Saturation height modeling: integrated application of core measurements and well logs

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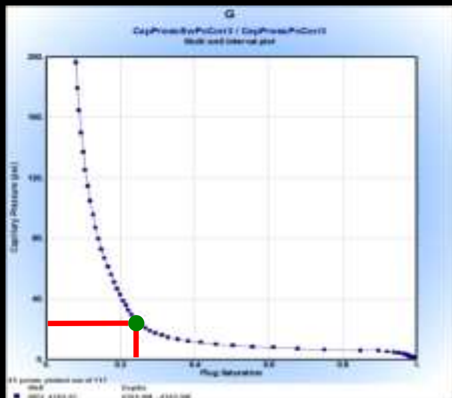
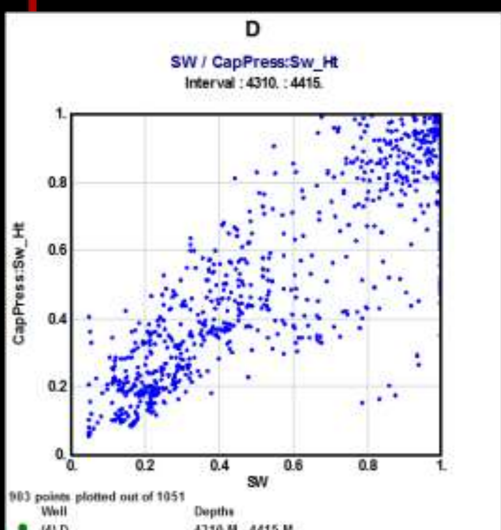
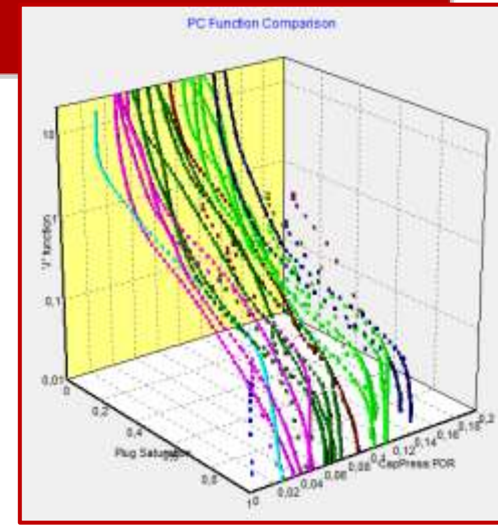
ISZA, Balatonföldvár, 28.03.2014.

Introduction



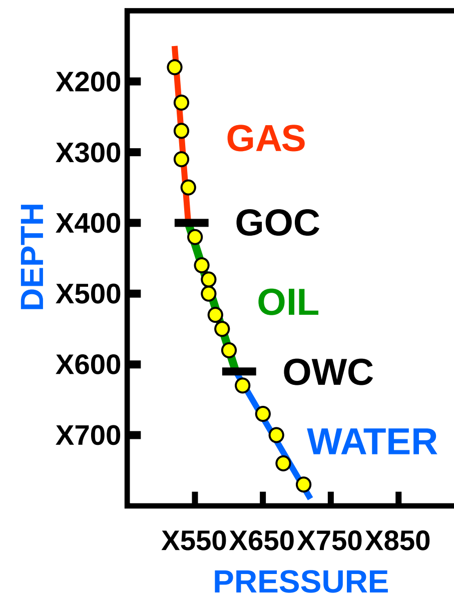




- ❖ Integrated application of laboratory measurements and log cuves leads to particular knowledge about the reservoir
- ❖ It makes possible to set universal saturation height relationships

Outline:

- ❖ Theory of capillary pressure measurements
- ❖ Building saturaton height functions
- ❖ Case study

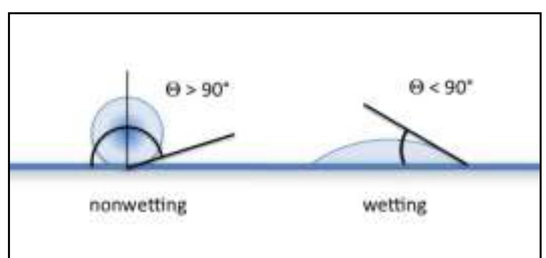


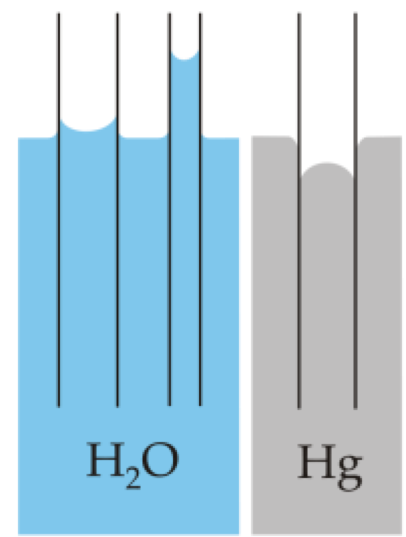
Capillary pressure

$$P_c = \frac{2\sigma\cos\theta}{r}$$

- The pore space in a rock is occupied by fluids (water-oil-gas)
- Fluid distribution in a multiphase phenomena is controlled by
  - gravity forces (buoyancy),
  - relative permeability and
  - capillary pressure

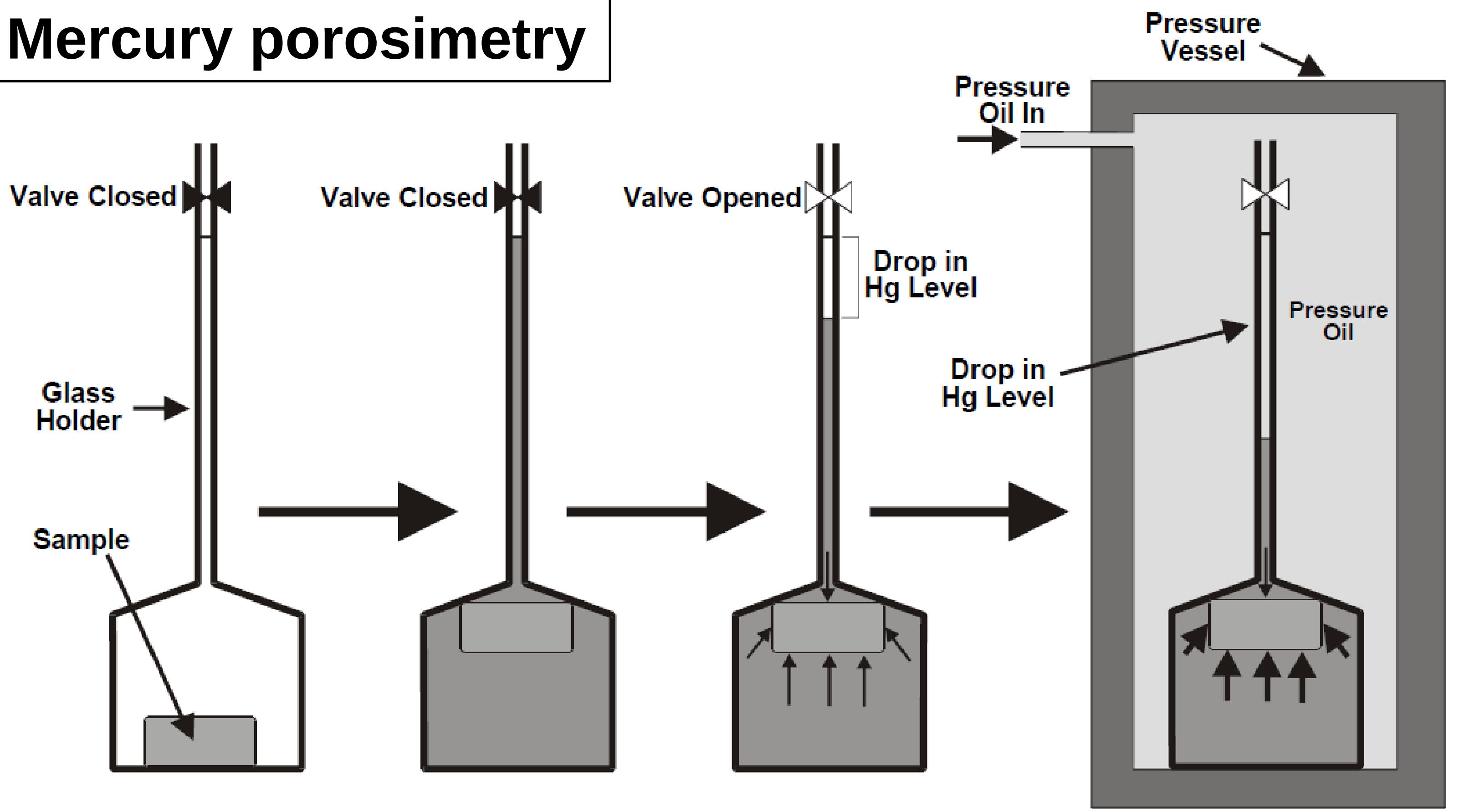
- Capillary pressure (P_c) is acting against HC migration
- It's magnitude depends on
  - surface tension (σ),
  - wettability (θ) and
  - pore throat radius (r)





Capillary pressure

Mercury porosimetry



Dried Sample is Evacuated

Mercury is added until mark while the system remains evacuated. The amount of mercury needed provides a measurement of bulk volume

Atmospheric pressure is applied to the system allowing mercury to enter the larger pores. Drop in Hg level gives volume of macropores.

Pressure is raised to 200 MPa allowing Hg to enter progressively smaller pores. The drop in the Hg level gives the volume of the pores saturated with Hg at each pressure level.

P. Glover

Capillary pressure

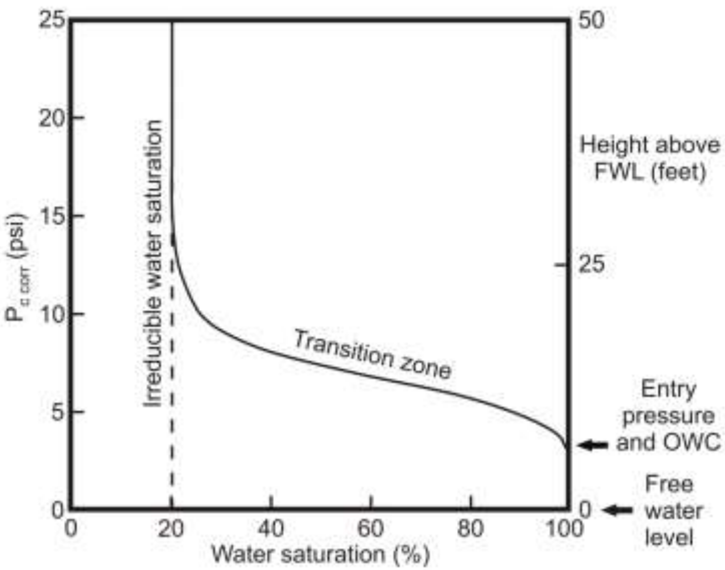
- Laboratory results are corrected to reservoir conditions
- Resultant P_c curves reflect the pore structure
  - entry pressure → largest pore openings
  - S_{wi} → smallest pores remain saturated with water
  - transition → pore size distribution (Φ, k)

