Good News and Bad News

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First, the ***Good News.***

When observed, ***mud filtrate invasion likely signals that the formation has at least some amount of permeability***. At the simplest level, and assuming a contrast in R_{mf} & R_w, there may be ***SP development***, which in the presence of potassium feldspars, or uranium, ***can allow one to identify a reservoir that would not be clear on the GR,*** and ***can even offer an estimate of*** $\boldsymbol{R_w}$.

At yet another level, applying Archie's equation to the invaded zone and taking R_{mf} from the Log Header, there ***arises the possibility of deducing the "m" exponent***, in the water leg (even though the local R_w is not known, a-priori).

$$S_{xo}^{n} = 1 = R_{mf} / [(Phi^{m}) * (R_{xo})] \Rightarrow \boldsymbol{m} = Log[R_{mf} / R_{xo}] / Log[Phi]$$

With 'm' in hand, one then applies Archie's equation to the deep resistivity, and estimates the local R_w.

$$S_{w}^{n} = 1 = R_{w} / [(Phi^{m}) * (R_{deep})] \Rightarrow \boldsymbol{R_w} = (Phi^{m}) * (R_{deep})$$

Alternatively, a ratio of the two equations above yields

$$\boldsymbol{S_w}^{n} / \boldsymbol{S_{xo}}^{n} = \boldsymbol{1} = (R_w / R_{mf}) * (R_{xo} / R_{deep}) \Rightarrow \boldsymbol{R_w} = R_{mf} * (R_{deep} / R_{xo})$$

This R_w estimate may (should be) be compared to that calculated from the SP.

In practice, the Resistivity Ratio R_w estimate will also be valid in a non-mobile heavy oil / tar zone, so long as the mud filtrate actually invades, and displaces the connate water (which does not always happen).

Next, the ***Bad News.***

In actual fact, ***a number of phenomena conspire to often make an evaluation in the presence of invasion, more difficult***. For example, repeat measurements of R_{mf}, in the Field vs in the Lab, will seldom be the same, and the R_{xo}-based 'm' has thus been compromised to some degree. An even more serious issue though, is likely the exact ***placement of the mud filtrate invasion front, with respect to the various tool responses, which are themselves each different, and which are being combined in the calculations.***

More ***Good News.***

If petrophysics were so relatively simple as find a water leg, deduce "m" from R_{xo}, estimate R_w from the R_{deep}, and then calculate S_w, we would find ourselves bored (and replaced by a computer). However, with an understanding of the physical phenomena at play, ***one is often able to recognize the presence of 'bad news', and in many situations compensate for, or minimize, the effects***.

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Invasion

At the simplest level, our wellbore environment may be thought of as consisting of an invaded and un-invaded zone (Figure 1).

Recognition of intervals for which invasion has taken place, will signal improved (relative to no invasion) ***rock quality***, and is hence a first step in formation evaluation.

Archie's equation, with appropriate and consistent attributes (ie R_{mf} & R_{xo}, R_w & R_{deep}, etc), is ***applicable to both domains***.

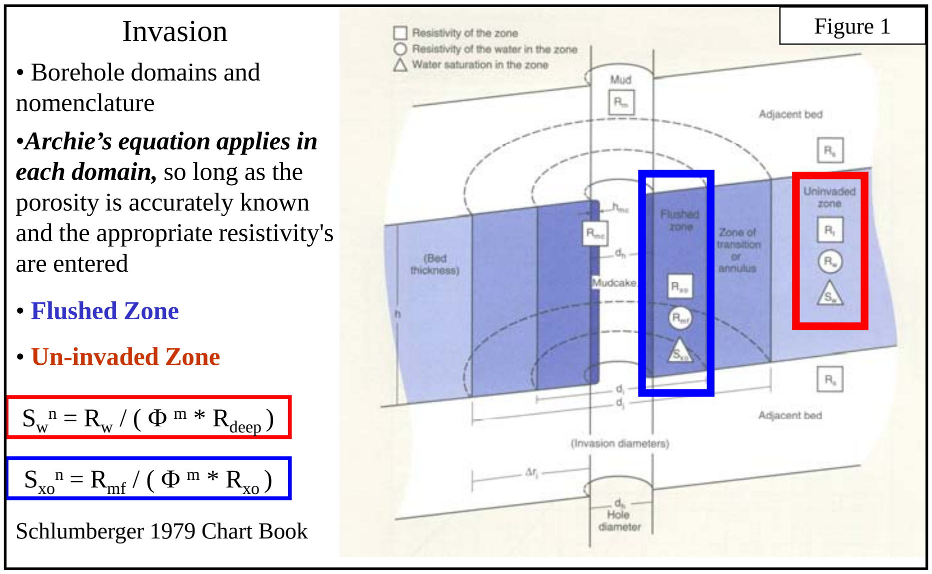

Figure 1

Complications and compromises will sometimes arise, however, within the context of the relatively innocent sounding "appropriate and consistent attributes" qualification.

Spontaneous Potential

The movement of ions, which causes the SP phenomenon, is possible only in formations having a certain minimum permeability (a fraction of a mD may be sufficient); Figure 2.

