

Permeability in the Eye of the Beholder



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Lecture Tour 2009

Contents

- Definitions
- Fundamentals
- Measurements
- Estimation
- Reconciliation

Definitions

COMPLEXITY

Single phase Gas
'Ambient' (k_{air})

Single Phase Gas
Overburden/Reservoir Pressure(k_{inf})

Reservoir Fluids
 k_{eff}/k_{rel}

Thin Section

Probe

Core Plug

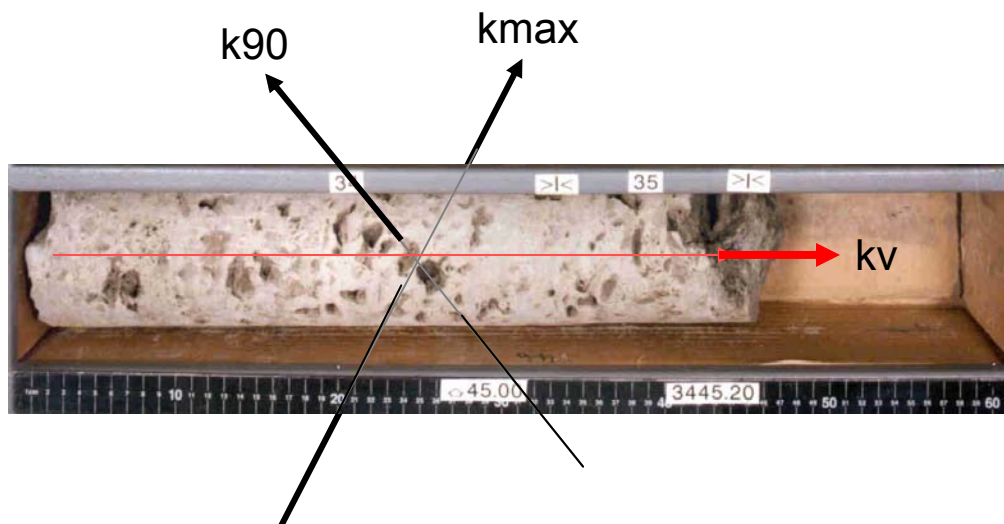
Whole Core
WFT

Well Test

EWT

SCALE

Directional Properties

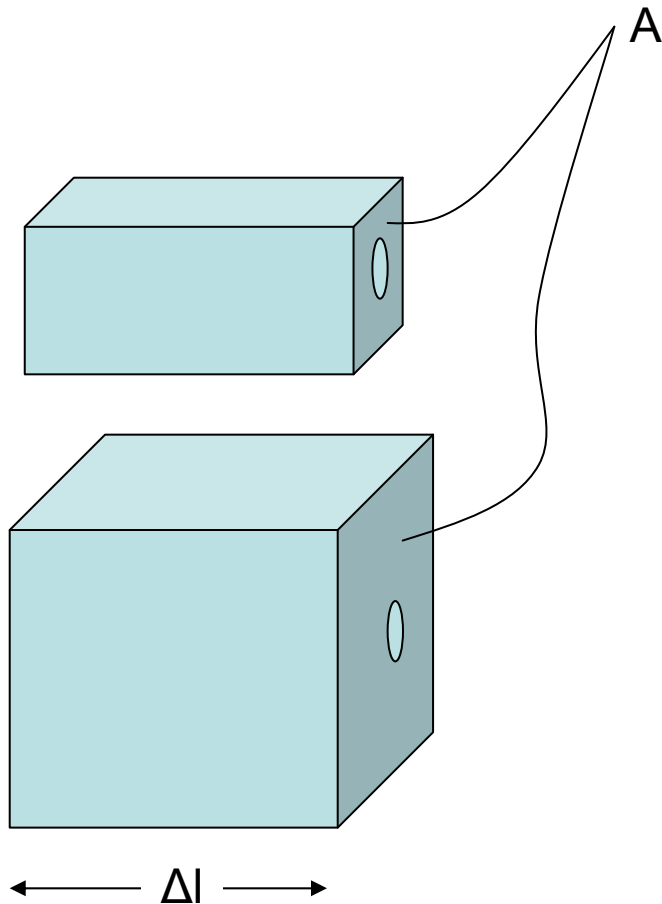


Characteristics

- Permeability
 - Dimensions L^2
 - 10^{-14} to 10^{+7} mD
 - Tensor (Anisotropic)
 - Resistivity, acoustic properties
 - Dominated by largest pores
- Porosity
 - Dimensionless
 - 0 to 0.5
 - Scalar (Isotropic)
 - density, neutron capture
 - All pores contribute equally

$$1 \text{ D} = 0.99 \text{ } \mu\text{m}^2$$

Permeability and Fluid Flow



$$Q = \frac{\Delta p \cdot a^4}{8 \Delta l \cdot \mu}$$

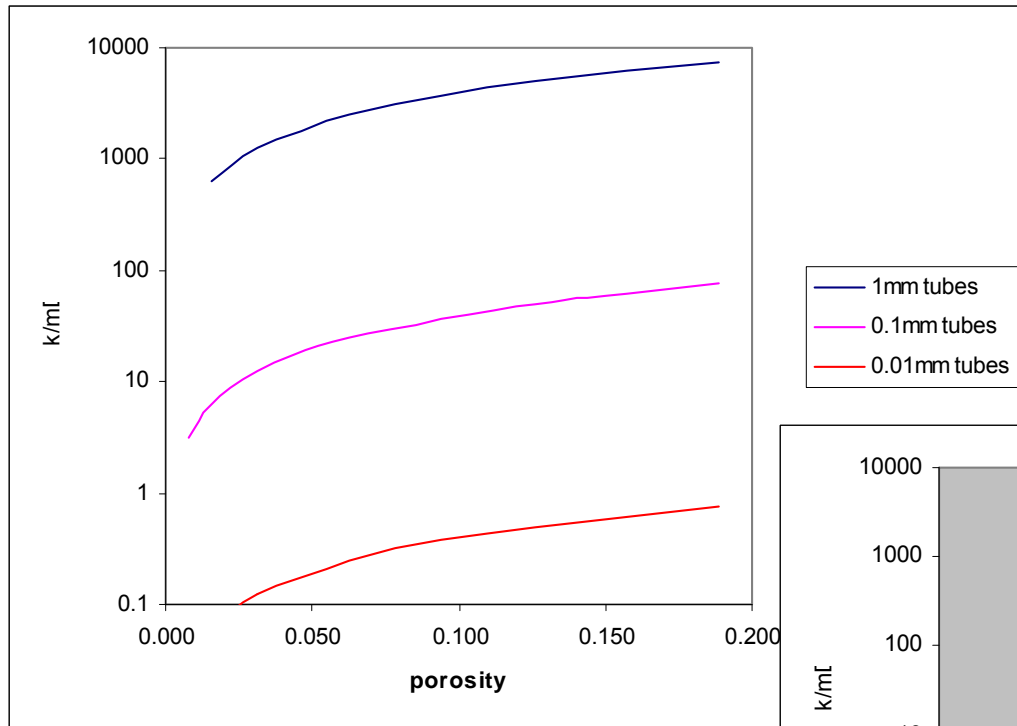
$$= \frac{k A \Delta p}{\Delta l \cdot \mu}$$

So...

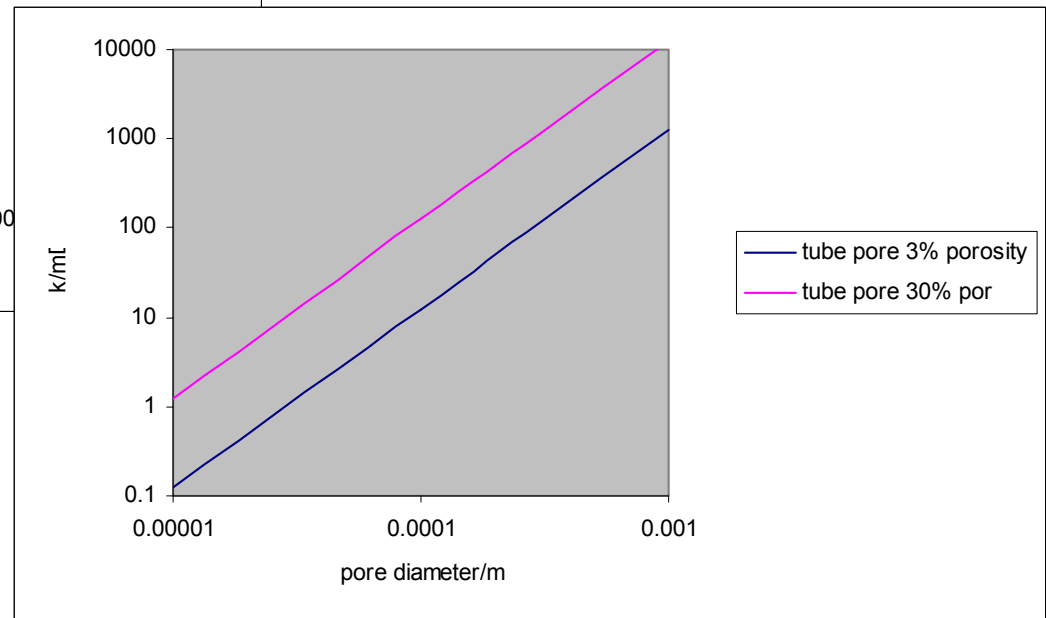
$$k = \frac{a^4}{8A}$$

Porosity-Permeability (Capillary Bundles)

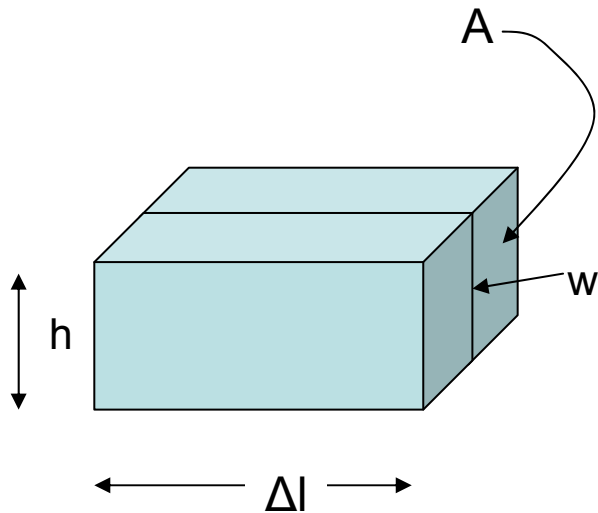
Permeability-Porosity



Permeability-Pore Size



Fracture Permeability



$$Q = \frac{\Delta p \cdot h \cdot w^3}{12 \Delta l \cdot \mu} \quad \text{Flow through a slot}$$

