Application of Saturation Height Model in Case of Depletion in Paleo Times*

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Abstract

In recent years, an increasing number of Middle East oil reservoir are believed to show indications of imbibition in paleo times as the result of tilting, quite possibly related to Late Tertiary orogeny (Al Kindi and Al Ismaili, 2016). Characteristics are 1) differences in apparent transition zone in opposite sides of the oil field, 2) misfit of core based (drainage) SHF to computed oil saturation, and 3) 'typical' residual oil observations (20-40%) below free water levels based on pressure data.

If present day free water level differs from the paleo free water level, estimates of in place oil volumes would benefit from a SHM that incorporates both the drainage and the imbibition stage. A publication by Pentland (2016) presents the concept based on reduction of the 'connected oil volume' during the imbibition stage, utilizing drainage based SHFs, FWL, PaleoFWL, and residual oil saturation.

This presentation will aim to present: 1) graphics that explain the concept, 2) the required equations broken down in easy steps, and 3) the (petrophysical) workflow to obtain the input variables required. The presentation is the result of its recent application to the reservoirs in the Shuaiba, Kharaib, and Lekwair of a Middle East oil field for an Abu Dhabi based EP Co. The presentation is intended for the benefit of petrophysical and geomodelling work and but will also try to incorporate the initial findings of the Reservoir Engineering team.

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Application of Saturation Height Model in Case of Depletion in Paleo Times

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3rd Edition: Carbonates of the Middle East AAPG Workshop

Implementation of (adapted) models proposed by Pentland and Land

Introduction

- Petrophysics => Geomodelling => Reservoir simulation
- Study of UAE oil field
  - Field shows gradual lateral change in oil-down-to observations
  - Oil observed below present-day FWL
  - Objective: to capture correct oil in place in geomodel
    - Oil leg
    - Transition zone
    - Residual

- This presentation: How to build SHM for reservoir that has undergone depletion?

Concept from the Pentland et al. 2016 SPE paper

- Pentland builds on publication by Land, 1968
- Concept of connected oil volume
- Imbibition curves based on 'rescaled drainage curves'

- SPE Reference 181573

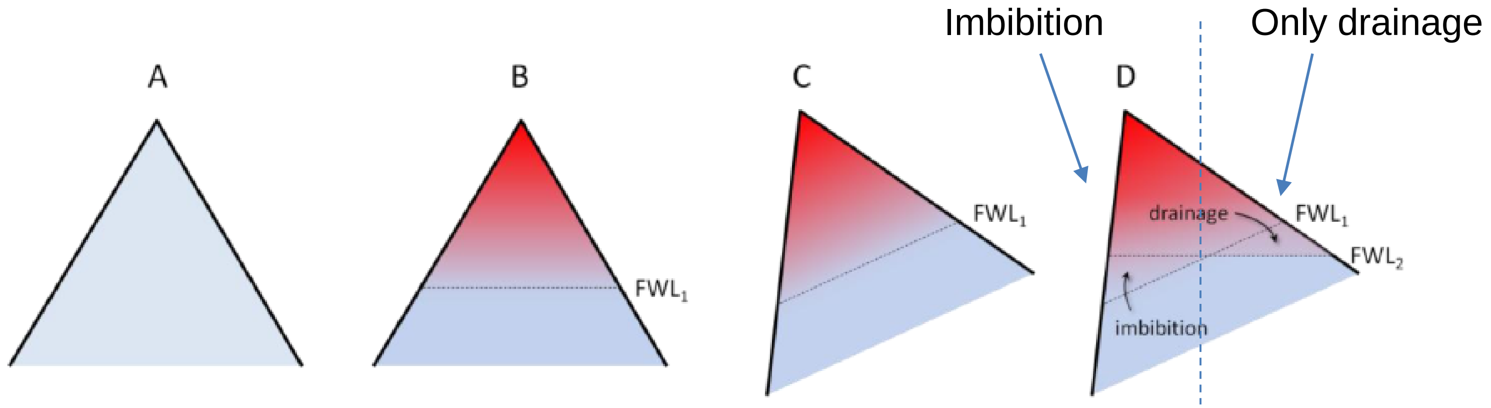
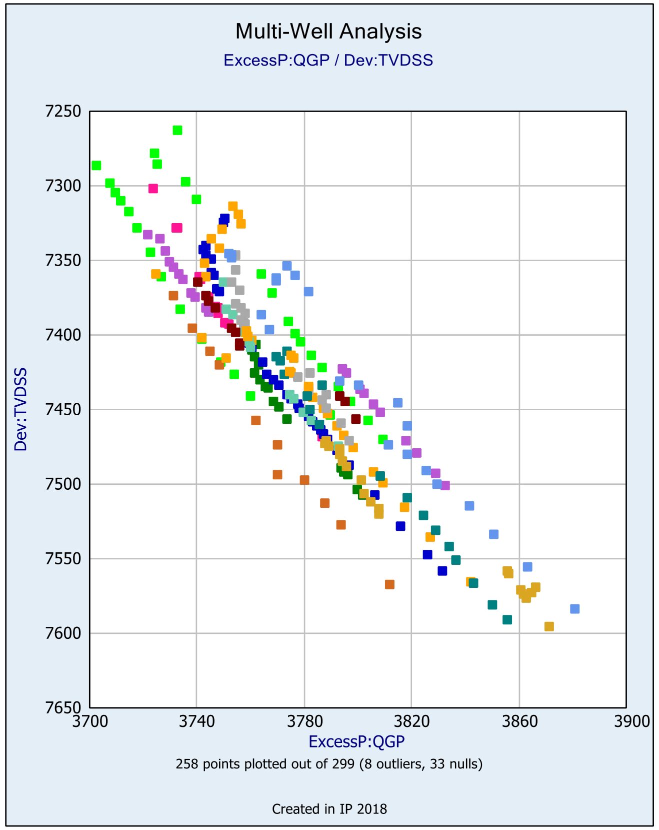


Figure 2—An illustration of fluid fill and subsequent redistribution in a field due to tilting. Initially the reservoir is brine filled (blue colour - A). Next it is partially filled with hydrocarbons (red colour) through a primary drainage charge (B) establishing a free water level (FWL_1). The field is then tilted (C) causing the fluids to redistribute (D). Tilting causes both drainage and imbibition flows and the result is a new free water level (FWL_2). The region above FWL_1 and below FWL_2 contains trapped hydrocarbons. Whether FWL_2 is encountered as horizontal or not will depend on a number of factors including the timescale of re-equilibration, lateral variations in fluid properties, and whether regional hydrodynamic flows are present.

