DEEP SALINITY-INDEPENDENT WATER SATURATION FROM LOW-FREQUENCY-DIELECTRIC ROCK PROPERTIES

Scott J. Jacobsen[1], Keith Bartenhagen[2], Barbara I. Anderson[1], Frank Shray[1], James Hemingway[1], Eric Decoster[1], Peter R. Swinburne[1]

[1]NoHiddenPay, LLC
[2]EOG Resources

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We thank the SPWLA for the opportunity to present our work.

This is actually a bit of a compendium of what we showed in Stavanger in June. I'm going to focus on our findings on deriving a deep salinity-independent water saturation from low-frequency – that is, in the LWD band – dielectric rock properties, with some added examples.

I want to recognize co-authors Keith Bartenhagen at EOG resources, and Barbara Anderson, Frank Shray, James Hemingway, Eric Decoster and Peter Swinburne from No Hidden Pay, LLC.

- INTRODUCTION
- PERMITTIVITY TO POROSITY
- RADIAL PROFILES: POROSITY, SW
- CONCLUSIONS

Here is an outline of the talk.

I will make a brief introduction as to our rationale for implementing this process and a quick review of the principles.

Then I'll describe the steps of deriving porosity from 2 MHz permittivity.

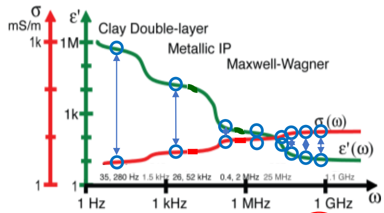
We will look at both porosity and subsequent water saturation at various tool spacings from a few log examples.

Then I will make conclusions and recommendations.

- **INTRODUCTION**
- PERMITTIVITY TO POROSITY
- RADIAL PROFILES: POROSITY, SW
- CONCLUSIONS

Let me introduce our motivation for this work.

INTRODUCTION: PERMITTIVITY DISPERSION



$$\varepsilon(\omega) = \varepsilon'(\omega) + i\,\varepsilon''(\omega) = \varepsilon'(\omega) + i\,\frac{\sigma(\omega)}{\omega\,\varepsilon_0}$$

- Diagram of fundamental electrical properties seen by logging tools in earth formations
- At any depth: characteristic frequency signature - "dispersion"
- High **permittivity** dispersion
- Polarization mechanisms due to physical texture/matrix of formation

Diagram of fundamental electrical properties seen by logging tools in earth formations at any given depth in the well. The Y axes of this graph are values of the two main EM formation properties – electric conductivity, and dielectric permittivity. The X-axis is the frequency range of petrophysical EM logging tools that are used, mostly for conductivity, that is, resistivity.

Note permittivity is on a logarithmic scale. And note the large frequency sensitivity of permittivity – or dispersion- across the band. This is due to various frequency dependent polarization mechanisms – seen posted on the figure - across the band that are governed by the microscopic texture or fabric of earth formations. We feel this is a very important relationship which can be exploited to better understand controls on well productivity, and on how to improve it.

Permittivity has not been used much in typical petrophysics over time, except at high-frequencies. In fact, high-frequency dielectric permittivity found initial use in the late 70's to deliver salinity-independent water-filled porosity. This is still a main application today everywhere in the world.

Later, more frequencies in the high range were added to measure dispersion for attributes like formation factor, a significant first step in using it for formation flow properties.

Our focus is on inversion for dielectric formation properties in the LWD band, for various reasons.

INTRODUCTION: LWD BAND FOCUS:

MOTIVATION

- Dielectric formation property potential for petrophysics un-explored in LWD-band frequency range
- LWD tools enable dispersion derivation
- WL dielectric tool issues can be significant
- LWD measurements are typically deep-reading, in un-invaded formation
- LWD TCOM increasingly replacing WL for OH data acquisition

Dielectric formation property potential for petrophysics is basically un-explored for all practical purposes in LWD-band frequency range. Some excellent laboratory work and field work has been published more recently. This needs to continue.

LWD tools enable dispersion derivation as most operate at two frequencies.

WL dielectric tool issues can be significant: invasion, borehole rugosity, oil based mud, conveyance in high deviation.

LWD measurements are typically deep-reading, in the usual un-invaded formations seen at LWD time.

LWD TCOM has increasingly replaced WL for OH data acquisition

INTRODUCTION: APPLICATION DEVELOPMENT GOALS

- Salinity-independent $\emptyset_w$ at 2 MHz
- Permittivity/conductivity dispersion interpretation for reservoir properties:
  - ➢LWD-band alone
  - ➢In conjunction with available HF (dielectric tool) and LF (resistivity tool) data

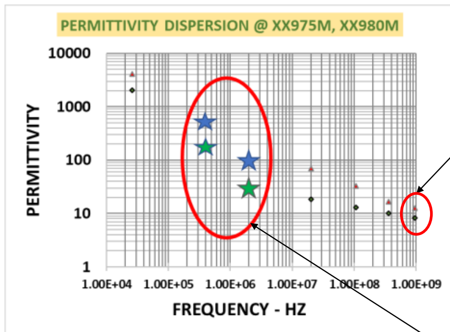
Operating in the LWD frequency band demands that we – and the petrophysical community at large- achieve some application development goals.