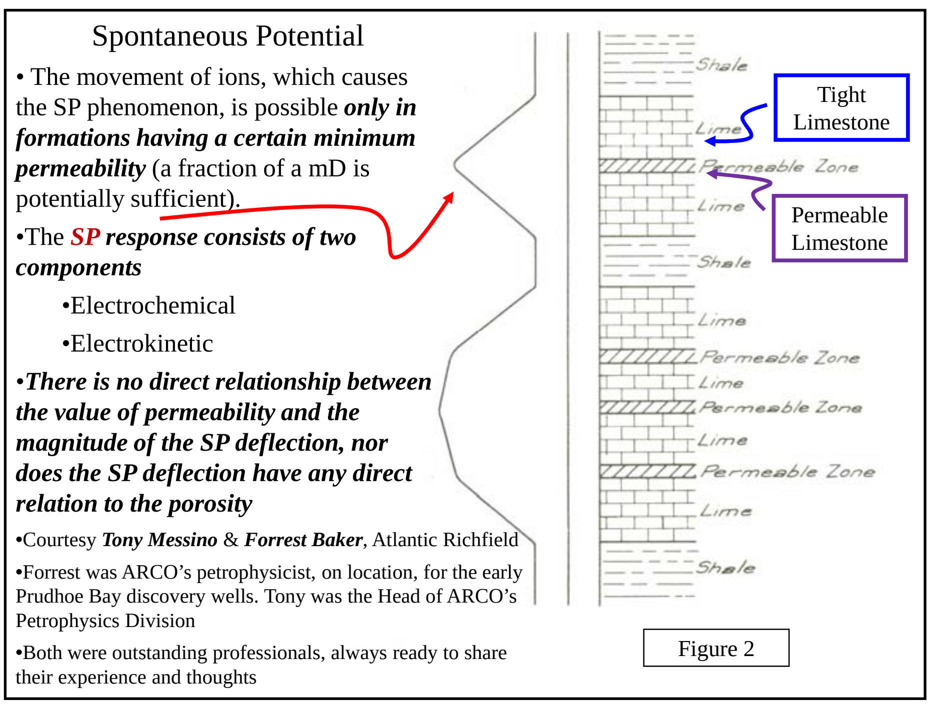

Figure 2

The ***SP consists of two components***, ***Electrochemical*** and ***Electrokinetic***. The Electrochemical arises as a result of a diffusion type of effect. Drilling mud and formation brine are typically NaCl dominated, and usually of different salinities; the ions will attempt to move out of areas of concentration. Shales are permeable to Na^+ but not Cl^- and movement of Na^+ ions

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through shale results in a potential drop, referred to as the membrane potential. At the mud filtrate - formation brine interface there also appears a liquid junction potential.

The Electrokinetic component arises from the physical movement of the mud filtrate (or formation brine) and is typically important when the mudcake has not yet formed, heavy drilling mud was used, or a depleted formation has been encountered. In these instances, SP deflection should not be used to estimate formation R_w

The ***Electrochemical SP Deflection can be used to estimate R_w*** if the interval is not shaly and NaCl is the dominant salt. Shale and / or salts other than NaCl will typically reduce SP deflection.

Across long intervals, ***SP Baseline shifts*** will usually be observed, and correspond to formation waters of different salinities separated by a shale bed that is not a perfect cationic membrane. The position of the Shale Baseline has no physical meaning and most petrophysical s/w packages will offer a 'baseline straighten' option to remedy this situation.

There is ***no direct relationship between the value of permeability and the magnitude of the SP deflection, nor does the SP deflection have any direct relation to the porosity***.

Mud Cake

The ***presence of mud cake will usually signal permeability***, and if of sufficient thickness, will appear as a difference between the caliper and bit size traces. The ***Microlog*** offers an alternative identification of mudcake.

The microlog consists of two short-spaced resistivity measurements, with different depths of investigation, sampling a sample small volume of mud cake and formation immediately adjacent the borehole.

- 1 inch micro-inverse
- 2 inch micro-normal, slightly deeper reading than micro-inverse

Typically, R(mud) < R(mud cake) < R(invaded formation), and ***a separation in the two microlog readings infers that invasion has occurred and that the formation is permeable***.

Doll (1951) documented a carbonate-specific application, as follows.

> In conventional electrical logging, the spontaneous potential (SP) log is used to delineate the permeable beds, and the resistivity logs are used primarily to provide indications concerning the fluid content of the beds.
>
> When the formations are much more resistive than the mud, as happens for example, in limestone fields, the SP currents are short-circuited by the more conductive mud column, with the result that the SP log is quite rounded. In that case, the SP log generally gives the approximate location of the permeable formations but it cannot be used for an accurate determination of the boundaries of each permeable bed.
>
> Solutions for the problem of obtaining a better determination of the permeable beds in limestone fields were developed from two angles. One approach consisted in improvements to the logging of the SP, as given by Selective SP logging and Static SP

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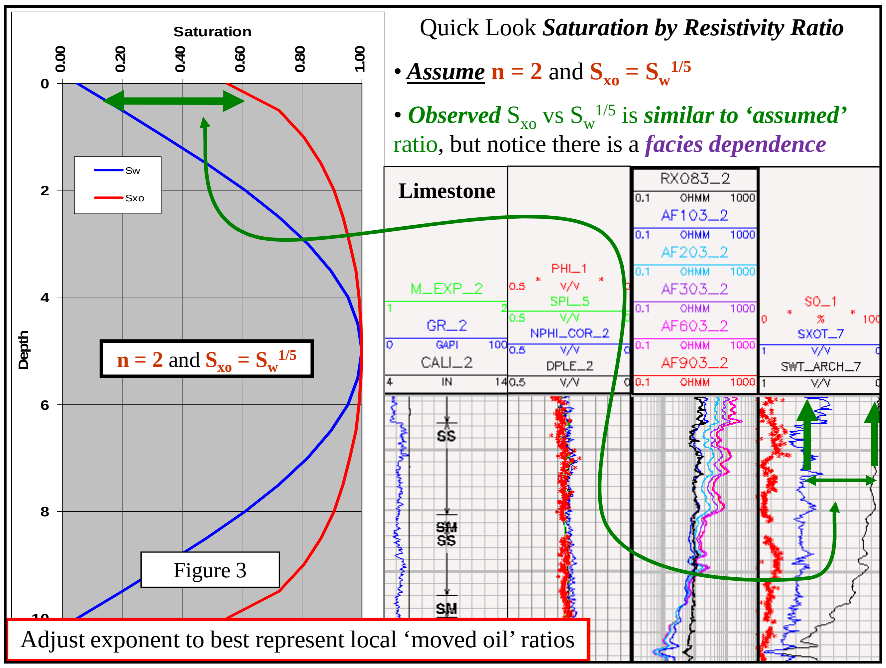
logging. These new methods, which have been described in an earlier paper, give good results when the mud is not too salty, but they are still in a somewhat experimental stage, mostly because the development efforts have lately been concentrated on another approach to the problem, i.e., the MicroLog.