Characteristics of UAE field (1/3) that lead to this AAPG presentation

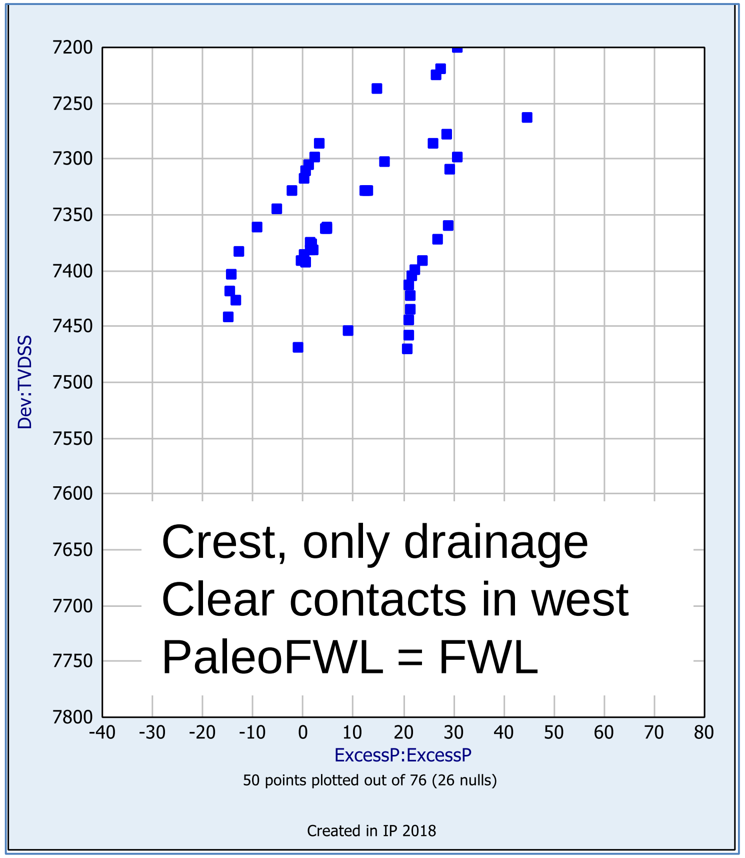
- Thamama reservoirs
- No gas cap

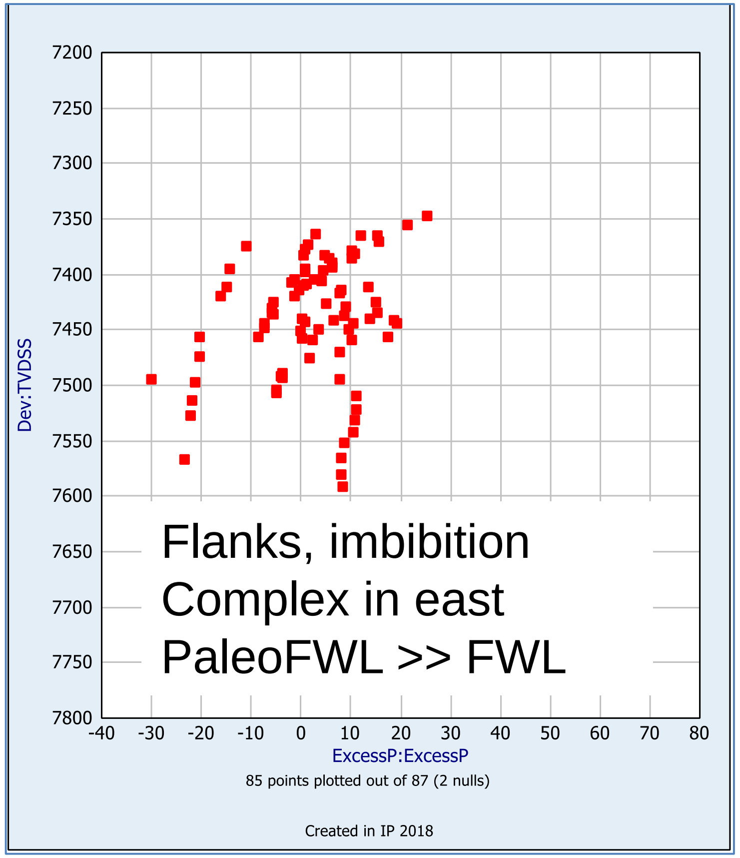
- No alignment of pressure gradients
- In some wells TZA appears disconnected from TZB
- Discussion about tilt FWL (variability pre-test pressure data)
- Deepest oil observations: one side ~flat, other side up to ~150 ft deeper (Core & SwArchie & Fluid Samples & Tests)



Characteristics of UAE field (2/3)
West vs east - excess pressure

- Interpretation FWL
  - West easy & crisp
  - East difficult & diffuse





- Subtraction of a common water gradient from pressures => ‘Excess pressure’ (Brown, 2003)