The first is to produce a salinity-independent $\emptyset_w$ from 2 MHz permittivity.
A chronic issue in formation evaluation is the dependency of water saturation accuracy on water resistivity accuracy, and the impact this has on resource estimates and operational and financial decisions. This is especially problematic in the expensive offshore exploration and development environments as well as in secondary recovery projects.
The application is well established in using high-frequency WL tools, it needs to be achieved with LWD tools.

Subsequent to this there is a perhaps even greater need to develop permittivity/conductivity dispersion interpretation for the reservoir texture/fabric properties that control well productivity in two data scenarios:

- LWD-band alone
- Potentially, in admittedly rare cases, in conjunction with available HF (dielectric tool) and LF (resistivity tool) data. E.g, Exploration wells with both LW and LWD; pilot hole and close lateral situations.

INTRODUCTION: APPLICATION DEVELOPMENT - $\emptyset_w$ AT 2 MHZ



- Permittivity change at 1 GHz due only to change in water-filled porosity , $\emptyset_w$, for a given lithology.
- No sensitivity to water salinity
- We focus on dielectric property inversion in LWD band.
- Can we still deliver $\emptyset_w$ with no dependence on water salinity from 2 MHz permittivity?

Starting with the $\emptyset_w$ application, here is actual combined AIT and ADT WL, and LWD permittivity data in an unconventional formation from two separate depths in the well plotted to see the dispersion behavior. Notice how it resembles the earlier generic dispersion diagram.

We are not going to interpret the dispersion here, but now note the permittivity change at 1 GHz. This is due only to change in water-filled porosity , $\emptyset_w$, for a given lithology. At this high frequency there is no sensitivity of dielectric permittivity to water salinity; thus the huge application for areas of fresh/unknown Rw values.

With our focus on dielectric property inversion in LWD band, can we still deliver $\emptyset_w$ with no dependence on water salinity from 2 MHz permittivity? This is a critical application to address and our current highest priority.

INTRODUCTION: LWD DIELECTRIC INVERSION PROCESS

- Field test concluded – 75 data sets, global coverage
- Mathematical improvements made to homogeneous medium algorithm
- Converges rapidly
- Numerically stable/accurate
- VENDOR NEUTRAL – via SPWLA RtSIG
- **Permittivity** outputs
- **Resistivity/Conductivity** outputs: dielectric constant assumption obviated
- QC:
  - Diagnosis for anisotropy /inhomogeneity
  - Dielectric independent resistivity
  - Loss tangent

$$\frac{\partial PS}{\partial \sigma} = -\frac{\partial AT}{\omega \partial \varepsilon}$$

$$\frac{\partial AT}{\partial \sigma} = \frac{\partial PS}{\omega \partial \varepsilon}$$

Of course we first have to process LWD field data with a dielectric inversion. This process has been implemented and our field test now concluded with about 75 data sets and global coverage.

Mathematical efficiency improvements have been made to a published homogeneous medium algorithm

It Converges rapidly, and is numerically stable/accurate

It is VENDOR NEUTRAL – via SPWLA RtSIG

Permittivity outputs

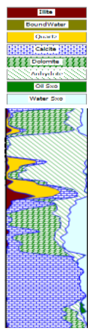
Resistivity/Conductivity outputs: dielectric constant assumption obviated

QC:

Diagnosis for anisotropy /inhomogeneity
Dielectric independent resistivity
Loss tangent

INTRODUCTION: DIELECTRIC PROPERTY MODELING (DPM) IMPLEMENTED

- Inputs: Volumetric analysis, formation parameters
- Outputs: Permittivity, conductivity curves at all common tool frequencies



Parameter	Units	Range
Frequency	Hz	10^1 to 10^9
Mineral volume fraction	v/v	0 - 1
Mineral DC permittivity		4 to 20
Mineral spherical grain radius	m	1×10^{-3} to 5×10^{-7}
Conductive mineral conductivity	S/m	1000 to 500
Conductive mineral diffusion coefficient	m^2/s	5×10^{-5}
Non-conductive mineral surface conductance	S	1×10^{-9} to 1×10^{-7}
Water salinity	S/m	1 to 50
Water diffusion coefficient	m^2/s	1×10^{-9}

(Adapted from Jin and Misra, SPWLA, 2020)

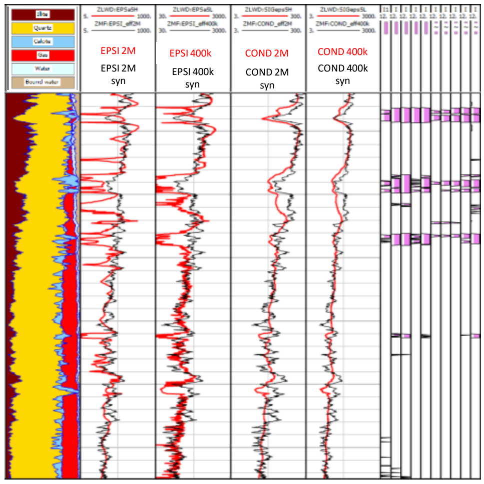
While testing the inversion itself, we wanted to investigate how the EM properties in the LWD band related to key petrophysical properties. So we also implemented a geo-electromagnetic model, published by Jin and Misra in 2020.