Quantitative determination of formation permeability with the microlog is not possible.

Saturation from Resistivity Ratios



Invasion is behind the SP and Microlog responses, which are then permeability indicators. In certain circumstances, ***invasion offers much more than a simple indication of rock quality, and can in fact provide a Phi / "m" exponent independent S_w estimate***.

Applying Archie's equation to the invaded and un-invaded zones, yields the following.

$$S_w^n = R_w / (Phi^m * R_{deep})$$

$$S_{xo}^n = R_{mf} / (Phi^m * R_{xo})$$

Divide (Ratio)

$$S_w^n / S_{xo}^n = (R_w / R_{mf}) * (R_{xo} / R_{deep})$$

Assume

$$n = 2 \text{ and } S_{xo} = S_w^{1/5}$$

then

$$S_w^2 / S_{xo}^2 = [S_w / S_w^{1/5}]^2 = [S_w^{4/5}]^2 = \mathbf{S_w^{8/5} = (R_w / R_{mf}) * (R_{xo} / R_{deep})}$$

While the $S_{xo} = S_w^{1/5}$ assumption may appear to be simplistic, it is in fact often (but not always) reasonably representative (Figure 3). Additional assumptions include.

- Environmental corrections?
  - If not done, we've assumed R_{deep} & R_{xo} adjustments 'cancel'
- Formation generally clay-free
  - Archie's equation applicable to 'clean' formations
- Significant, but not excessive, invasion has occurred

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- o R_{xo} and R_{deep} must represent the invaded, and non-invaded, rock respectively
- o *More on this, soon*

If there is any question of porosity log quality, one now has an independent saturation estimate, which may be cross-checked against the porosity-referenced results. Perhaps more important, ***since the cementation exponent has also dropped out, this independent evaluation can provide a valuable reference in carbonate environments which are suspected of having variable 'm' exponents***.

Locally specific saturation ratios are easily implemented Hamada (2004), and additional on-line applications are to be found at the below links.

- Ross Crain's On-line Tutorial @ www.spec2000.net
- Kansas Geological Survey (John Doveton) Tutorial @ www.kgs.ku.edu/Gemini
- Combining Water Saturation by Ratio Method, Moveable Hydrocarbon Index, Bulk Volume Water and Archie Water Saturation. Found with Google. Author, date and publication details n/a.

Things get complicated

We all know there is 'no free lunch' and if we're told otherwise, then we're probably not getting the full story. ***A number of phenomena conspire to compromise*** (but not eliminate) ***the utility of invasion***, with one of the basic limitations being ***differing depths of investigation of the various tools which are being combined in an evaluation*** (plus the different vertical resolutions); Figure 4.

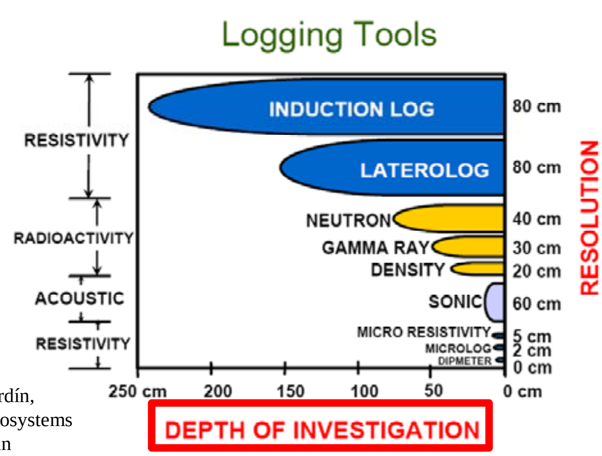
Depth of Investigation

Figure 4

• There is 'no free lunch' and ***a number of phenomena conspire to compromise*** (but not eliminate) ***the utility of invasion***, with one of the basic limitations being differing depths of investigation of the various tools which are being combined in an evaluation (plus the different vertical resolutions).

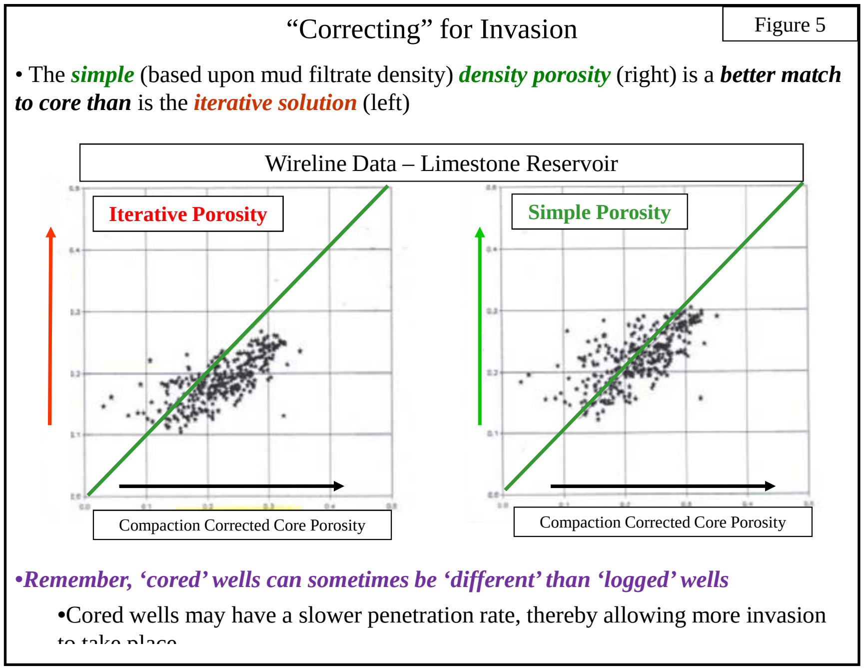
•In actual fact, ***the net tool response is a radial integration and thus a convolution of 'invasions' and 'saturations'.***