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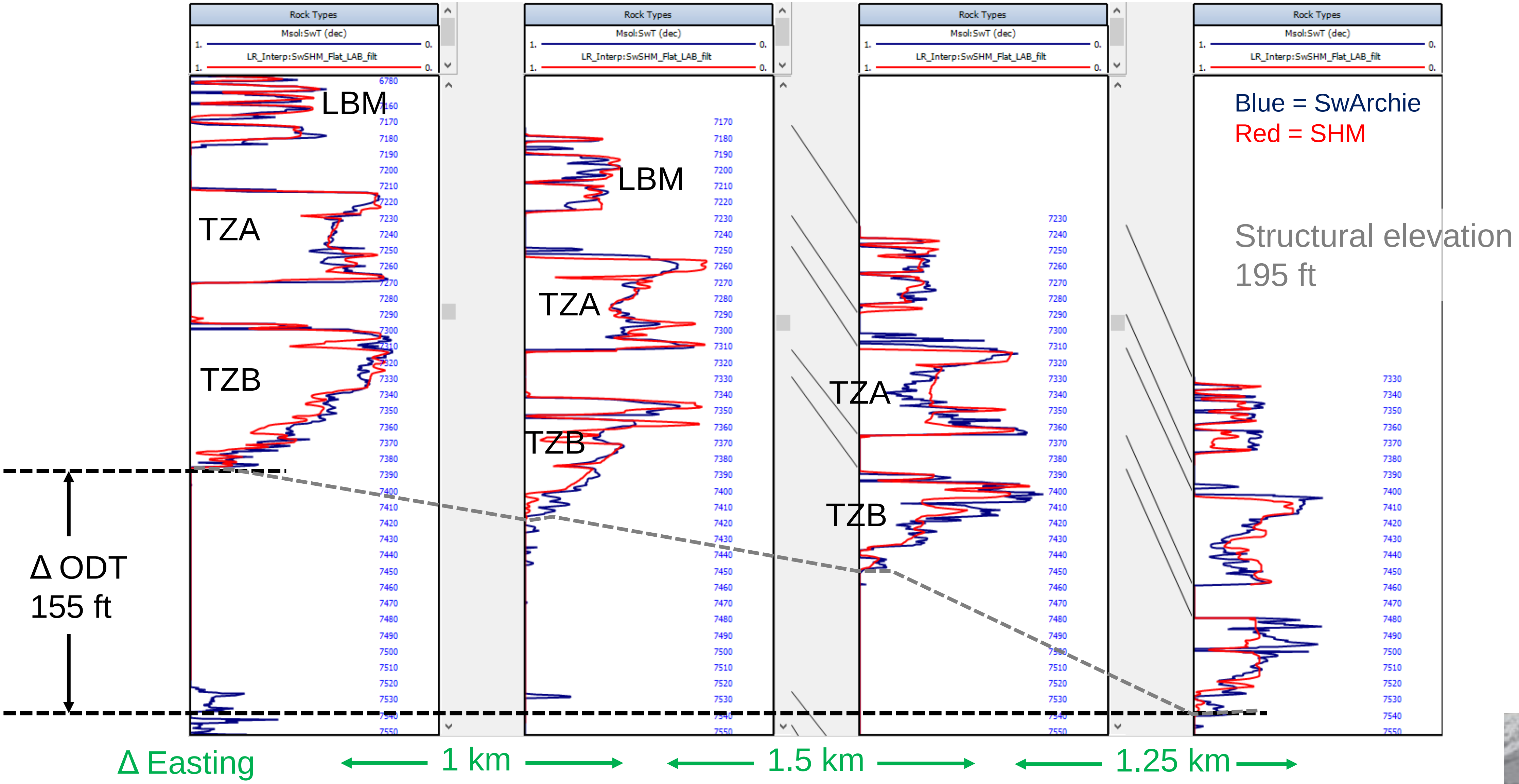
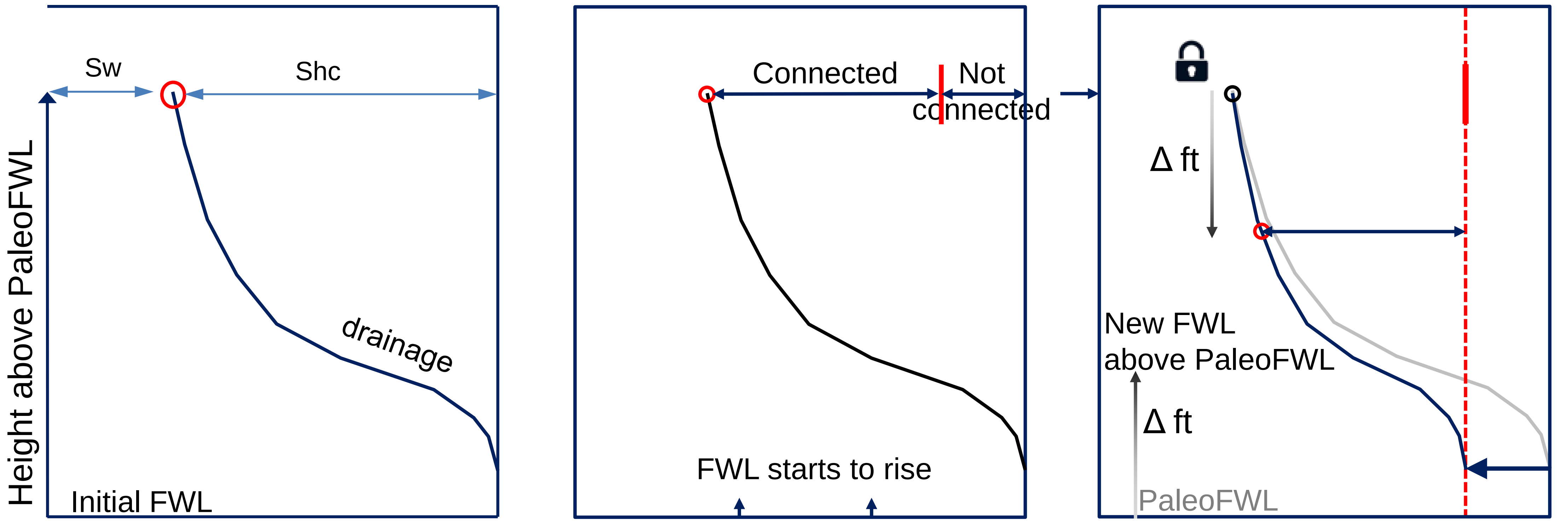
Characteristics of UAE field (3/3)
Observed gradient in ODTs