The process takes volumetric analysis from log data, plus other formation properties, and simulates permittivity and conductivity in the LWD band and in fact, at all common tool frequencies.

We see that some of the key sensitivities of the model are of course to water salinity, but also to clay particle size and clay surface conductance, essentially CEC.

So, how do we use this?

INTRODUCTION: CROSS-VALIDATION



- Dielectric inversion
- Dielectric property modeling

For the majority of the data sets in our field test campaign, we performed both LWD band dielectric inversion on the propagation tool data, and dielectric property modeling using the nuclear and resistivity data.

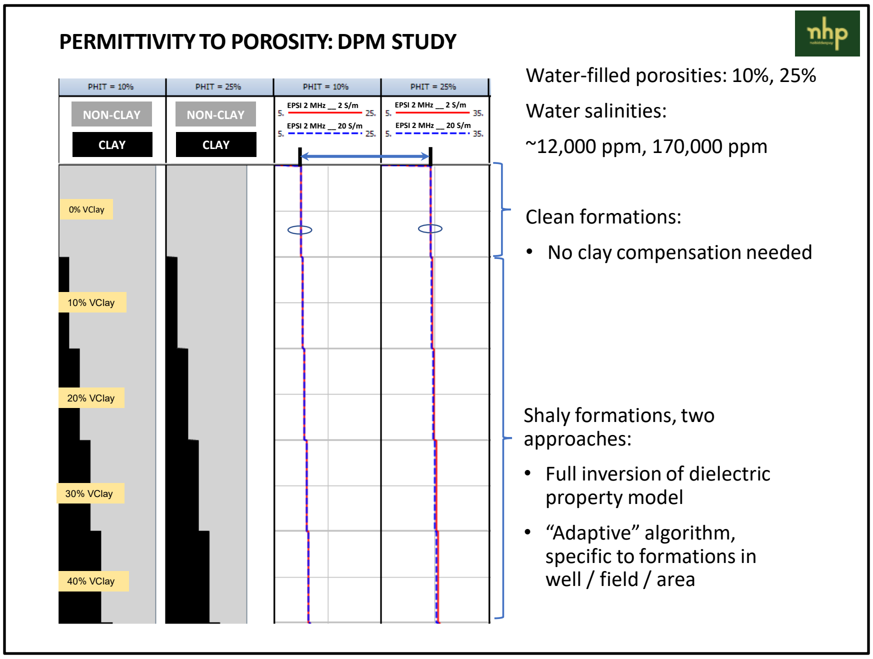
We then compared the results from both processes and see that the modeled and actual inverted permittivities and conductivities reconstruct each other rather well, as seen in the figure. And because of this we assert that the two processes cross-validate each other in terms of accuracy, via their respective dependencies on the actual formation characteristics that drive both the inverted data and the dielectric property modeling.

This gives us good confidence in both processes. And this in fact allows QC on the dielectric inversion, and it allows an iterative forward-modeling inversion for key formation properties simultaneously: we can vary the petrophysical interpretation to produce dielectric property results which reconstruct the inverted quantities from the tool data.

The figure also highlights the situations where the formation is not well-described by a homogeneous medium. The diagnostic flags show excessive inversion iterations in intervals where there are known thin, tight calcite stringers. These would certainly present a strong anisotropic condition to the measurement, and confidence in the inverted permittivity is reduced to some degree.

- INTRODUCTION
- **PERMITTIVITY TO POROSITY**
- RADIAL PROFILES: POROSITY, SW
- CONCLUSIONS

So, let’s take permittivity to porosity. Our first step was to create a synthetic formation case study.



We constructed two synthetic sandstone formations with water-filled porosities of 10% and 25%. We then used the dielectric property model to derive 2 MHz permittivities at water salinities of about 12,000 ppm and 170,000 ppm. These represent water conductivities of 2 S/m and 20 S/m at 20 deg C. We also increased the clay content in steps from 0% to 40% with depth.

The first key result is that the 2 MHz permittivity is very sensitive to the increase in water-filled porosity – almost linearly in fact – if the formation has no clay. And simultaneously the model shows little to no sensitivity to water salinity.