$$= \frac{k A \Delta p}{\Delta l \cdot \mu} \quad \text{permeability equation}$$

$$k = \frac{h \cdot w^3}{12 A}$$

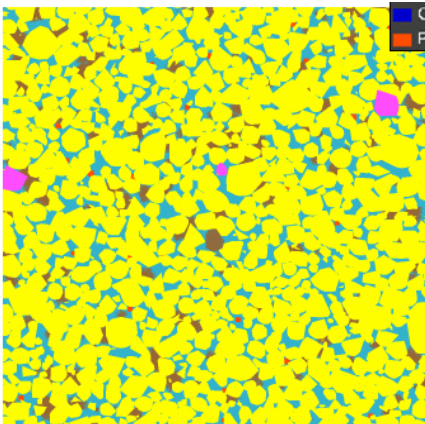
$$k_{if} = \frac{w^2}{12}$$

Intrinsic permeability of a fracture

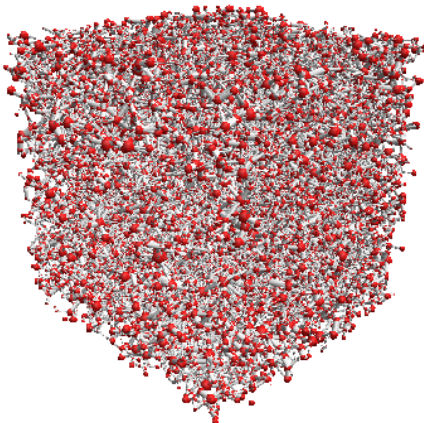


Permeability Controls in Real Rocks

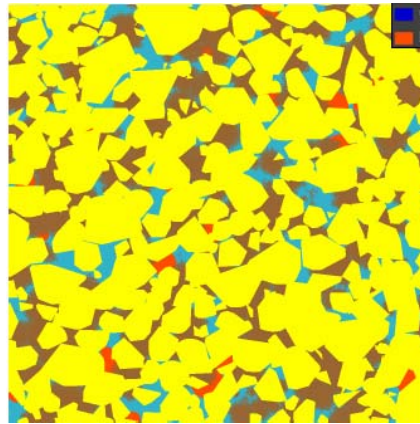
Field A



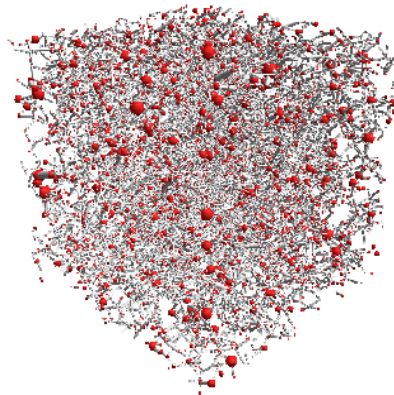
Porosity = 0.18
Kh = 470mD



Field B



Porosity = 0.16
Kh = 2 mD



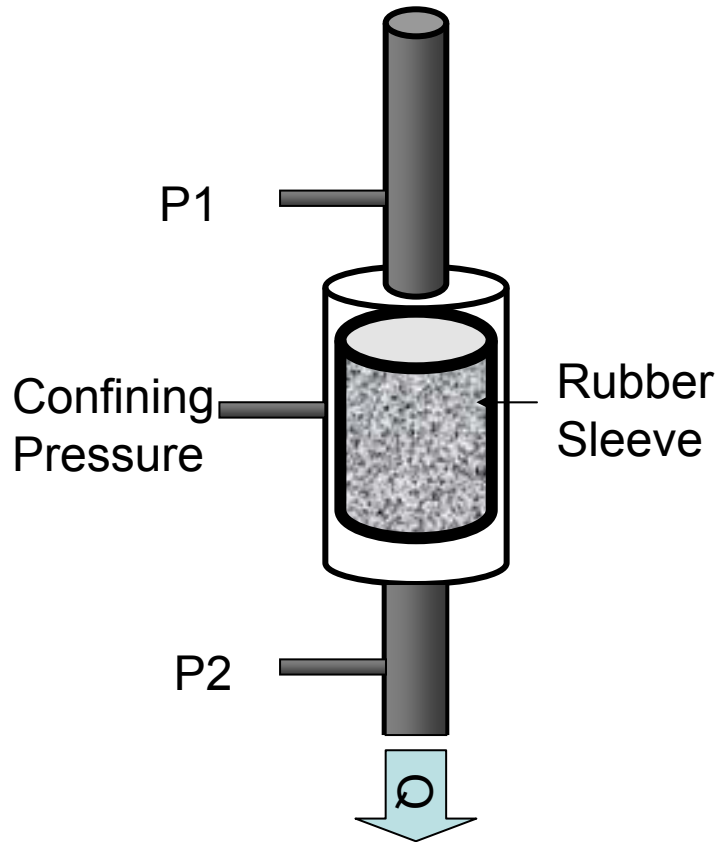
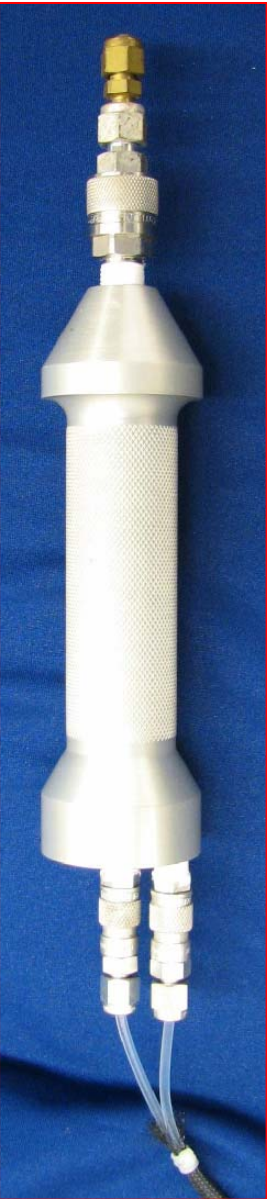
Realisations of SEM Images from the Plover sands in the Browse Basin. (2mmx2mm). Although coarser grained, the B sand has fewer paths that are more tortuous.

Pore network models constructed from the SEM images

Measurement

- Fluid has to move...
 - Laboratory
 - Test (including WFT)
- Uncertainty and Errors.
 - Measurement.
 - Geological.
- Scale.
 - Probe $<1\text{cm}$
 - Plug 5cm
 - Whole Core $10 - 20\text{cm}$
 - WFT
 - DST 10^5 cm
 - EWT 10^6 cm

Laboratory



$$Q = \frac{k.L.\Delta P}{A.\eta}$$

η is viscosity of the fluid used for the measurement

Uncertainty Issues

Simple Geometry

A, L – high accuracy

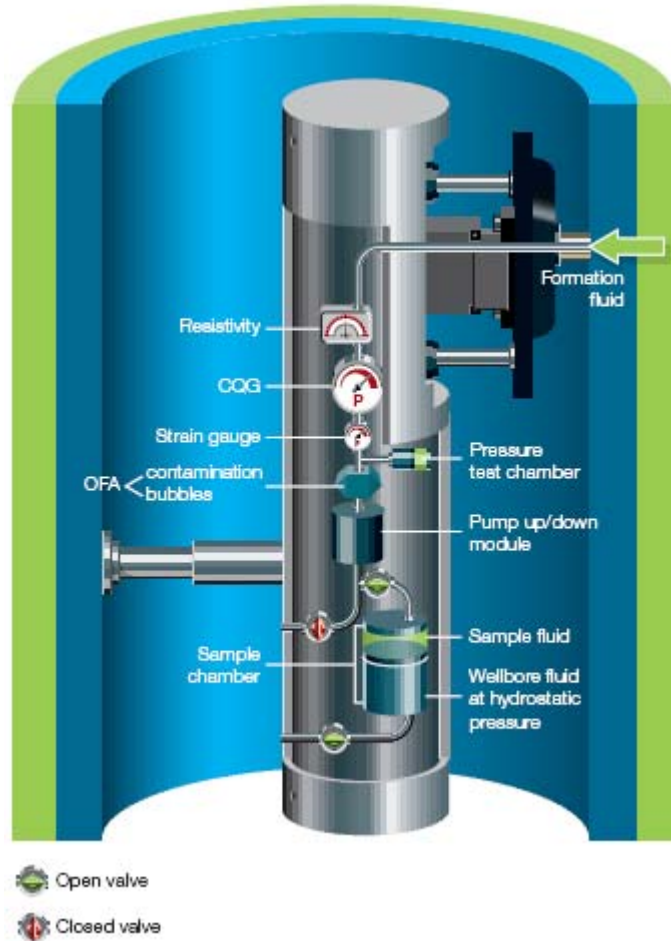
η – known for simple fluids

Q – cc/min can be difficult to measure

P – high accuracy but normally low.

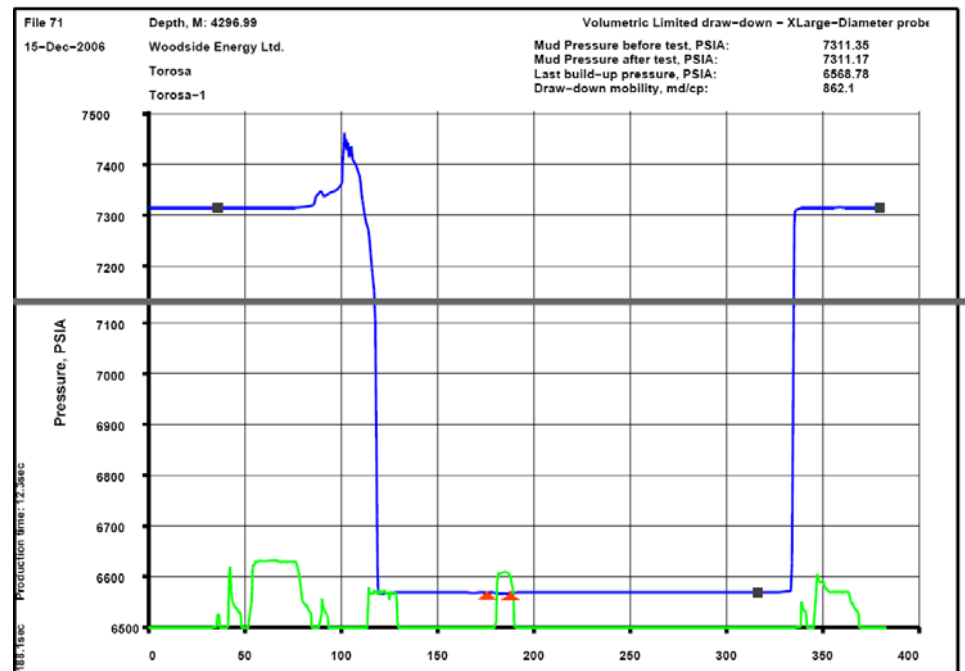
Wireline Formation Testers.

The tools are primarily designed to measure formation pressure.
Permeability is actually mobility (permeability/viscosity)



Typical flow-rate 5-50cm³/min.

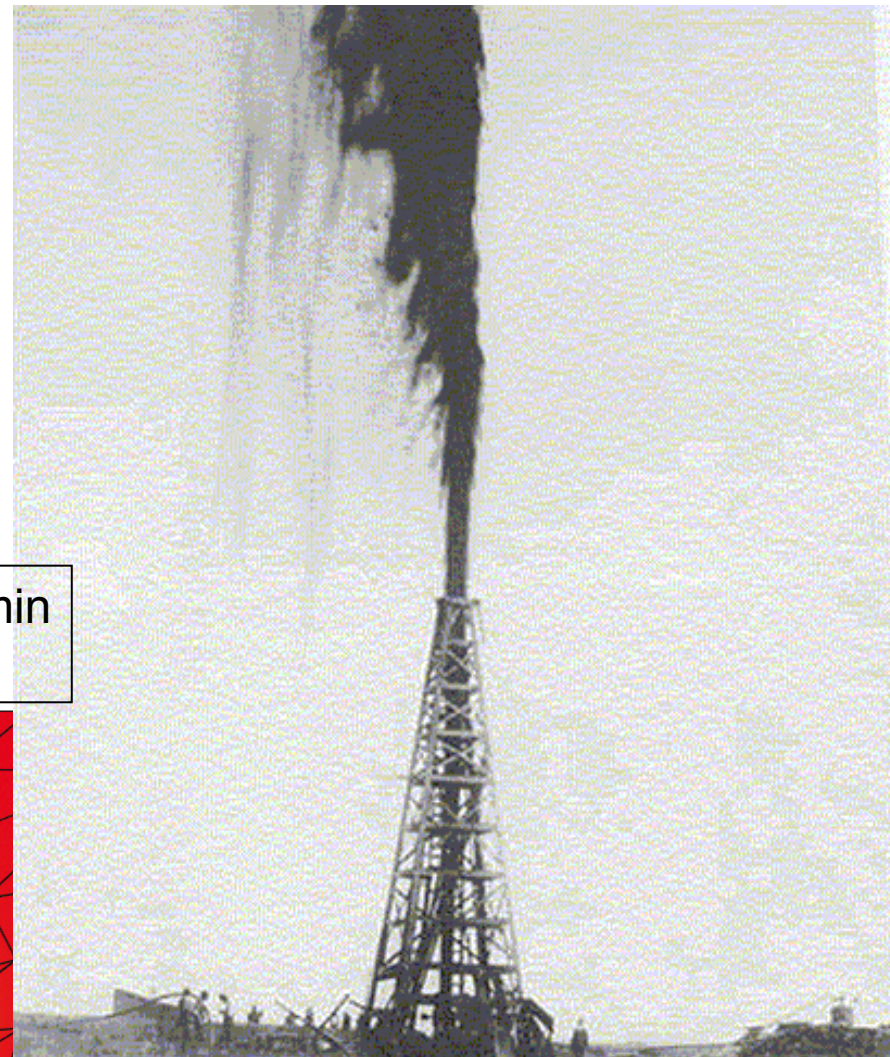
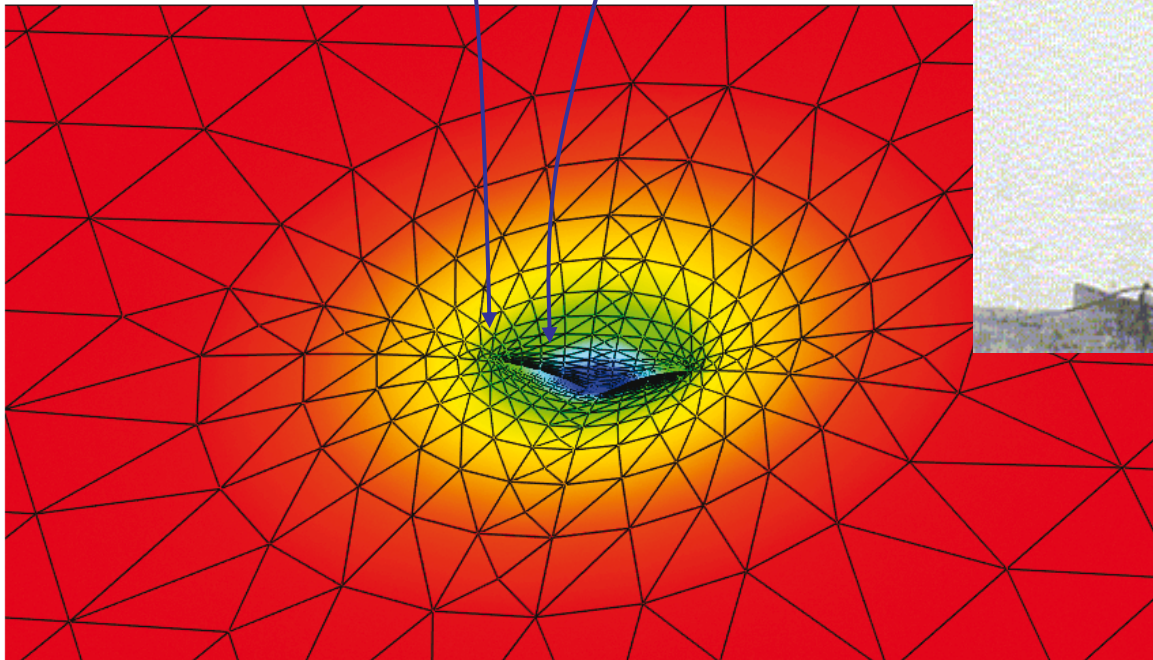
0.05 – 0.5 BOPD (100 – 1000scf/d).
(through a single 1cm diameter hole)