SHM: Drainage, split, imbibition



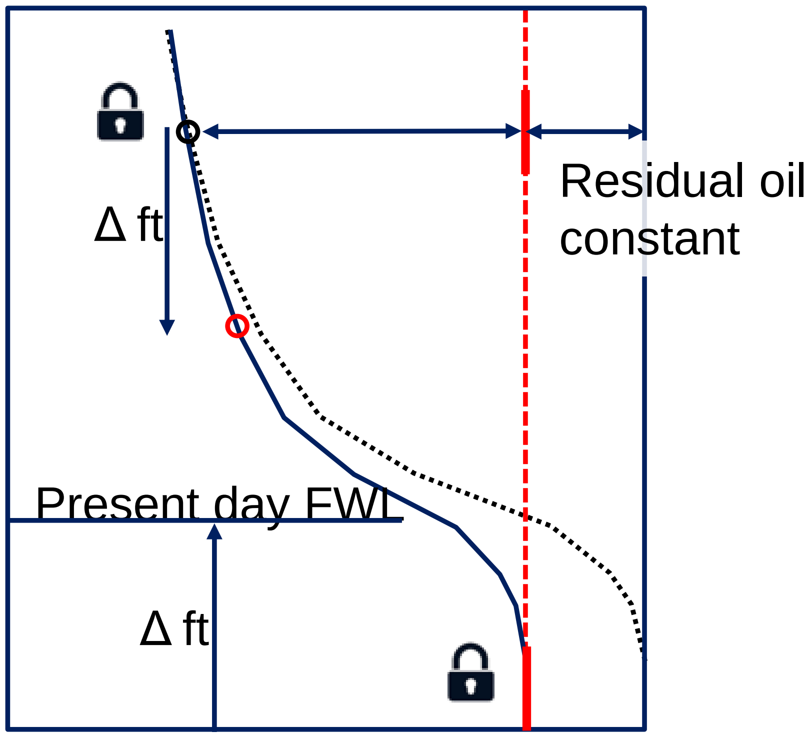
Situation 1: sample of rock at given height above (paleo) FWL at end of drainage stage

Situation 2: at start of imbibition, split of oil into connected, and not-connected

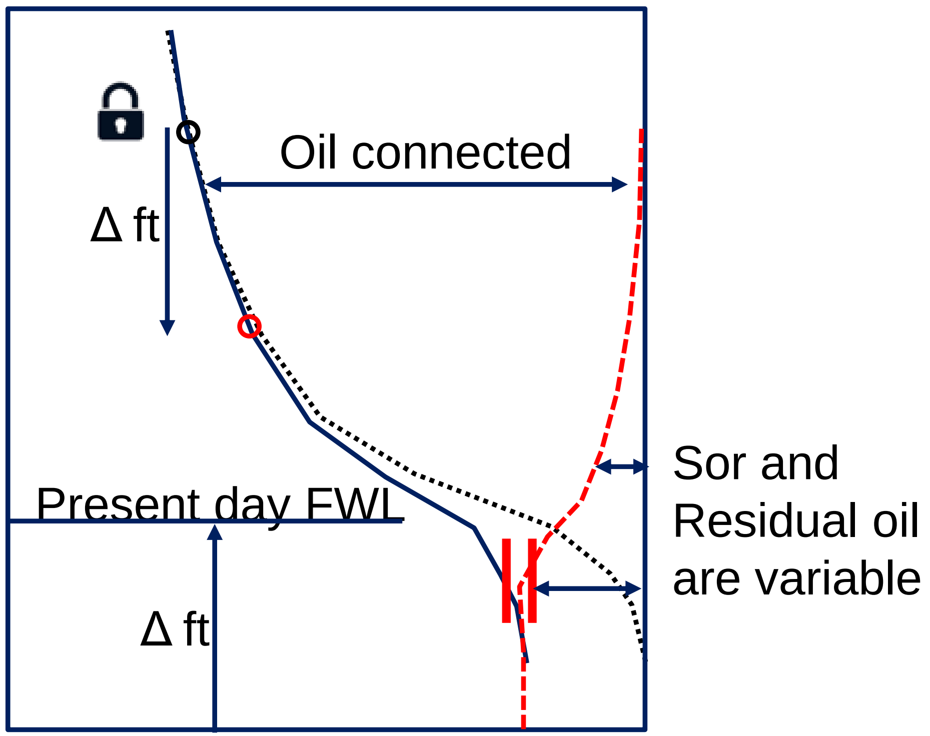
Situation 3: under imbibition, connected volume decreases

SHM difference simple model vs Pentland/Land

Simple application



Pentland / Land



What input is required

- For SHMs with imbibition
  - SHF, FWL, possible insitu ift x cos(theta)
  - PaleoFWL
  - Residual oil saturation Sor (or for gas Sgr)

- SHM is composite of 10 equations (next slides)
  - 5 for drainage
  - 5 for imbibition

SHM Equations – Part 1: Drainage stage (1/4)

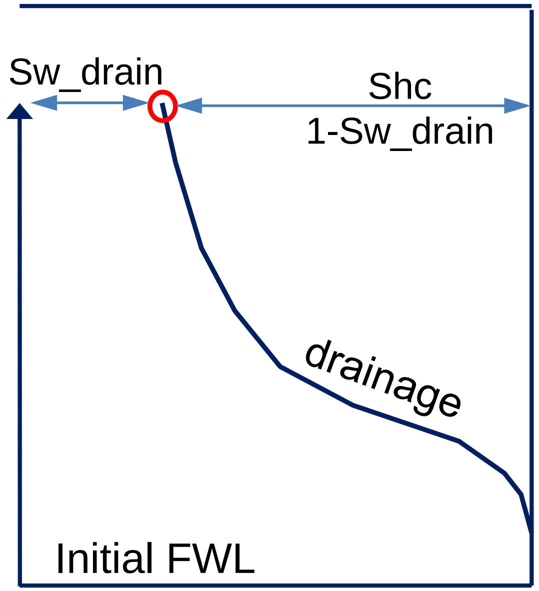
SHM Equations – Part 2: Imbibition stage

- 1. Drainage Stage

- Sw_drain = SHF(HtAbPaleo)
- Shc_drain = 1 – Sw_drain
- Sor_max = maximum residual oil
- Sor = min (Shc_drain, Sor_max)
- Shc_connected = Shc_drain – Sor