•Furthermore, ***the tool response at any single radius is a function of the specific conditions, at that point in time.***



Courtesy Carlos Torres-Verdín, Department of Petroleum & Geosystems Engineering, UT - Austin

And while 'depth of investigation' is routinely reference by all of us, we also realize that the exact tool response is driven by time- and locale-specific conditions, so that ***there is not a 'single depth of investigation'***.



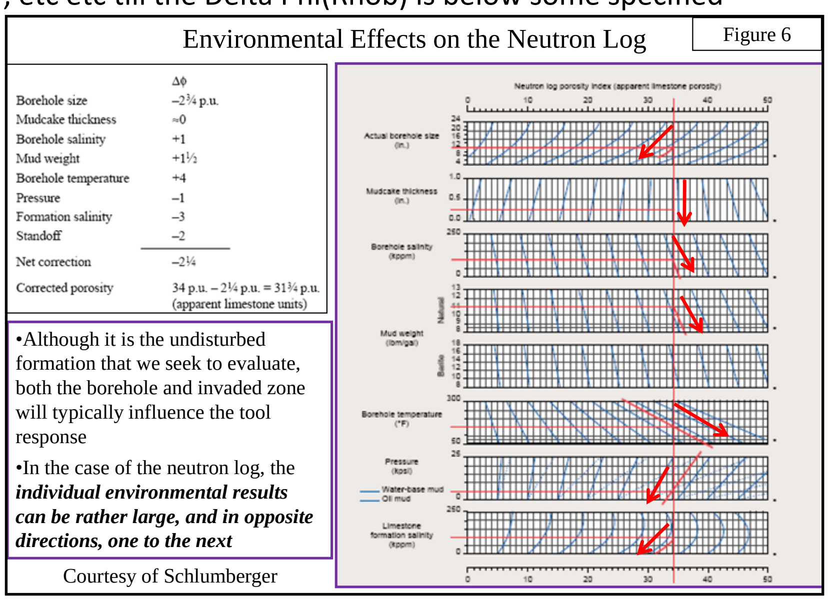
For example, as porosity increases, neutrons are slowed and captured closer to the borehole, and depth of investigation decreases. Compton scattering, on the other hand, will take place deeper within the reservoir, so that Rhob depth of investigation increases. Resistivity measurements are subject to similar concerns, plus the issue of parallel (induction log) and series (laterolog) circuits, and the potential for an 'annulus' effect.

One consequence of this arises when an attempt to 'correct' for invasion is made, in an iterative sense, as below.

- As a first approximation, calculate Phi(Rhob) assuming the appropriate fluid is mud filtrate (the density is a shallow reading tool, and in the case of wireline measurements is often dominated by mud filtrate)
- Calculate Sxo(1), with above Phi(Rhob) and measured Rxo, and then estimate the net fluid density, per the weighted average of S_{xo} * (mud filtrate) and (1 – $_{Sxo}$) * (hydrocarbon density).
- Re-calculate Phi(Rhob) with above, weighted average fluid density, re-calculate S_{xo}, re-estimate net fluid density, etc etc till the Delta Phi(Rhob) is below some specified increment.

When compared to core porosity (Figure 5), this reasonable, iterative approach may be found inferior to simply interpreting the bulk density data with the mud filtrate density.

The situation is yet more complicated when working with the neutron log (Figure 6), as the environmental corrections are both more numerous, larger in magnitude



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and may easily simultaneously involve the invaded and uninvaded domain within a single correction (salinity effects, for example).

The Ideal World and the Real World

Peeters et al (1999) review invasion within the context of a variety of mud types and actual field examples, and suggest log suites which facilitate the greatest opportunity to minimize invasion and borehole effects.

They find that ***while the usual piston invasion model is often reasonable for deep resistivity interpretations, a more sophisticated simulation is required for porosity logs***. Then, even ***while it's not possible to eliminate borehole and invasion issues, one is able to avoid an incorrect conclusion and identify the 'most likely' solution.***

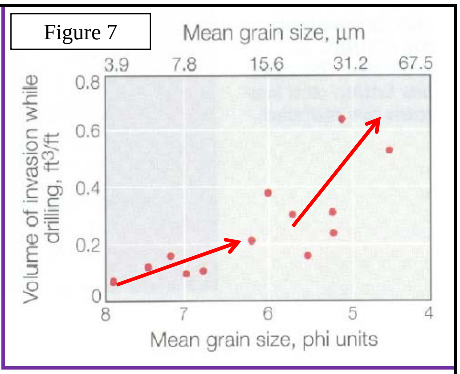
Spurt vs Filtration

•Invasion occurs in two phases, Spurt and Filtration. ***Spurt invasion corresponds to exposure of freshly penetrated rock*** to the drilling mud, and is followed by ***Filtration,*** which is ***mud filtrate passage through the mud cake.***

•The ***magnitude of the Spurt effect is dependent upon the relative sizes of the mud solids***, and the ***formation pore throats***, with large grains corresponding to large pore sizes, which the mud solids find more difficult to bridge.