Drill Stem Test

10 Cm³/min
2-3 m in)

500 cm³/min
(at well)



Uncertainty Issues

Unknown Geometry

A, L – low accuracy

η – un-reliable and variable

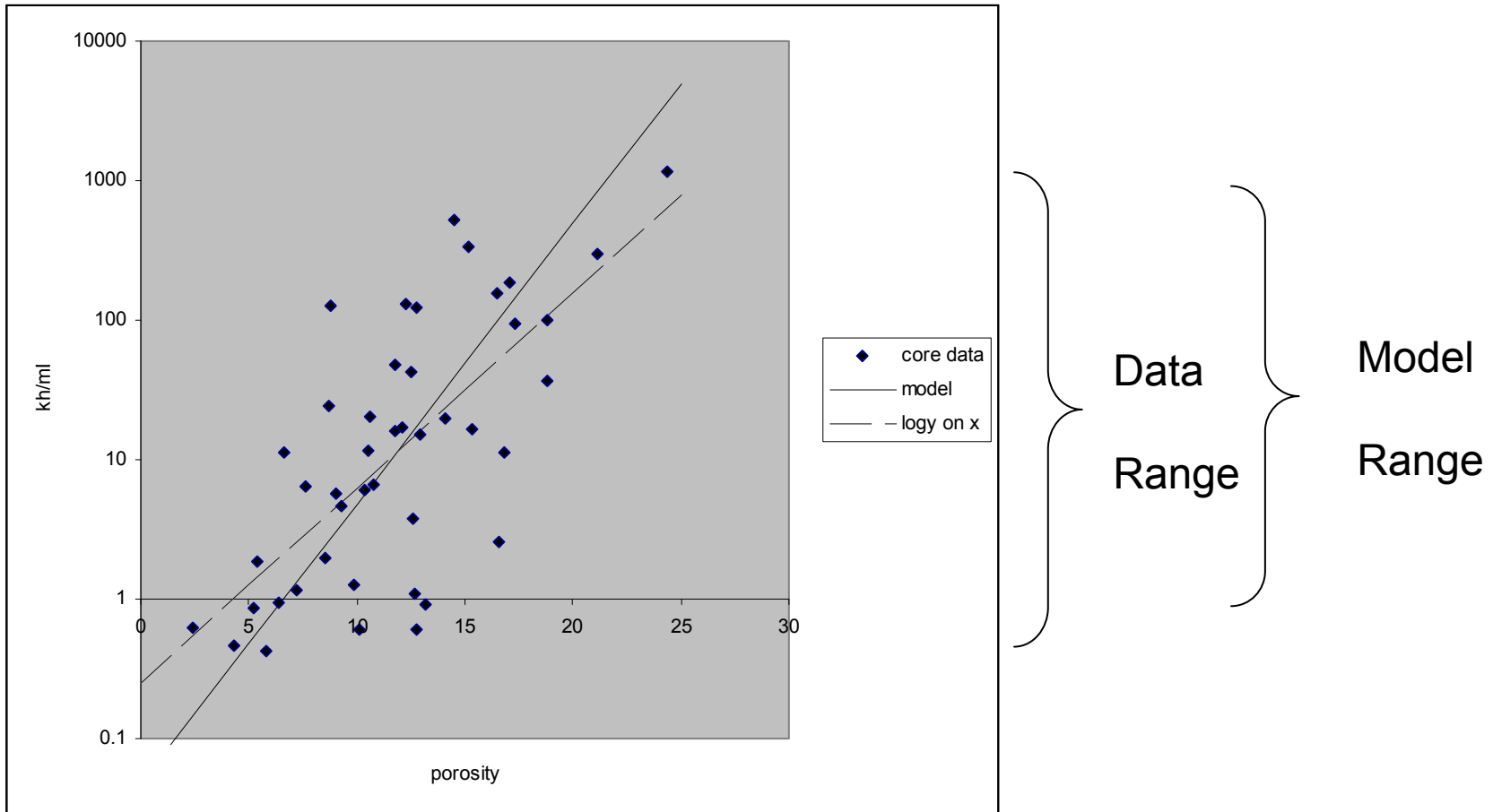
Q – ca 1000cc/min (at well)

P – high accuracy/precision.

Estimation Methods

- LOG BASED
 - Empirical Correlation.
 - Field Specific (probably based on core)
 - $K = k(\phi, S_{wir})$
- CUTTINGS BASED
 - Image Analysis of Pore System.
 - Rock Typing.
 - Model the Pore System.

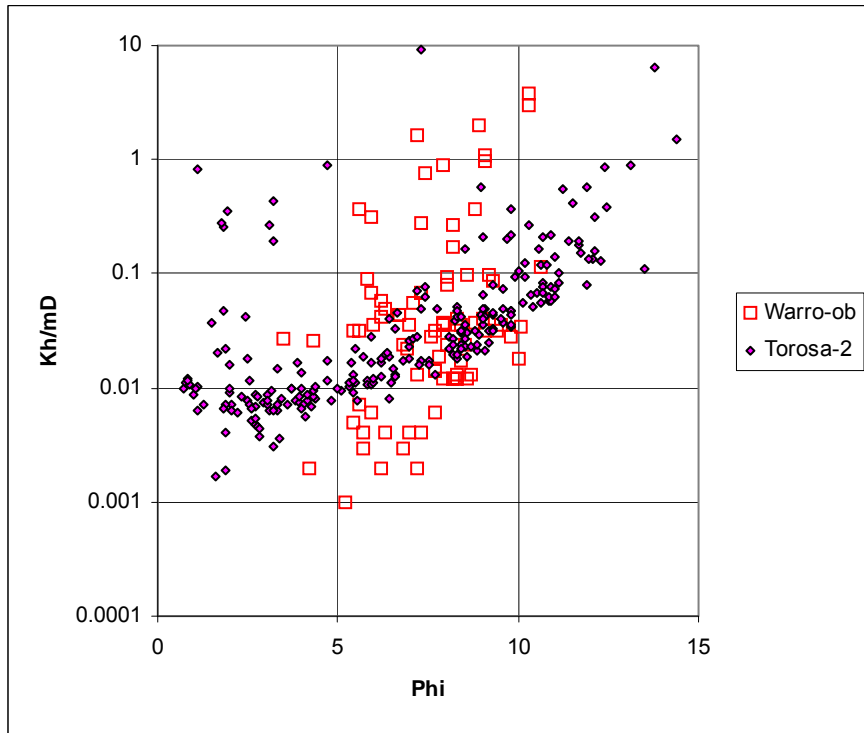
Estimation: the pitfalls



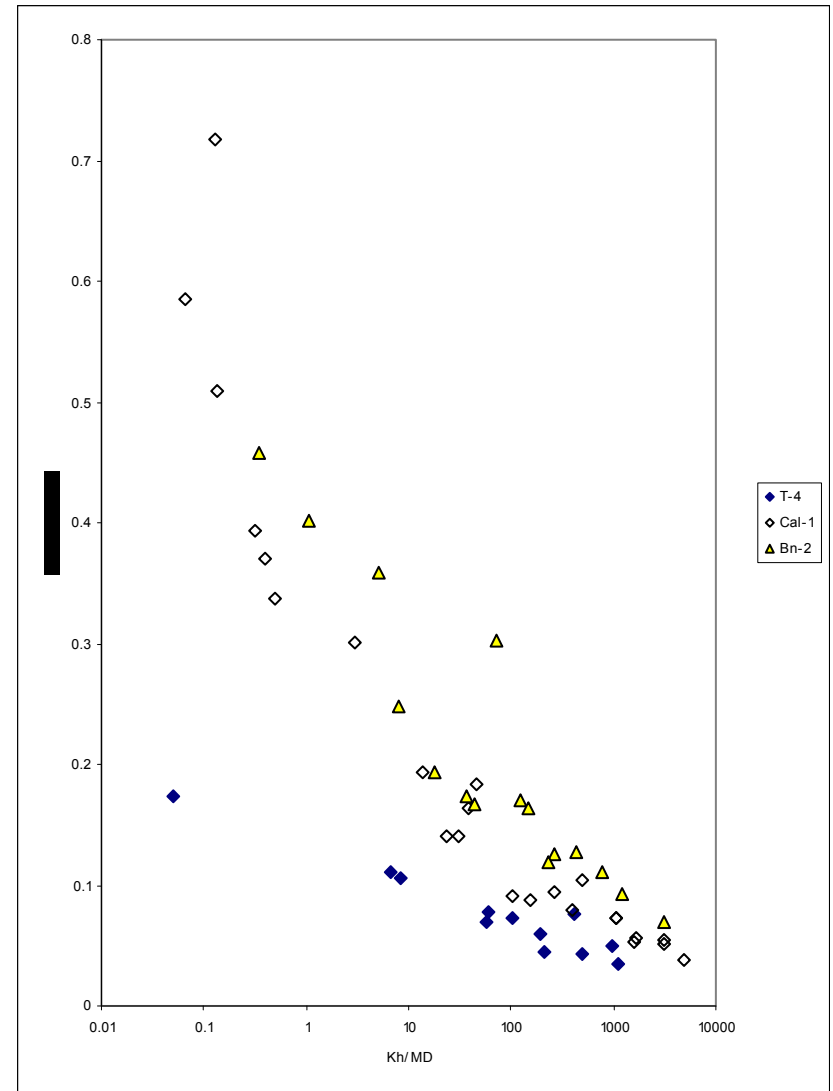
Available core data is used to generate a porosity-permeability transform.
This is applied to log porosity in un-cored intervals.

IT WILL NOT REPRODUCE THE FULL VARIABILITY

Relationships between Properties.