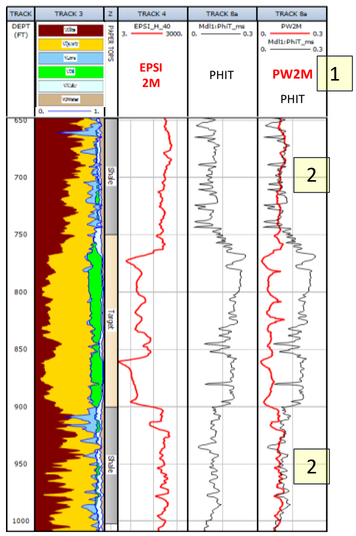
But it also showed the necessity of compensating for the influence of increasing clay volumes on the permittivity response in order to deduce a correct 2 MHz porosity in these cases. So, to arrive at a valid salinity-independent water-filled porosity in shaly sands, we narrowed down the solution process to two approaches:

- A full mathematical inversion of the dielectric property model, or
- A “adaptive” algorithm which is specific to formations in a given well, field, or area.

The full inversion approach is still under investigation and development. The major issue here is how badly underdetermined the problem can be and how to deal with that.

In the meantime, we have tested an adaptive process which is empirically based on the whole range of shaly sand formations in our field test data base.

PERMITTIVITY TO POROSITY: ADAPTIVE ALGORITHM



- Shaly sand example 1:
  - WBM
  - 13-27 deg. Deviation
  - ARC 675 LWD tool

2 MHz porosity adaptive algorithm:

$\emptyset_{wH}=((\frac{\varepsilon_{r,H}-\varepsilon_{r,ma}}{1+b})^{a})\ d$

- $\varepsilon_{r,H}$ is EPSI_2M
- $\varepsilon_{r,ma}$ is matrix permittivity from mineral fractions
- Term $b = c * F_{clay}$
- a exponent ~ .2 to .7
- Term d: scaling coefficient

1. Curve is PW2M
2. Parameters a, c, d adjusted for PW2M - PHIT overlay in shale

No estimate of water salinity is required.

Here is a first case example in a deviated WBM mud logged with an ARC675 tool.

The log graphic shows the volumetric analysis, the 2 MHz permittivity from the LWD dielectric inversion, the total porosity from the volumetric analysis. Note the range of values of the 2 MHz permittivity and total porosity as we move from the shale, into the cleaner oil-filled reservoir, and than back into the shale.

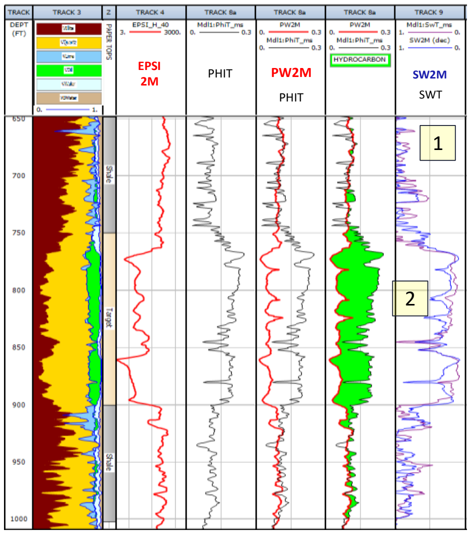
The last track is the new 2 MHz water-filled porosity and total porosity in the same track The adaptive 2 MHz water-filled porosity, $\emptyset_{wH}$, algorithm that produced this is seen here. We first determine the formation matrix permittivity in the petrophysical mineral solver routine from published values. This is subtracted from the formation 2 MHz permittivity. This is then divided by a clay compensation term which is derived from the fraction of clay from volumetric analysis. The result is raised to an exponent – usually between 0.3 and 0.9 Finally an overall scaling coefficient is applied. The resultant curve is labelled **PW2M**.

These coefficients and the exponent are adjusted to produce an overlay of PW2M with the PHIT from volumetric analysis in the shale zone or zones adjacent to the target reservoir, as is seen in the graphic. We refer to this as adaptive as we find that the model parameters need to be adjusted somewhat for given formations.

The adjustments are essentially compensating for the volume of clay and its CEC, and the dielectric effects of the interaction of this with whatever the salinity of the water is.

No water salinity input is involved.

PERMITTIVITY TO POROSITY: POROSITY TO DEEP, SALINITY- INDEPENDENT SW



Shaly sand example 1:

- Green shading: HC flag
- Deep, salinity-independent water saturation:

1. SW2M = PW2M / PHIT
2. Corroborated by SWT from operator's volumetric analysis

In this next slide, we have just shaded where PW2M has values less than PHIT.

Since PW2M is only water-filled porosity, it will exhibit a deficit when compared to PHIT in hydrocarbon-bearing zones. And in typical while-drilling acquisition cases of minimal mud filtrate invasion, it can be assumed that it represents hydrocarbons in the virgin reservoir.