Any function (Lambda, Brooks-Corey, Skelt-Harrison, etc)
Core or log based

Input: Height above PaleoFWL



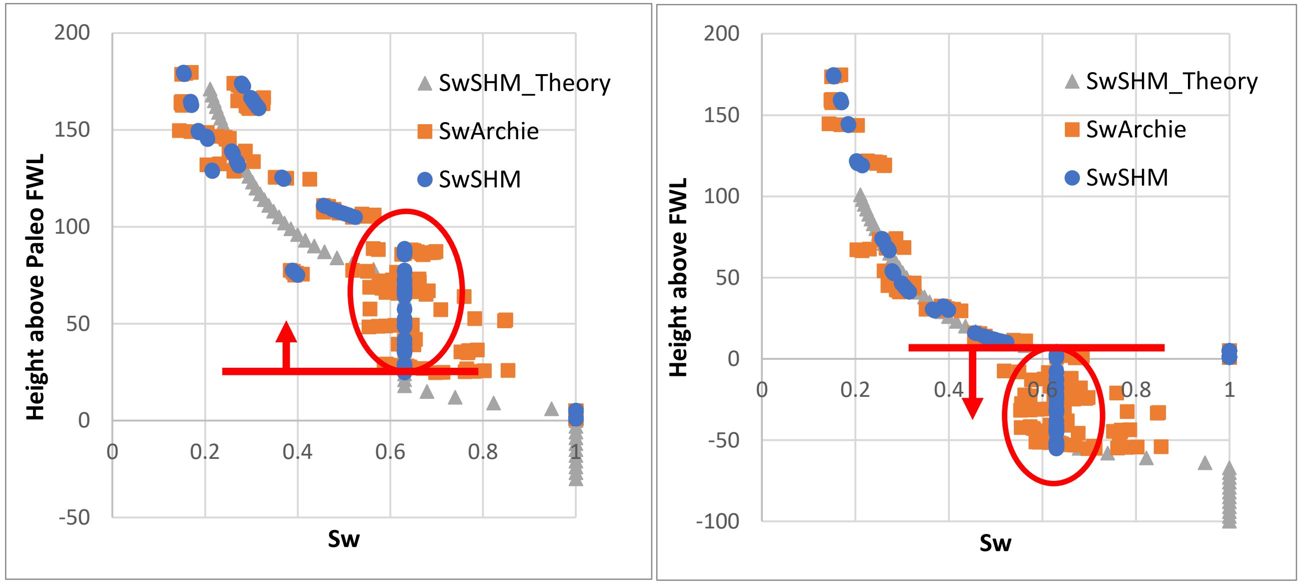
SHM Equations – Part 1: Drainage stage (2/4)
SHM Equations – Part 2: Imbibition stage

- 1. Drainage Stage

- Sw_drain = SHF(HtAbPaleo)
- Shc_drain = 1 – Sw_drain
- **Sor_max = maximum residual oil**
- Sor = min (Shc_drain, Sor_max)
- Shc_connected = Shc_drain – Sor

Options
- SwArchie
- Sxo (micro res, dielectric)
- Centrifuge PcSw
- Dean-Stark Sw if OBM

For SwArchie, residual interval 1) Ht Ab FWL < entry height, and 2) Ht Ab Paleo > entry height



SHM Equations – Part 1: Drainage stage (3/4)

SHM Equations – Part 2: Imbibition stage

- 1. Drainage Stage

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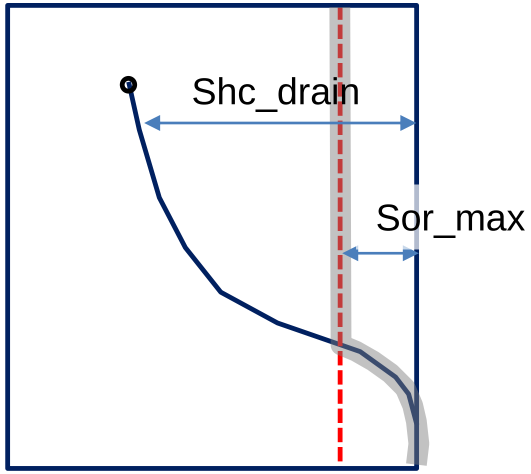


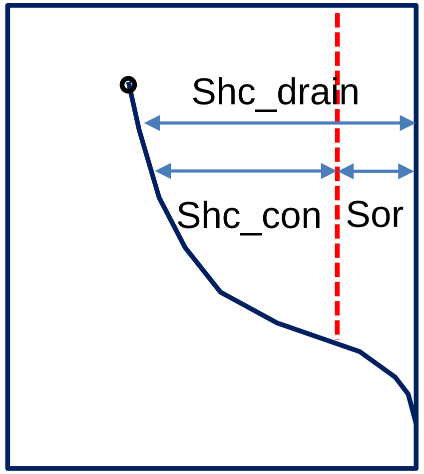
In this model, Sor is a constant equal to Sor_max. Consistent with forced imbibition curves from centrifuge drainage.

In Land model, Sor is variable

- Land Sor based on snap-off concept
- Zero snap-off at start of imbibition
- Maximum snap-off (Sor_max) when Ht Ab FWL returns to zero

SHM Equations – Part 1: Drainage stage (4/4)
SHM Equations – Part 2: Imbibition stage

- 1. Drainage Stage



- Sw_drain = SHF(HtAbPaleo)
- Shc_drain = 1 – Sw_drain
- Sor_max = maximum amount of residual oil
- Sor = min (Shc_drain, Sor_max)
- Shc_connected = Shc_drain – Sor ← Connected oil = total oil minus residual oil

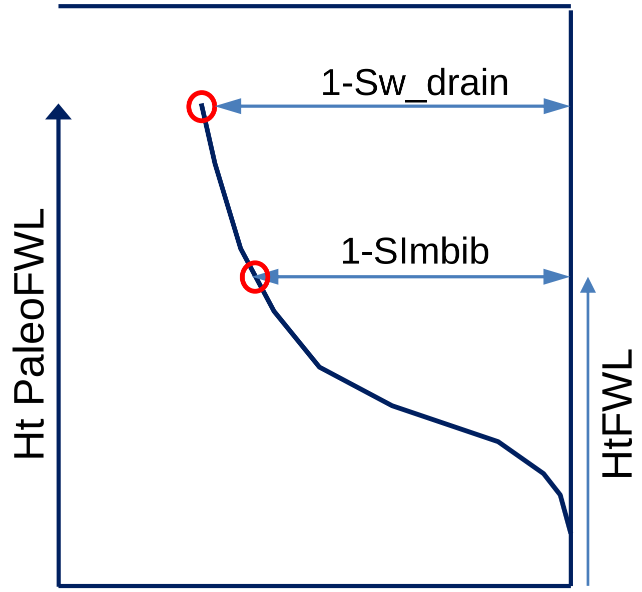
SHM Equations – Part 1: Drainage stage

SHM Equations – Part 2: Imbibition stage (1/3)