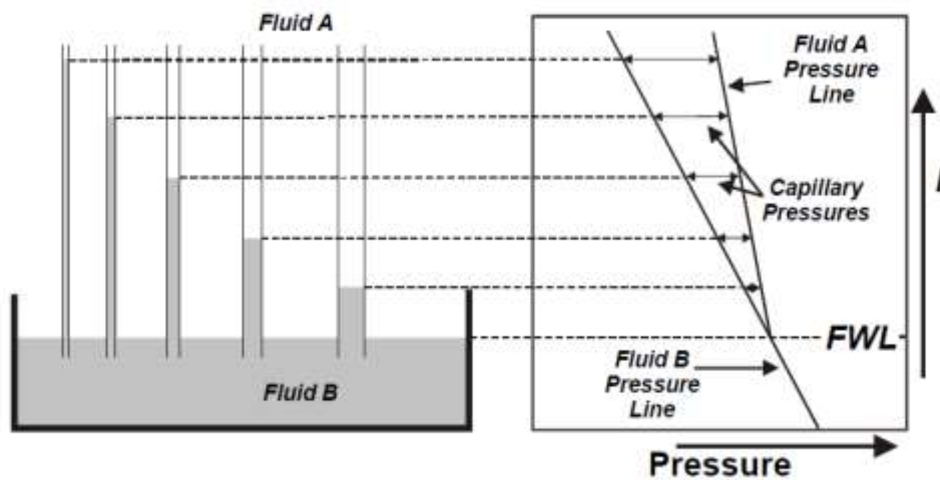
$$P_{c(res)} = P_{c(lab)} \frac{(\sigma \cos\theta)_{res}}{(\sigma \cos\theta)_{lab}}$$

$$P_c = \Delta\rho g h$$

- The entry pressure defines the height of the OWC above FWL

OWC: oil water contact
FWL: free water level





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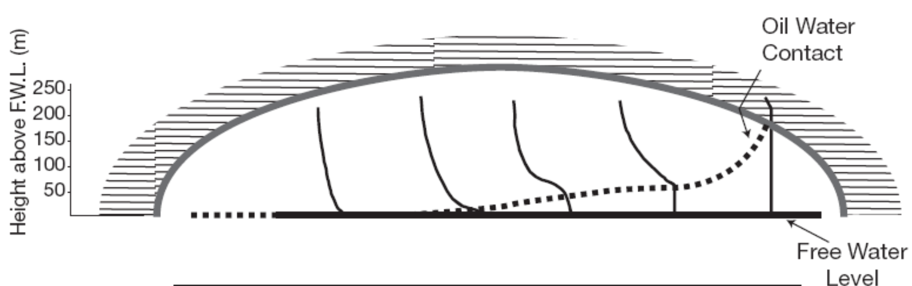
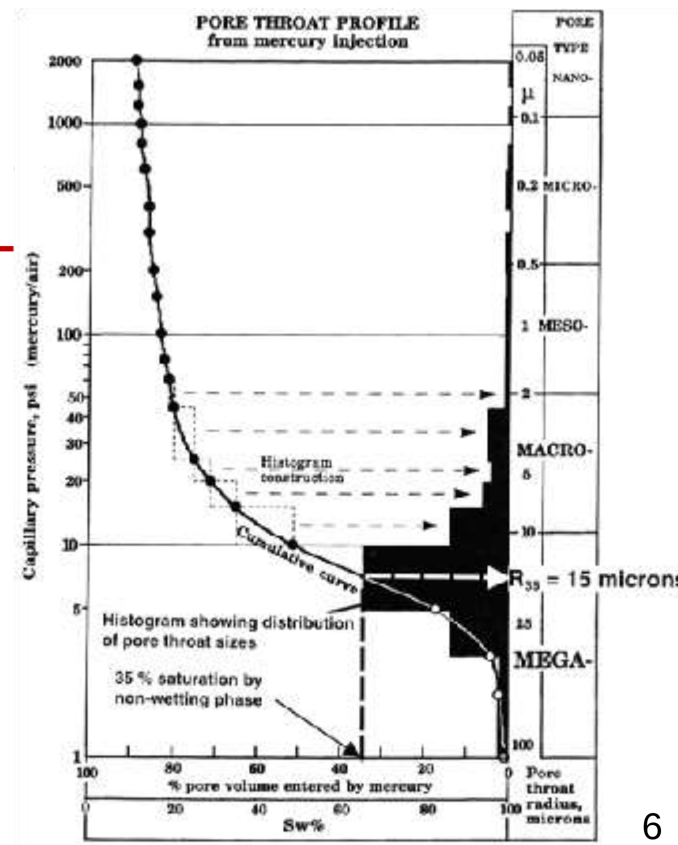


	1	2	3	4	5
ϕ K (mD)	0.33 300	0.23 7	0.22 1	0.15 03	0.10 0.01



Saturation height functions

- Core plugs represent only minor portions
- Through combining all capillary data the whole reservoir can be classified
- Mathematical expressions are used to evaluate S_w from height above FWL (h)

Single-predictor Algorithms

$$S_w = a \cdot h^b$$

created for many porosity ranges

Multipredictor Algorithms

$$\log(\Phi \cdot S_w) = c + d \cdot \log h + e \cdot \log \Phi$$

involves porosity/permeability

Normalized functions

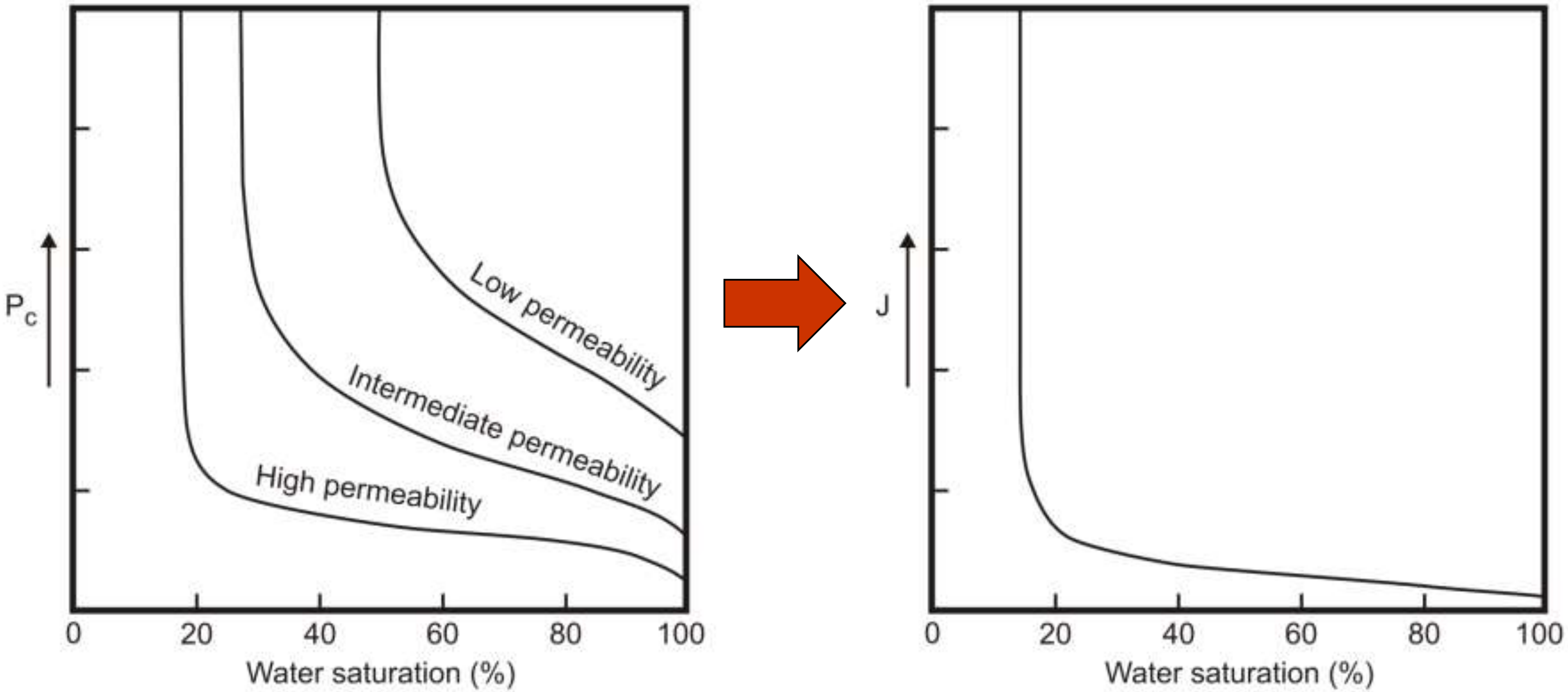
$$J(S_w) = \frac{P_c}{\sigma \cos\theta}\sqrt{\frac{k}{\Phi}}$$

$\sqrt{k/\Phi}$: reservoir quality index

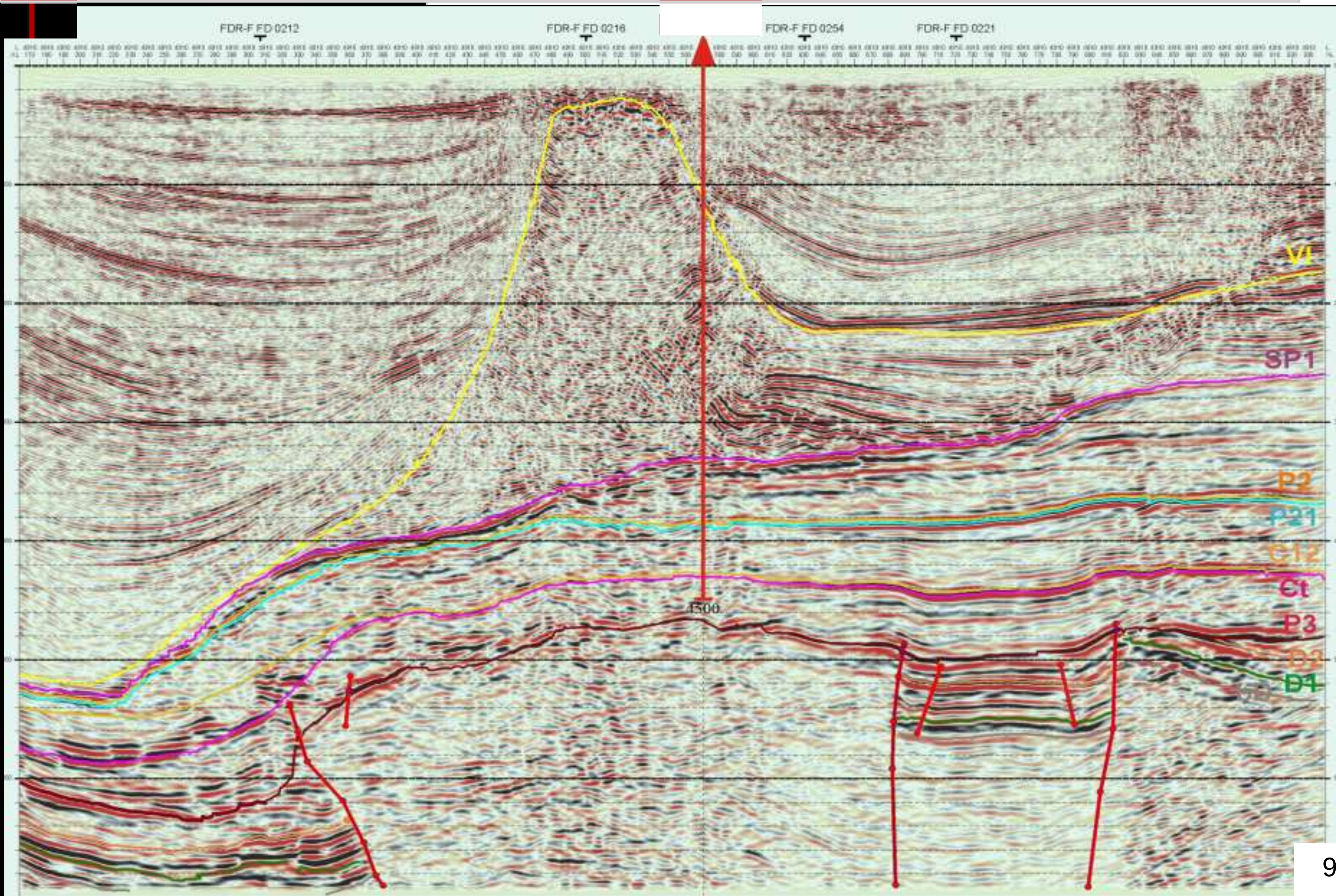
Saturation height functions

Leverett's J-function

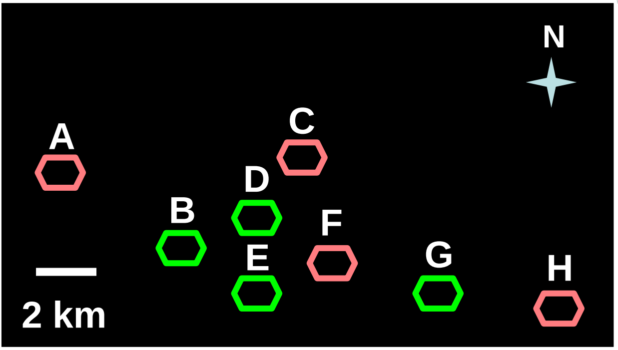
- Normalizing capillary pressure curves
- Fit a common function – lambda, hyperbola, exponential