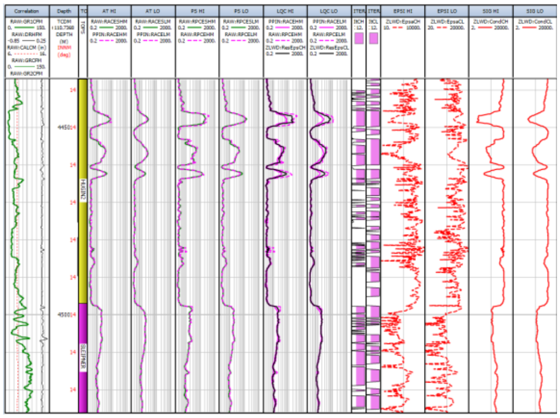
The calculation of water saturation is straightforward as the ratio of the porosities. We refer to this as SW2M in the figure.

The last track in the figure shows SW2M vs SWT calculated by the well operator from resistivity and his knowledge of the connate water resistivity.

We did not have access to the operator's Rw information, only to his SWT curve. And we see very good overlay of the two saturation derivations. We also note that the Sw = 1 condition is holding in the shales above and below the target.

This validation from the conventional Sw derivation in this and other examples in our test data gives us confidence in asserting that this is a reasonable approach to generating salinity-independent, water-filled porosity from 2 MHz permittivity in shaly sands.

PERMITTIVITY TO POROSITY: EXAMPLES FROM VOLVE FIELD HUGIN SS RESERVOIR



Shaly sand example 2:

Volve Field public database, Hugin SS fm:

- Well 15/9 F-11 T2
- MPR 675 LWD Tool
- Raw + inverted data
- LQC tracks show valid conductivity/resistivity inversion
- Diagnostic tracks show non-homogeneous intervals.

Credit to: Equinor and the former Volve license partners

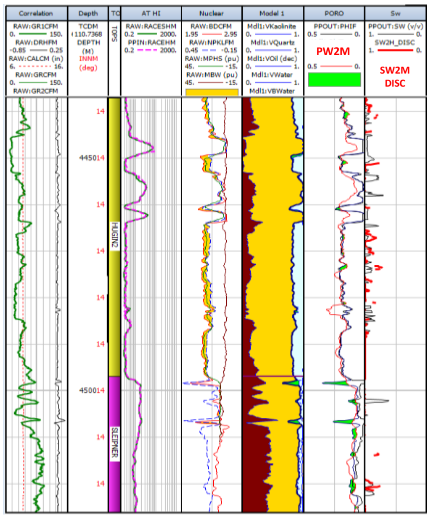
After the papers were presented in Stavanger we became aware of an extensive database made public bay Equinor and its license partners in the now-decommissioned Volve Field in the Norwegian Sea. The produced reservoir was the Jurassic Hugin SS formation.

There and 17 wells with LWD resistivity and nuclear data, and we have downloaded and performed the dielectric inversion and property modeling processes on all of these.

We will show two examples. This first example, “Shaly sand #2”, is in completely water-filled formation.

- Well 15/9 F-11 A
- MPR 675 LWD Tool
- Raw + inverted data
- LQC tracks show valid inverted resistivity falling between the field phase and attenuation resistivities- for both frequencies, as required by the physics.
- Diagnostic tracks show non-homogeneous intervals – both frequencies

PERMITTIVITY TO POROSITY: 2 MHZ POROSITY CORROBORATION



- Well 15/9 F-11 T2
- PW2M derived from 2 MHz permittivity
- **Salinity-independent** SW2M_DISC corroborated by operator's **Salinity-dependent** Sw in water-bearing intervals

Credit to: Equinor and the former Volve license partners

Well 15/9 F-11 T2

The Equinor petrophysical analysis indicates 100% water saturation in this particular well.

PW2M derived from 2 MHz permittivity by adjusting the adaptive equation coefficients and exponent so that an overly was obtained in the Sleipner shale below, and in the overlying Heather shale above.

We see almost zero difference between PW2M and the Equinor petrophysical derivation of PHIT.

Water saturation was calculated using this PW2M divided by the Equinor PHIT. In these cases, to add more confidence to the Sw comparison, we discriminated the SW2M to be derived only when there was no diagnostic flag present, resulting in the SW2M_DISC points seen in the graphic. Again, no water salinity input is involved.

These are corroborated by Equinor's WATER-SALINITY-DEPENDENT Sw in the water-bearing intervals seen.