- 2. Imbibition stage:

Identical SHF, but now input Ht Above FWL
Result between 0 and 1

- SImbib = SHF(HtAbFWL)
- Frac_Connected = (1- SImbib) / (1 – SwDrain)
- Shc_imb_con = Shc_con * Frac_con
- Shc_imb_total = Shc_imb_con + Sor
- Sw_SHM = 1 – Shc_imb_total



SHM Equations – Part 1: Drainage stage

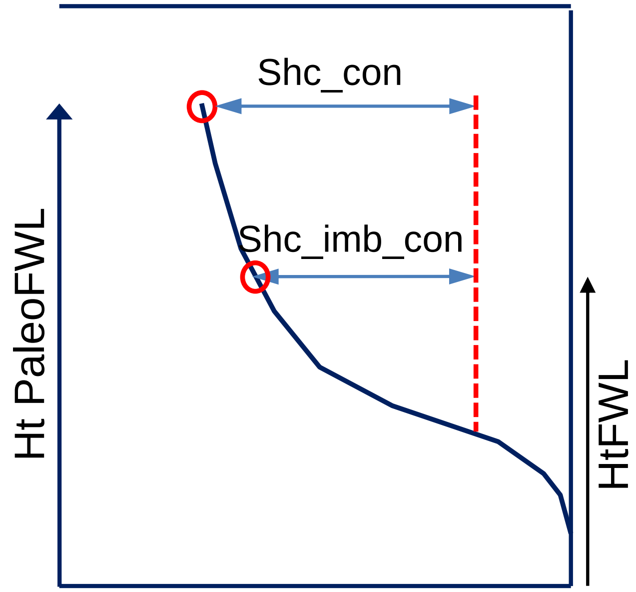
SHM Equations – Part 2: Imbibition stage (2/3)

- 2. Imbibition stage:

- Simbib = SHF(HtAbFWL)
- Frac_con = (1- Simbib) / (1 – SwDrain)
- Shc_imb_con = Shc_con * Frac_con
- Shc_imb_total = Shc_imb_con + Sor
- Sw_SHM = 1 – Shc_imb_total

Frac_con is: ratio of…
amount of hydrocarbon computed with FWL and that of PaleoFWL

Only *connected* oil volume is reduced



Example:
HC after drainage in paleo time = 50%
HC from SHF using FWL (Simbib) = 40%
Ratio = 40/50 = 90%
Ratio applied as fraction on connected hc

SHM Equations – Part 1: Drainage stage

SHM Equations – Part 2: Imbibition stage (3/3)

- 2. Imbibition stage:

- SImbib = SHF(HtAbFWL)
- Frac_con = (1- SImbib) / (1 – SwDrain)
- Shc_imb_con = Shc_con * Frac_con
- Shc_imb_total = Shc_imb_con + Sor
- Sw_SHM = 1 – Shc_imb_total

Re-combine

Typical workflow

1. Reservoir Rock Type (RRT) study
2. Build core based SHFs per RRT
3. Analysis observed fluids (MDT samples, production tests, core samples)
4. Define of Free Water Level (from pressure data)

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5. Optimise insitu IFT x cos(theta) – *based on 'drainage side of field'*
6. Define Sor per RRT (Sxo micro, Dean Stark, SwArchie in residual zone)
7. Estimate PaleoFWL per well - *deepest ODT minus entry height*
8. Optimise PaleoFWL per well by fitting the SHM

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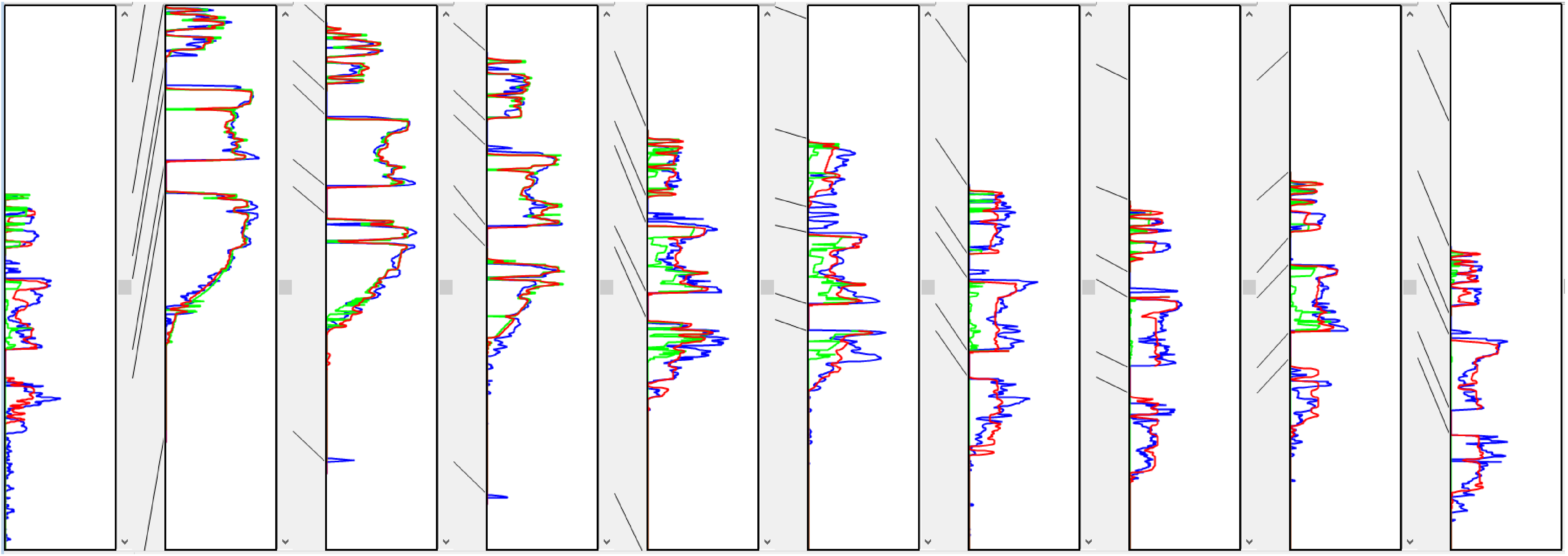
Comparison