Allen, David et al. Invasion Revisited. Oilfield Review. July 1991

Figure 7



Volume of invasion in the first 15 minutes after drill bit penetration as a function of mean sand grain size, measured on core thin sections

Allen et al (1991) provide detailed laboratory, and field, examples of invasion. ***Invasion occurs in two phases, Spurt and Filtration***. Spurt invasion corresponds to exposure of freshly drilled rock to the drilling mud, and is followed by Filtration which is mud filtrate passage through the mud cake.

During the Spurt stage, whole mud can actually enter the formation, for a short period of time, after which the mud particles begin to establish the mud cake (and thereby minimize Spurt).

The magnitude of the Spurt effect is dependent upon the relative sizes of the mud solids, and the formation pore throats (Figure 7), with large grains corresponding to large pore sizes, which the mud solids find more difficult to bridge.

With the formation of a mud cake, invasion proceeds to the Filtration stage, which is itself comprised of

Dynamic vs Static

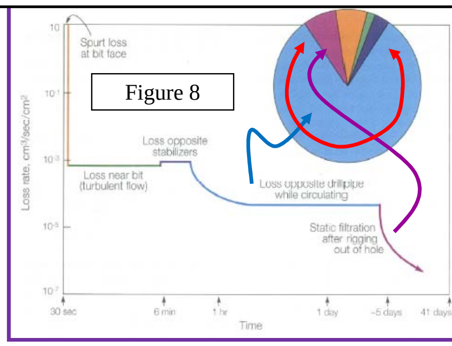
•With the formation of a mud cake, invasion proceeds to the ***Filtration stage***, which is itself comprised of two phases, ***Dynamic*** and ***Static***.

•***Dynamic filtration tends to dominate*** the Filtration phase, and is ***the invasion that occurs while the drilling mud is circulating*** whereas ***Static refers to the 'no circulation' time window.***

•***Filtrate*** stage invasion ***depends upon events at the*** mud / mud cake / formation ***interface, and not on formation properties*** such as permeability.

•***Filtrate loss is then similar in every permeable zone, but the diameter of invasion is expected to vary inversely with porosity*** (as porosity increases, the diameter of invasion decreases).

Figure 8



Filtrate loss rate into a permeable zone.

The greatest fluid loss is during the Dynamic phase, when the drill pipe is opposite the zone of interest

Allen, David et al. Invasion Revisited. Oilfield Review. July 1991

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Permeability & Time Dependence

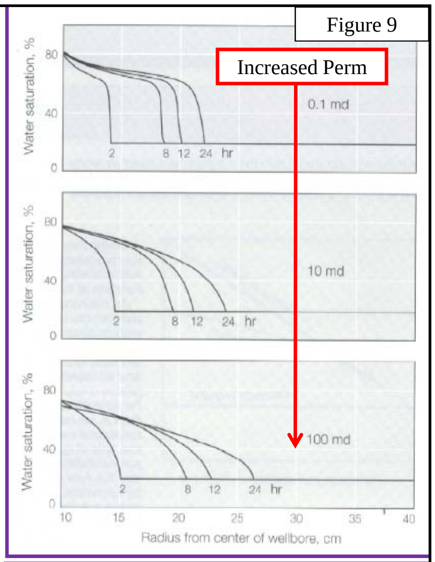
•The ***distribution of mud filtrate, within the pore system*** and as a ***function of time***, is dependent upon mud type, the original formation fluids and the formation wettability.

•In the case of ***water base mud invading a hydrocarbon charged water wet reservoir at Swirr***, oil saturation is flushed to residual (ROS) near the formation face, and the radial distribution of mud filtrate (and Sxo) across time, is a function of permeability.

•At 24 hours, in 25 pu rock, there is a relatively ***sharp transition face*** from Sxo to Swirr, in ***lower permeabilities***, while in ***higher perm rock*** the ***transition face is more gradational***

Allen, David et al. Invasion Revisited. Oilfield Review. July 1991

Figure 9



Low perm rock exhibits sharper invasion front

two phases, Dynamic and Static. Dynamic filtration, which tends to dominate the ***Filtration*** phase (Figure 8), is the ***invasion that occurs while the drilling mud is circulating*** whereas ***Static refers to the 'no circulation' time window***.

Interestingly, and perhaps a bit unexpected, is the laboratory (Cambridge Research, England) observation that, ***except for tighter rock (perm < 10 mD), Filtrate stage invasion depends upon events at the mud / mud cake / formation interface, and not on formation properties such as permeability***. Mud cake build-up competes with the shear of the circulating mud, and at some point (mud cake thickness) the shear effects will limit the further growth of the mud cake. ***Filtrate loss is***, as a result, ***similar into every permeable zone but the diameter of invasion is expected to vary inversely with porosity*** (as porosity increases, the diameter of invasion decreases).

The distribution of mud filtrate, within the pore system and across time, is dependent upon mud type, the original formation fluids and the formation wettability. Experiments by Schlumberger for water base mud invading a hydrocarbon charged water wet reservoir at Swirr, reveal that oil saturation can be flushed to residual (ROS) near the formation face, and that ***the radial distribution of mud filtrate (and S_{xo}), as a function of time, is a function of permeability***.

In ***lower permeability rock,*** there is ***a relatively sharp transition face from S_{xo} to S_{wirr}***, while ***the better quality rock*** exhibits a ***gradational change in S_w***; Figure 9.