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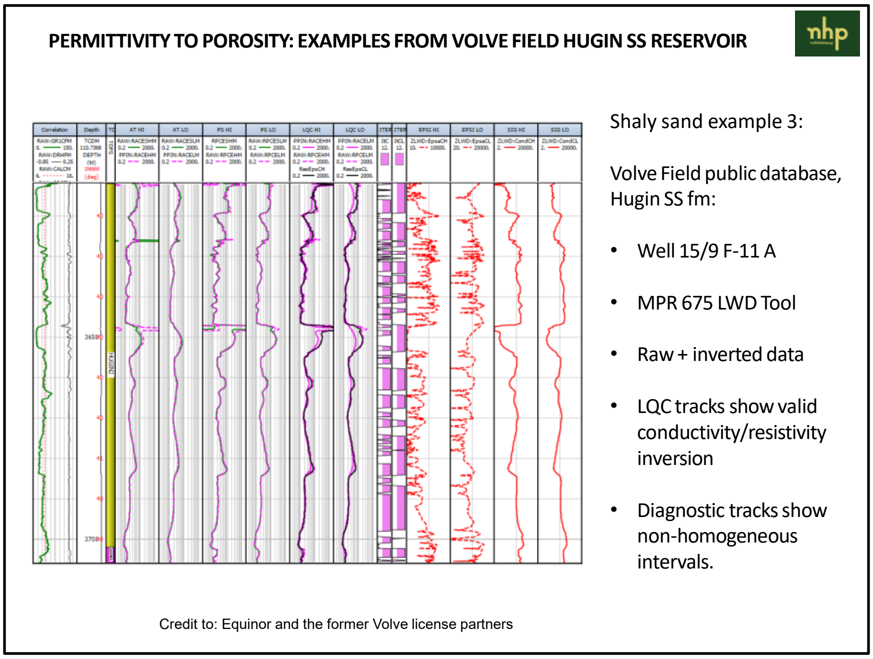
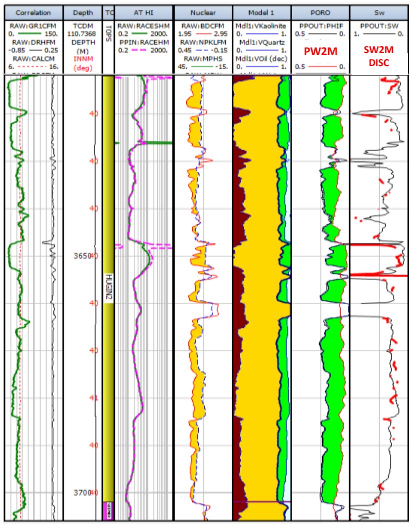


This second example, “Shaly sand #3”, is in a productive hydrocarbon-bearing formation Hugin SS formation.

- Well 15/9 F-11 A
- MPR 675 LWD Tool
- Raw + inverted data
- LQC tracks show valid inverted resistivity falling between the field phase and attenuation resistivities- for both frequencies, as required by the physics.
- Diagnostic tracks show non-homogeneous intervals – both frequencies

PERMITTIVITY TO POROSITY: 2 MHZ POROSITY CORROBORATION



- Well 15/9 F-11 A
- PW2M derived from 2 MHz permittivity
- **Salinity-independent** SW2M_DISC corroborated by operator's **Salinity-dependent** Sw in hydrocarbon-bearing intervals

Credit to: Equinor and the former Volve license partners

The Equinor petrophysical analysis indicates very low water saturation in this particular well, which was a producer in the field.

Again, PW2M derived from 2 MHz permittivity by adjusting the adaptive equation coefficients and exponent so that an overly was obtained in the Sleipner shale below, and in the overlying Heather shale above. These particular values were identical to those used in the previous well, as would be expected.

Here we see a large separation between PW2M and the Equinor petrophysical derivation of PHIT, indicating porosity filled with hydrocarbon.

Water saturation was calculated using this PW2M divided by the Equinor PHIT. Again, we discriminated the SW2M to be derived only when there was no diagnostic flag present, resulting in the SW2M_DISC points seen in the graphic. As before, no water salinity input is involved.

These are corroborated by Equinor's WATER-SALINITY-DEPENDENT Sw in the hydrocarbon-bearing intervals seen.

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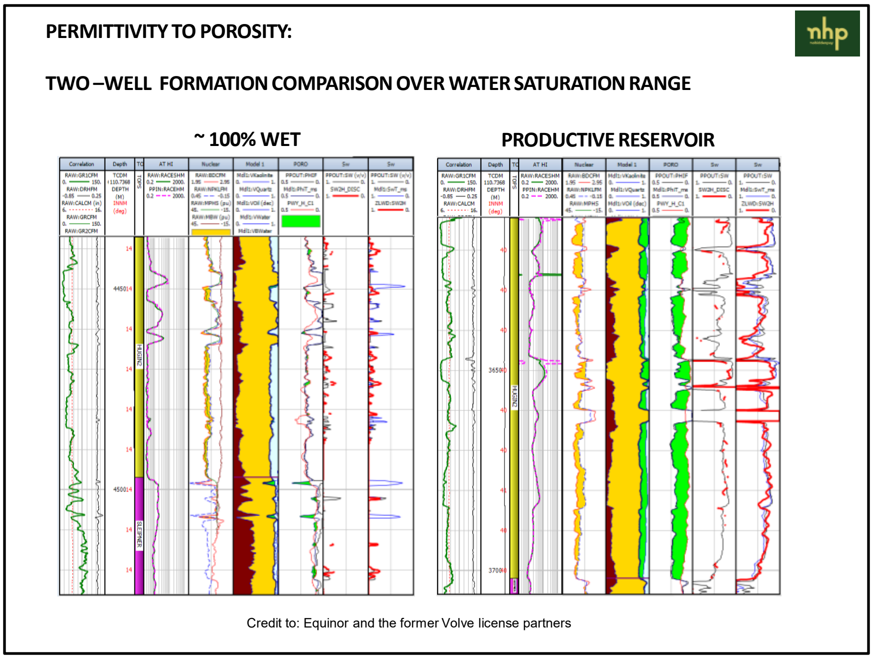