SwArchie, SHM_imb, SHM_no imb

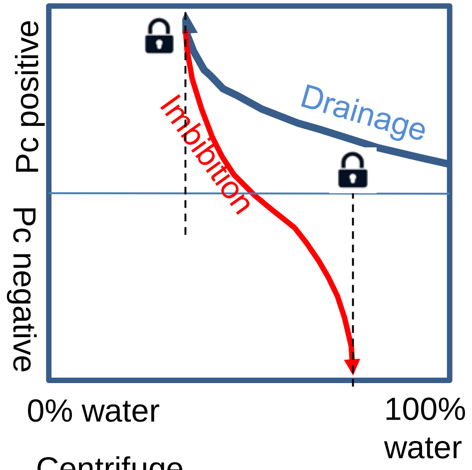


Summary

- Imbibition SHM can give Oil In Place in case of paleo depletion (oil leg, transition zone, residual)
- SHM composite of 10 simple equations
- The SHM also requires PaleoFWL and Sor

- Simplest model uses fixed Sor, in line with PcSw centrifuge data, and seems fit-for-purpose
- However, possible to incorporate variable Sor using - often cited - equations from Land, 1968
  - Iterative => would require bit more programming
  - Or simpler approximations

Example of centrifuge



Centrifuge conducted really fast!

Conclusion

- A simple SHM method for improved static models in case of paleo depletion

- Quite possibly more fields in UAE with depletion
- Some Paleo - depletion characteristics:
  - Core-based SHFs do not match SwArchie
  - Oil saturations (20-40%) below 'FWL + entry height'
  - ODTs vary across field
  - Pressure data (from pre-production wells) not showing sharp contacts
  - Pressure gradients offset from well to well (without geospatial relation)

- May be worth to try presented model (it's quick!)

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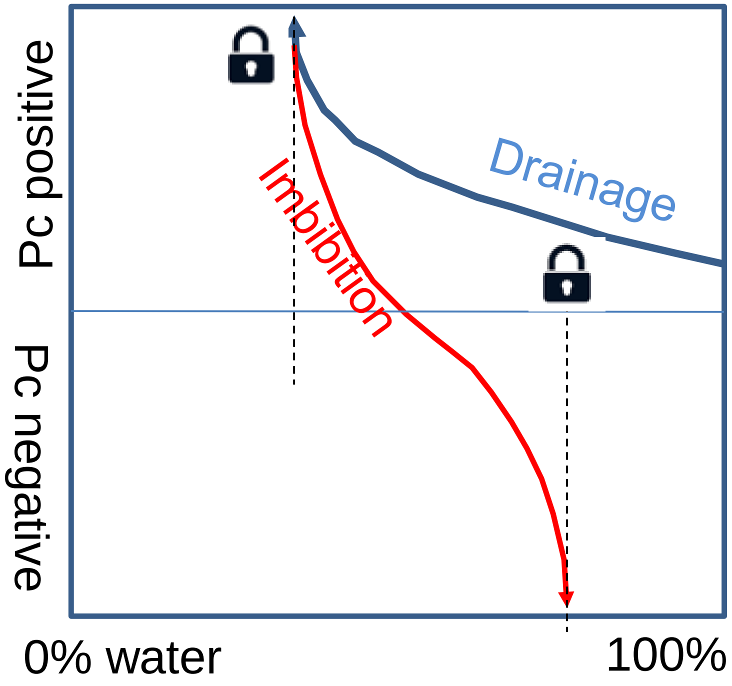
Centrifuge data

- Pentland proposed: for imbibition, use scaled drainage curve

- Presented today: most simple application of above concept
- Scaling based on Sw_initial, Sor
- Drainage curve rescale by anchoring at 2 points

Example of centrifuge



Centrifuge conducted really fast!

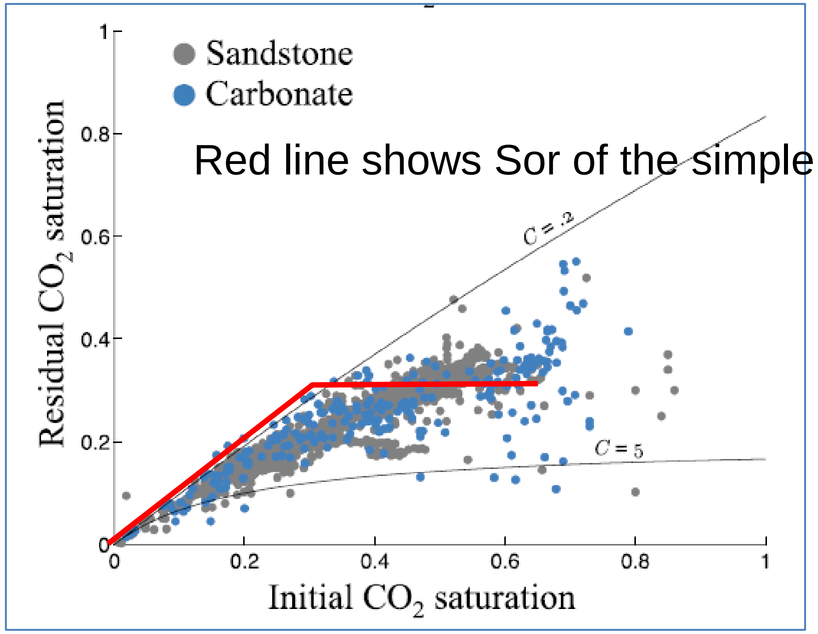
Sor from Land paper (1/3)