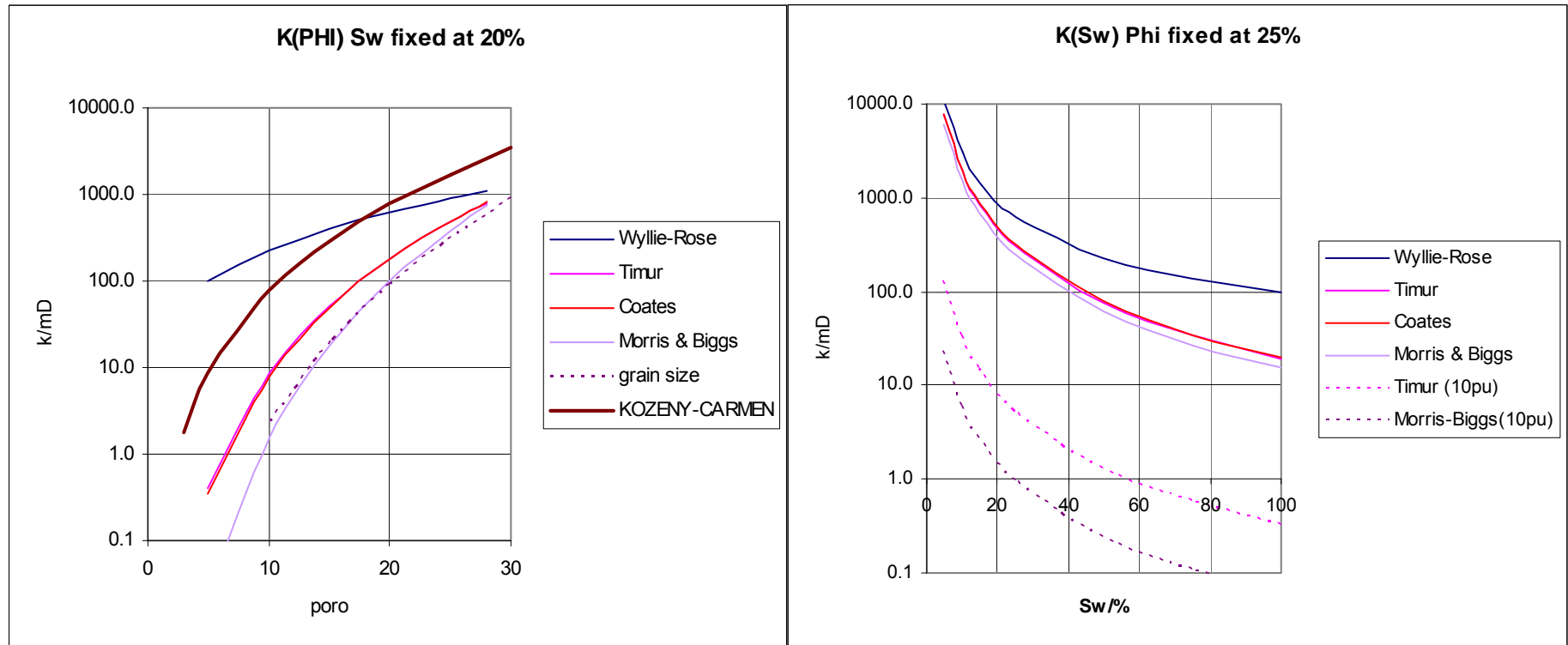


Porosity and Permeability



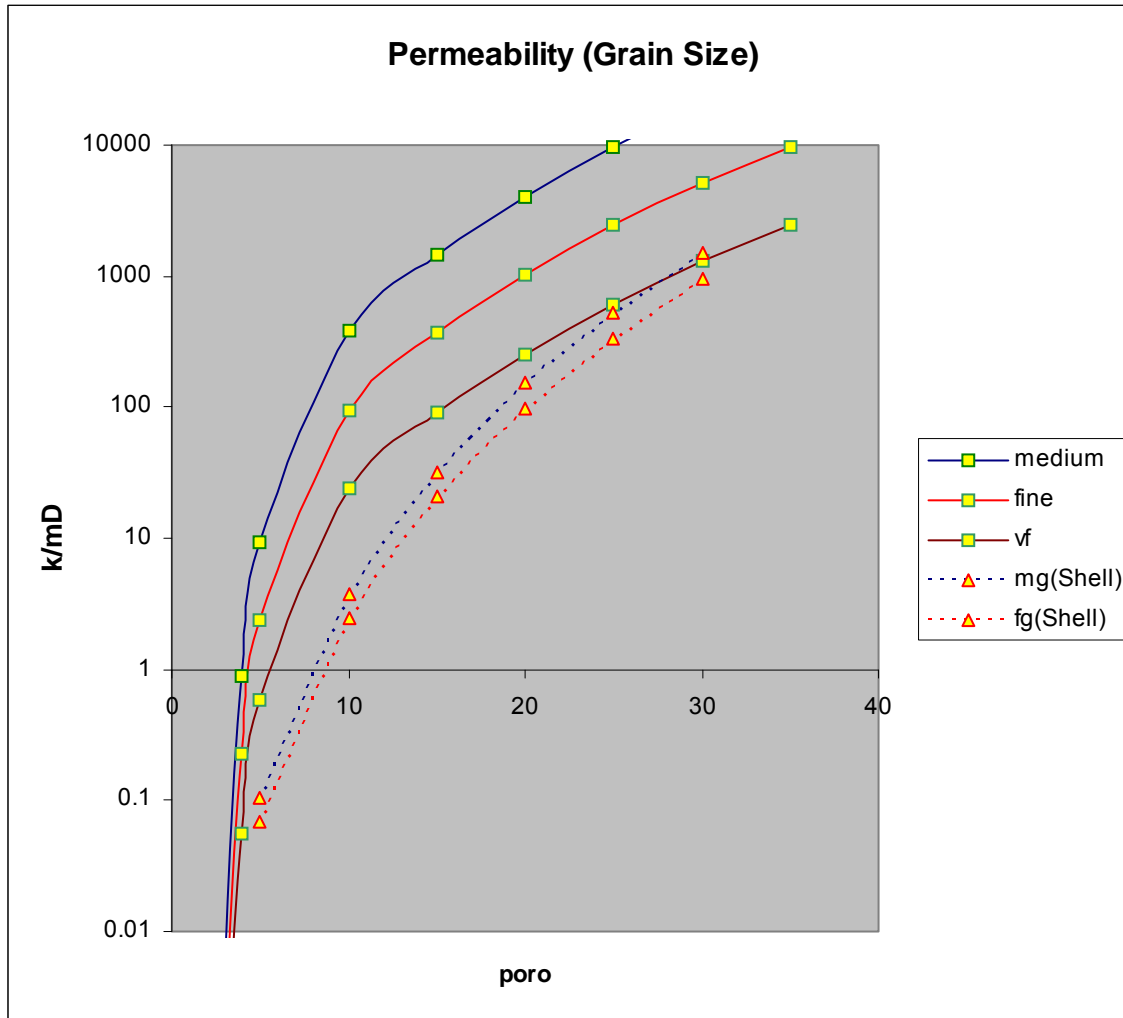
Saturation and Permeability

Published Porosity, Swir - Permeability Relationships (Used to produce the NMR log Permeability)



Often quite robust but they can only be used above the Transition Zone
(unless you have an NMR log).

Grain Size Relations



The Shell models were developed in the GOM so buyer beware.

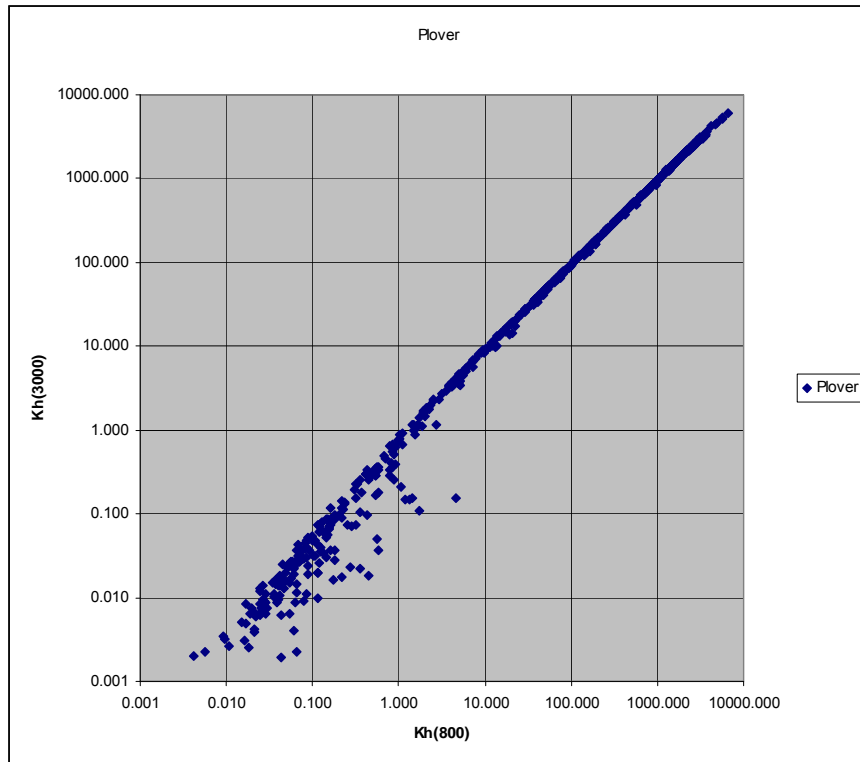
The BP/ARCO models are more general but do need a good knowledge of grain size, sorting, cementation/consolidation.

Interpretation

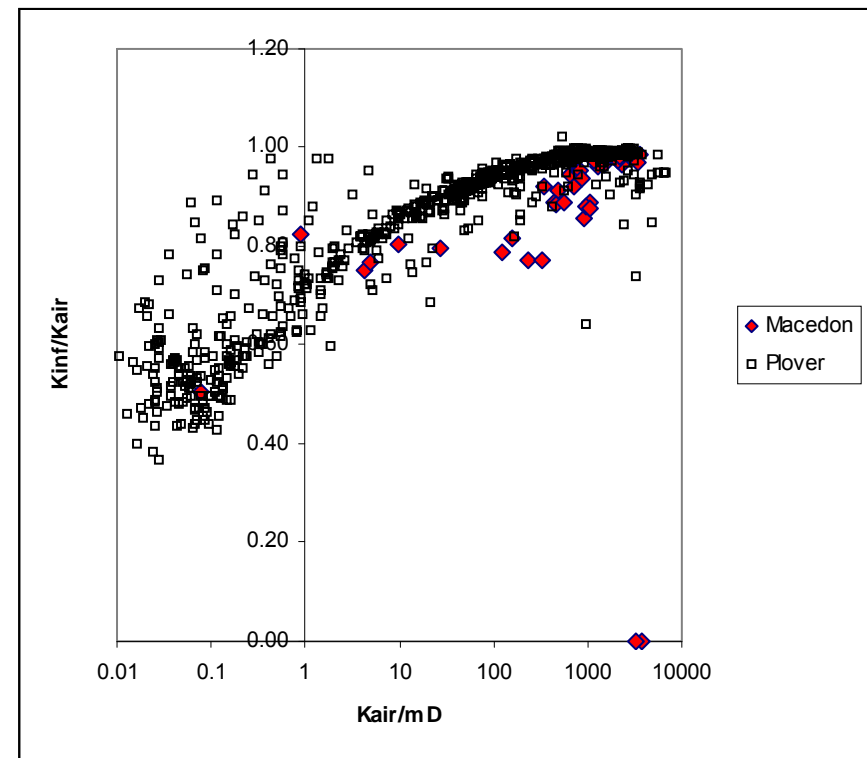
- Why don't my Test Perms match the Core?
- What?
 - Scale (plug, log, layer)
 - Ambient/overburden.
 - Effective/Absolute
 - Air/Brine
- Why?
 - Net/Pay definition.
 - Well In-flow prediction.
 - Reservoir Modeling.
 - Fluid Distribution Modelling.

What Permeability?