Field application



Field application



- 4 of 8 wells contain core samples
- Each of them with 10-15 capillary pressure measurement points (altogether 51 plugs)
- Laboratory conditions: up to 60 000 psi (400 MPa), except well B – only 120 psi

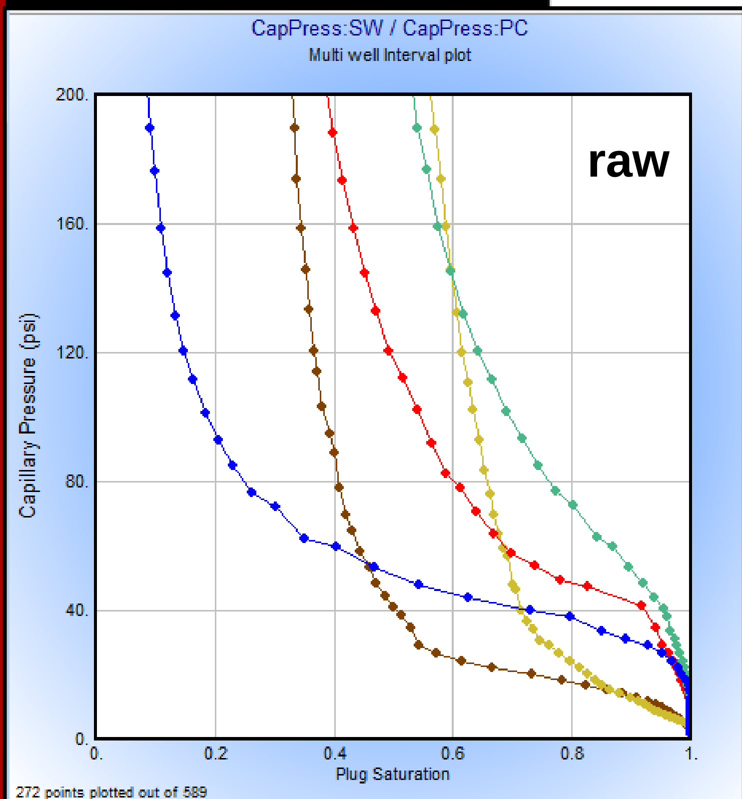
Corrections

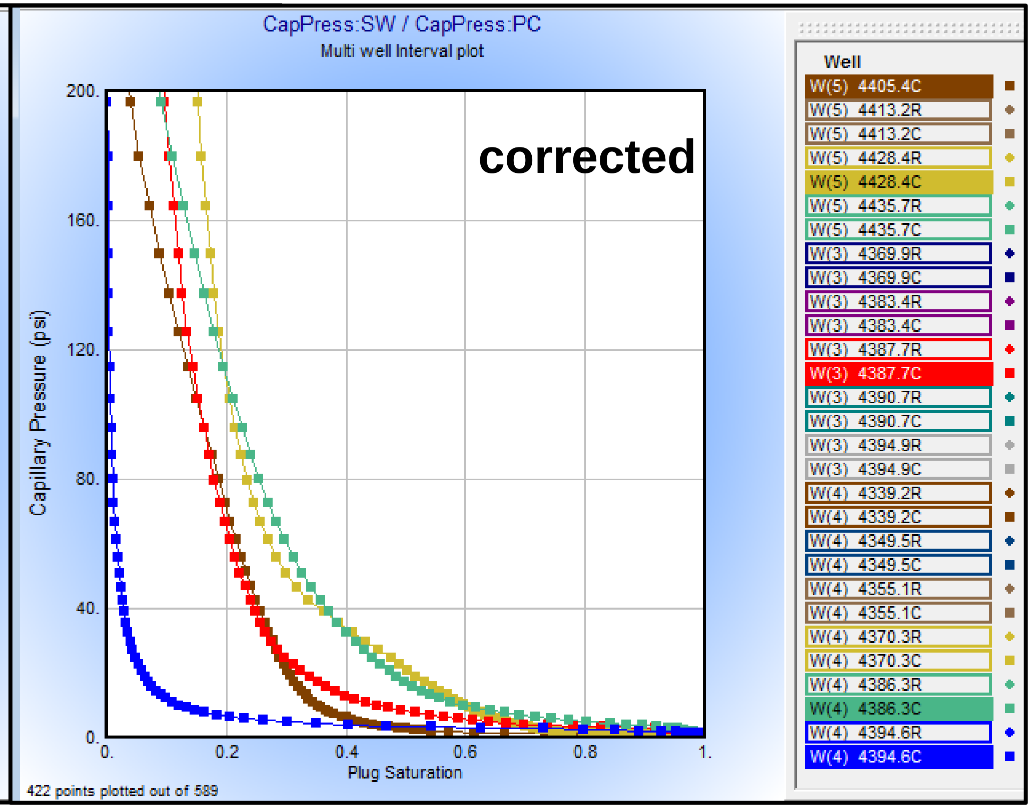
- Laboratory (mercury-air): *θ=130°, σ=485 dynes/cm*
- Reservoir (HC-water): *θ=30°, σ=25 dynes/cm*

Sorting

- QC (quality check)
- Formations
  - Bobrikovsky – 7 plugs
  - Tournaisian – 31 plugs

Field application





Corrections

$$P_{c(res)} = P_{c(lab)} \frac{(\sigma \cos\theta)_{res}}{(\sigma \cos\theta)_{lab}} = \frac{P_{c(lab)}}{14.4}$$

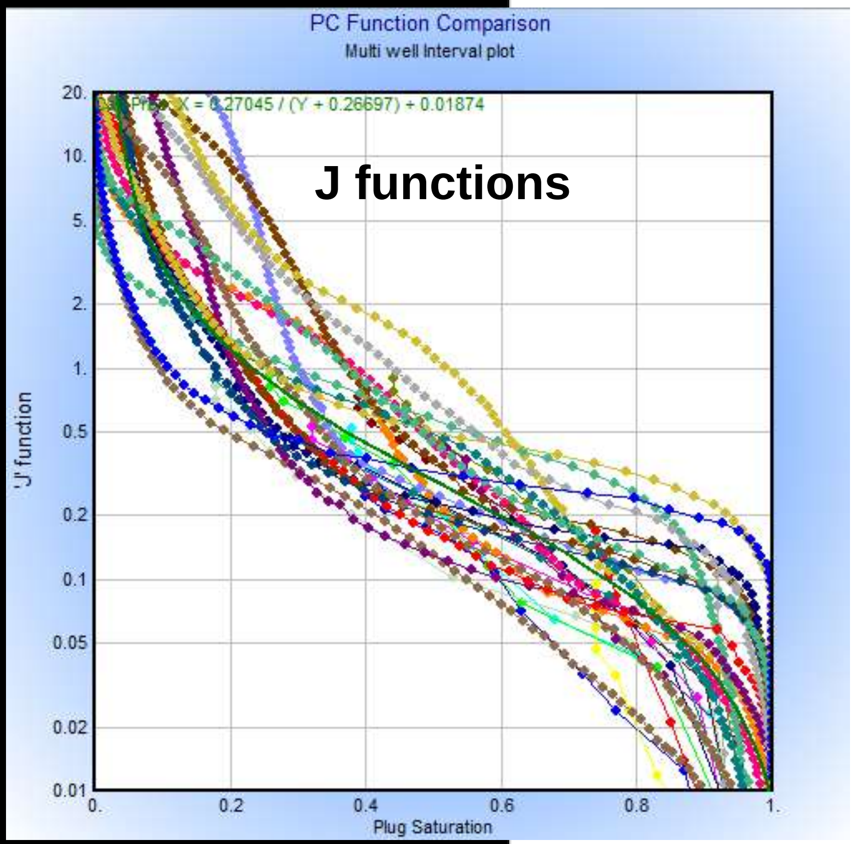
Field application

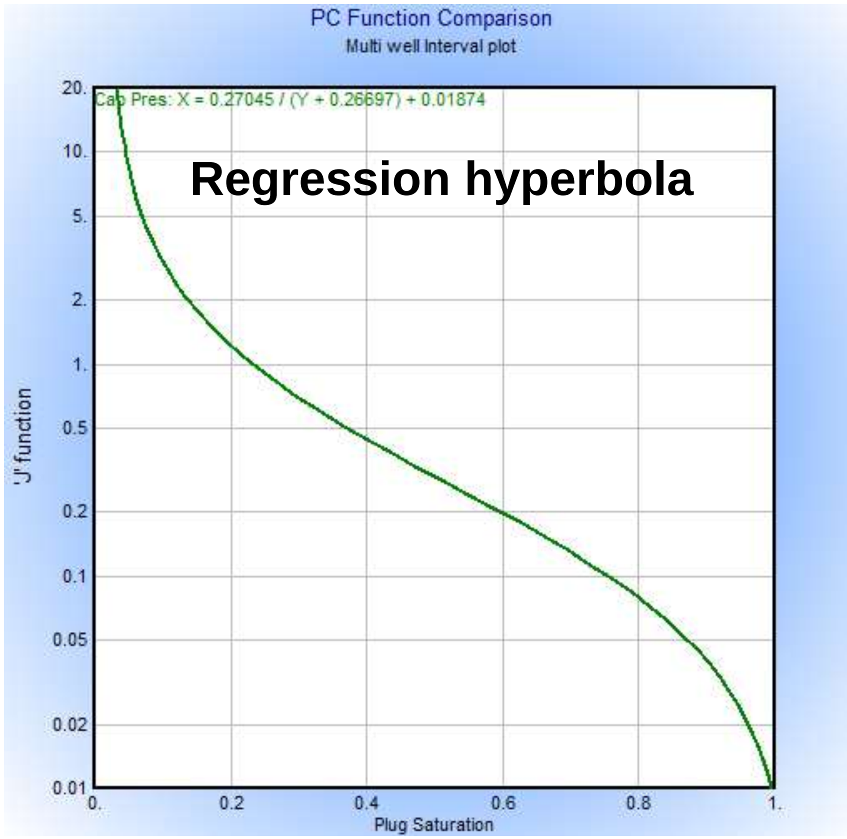
Capillary pressure functions

$$J(S_w) = \frac{P_c(S_w)}{\sigma \cos\theta}\sqrt{\frac{k}{\Phi}}$$

$$S_w = \frac{a}{J-b} + c$$

R^2	0.9462
a	0.27045
b	0.26697
c	0.01874





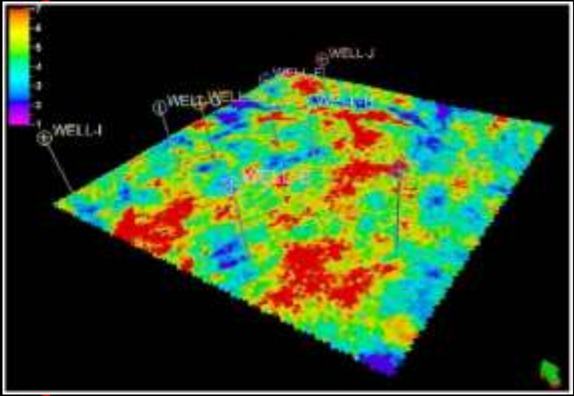
Field application

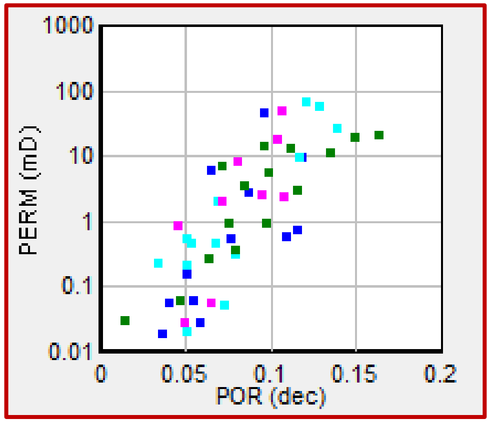
Extending model

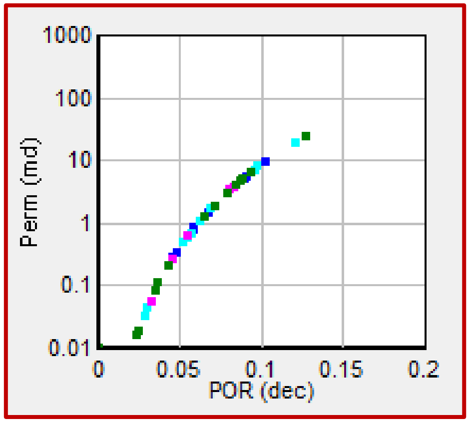
- Using log derived porosity and permeability curves it is able to compute S_w with this relationship

$$J = \frac{\Delta\rho g h}{\sigma \cos\theta}\sqrt{\frac{k}{\Phi}}$$

- Saturation height models are extendable to the whole petrofacies unit, as long as there is no sealing fault to change fluid flow