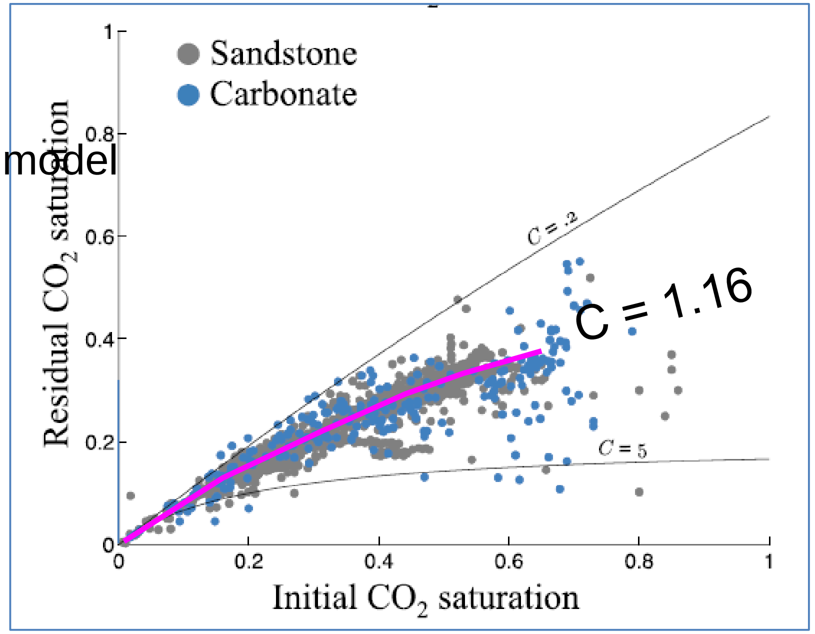
- Krevor et al, 2015

$$S_{o,c} = \frac{1-S_{wc}}{2}\left[\left(\frac{S_o-S_{or}}{1-S_{wc}}\right) + \sqrt{\left(\frac{S_o-S_{or}}{1-S_{wc}}\right)^2 + \frac{4}{C}\left(\frac{S_o-S_{or}}{1-S_{wc}}\right)}\right]$$

$$C = \frac{S_{oi}-S_{or}}{S_{oi}S_{or}}$$

Soi = Saturation oil initial
Sor = Saturation oil residual





Understanding residual oil saturation (Sor)

- The model presented in this presentation is a simplified application of Pentland/Land:
  - Fixed value of Sor per rock type
  - Maximum difference between FWL and PaleoFWL is about 100 ft

- How well do we know/understand Sor?
- Lab-experiment vs insitu
- Wettability
- Speed of lab experiments vs geological time

Sor from Land paper (1/3)

- Oil = Oil_connected + Oil_notconnected
- Oil_notconnected ≠ Oil_residual

$$S_{o,c} = \frac{1-S_{wc}}{2}\left[\left(\frac{S_o-S_{or}}{1-S_{wc}}\right) + \sqrt{\left(\frac{S_o-S_{or}}{1-S_{wc}}\right)^2 + \frac{4}{C}\left(\frac{S_o-S_{or}}{1-S_{wc}}\right)}\right]$$

- In general: Con_land >> Con_simple

$$S^*_{gF} = 1/2\left[(S^*_g - S^*_{gr}) + \sqrt{(S^*_g - S^*_{gr})^2 + \frac{4}{C}(S^*_g - S^*_{gr})}\right] \quad . . . (4)$$

Eq. 4 is an expression for the gas saturation that remains mobile after the gas saturation has been reduced from S^*_{gi} to S^*_g. This gas saturation

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Sor from Land paper (2/3)

- Connected oil volume by Land
  - So,c = f(Swc, Sor, C)
  - C = f(Soi, Sor)

- For a given rock: 1/Sor – 1/Soi = C
  - Hence: amount of residual gas (or oil) is a function of initial gas (or oil) saturation
  - More initial oil => more residual (trapped) oil

- But how variable is residual oil really?? (see next slide)

$$S_{o,c} = \frac{1-S_{wc}}{2}\left[\left(\frac{S_o-S_{or}}{1-S_{wc}}\right) + \sqrt{\left(\frac{S_o-S_{or}}{1-S_{wc}}\right)^2 + \frac{4}{C}\left(\frac{S_o-S_{or}}{1-S_{wc}}\right)}\right]$$

So,c = Saturation oil, connected
So = Saturation oil
Sor = Saturation oil residual
Swc = Saturation water connate

$$C = \frac{S_{oi}-S_{or}}{S_{oi}S_{or}}$$

Soi = Saturation oil initial
Sor = Saturation oil residual

$$C = \frac{1}{(S^*_{gr})_{max}} - 1$$

(S*gr)max = Saturation residual maximally achievable after maximum hydrocarbon fill

So_residual from the Land paper (3/3)

$$C = \frac{S_{oi}-S_{or}}{S_{oi}S_{or}}$$

$$Sor = \frac{Soi/C}{Soi + {}^{1}/_{C}}$$

$$C = \frac{1}{(S^*_{gr})_{max}} - 1$$

- Examples:

Sor_max	C	Soi	Sor	Sor_max - Sor
0.40	1.50	0.8	0.36	0.04
0.40	1.50	0.7	0.34	0.06
0.35	1.85	0.6	0.28	0.07
0.30	2.33	0.6	0.25	0.05
0.30	2.33	0.45	0.22	0.08
0.25	3.00	0.6	0.21	0.04

- Differences between Sormax and Sor are small ~ 0.04 to 0.08
- Conclusion: difference too small for identification as a variable.

Simple concept in alternative wording

- At end of drainage stage:
  - Amount of water = Initial water * fraction of water to remain [0-1]
  - SwSHF = 1.0 * SHF(paleo_fwl)

- At 'end of drainage' – and equivalent to - 'start of imbibition':
  - Amount of oil = Oil_notconnected + Oil_connected

- At end of imbibition:
  - Amount of oil = Oil_notconnected + Oil_connected * fraction of oil to remain [0-1]
  - Shc = So_residual + Soil_enddrainage * (1-SHF(fwl))