Be aware that in the Real World, Mother Nature can put forward complications

Invasion & Time Dependence

Figure 10

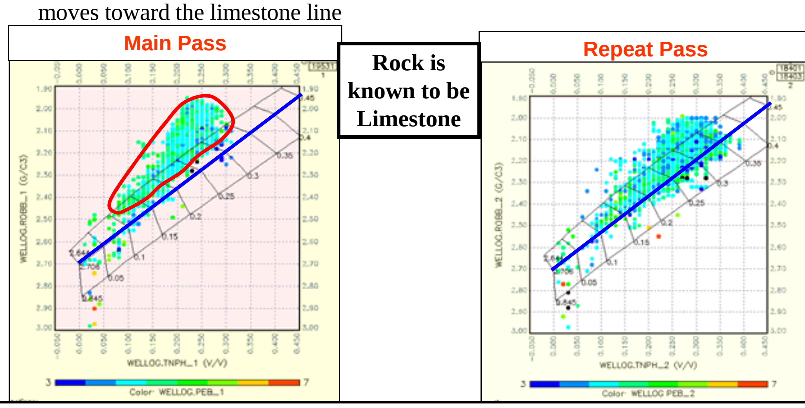
• Density-Neutron (LWD) crossplot in oil (~ 40 API) charged limestone reservoir

• ***Main Pass*** (left) measured ***just behind the bit. Repeat Pass*** (right) acquired later, after ***some invasion*** has occurred

• ***Note the time-lapse movement towards the limestone line***

  • Main Pass data is experiencing significant light hydrocarbon effects

  • As invasion proceeds, and hydrocarbon is replaced by mud filtrate, the crossplot moves toward the limestone line



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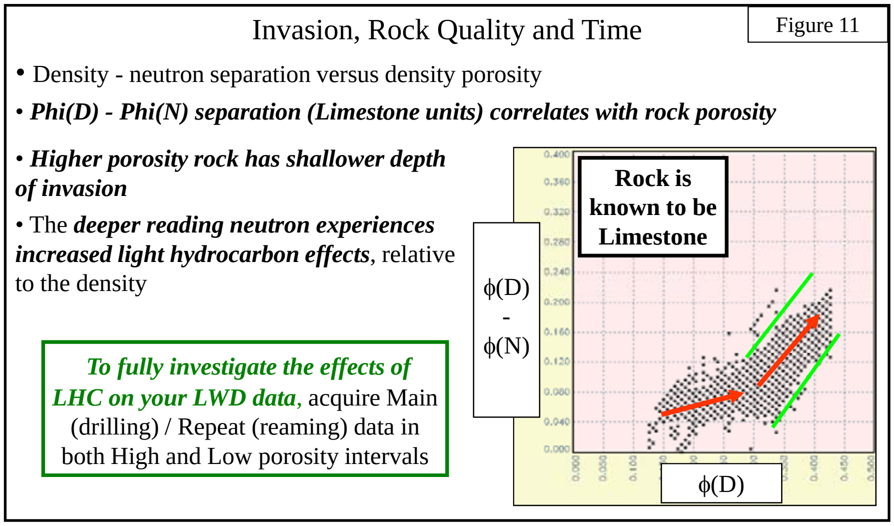
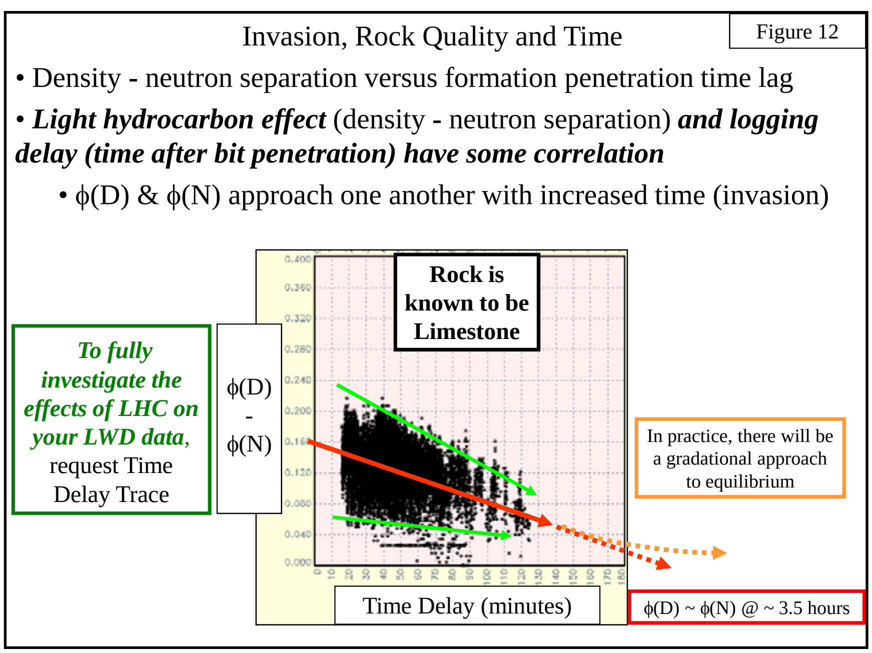


such as variations in heterogeneity and a tendency for fingering, from low perm to high perm intervals, such that ***observed results in a specific instance may sometimes differ from Figure 9*** (Maria Gabriela Briceo. Invasion Profiles Derived from Shallow Wireline Logs. Thesis, Colorado School of Mines.).

The ***interrelation of invasion, time and rock quality can be clearly demonstrated when LWD measurements, acquired just behind the bit, are compared to measurements made with the same tool, later in time while back reaming*** (Figure 10).

This reservoir is known to be limestone, and with the passage of time (and invasion), the light hydrocarbon effect diminishes (invasion increases) moving the crossplot towards the (correct) limestone trend.

When the density and neutron porosity estimates are contrasted as a Delta Porosity (in limestone units, knowing the rock to be limestone), and displayed against Phi(Rhob), the ***dependence upon rock quality*** becomes apparent (Figure 11). Phi(D) – Phi(N) separation, in limestone units and based upon environmentally corrected measurements, increases with porosity.