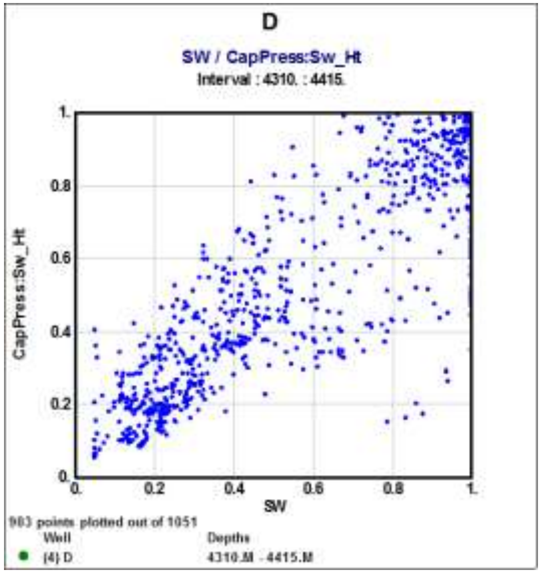




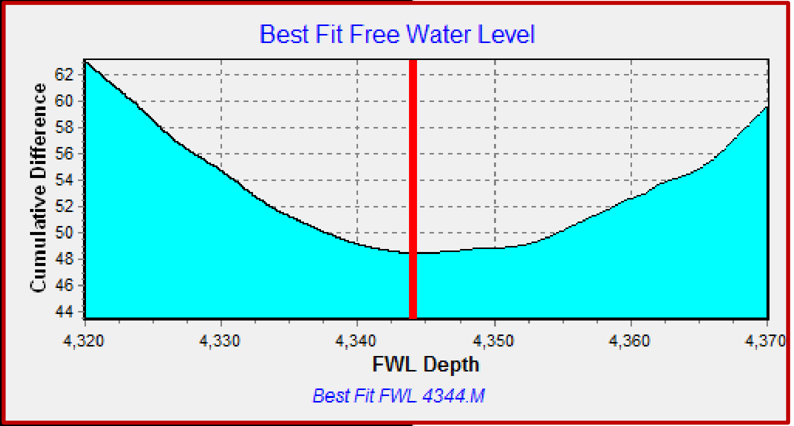


Field application

Extending model

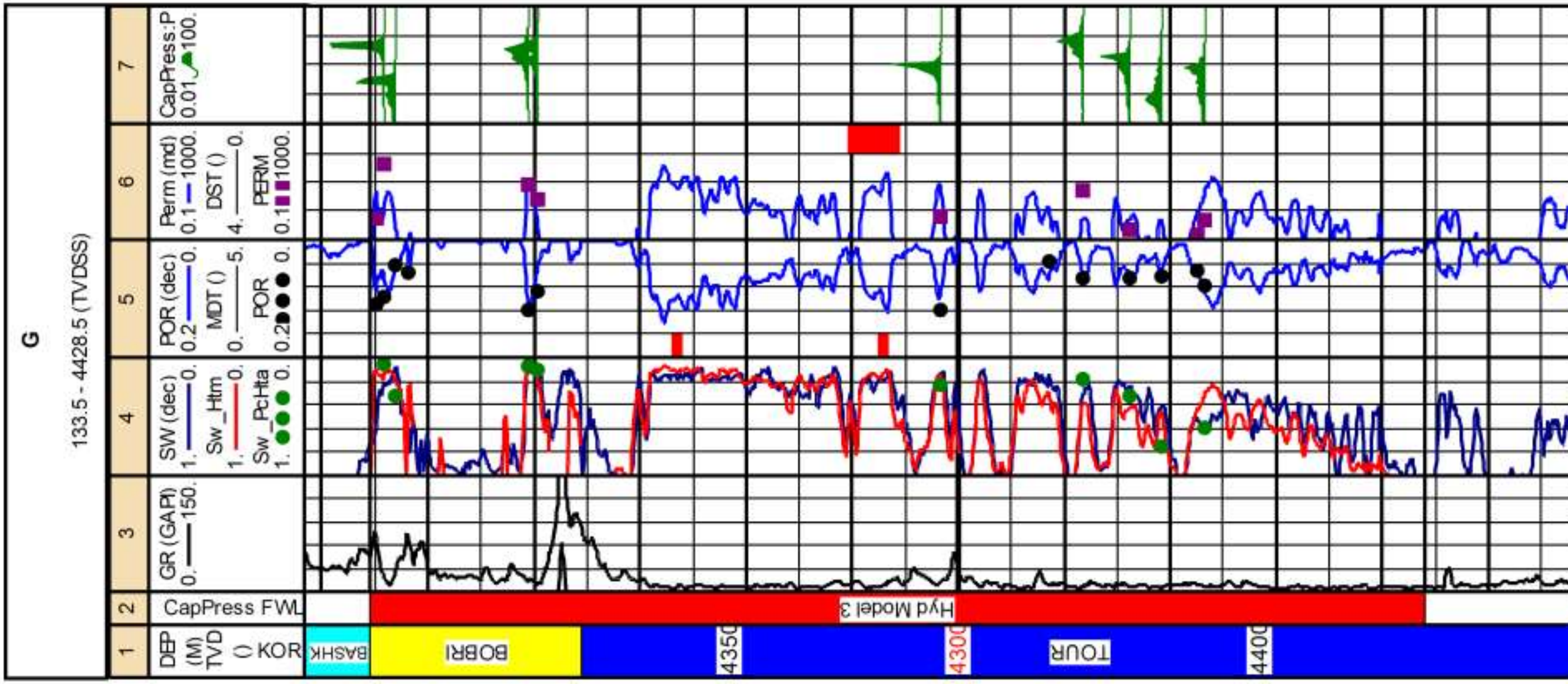


- FWL can be calculated from the S_w curves
  - Cumulative difference is the sum of differences of the HC volumes for each depth step above the current FWL for all selected wells



Field application

FWL in 4344 m (TVDSS)