Rock: Overburden Correction



Fluid: Klinkenberg Correction



**These corrections are normally important for low permeabilities (<1mD).
For High Permeabilities we are getting into Hair Splitting Territory (>100mD).**

Up-scaling and Averaging

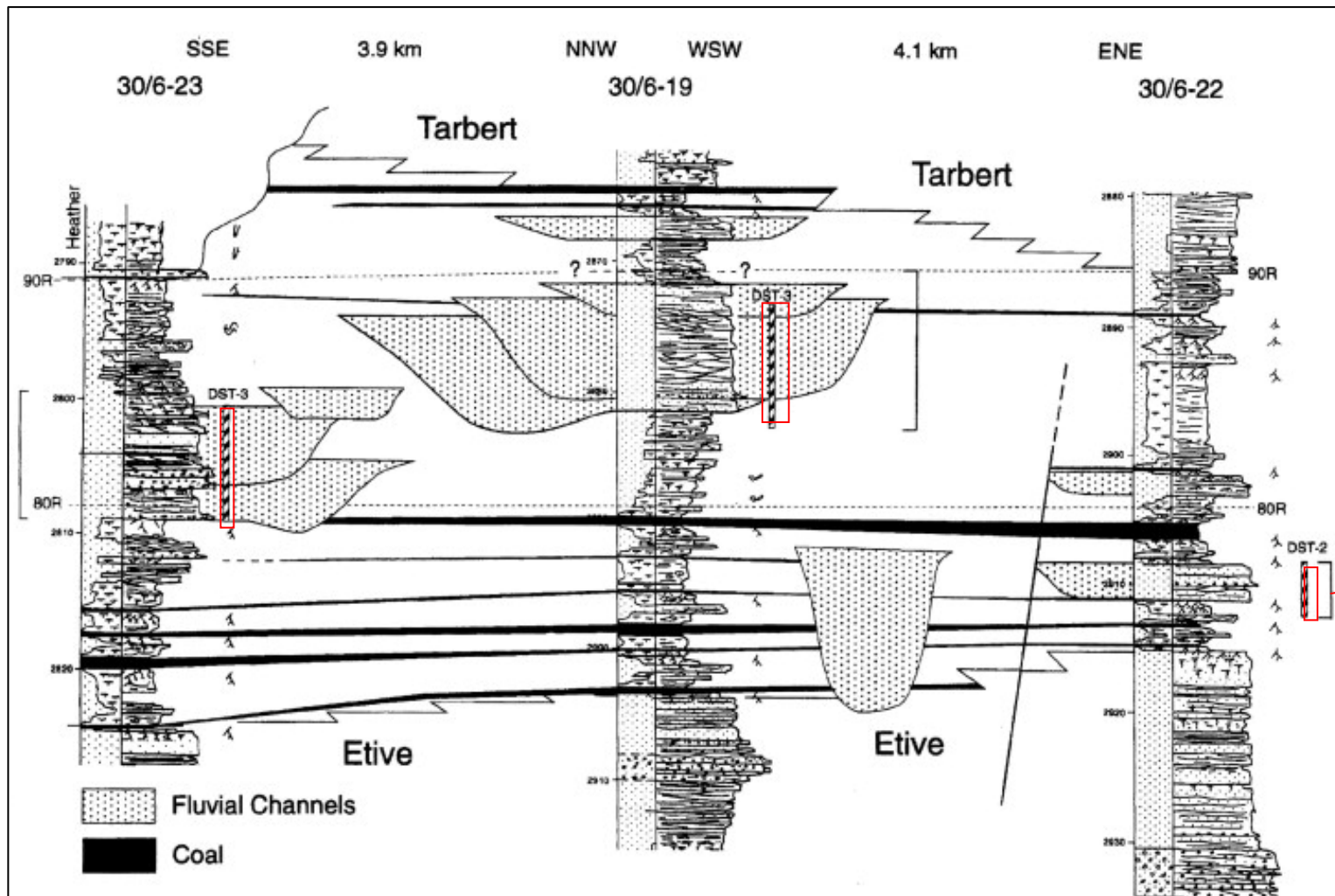


..and Moving Away from the Borehole

Heterogeneity and Anisotropy

- Scale Dependence – aka “My Perms don’t match!” –
 - May be due to measurement error(s) or...
 - May indicate heterogeneity.
- Heterogeneity can be quantified using some old –unfashionable– methods..
 - C_v
 - Lorenz Coefficient
 - Dykstra-Parsons
- It Determines how the Core Data Should be Averaged.

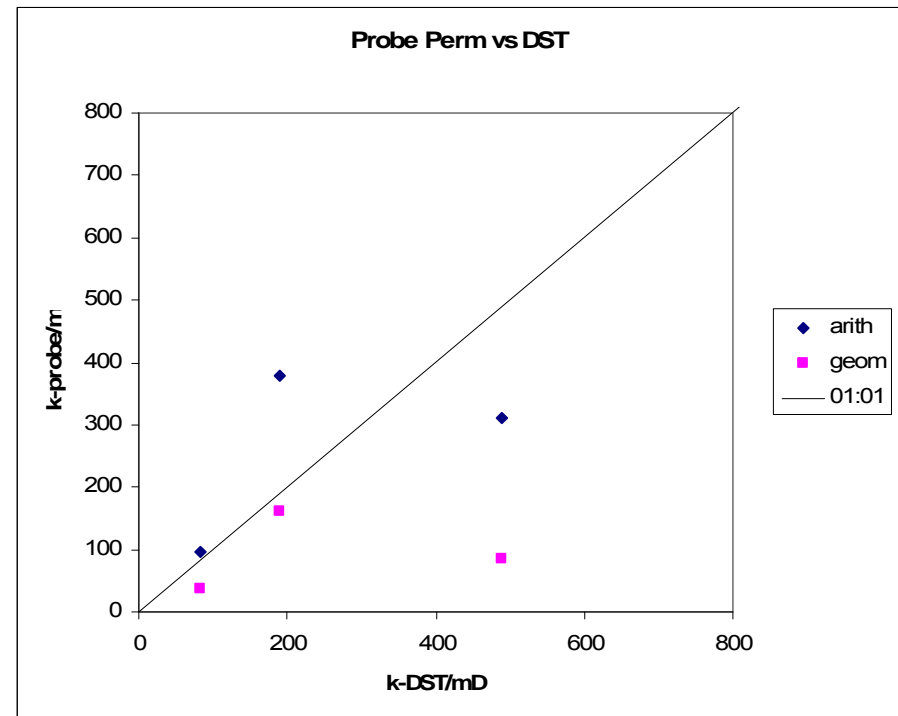
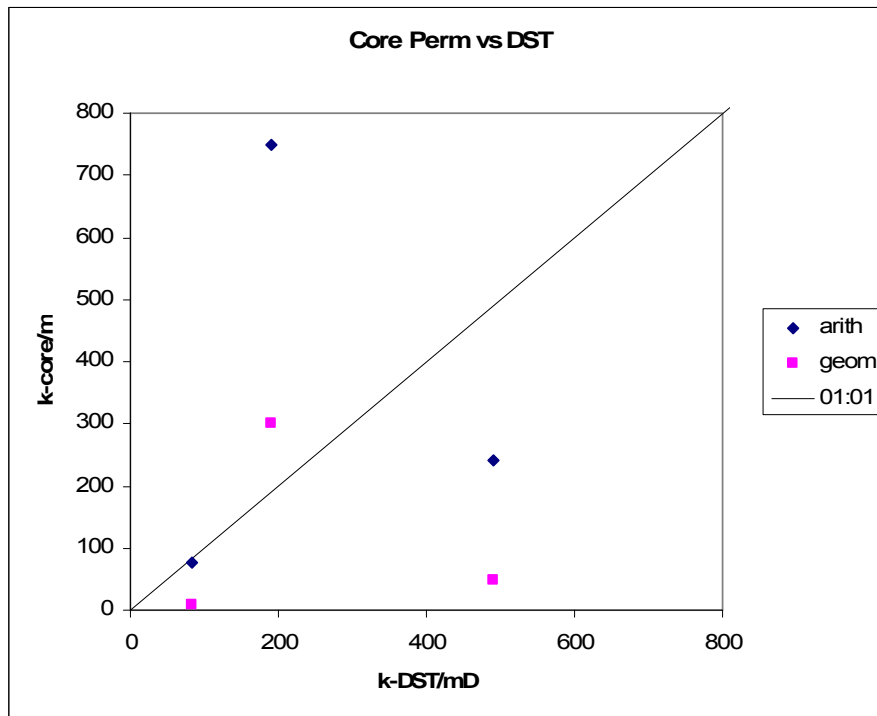
Matching Core to DST Results (Choice of Average)



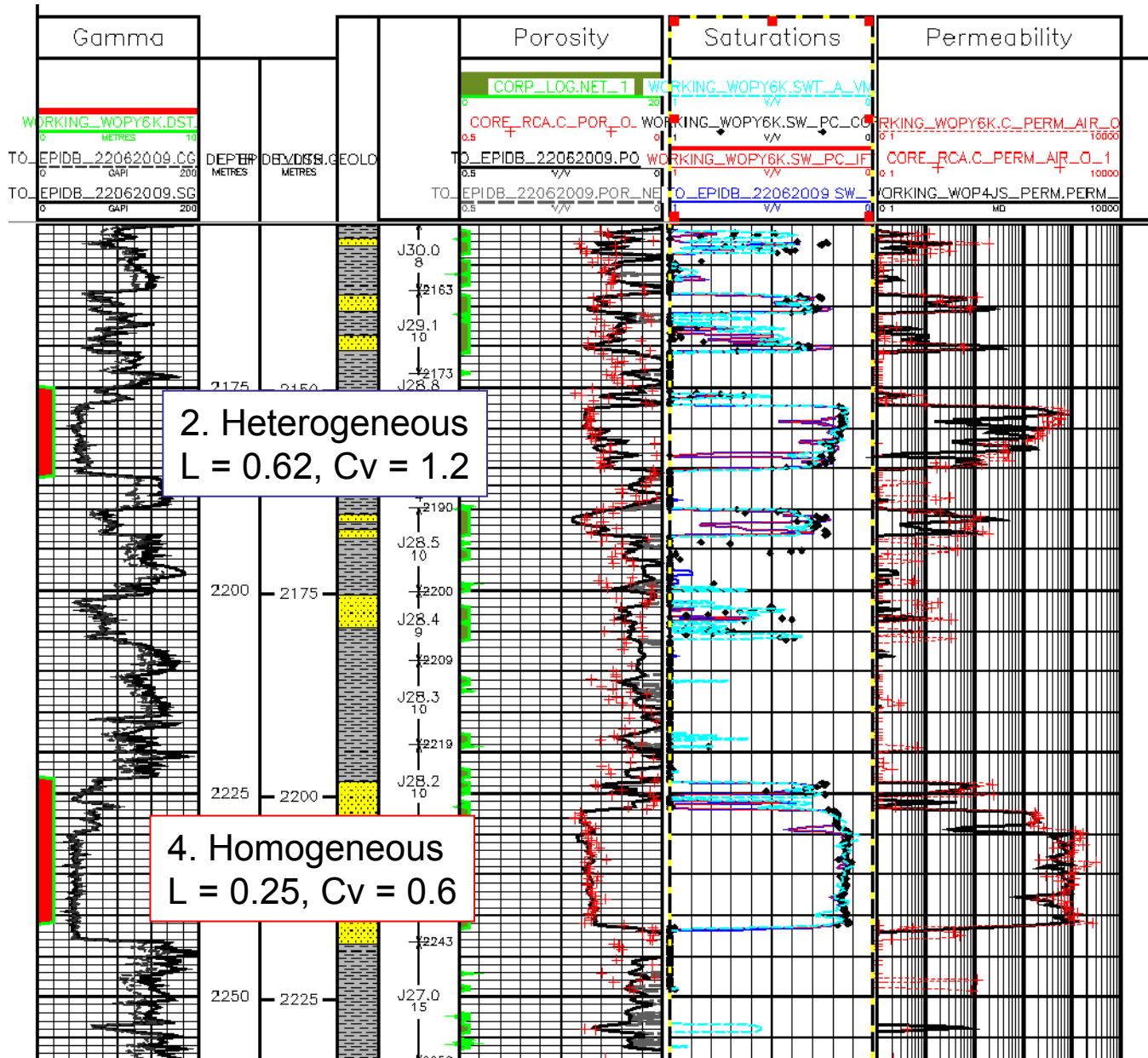
WELL	DST			Core		Cv		Probe		Cv
	H/m	K/mD		arith	geom			arith	geom	
19	8	83		77	8.4	3.2		96	38	1.2
22	3.5	190		750	300	1		380	160	0.9
23	9	490		240	49	1.8		310	85	1.3

Matching Core to DST Results (Sampling)

WELL	DST			Core		plugs	Cv		Probe		samples	Cv
	H/m	K/mD		K /mD					K /mD			
19	8	83		arith 77	geom 8.4	28	3.2		arith 96	geom 38	180	1.2
22	3.5	190		750	300	11	1		380	160	39	0.9
23	9	490		240	49	31	1.8		310	85	150	1.3



