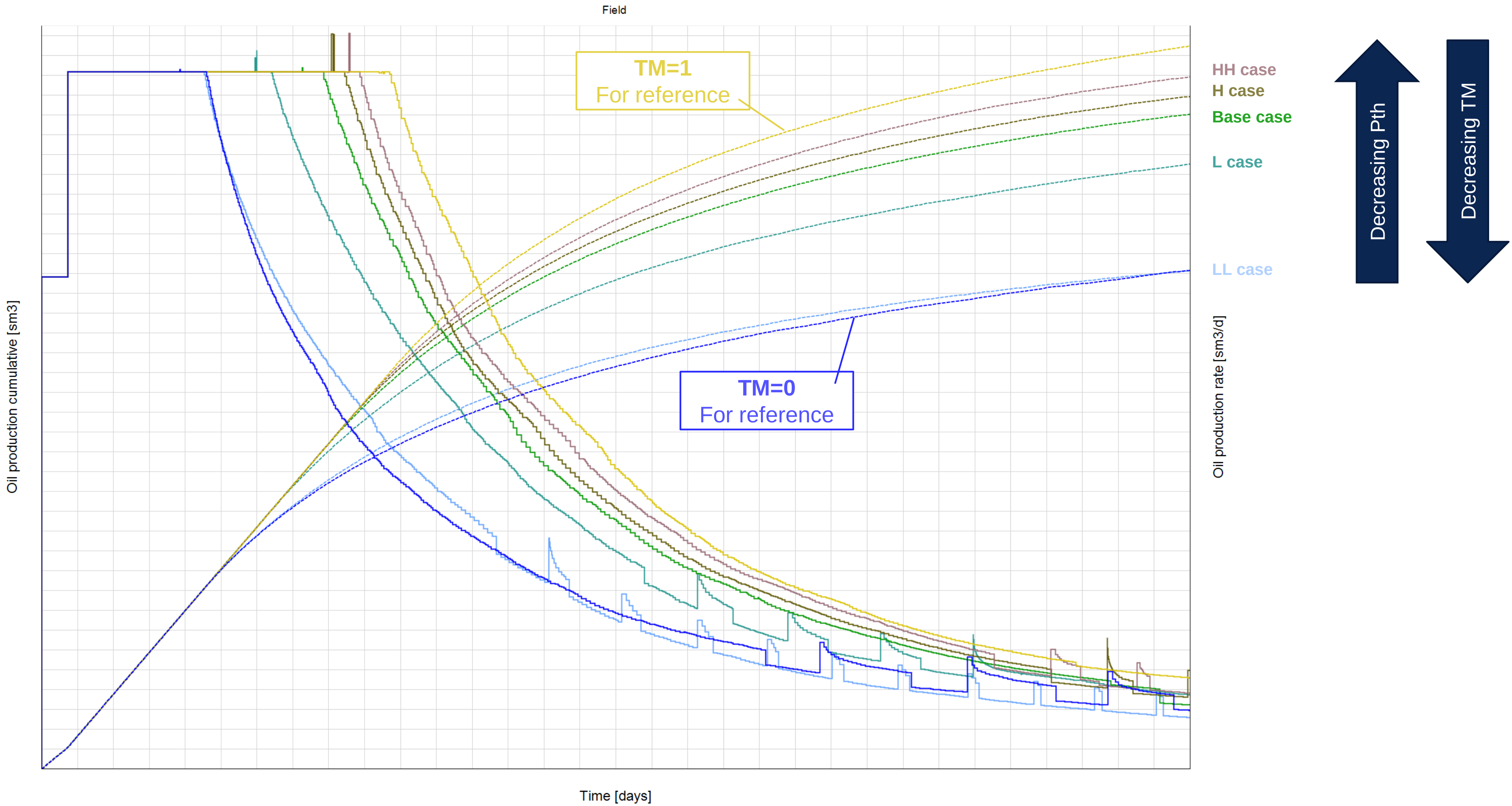
* The tabulated Pth needs to be multiplied by 100000 due to a bug in Petrel

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

RESULT

Production profiles | Depletion through time

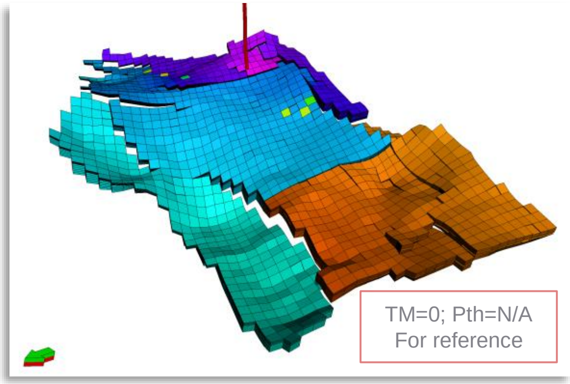
Result
Production profiles [FIELD] | One realization (P50)