The higher porosity rock drills faster, and is thus less exposed to filtrate invasion at the time of drilling (although the spurt loss can conceivably increase, and counter this effect). ***As porosity increases, the radial depth of invasion will generally decrease, and the deeper reading neutron will be more affected by light hydrocarbons***.

Figure 12 demonstrates the ***time dependence***. Now the Delta Porosity is displayed against Time Delay, as determined from the Drill Rate and LWD

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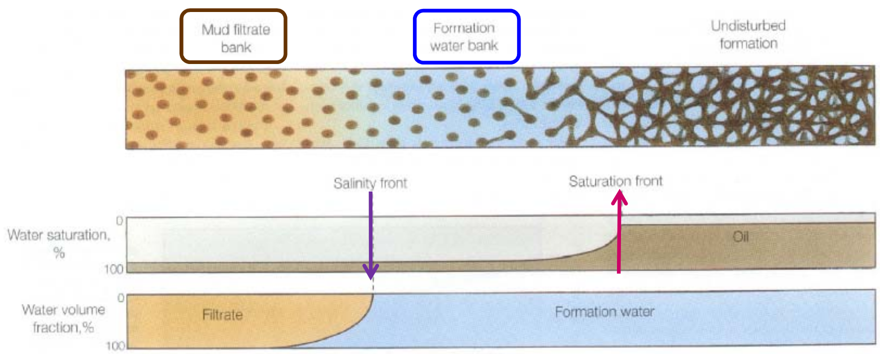
Tool String configuration. Again, the porosity calculation is based upon environmentally corrected data, and cast in terms of limestone units. Linear extrapolation would forecast Delta Porosity → 0 (as expected) at about 3.5 hours. In actual fact, there is a kind of half-life behavior.

Two Fronts

Figure 13

• In a hydrocarbon interval, the mud filtrate can push formation water ahead of it, which itself moves hydrocarbons. There can then be ***two fluid banks created***

- the first having ***mud filtrate salinity***
- the second of ***connate water salinity***



• ***Saturation*** / ***salinity*** fronts and fluid banks as ***water base filtrate invades water wet, hydrocarbon bearing formation.***

Allen, David et al. Invasion Revisited. Oilfield Review. July 1991

El-Wazeer et al (1999) have also investigated invasion effects, on both the nuclear and resistivity tools, with both LWD (while drilling, and while pulling out) and wireline tools, in carbonates. They found that ***a comparison of the resistivity profile, while drilling vs while pulling out, could identify fractured intervals that were confirmed with borehole images***.

In general, the salinity of the mud filtrate will differ from that of the formation water, and in the case of a relatively fresh mud, invading a hydrocarbon charged salty water formation (for example), ***fluid fronts of two salinities can arise, consisting of the fresh mud filtrate (near the wellbore) and the salty connate water***; Figure 13.

The ***potential for two salinity fronts, in contrast to the normally assumed step profile***, Figure 14, immediately challenges an interpretation of the data, and associated calculations. David ***Allen et al (1991)*** illustrate the consequences of failing to recognize an invasion annulus, provide ***guidelines on when Resistivity Tornado Charts are appropriate, and discuss / illustrate this issue in much greater detail than is done here***.

Two Fronts

• Resistivity profiles for Two Front model of ***water base mud invading water wet, hydrocarbon charged, reservoir with various Rw & Rmf combinations***

• There will, in general, be ***both Saturation / salinity fronts and fluid banks***

• The ***fluid banks*** are

- ***Mud filtrate salinity***
- ***Connate water salinity***

• ***Formation Resistivity*** **(ohm-m)** is displayed along the vertical axis, and ***Distance from Wellbore*** along the horizontal, for each combination

Allen, David et al. Invasion Revisited. Oilfield Review. July 1991

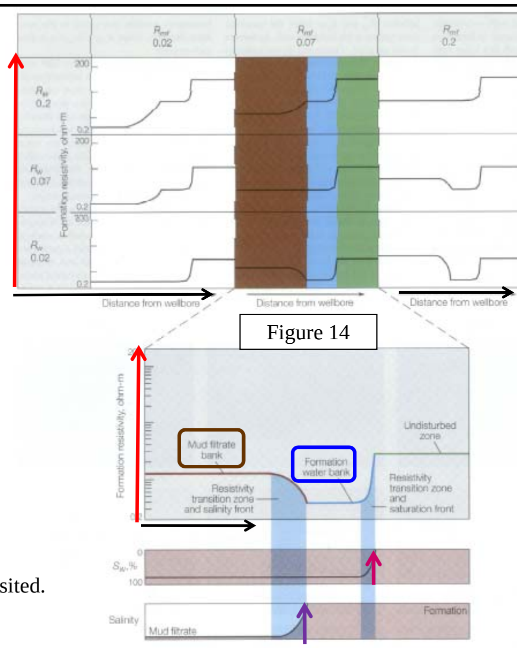


Figure 14

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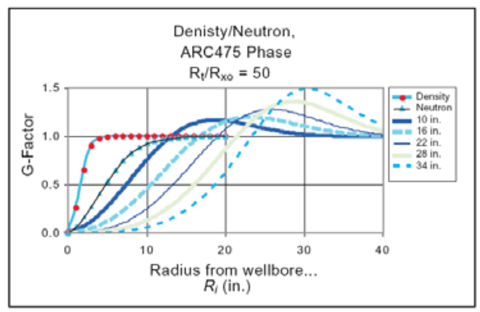
George et al (George, Bovan, Carlos Torres-Verdin, Mojdeh Delshad, Richard Sigal, Farid Zouioueche and Barbara Anderson. A Case Study Integrating the Physics of Mud Filtrate Invasion with the Physics of Induction Logging; Assessment of In-situ Hydrocarbon Saturation in the Presence of Deep Invasion and Highly Saline Connate Water.) investigate the ***annulus issue in a 30 foot thick salty water carbonate, drilled with fresh water base mud***, to find that ***artificially low, induction log resistivity, pay can result***.