We compare the two interpretations here. We have also added the continuous SW2M in an overlay with the Equinor Sw derivation.

These two recent examples serve to give us more confidence in the adaptive algorithm approach to produce salinity-independent, water-filled porosity from 2 MHz permittivity LWD inversions.

As I said there are a total of 17 wells in this database and we are continuing to analyze these for both improved porosity and permittivity dispersion interpretation techniques.

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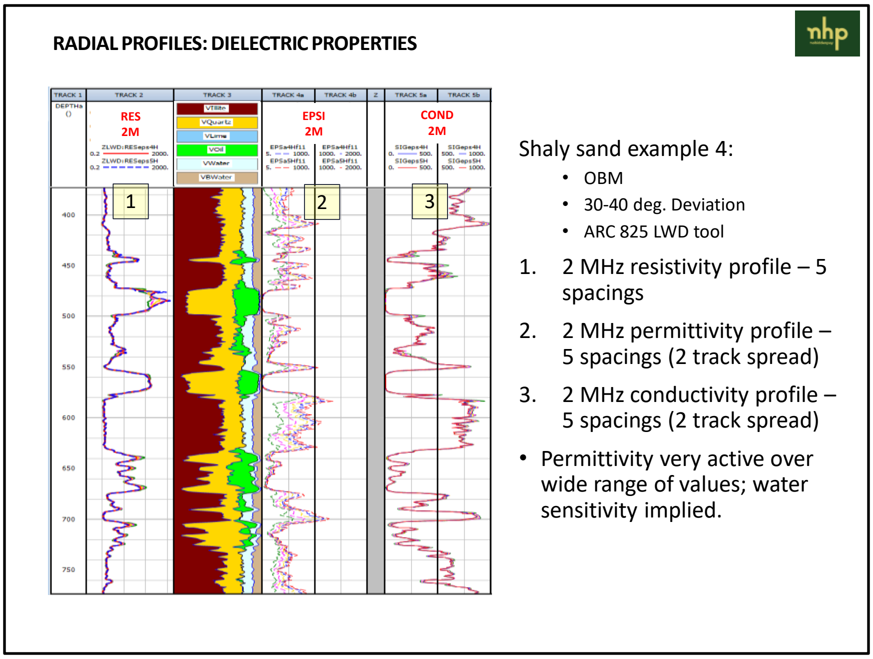
With this confidence in the 2 MHz porosity derivation, we can apply it to all the given tool spacings and observe radial changes of water-filled porosity with depth of investigation in our examples, and further derive radial behavior of water saturation.



Here is shaly sand example 4. This well was drilled with oil-based mud, is fairly deviated, and logged with an ARC825 LWD resistivity tool and nuclear tool combination.

Here we show the inverted, 2 MHz dielectric- assumption-free resistivities from the five tool spacings in track 2 as a radial resistivity profile.

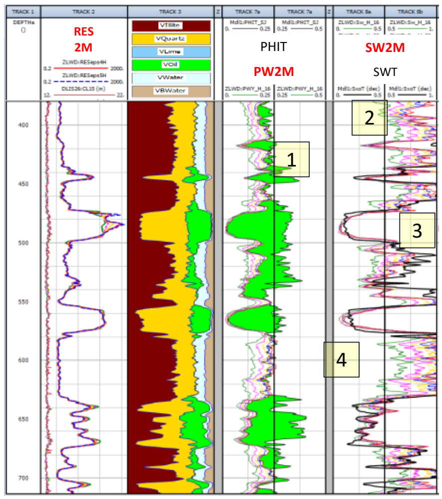
The operator’s volumetric analysis is in track 3.

We also display the 2 MHz permittivity and conductivity curves from all the tool spacings on expanded scales in two tracks to highlight the radial profiles.

We immediately observe very active 2 MHz permittivity radial profiles which converge in the oil-bearing sands, indicating minor water quantity changes from across the 16” to 40” tool spacings.

We also observe in other zones in the well, only very slight conductivity profile gradations, in contrast to the permittivity gradations.