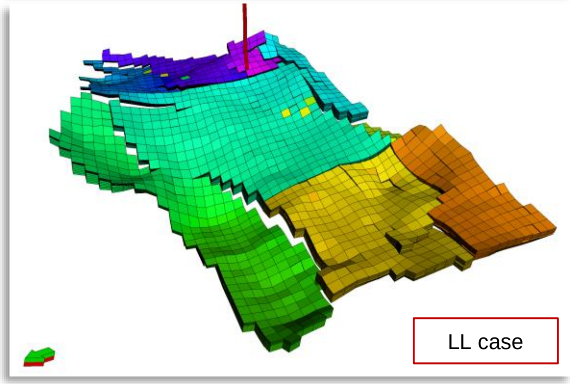


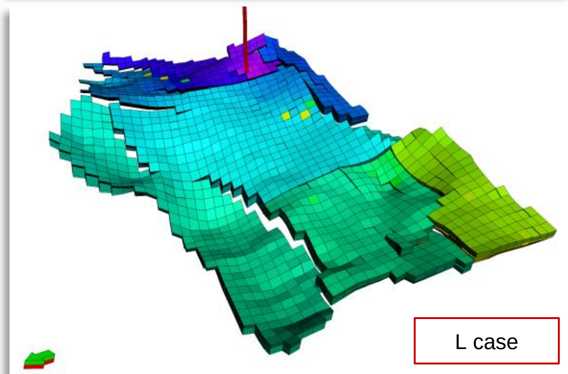
Result
Pressure @ Field End | One realization (P50)

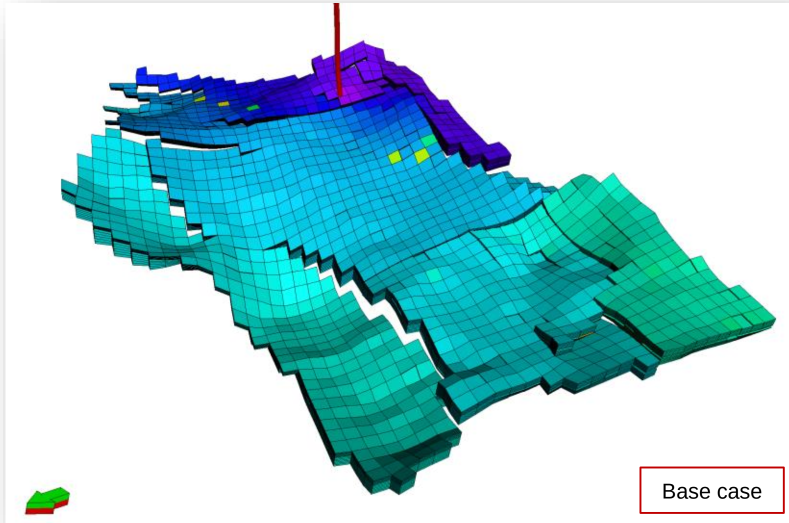
Initial pressure

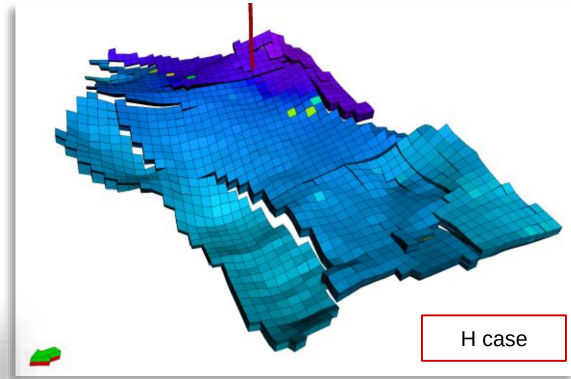
Fully depleted

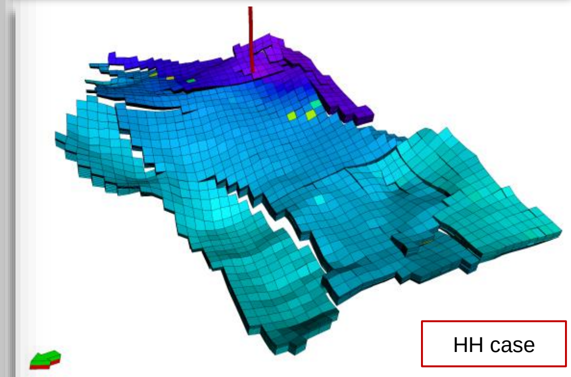


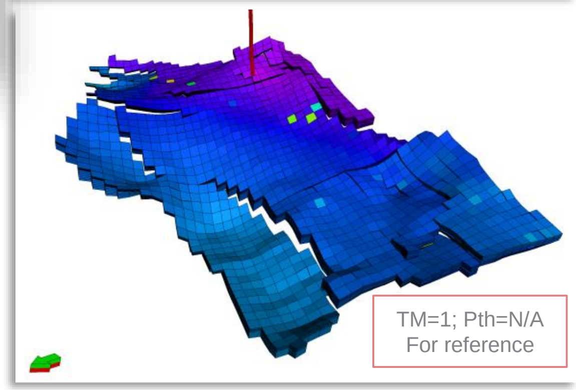












Conclusions

- 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

- Bayerngas Norge would like to thank:
  - DONG E&P for allowing us to present this topic.
  - Russell Davis, Schlumberger, for discussions.
  - Susanne Sperrevik, MVEST Energy, for discussions.
  - …and YOU for listening!