Field application

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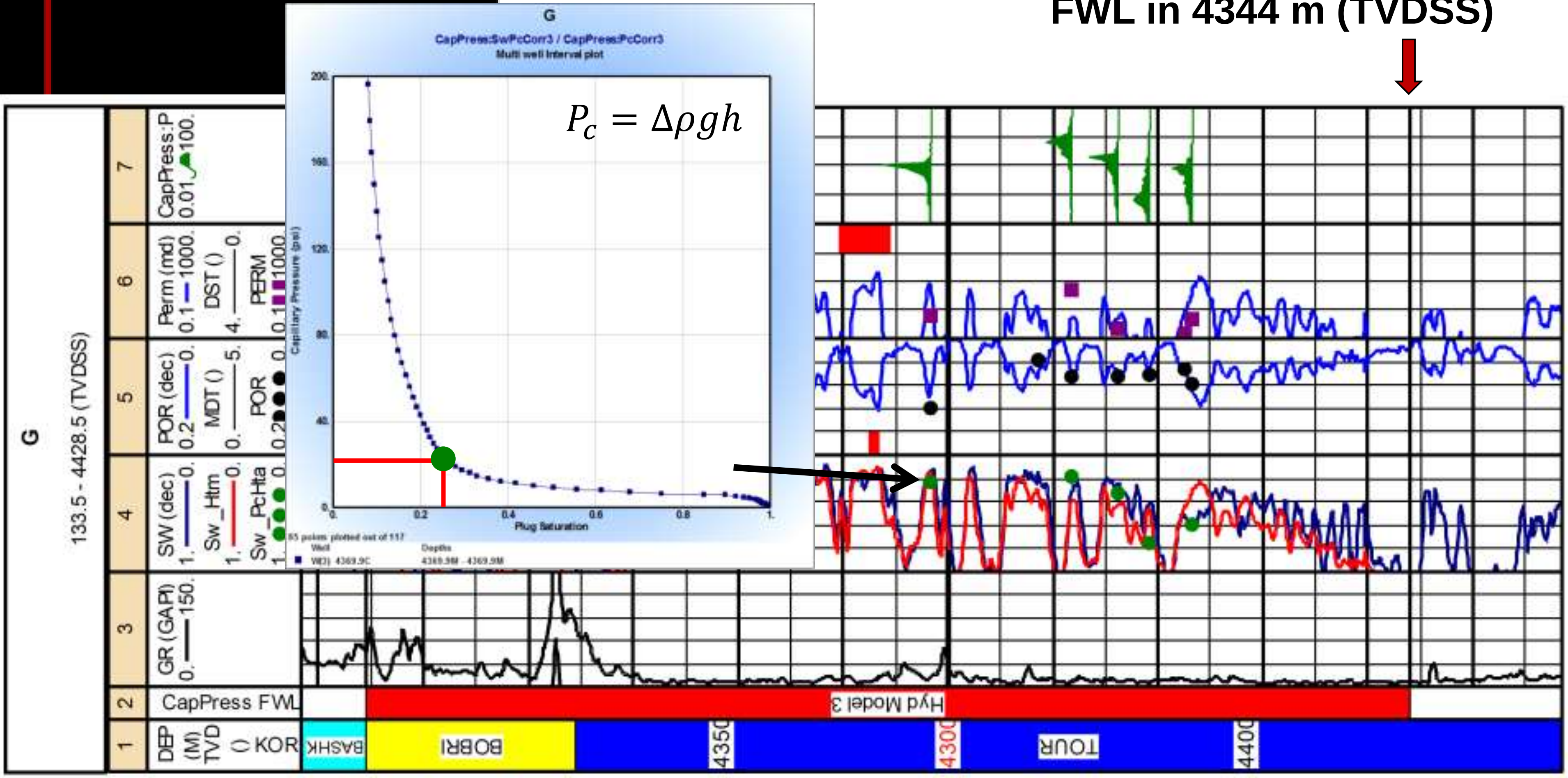
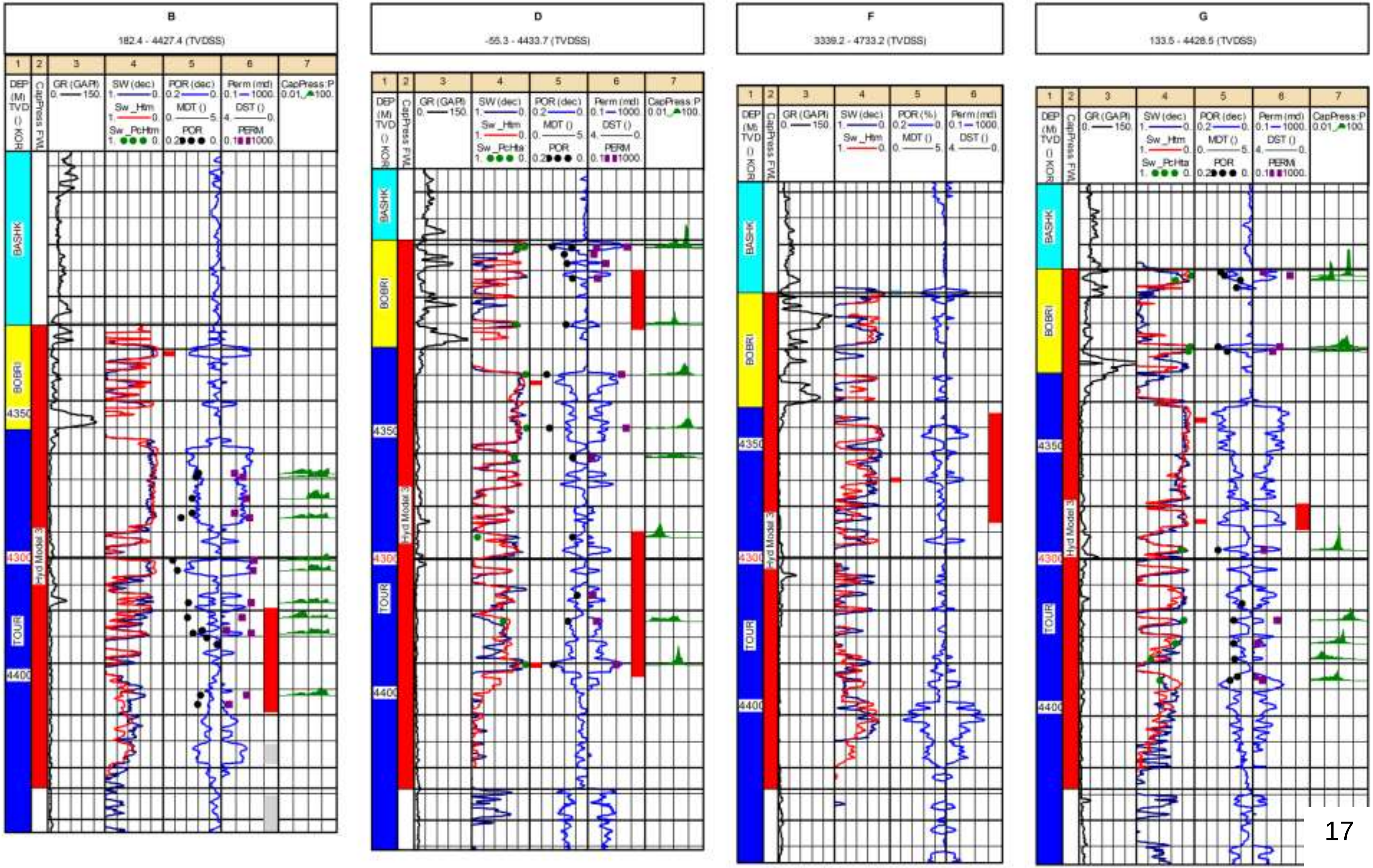
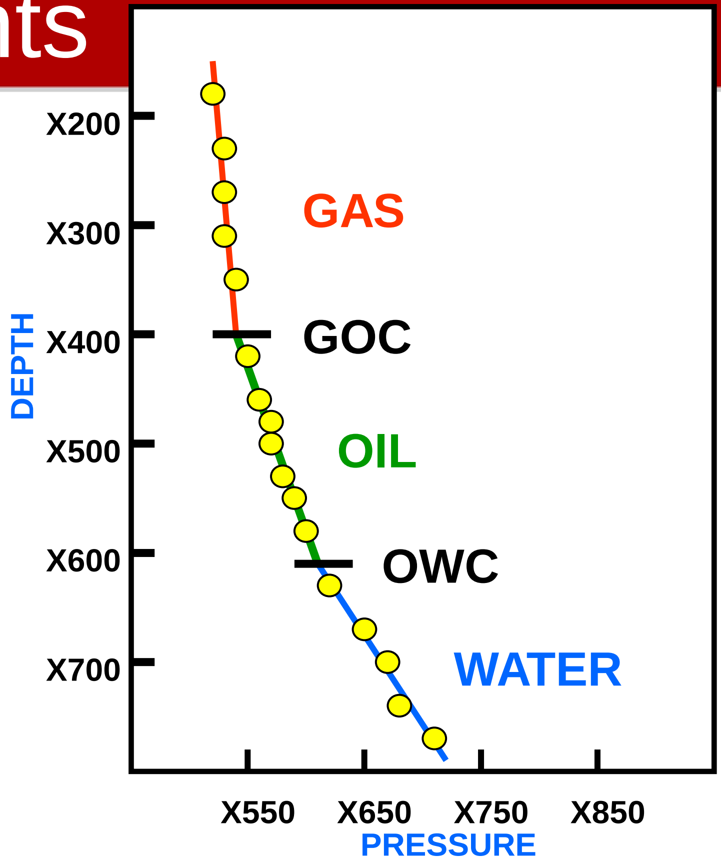


Field application

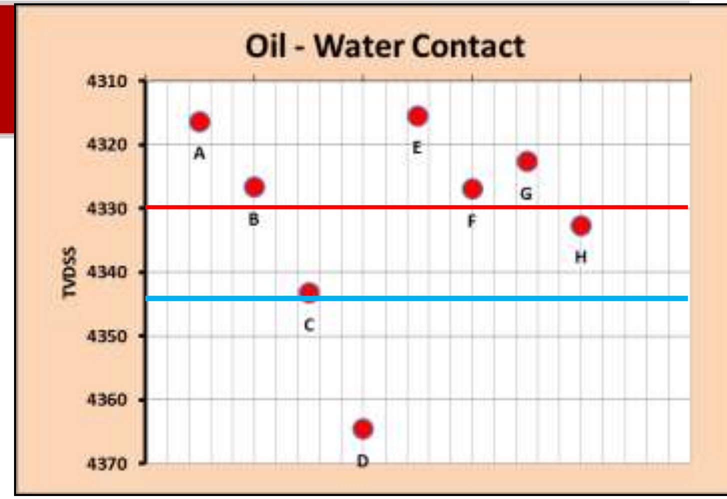


Pressure measurements

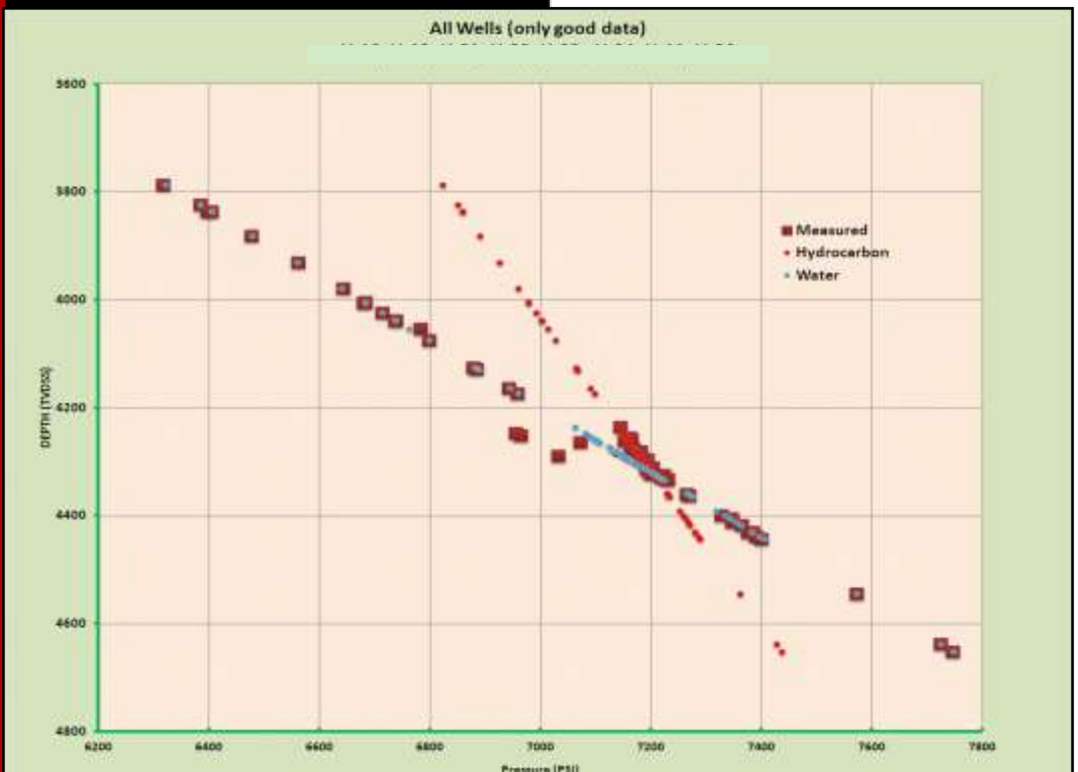
XPT data



Pressure measurements



- upper water: 1.1598 g/cc
- lower water: 1.1587 g/cc



Well	Fluid density (g/cc)	OWC (m TVDSS)
A	0.540	4316.34
B	0.649	4326.66
C	0.625	4343.24
D	0.848	4364.57
E	0.665	4315.45
F	0.441	4326.99
G	0.591	4322.67
H	0.682	4332.65
all	0.69	4329.87

Summary

- Using capillary pressure curves, saturation relations in the reservoir can be described
- Free water level is determined by involving log derived curves
- Oil water contact is the function of local rock properties
- OWC can be estimated from pressure measurements

$$J = \frac{\Delta\rho g h}{\sigma \cos\theta}\sqrt{\frac{k}{\Phi}}$$

Bobrikovsky

$$S_w = 0.199 \cdot J^{-0.584} + 0.003$$

Tournaisian

$$S_w = \frac{0.27}{J - 0.267} + 0.019$$

Thank you for your attention!