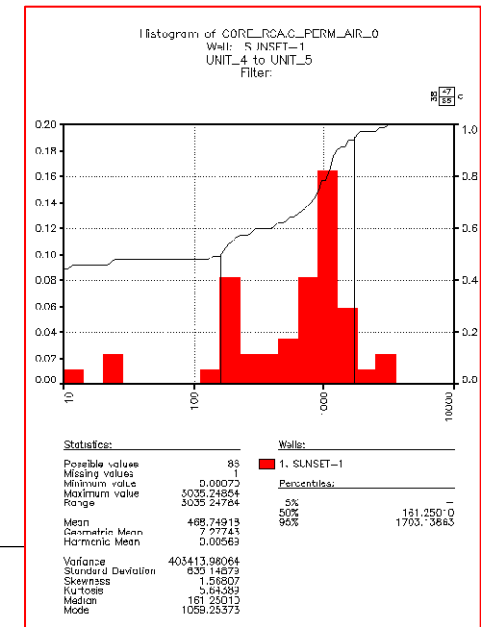
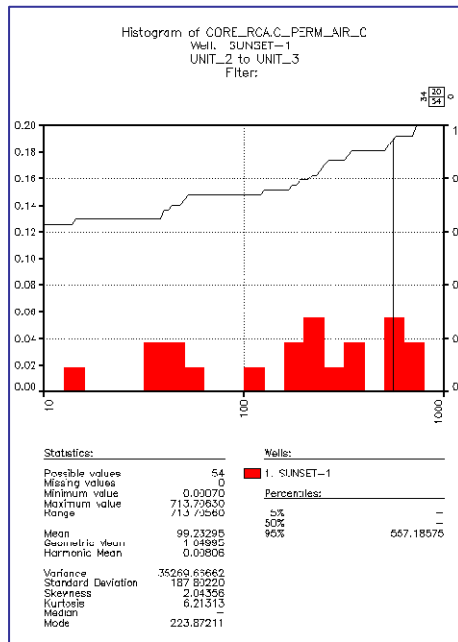
Matching Test and Core: Indications of Heterogeneity



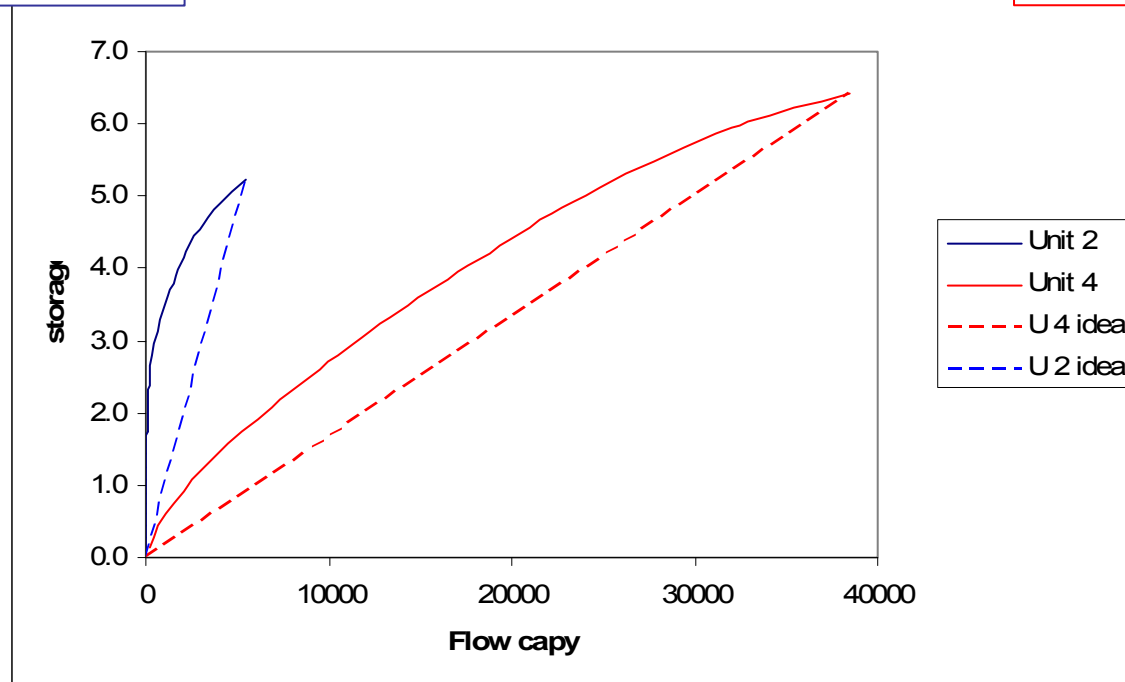
Core Arith: 200mD
Core Geom: 50mD
TEST: 60mD

Core Arith: 1000mD
Core Geom: 700mD
TEST: 1100mD

Heterogeniety Measures



Lorenz Plot



An Example: Dolomite Oil Field

Large Oil Field
Producing Below Bubble Point

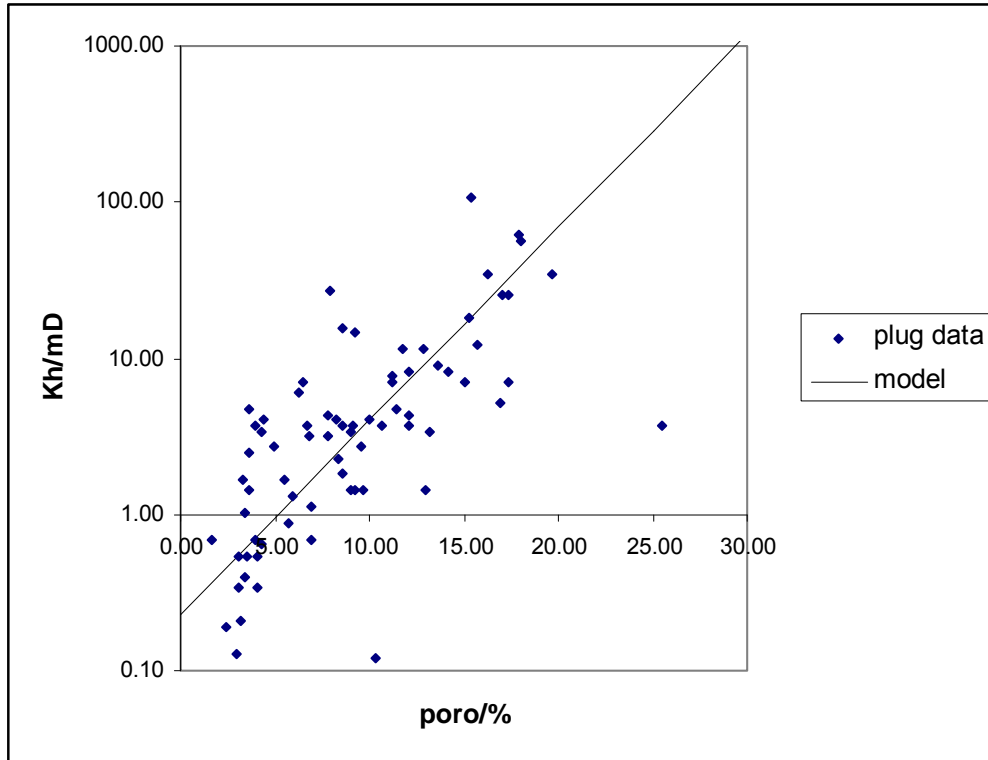
Issues
STOIIP (porosity, N/G)
Production Profile.
Water Flood Behaviour.
Perforation Strategy.

Permeability Prediction



Silurian Shallow Inland Sea.

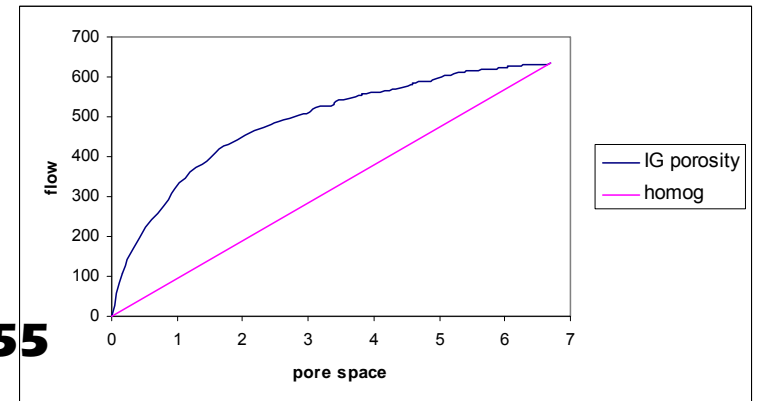
Dolomite Reservoir: Description Based on Core Plugs



Net Average Poro = 10pu
N = 71 plugs
58 with k>1mD

But is this representative?

Lorenz Coefficient 0.55



Reservoir Rock

Pure Dolomite

3 phases of dolomitisation.

3 Porosity Types:

Micro-crystalline

Inter-granular

Vuggy (or Leached)