RADIAL PROFILES: POROSITY, SW



Shaly sand example 4:

- OBM
- 30-40 deg. Deviation
- ARC 825 LWD tool

1. 2 MHz Porosity profile: 5 spacings (2 track spread)
2. 2 MHz Saturation profile: 5 spacings (2 track spread)
3. Pay zones: PW2M < PHIT, SW2M ~ SWT.
4. Porosity and saturation profiles in shales – need investigation

The 2 MHz permittivity radial profiles are transformed into 2 MHz salinity-independent, water-filled porosity radial profiles via the adaptive algorithm

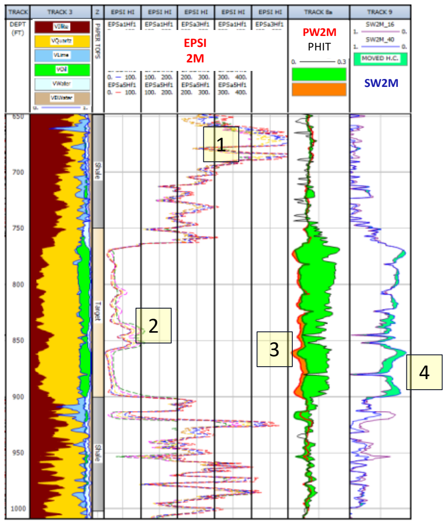
These are further transformed into salinity-independent radial water saturation profiles via the SW2M algorithm.

The SW2M water saturation radial profiles show very little gradation in the obvious reservoir zones, implying very little invasion, as expected at LWD time, and thus virgin zone Sw values.

We also see that the ensemble of converged 2 MHz water saturation values is very close to the standard water-salinity-based resistivity determination of water saturation, SWT in this well, shown here as the black curve.

We speculate on the cause of water saturation radial profiles in the shales, and several hypotheses have been raised. But these are in need of further investigation to provide some petrophysical explanations.

RADIAL PROFILES: POROSITY, SW



Return to Shaly sand example 1:

- WBM
- 13-27 deg. Deviation
- ARC 675 LWD tool

1. 2 MHz permittivity profile – 5 spacings (expanded tracks)
2. Focus on Target zone: some fresh mud invasion seen
3. PW2M_40: 40”
   PW2M_16: 16”
   -orange shading: shallow to deep PW2M decrease
4. SW2M_16 > SW2M_40
   -green shading: moved H.C.

All quantities water-salinity independent.

Returning to our first example, we have expanded the five-spacing 2 MHz permittivity tracks even further.

We focus on the target reservoir zone and note the radial gradation where the deepest 40” spacing shows the lowest 2 MHz permittivity, and the shallowest 16” spacing showing the highest.

This implies fresh mud invasion into an oil-bearing sand.

PW2M porosities were calculated and the 40” and 16” values are compared to PHIT in Track 9. The orange shading is between these deep and shallow spacings, and shows how the water-filled porosity is lower at the deeper spacing.

Then in track 10 we computed the salinity-independent 16” and 40” water saturations. We can interpret the shallower value as Sxo and the deeper value as Sw. The green shading then can be interpreted as moved oil.

Again, all of the porosity, and thus water saturation, quantities derived from the inverted 2 MHz permittivity data are salinity-independent.

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Let me close with some conclusions.

CONCLUSIONS

- 2 MHz water-filled porosity derived via an adaptive algorithm
- Sw from 2 MHz LWD data: demonstrated to be deep, salinity independent in clean and shaly sand formations
- Porosity / Sw profiles can show invasion, moved hydrocarbons
- Going forward, there is need to:
  - Continue to substantiate PW2M and SW2M in carbonates
  - Improve algorithm in shaly formations
  - Develop a robust mathematical inversion of the dielectric property model
  - Investigate petrophysics of permittivity profiles in shales/non-reservoir intervals

Using our current field test database, we have empirically formulated an adaptive approach to calculating salinity-independent, water-filled porosity from 2 MHz permittivity data.

Subsequent Sw from 2 MHz LWD data exhibits salinity independence in shaly sand and is corroborated by operators' independent calculations.

Applying the algorithm to various LWD tool spacings provides Porosity / Sw profiles which can show invasion and moved hydrocarbons

Going forward, there is need to:

- Continue to substantiate PW2M and SW2M in carbonates
- Improve algorithm in shaly formations
- Develop a robust mathematical inversion of the dielectric property model
- Investigate petrophysics of permittivity profiles in shales/non-reservoir intervals

CONCLUSIONS: RECOMMENDATIONS

- ***Legacy LWD data sets can now easily be reviewed - and should be - for continuous refinement of these ideas.***

- ***WHY LEAVE PERMITTIVITY (AND PERMITTIVITY DISPERSION) OUT OF YOUR PETROPHYSICS TOOLBOX???***

Legacy LWD data sets can now easily be reviewed via these processes by operators - and should be - for continuous refinement of these ideas.

- ***WHY LEAVE PERMITTIVITY AND PERMITTIVITY DISPERSION OUT OF YOUR PETROPHYSICS TOOLBOX???***

- **INTRODUCTION**
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QUESTIONS?

Thank you for your time, and I will take questions.