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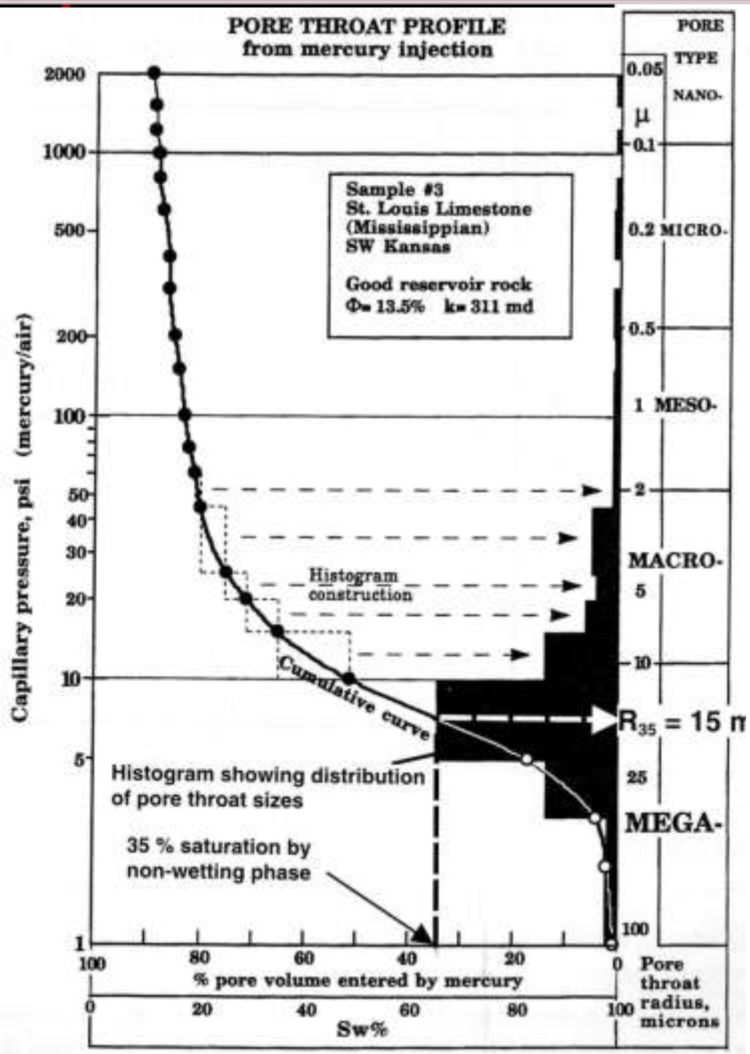
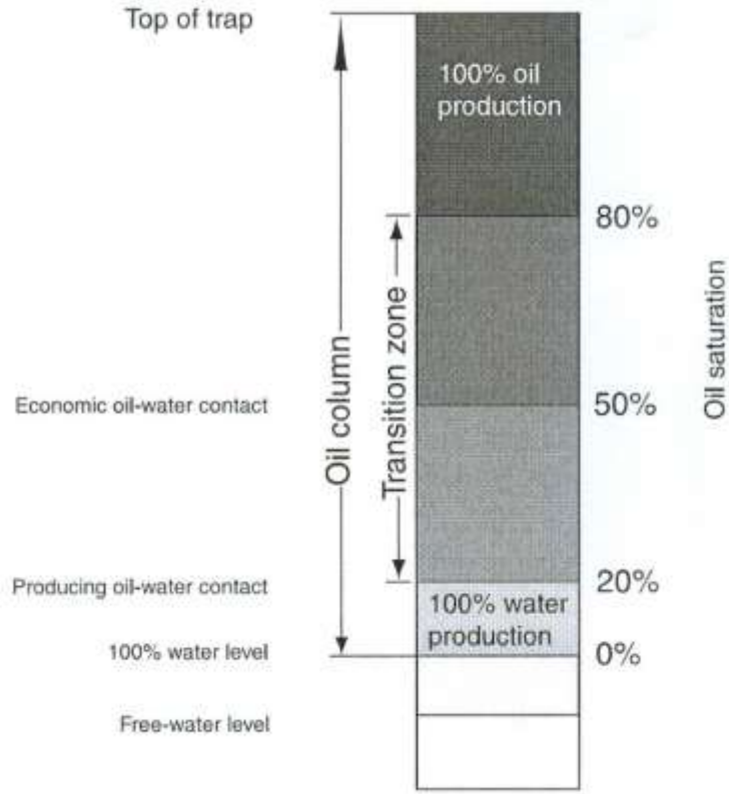
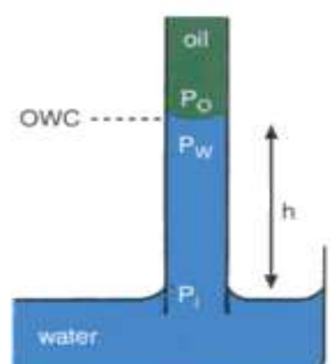
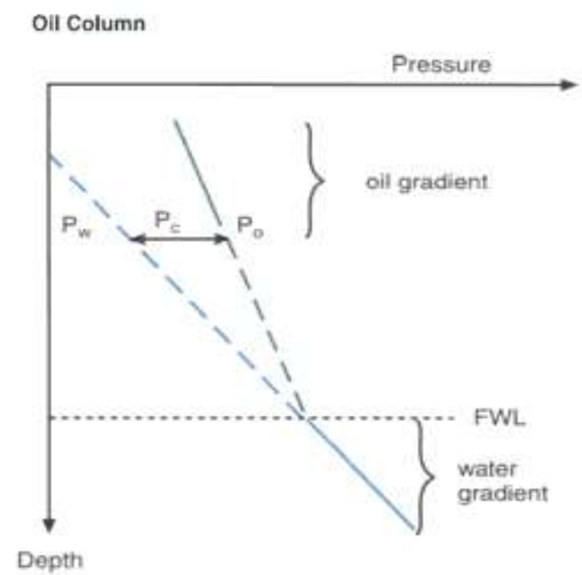
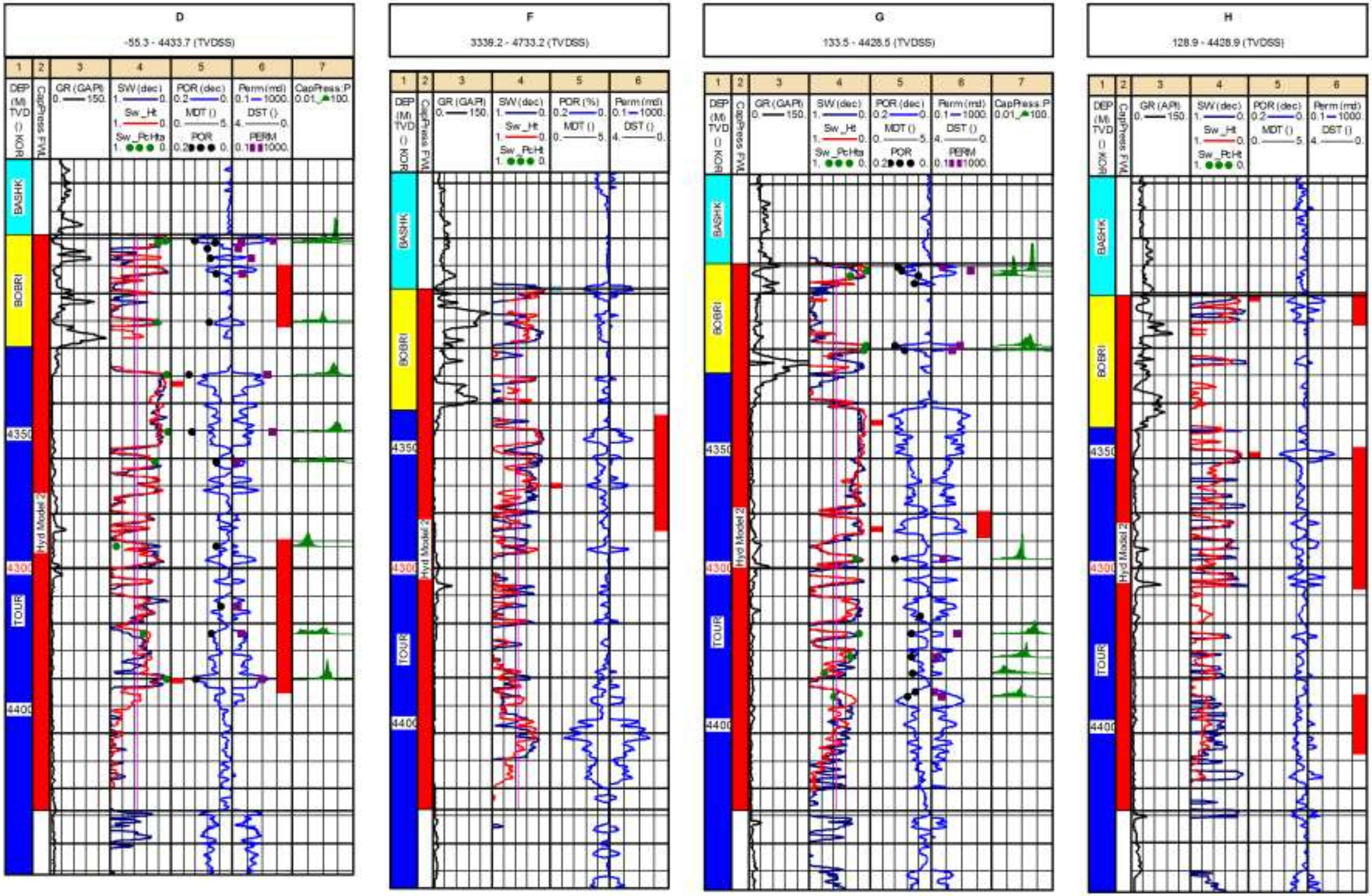
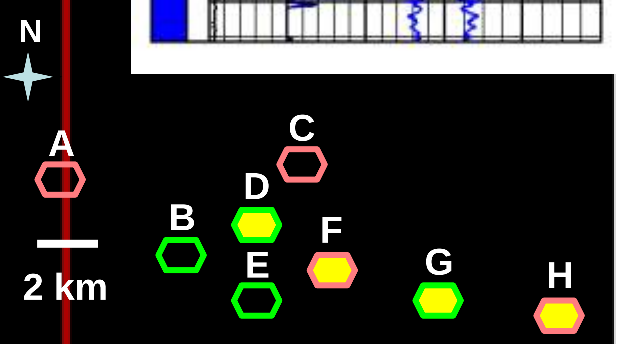

PORE THROAT PROFILE
from mercury injection
PORE TYPE
NANO-
MICRO-
MESO-
MACRO-
MEGA-
μ
0.05
0.1
0.2
0.5
1
2
5
10
25
100
2000
1000
500
200
100
50
40
30
20
10
5
1
Capillary pressure, psi (mercury/air)
Sample #3
St. Louis Limestone
(Mississippian)
SW Kansas
Good reservoir rock
Φ= 13.5% k= 311 md
Histogram construction
Cumulative curve
R35 = 15 m
Histogram showing distribution
of pore throat sizes
35 % saturation by
non-wetting phase
100
80
60
40
20
0
% pore volume entered by mercury
0
20
40
60
80
100
Sw%
Pore throat radius, microns


Top of trap
100% oil production
80%
Transition zone
Oil column
Oil saturation
Economic oil-water contact
50%
Producing oil-water contact
20%
100% water production
100% water level
0%
Free-water level


oil
Po
OWC
Pw
h
Pi
water


Oil Column
Pressure
oil gradient
Pw
Pc
Po
FWL
water gradient
Depth


D
-55.3 - 4433.7 (TVDSS)
F
3338.2 - 4733.2 (TVDSS)
G
133.5 - 4428.5 (TVDSS)
H
128.9 - 4428.9 (TVDSS)
DEP (M) TVD
GR (GAPI)
SW (dec)
Sw_Ht
Sw_PcHt
POR (dec)
POR (%)
MDT ()
POR
Perm (md)
DST ()
PERM
CapPress.P
BASHK
BOBRI
TOUR
Hyd Model 2
4350
4300
4400