3 depositional settings

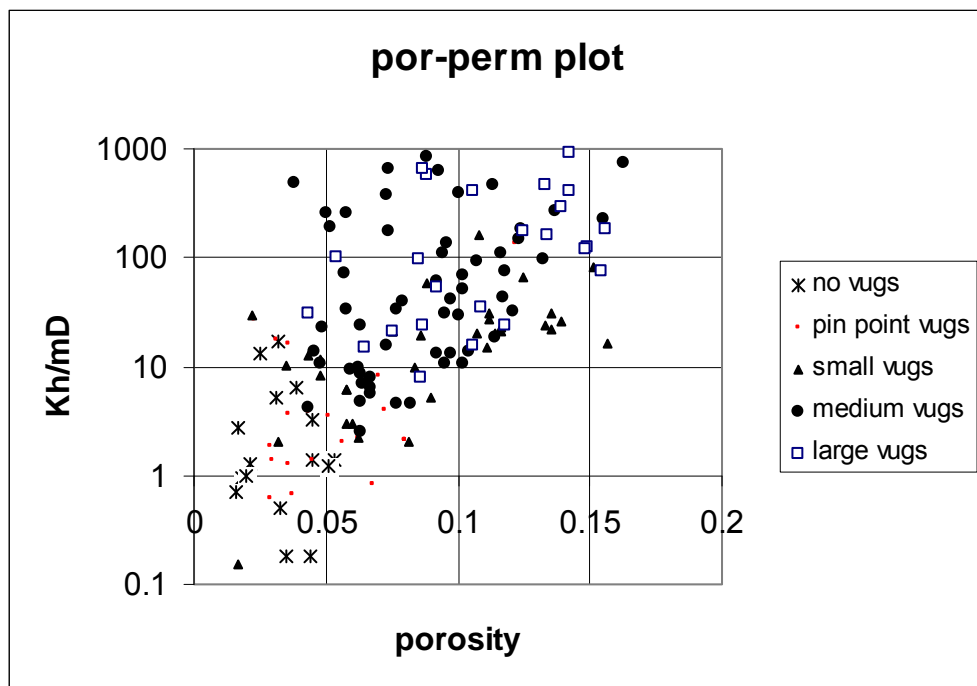
Supratidal - micro-xt

Intertidal - intergranular/Vuggy

Sub-tidal - intergranular/Vuggy

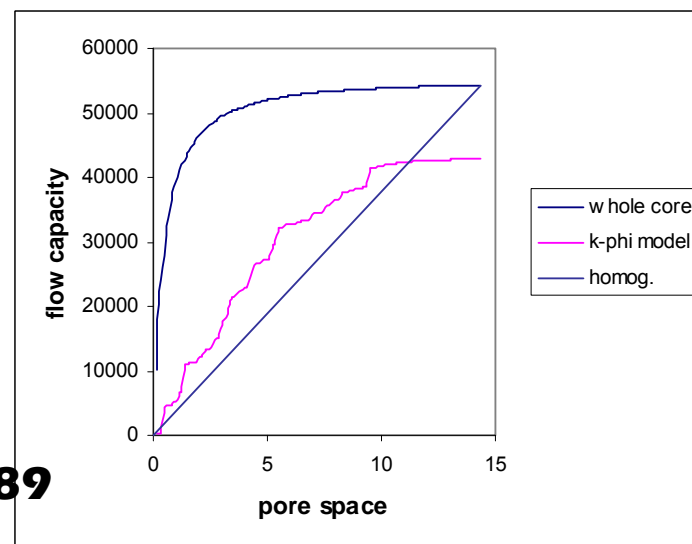


Dolomite Reservoir: Description Based on Whole Core



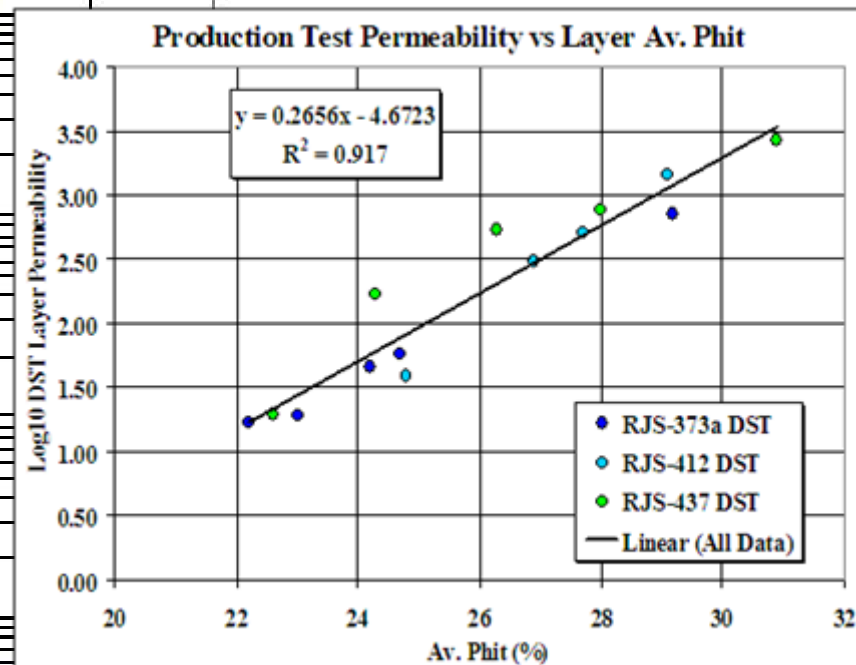
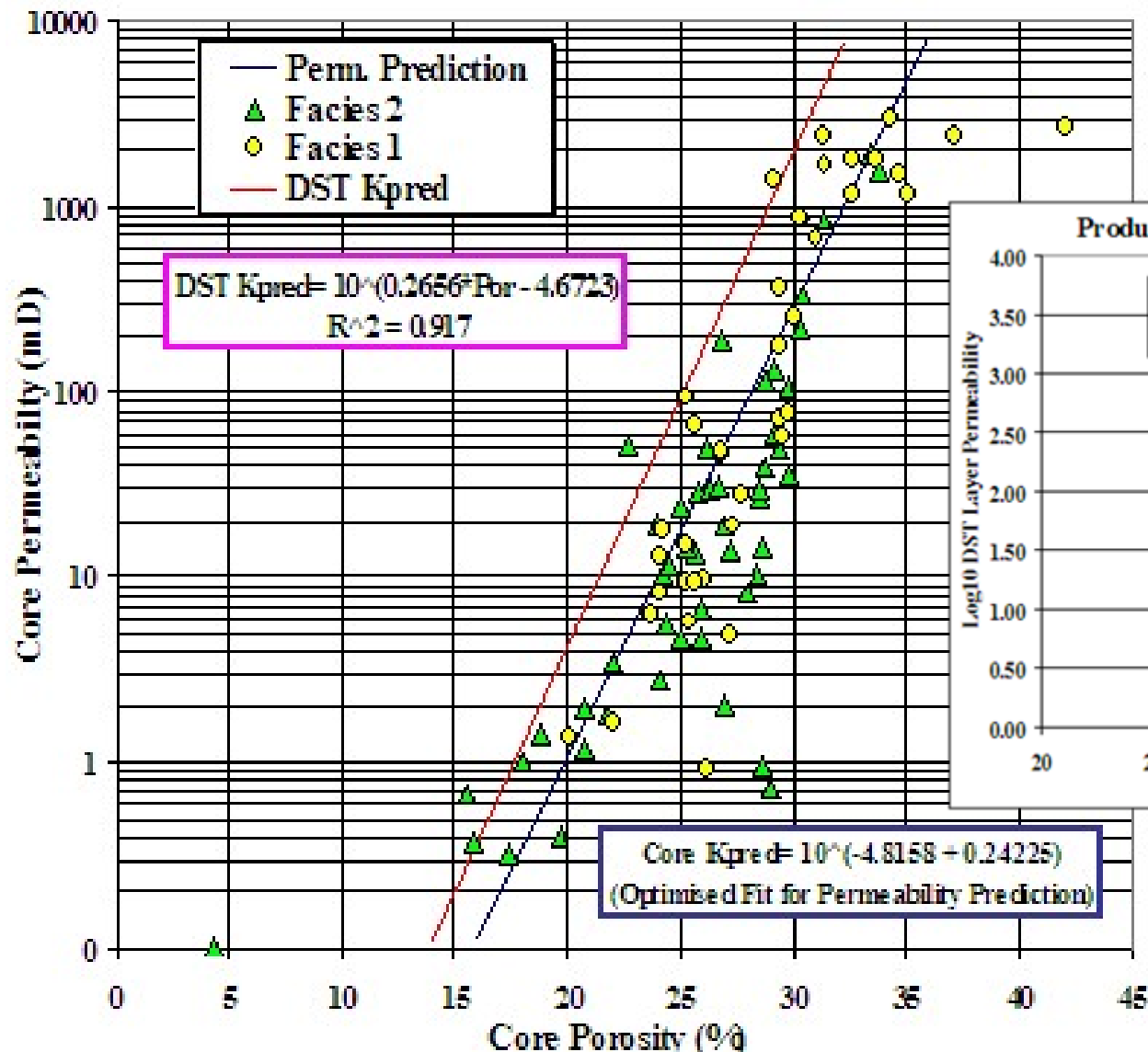
Net Average Poro = 4.3 pu
N = 179 plugs
166 with $k > 1$ mD

Lorenz Coefficient = 0.89



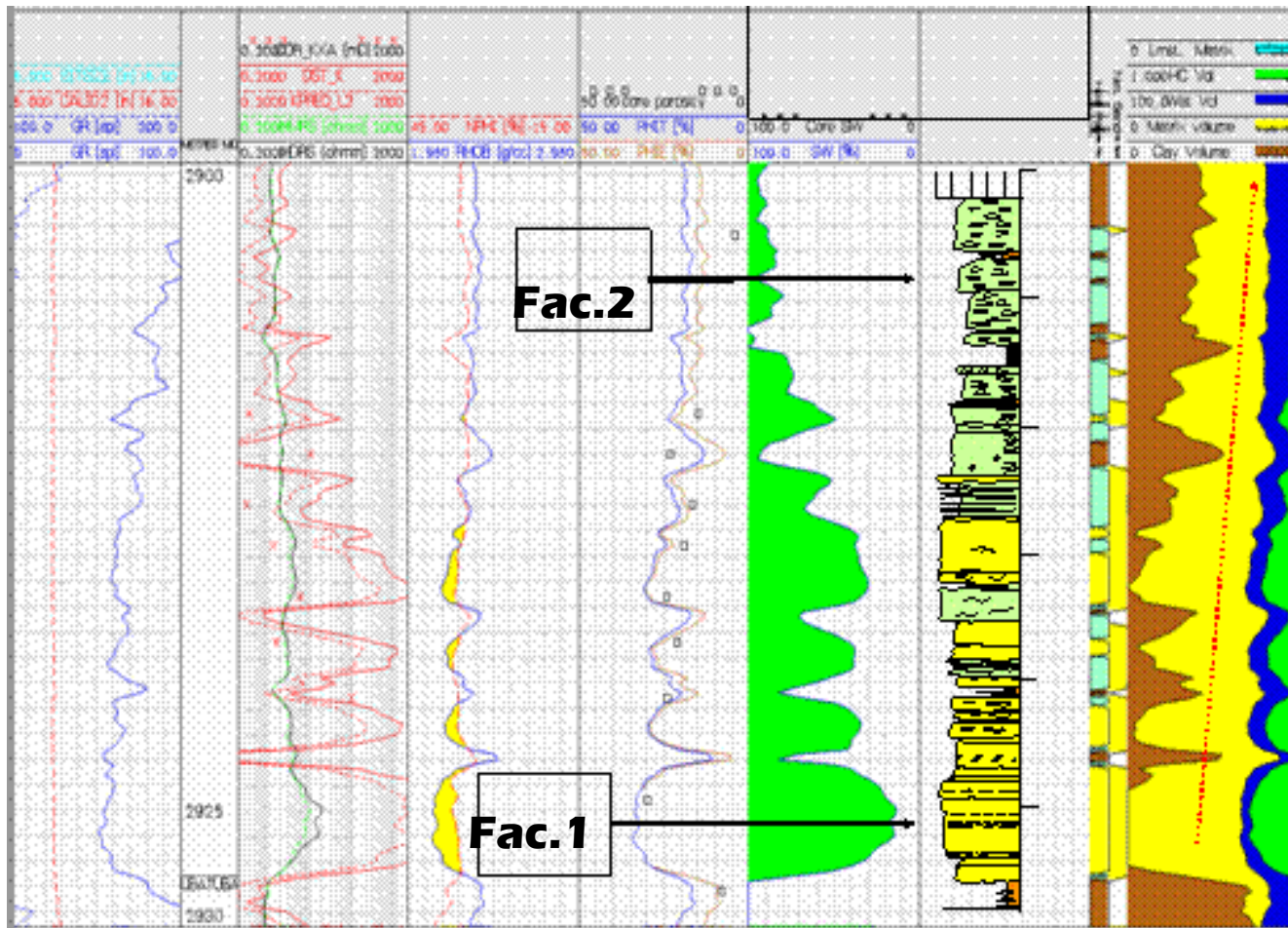
Campos Basin: Test and Core Permeability

Test Permeability consistently higher than Core (3 wells, 14 DSTs).

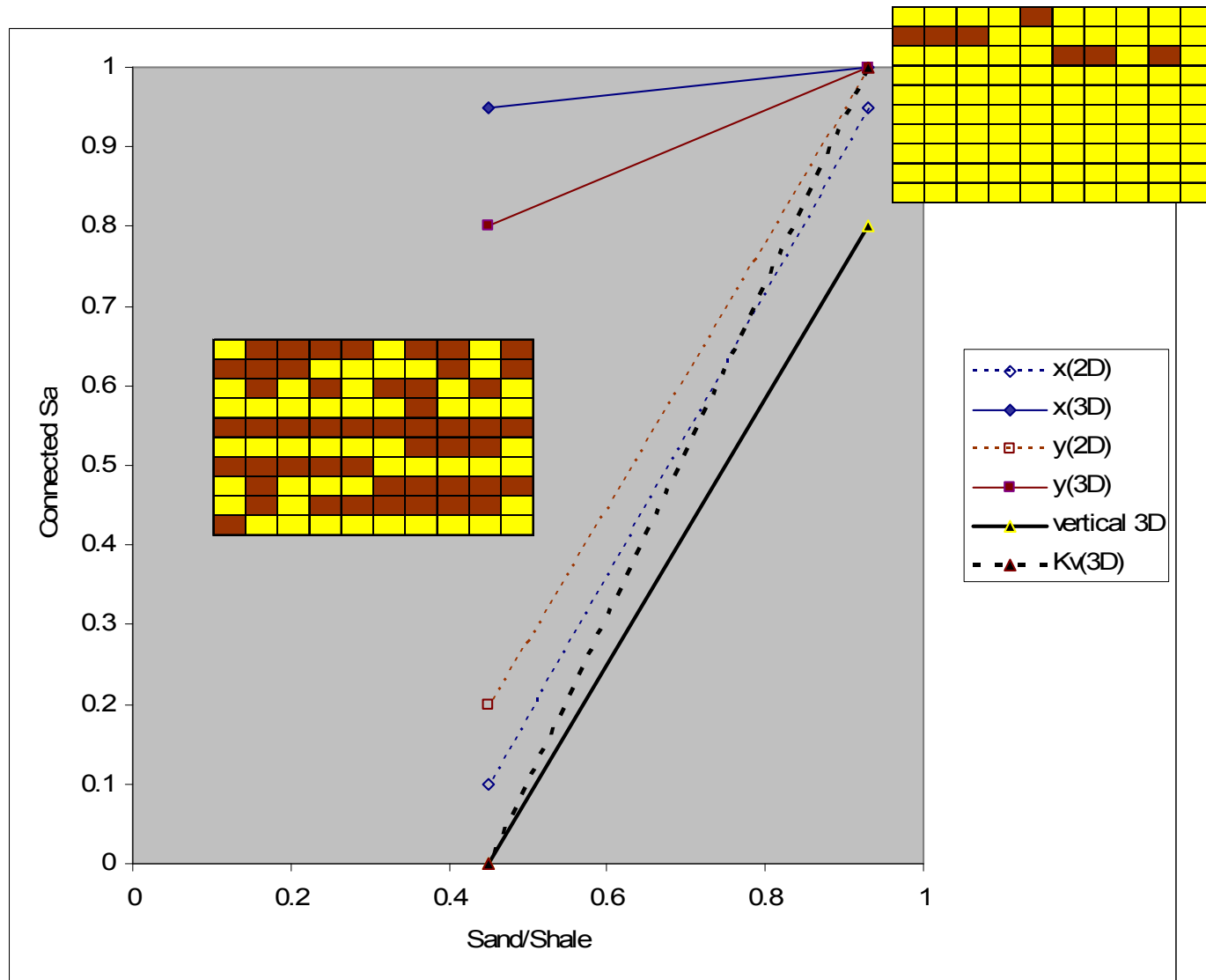


Note: This is Unusual in that the core data has not been averaged

The ‘H’ in kH is too small.



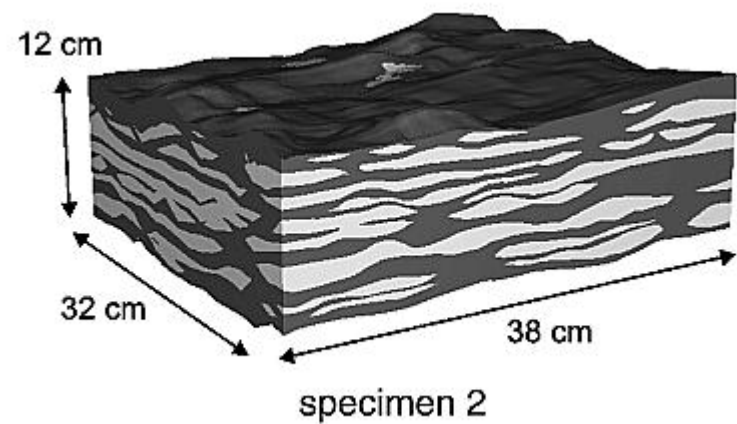
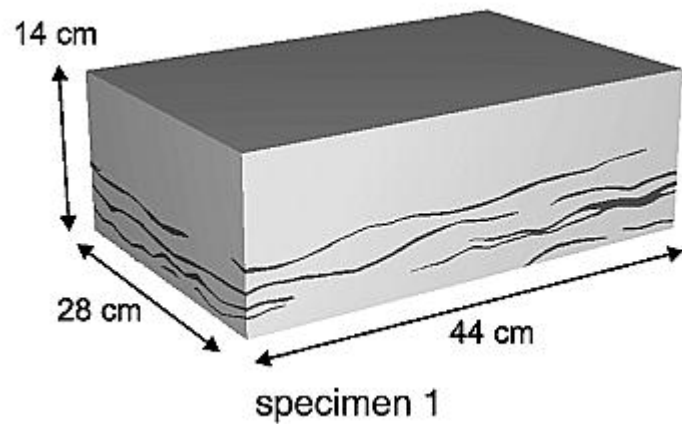
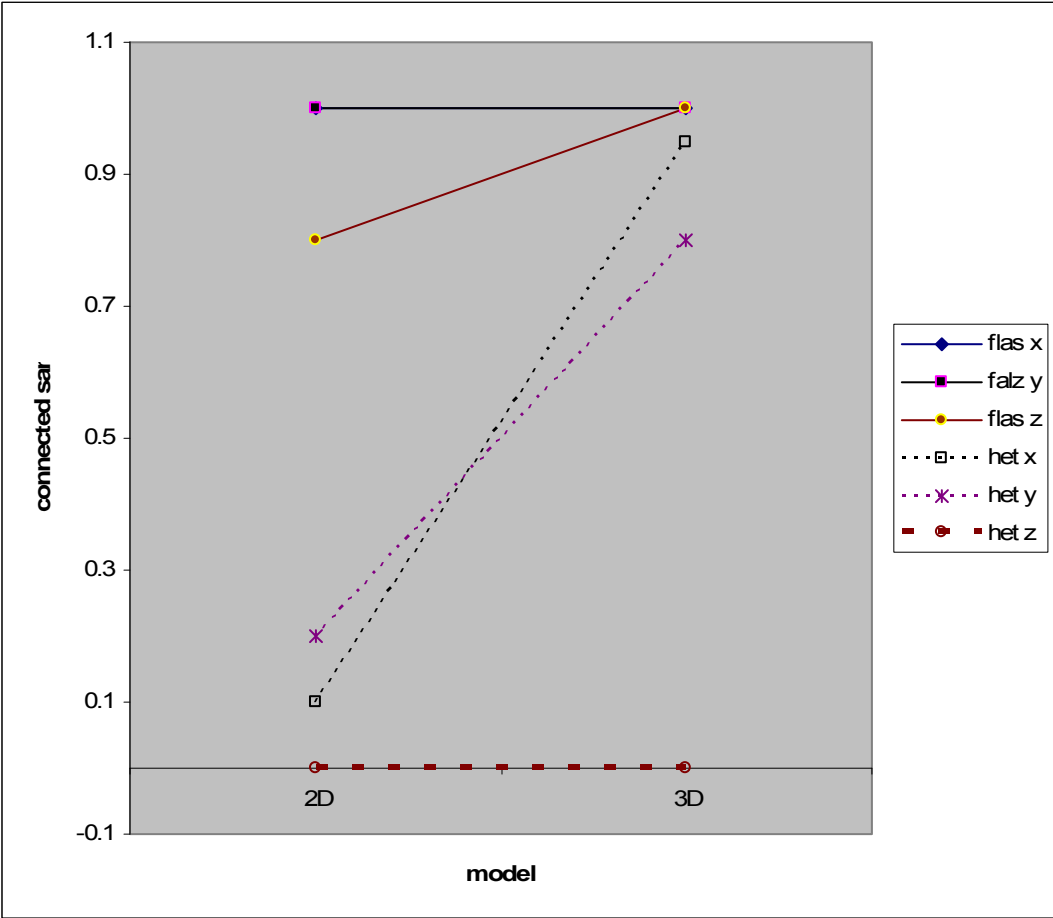
Connectivity and Permeability.



Sand connectivity for 2D and 3D realisations.

After M. D. Jackson (et al) AAPG Bull 89(4) p507-528

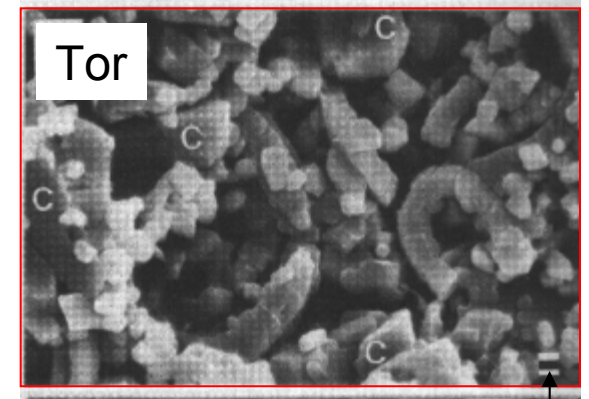
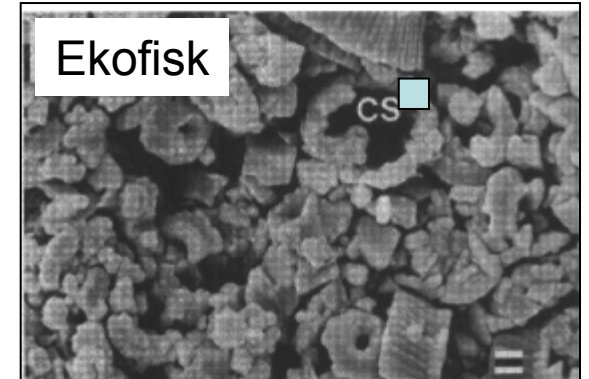
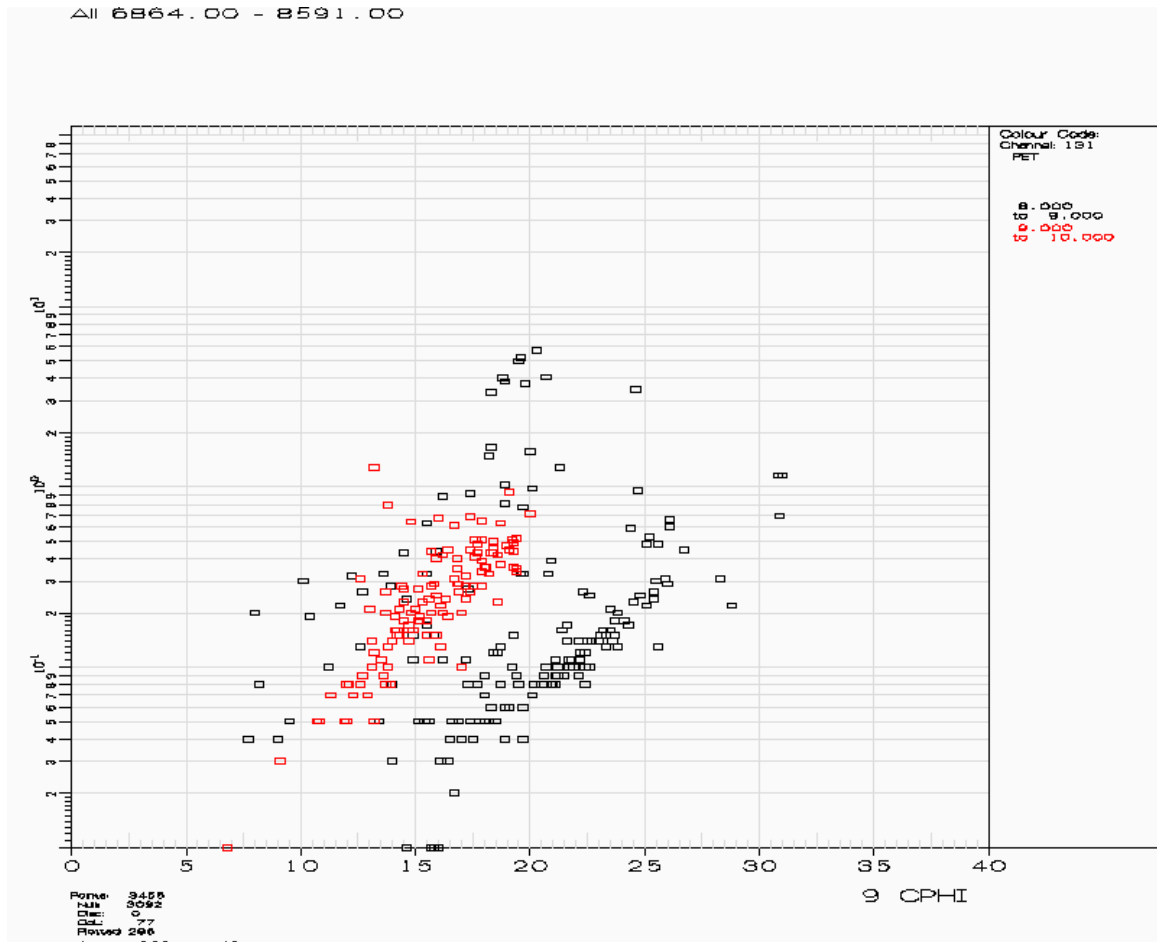
Moving from 2D to 3D



Conclusion

- Permeability is not just another property curve.
 - It has units and dimensions and is directional.
- It cannot be measured as a continuous curve.
 - Imposes a limit on accuracy.
 - Probe permeameter is as close as we get.
- Different scale measurements need not agree.
 - Depends on averaging applied to the finer scaled data.
 - Disagreements may actually be telling us about the reservoir.

Post-script: North Sea Chalk



1 μ m