N
A
B
C
D
E
F
G
H
2 km

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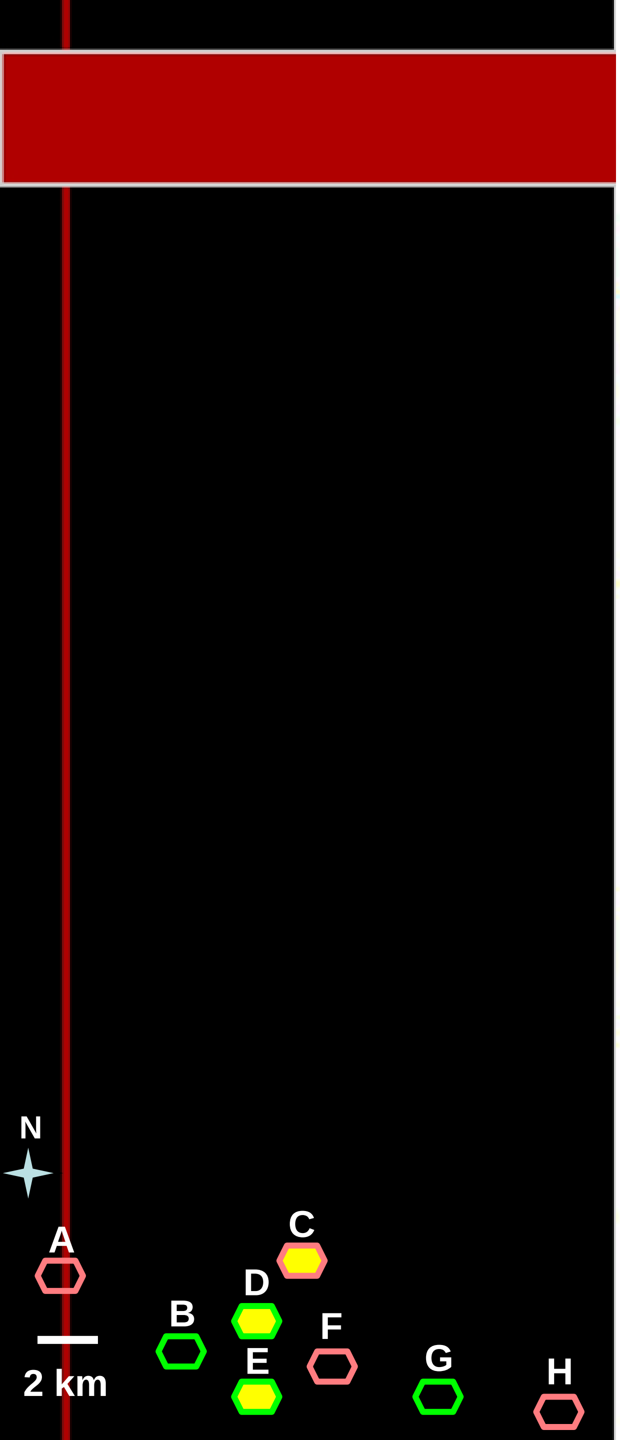
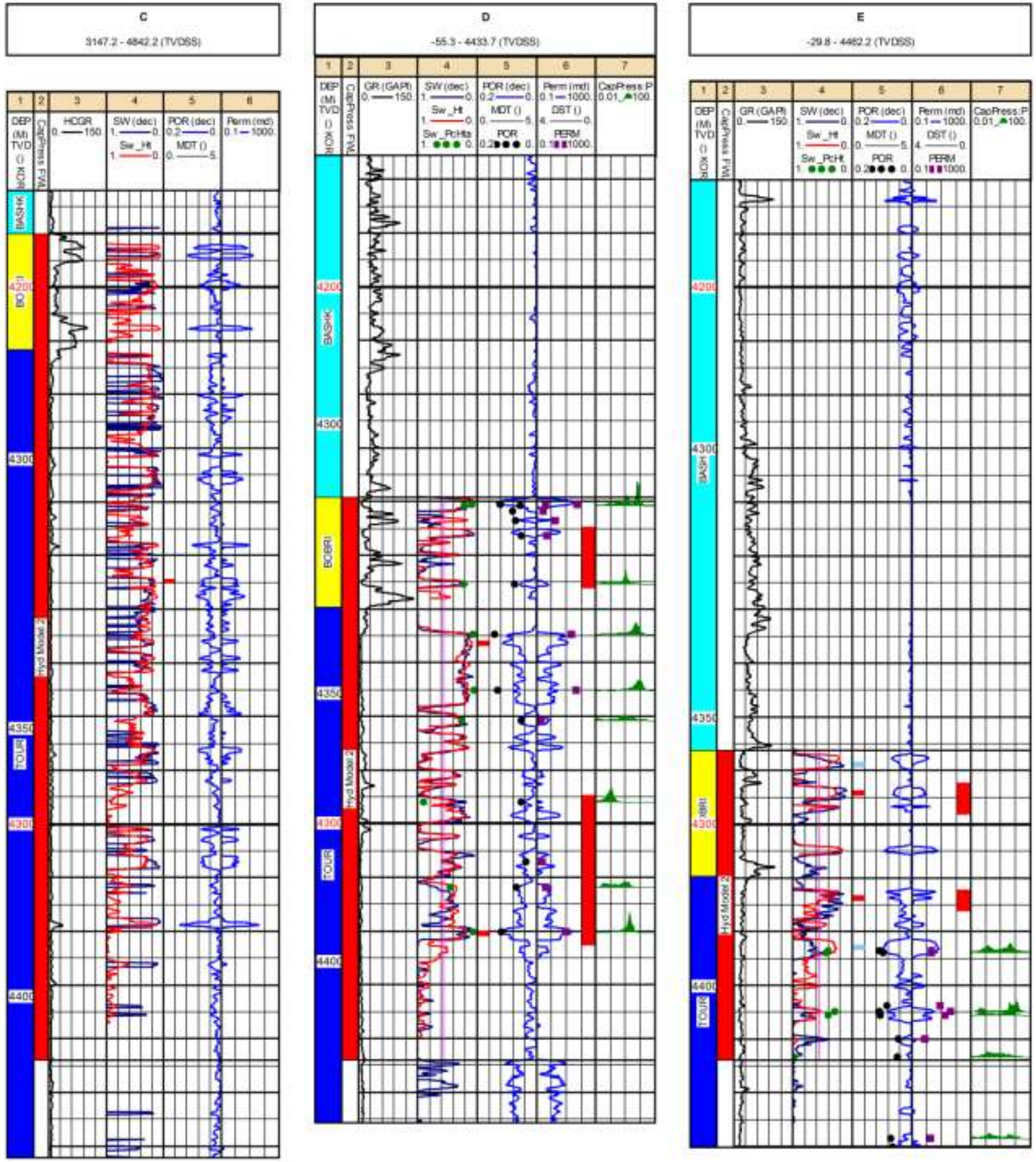
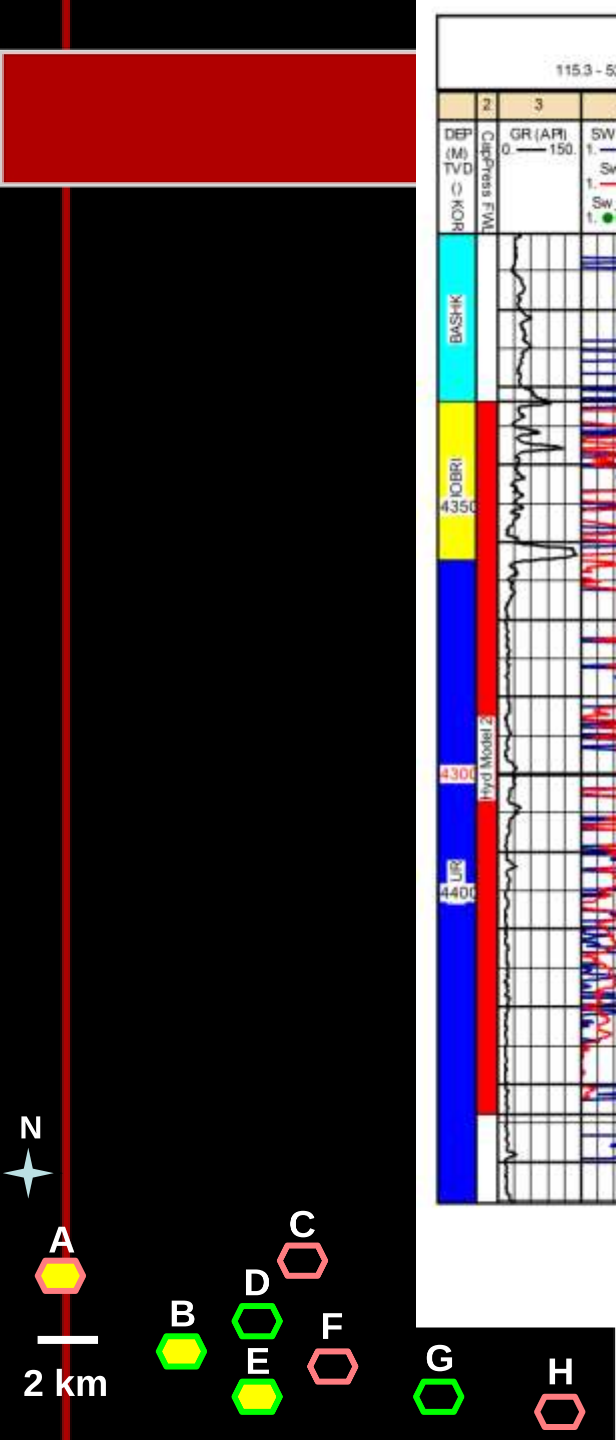
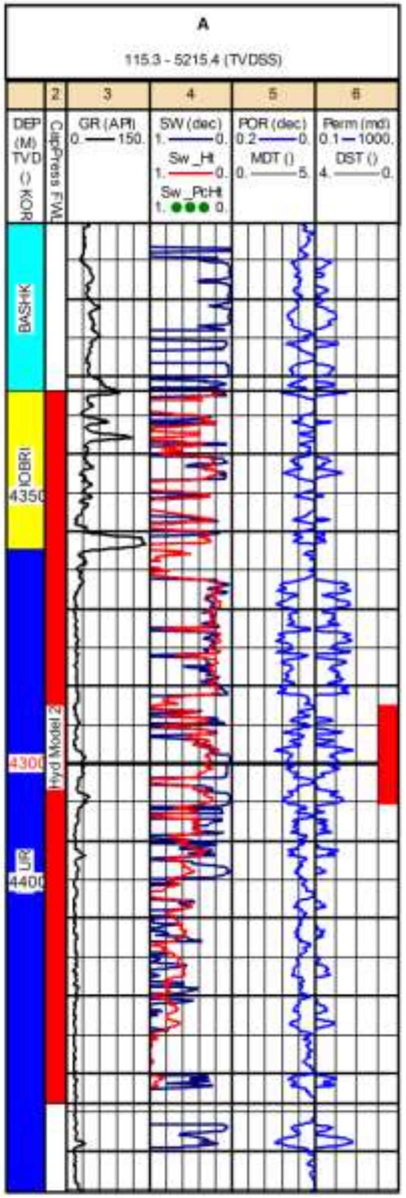
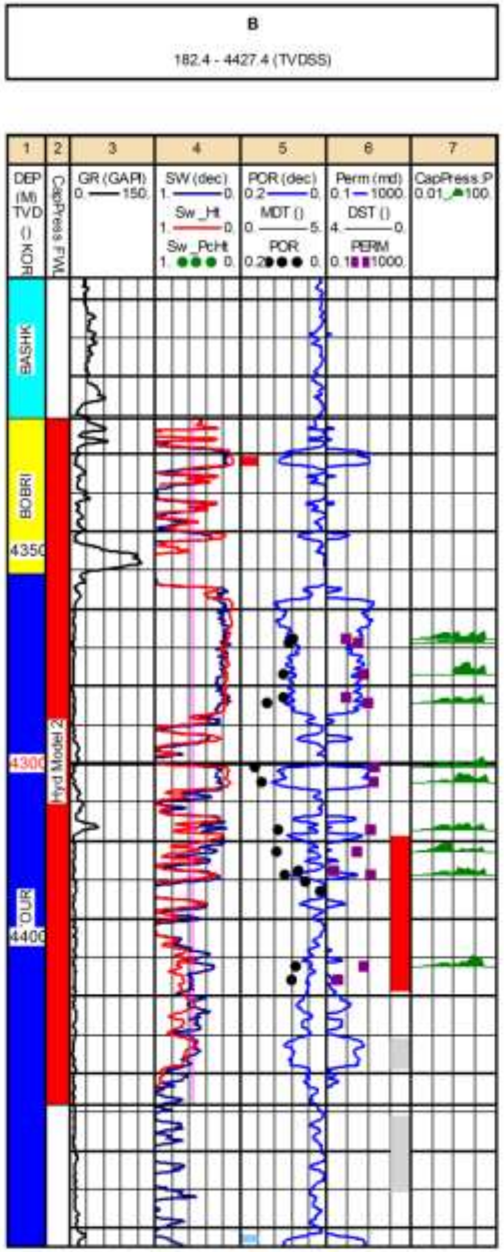
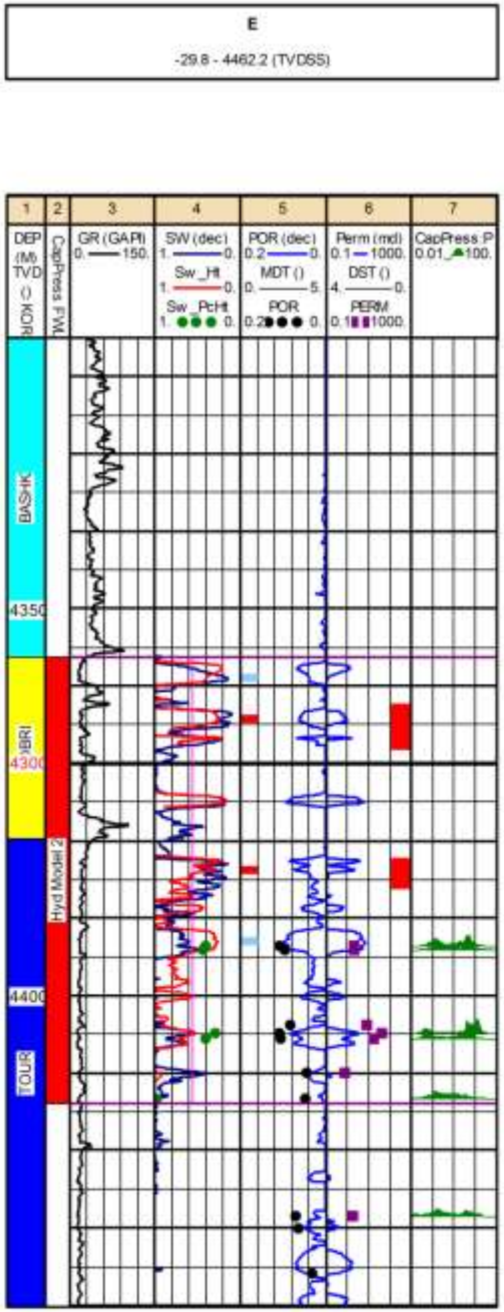

N
A
B
C
D
E
F
G
H
2 km


C
3147.2 - 4842.2 (TVDSS)
D
-55.3 - 4433.7 (TVDSS)
E
-29.8 - 4482.2 (TVDSS)
Hyd Model 2


N
A
C
D
B
F
E
G
H
2 km


A
115.3 - 5215.4 (TVDSS)
2 3 4 5 6
DEP (M) TVD () KOR
CapPress FWL
GR (API) 0. 150.
SW (dec) 1. 0.
Sw_Ht 1. 0.
Sw_PcHt 1. 0.
POR (dec) 0.2 0.
MDT () 0. 5.
Perm (md) 0.1 1000.
DST () 4. 0.
BASHK
BOBRI
TOUR
4350
4300
4400
Hyd Model 2


B
182.4 - 4427.4 (TVDSS)
1 2 3 4 5 6 7
DEP (M) TVD () KOR
CapPress FWL
GR (GAPI) 0. 150.
SW (dec) 1. 0.
Sw_Ht 1. 0.
Sw_PcHt 1. 0.
POR (dec) 0.2 0.
MDT () 0. 5.
POR 0.2 0.
Perm (md) 0.1 1000.
DST () 4. 0.
PERM 0.1 1000.
CapPress:P 0.01 100.
BASHK
BOBRI
TOUR
4350
4300
4400
Hyd Model 2


E
-29.8 - 4462.2 (TVDSS)
1 2 3 4 5 6 7
DEP (M) TVD () KOR
CapPress FWL
GR (GAPI) 0. 150.
SW (dec) 1. 0.
Sw_Ht 1. 0.
Sw_PcHt 1. 0.
POR (dec) 0.2 0.
MDT () 0. 5.
POR 0.2 0.
Perm (md) 0.1 1000.
DST () 4. 0.
PERM 0.1 1000.
CapPress:P 0.01 100.
BASHK
BOBRI
TOUR
4350
4300
4400
Hyd Model 2

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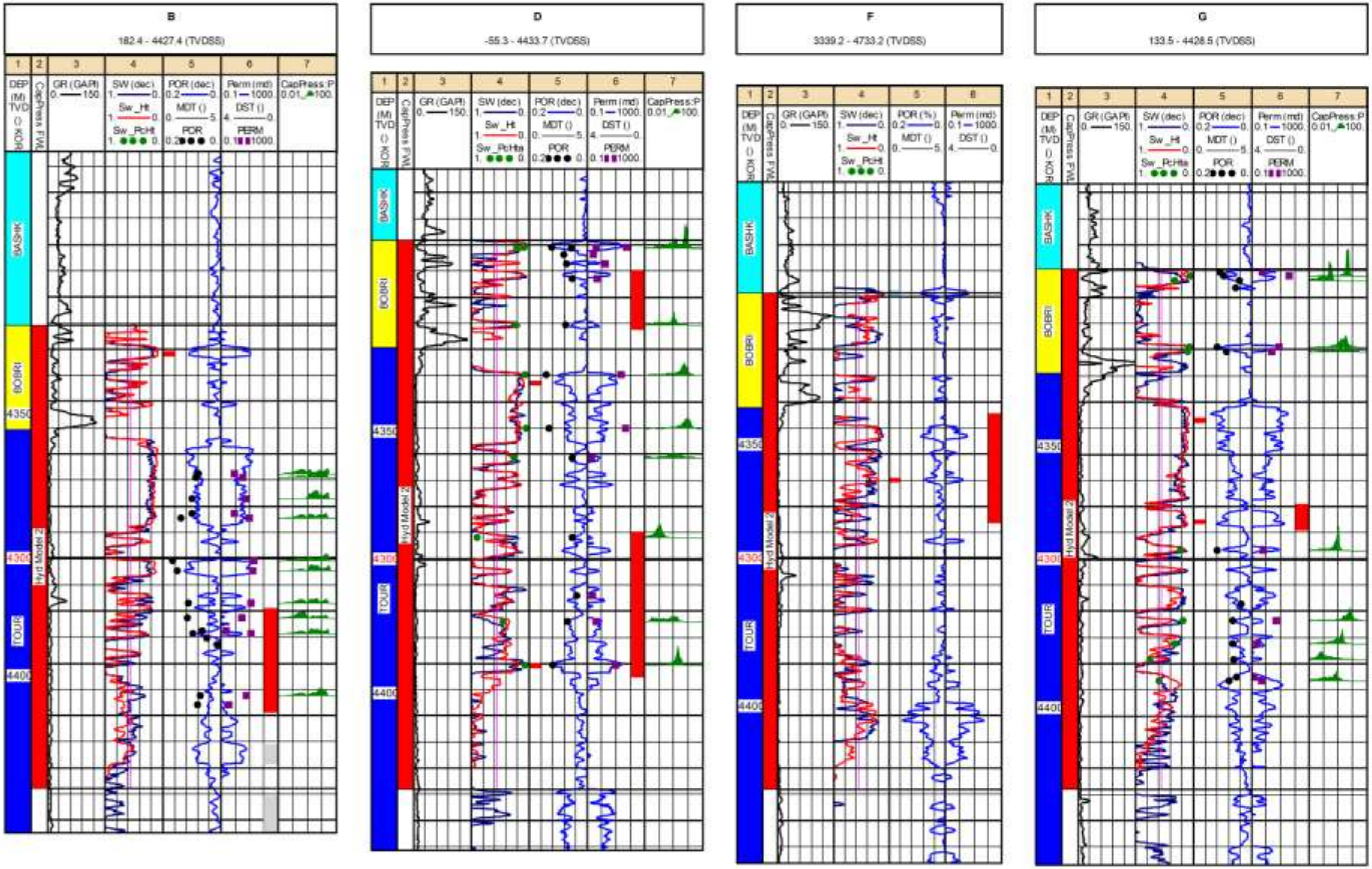
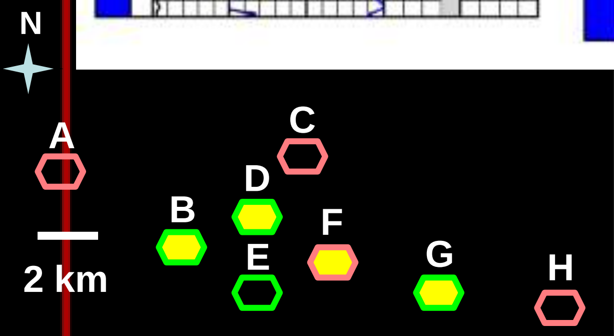
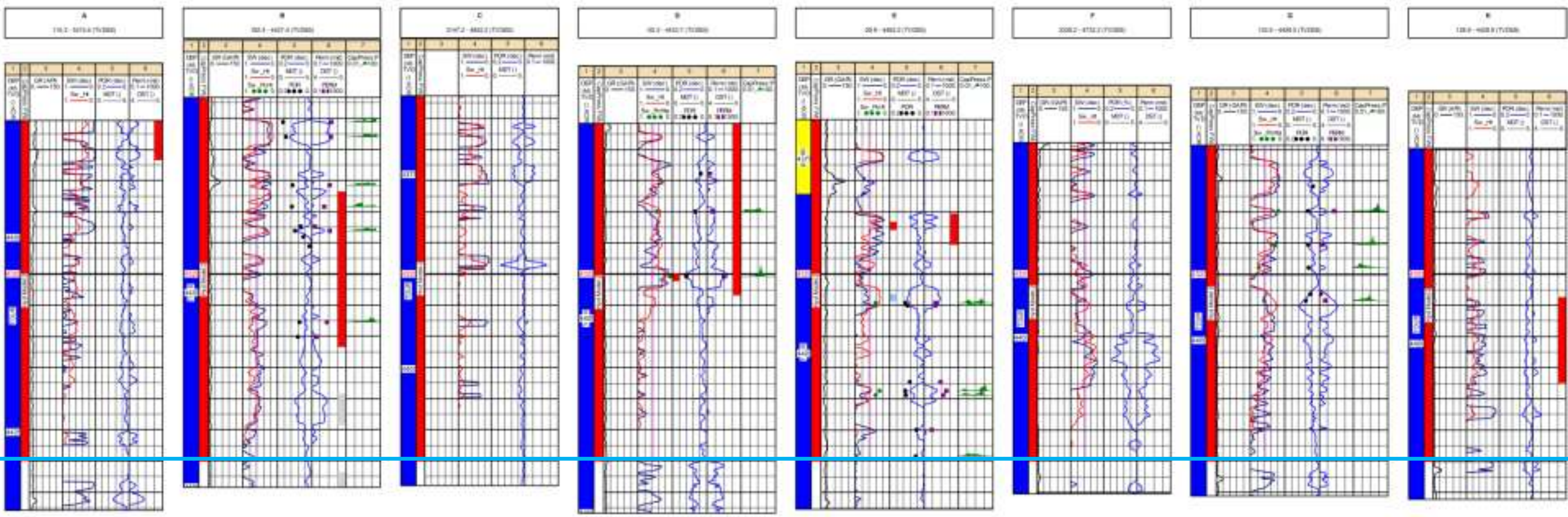
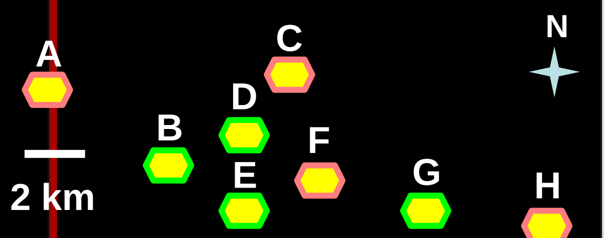

B
182.4 - 4427.4 (TVDSS)
D
-55.3 - 4433.7 (TVDSS)
F
3339.2 - 4733.2 (TVDSS)
G
133.5 - 4428.5 (TVDSS)
GR (GAPI)
SW (dec)
Sw_Ht
POR (dec)
MDT ()
POR
Perm (md)
DST ()
PERM
CapPress
BASHK
BOBRI
TOUR
Hyd Model 2
4350
4300
4400


N
A
C
D
B
F
E
G
H
2 km

MOL GROUP





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