The appearance and geometrical characteristics of the annulus is determined by a combination of parameters, including time, porosity, permeability, relative permeability curves, capillary pressure, initial water saturation, connate water salinity, mud salinity, and cementation factor. The low-resistivity annulus seriously compromises the radial depth of investigation of the induction tool, and ***existing induction measurements cannot be corrected***. If environmental conditions allow, the laterolog can provide an alternative, more representative, resistivity measurement.

Salty connate water, present within even the smallest pores will gradually 'mix' with the fresher mud filtrate, and the result will approach the mud filtrate salinity near the wellbore. ***Both the saturation and salinity fronts move away from the wellbore, with the salinity front in general lagging the saturation front***. Only the salinity front will be created in the water leg. Further complicating the situation is the fact that ***local reservoir heterogeneities are usually present, which will lead to fluid fingers which may propagate relatively independent of one another***. Even LWD data, acquired just behind the bit, can be challenged; Figure 15.

Two Fronts and LWD Depth of Investigation | Figure 15

- The potential for ***two fronts, saturation and salinity, will challenge even the interpretation of LWD data***
- Density, Neutron and R_{xo} have ***different depths of investigation***
- ***Attenuation resistivity's*** (not displayed) are ***even deeper reading***
- What is the ***'net salinity & saturation' that is 'seen' by the various tools?***



Carrel Cannon, Schlumberger.
Interpretation of Asymmetrically Invaded Formations with Azimuthal and Radial LWD Data

As lateral movement of the front progresses (assuming a vertical well), gravity will also be at work, since in general the mud filtrate and formation fluids will have different densities. The ***magnitude / rate of change due to gravity depends upon the fluid density differences, and vertical & horizontal permeabilities***.

In the case of fresh mud invading a salty water formation , it's possible for the invasion profile to be relatively deep at the top of the formation, and much shallower at the base, due to the low density fresh mud 'floating' upwards (F Segesman & M Tixier, 1959).

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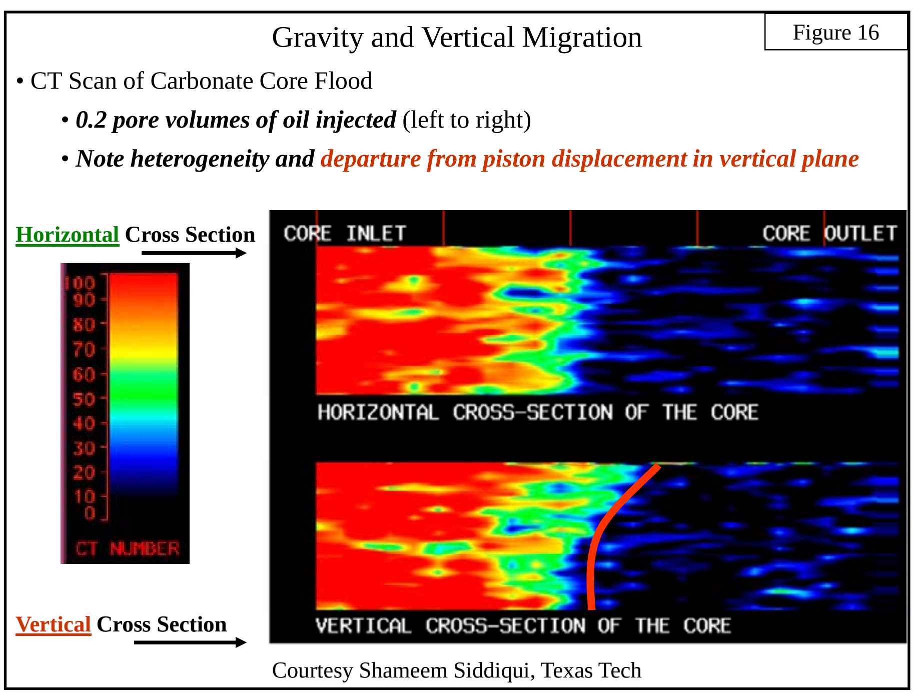
Dussan et al (1994) take advantage of the buoyancy effects to estimate vertical permeability.

- The vertical segregation effect causes a distortion of the invasion front, which in turn produces characteristic ''signatures'' on resistivity logs
- Combining modeled and experimental results, we derived a procedure to estimate vertical permeability. This procedure uses:
  - the magnitude of the buoyancy signatures from resistivity logs,
  - the time-lapse between drilling and logging,
  - porosity from logs or cores,
  - fluid density information,
  - mud-filtrate viscosity,
  - to give a value for the vertical permeability, k_v.
- Values obtained for vertical permeability using this procedure agree with estimates based on particle size distribution of sidewall core samples.

In today's ***highly deviated and horizontal wells, gravity effects can lead to an asymmetrical distribution of the filtrate, around the wellbore***.

- Stephen Bonner, et al. Logging While Driling: A Three Year Perspective. Oilfield Review, July 1992.
- Dick Woodhouse, et al. Vertical Migration of Invaded Fluids in Horizontal Wells. SPWLA 32nd Annual Logging Symposium. June, 1991.

Those who have conducted pulsed neutron log-inject-log programs may have 'seen' this vertical migration happen, in real time, on the various time-lapse PNL signatures. ***Gravitation effects can also be visualized in the laboratory, with time lapse CT Scans*** (Figure 16, Shameem Siddiqui, Texas Tech University).



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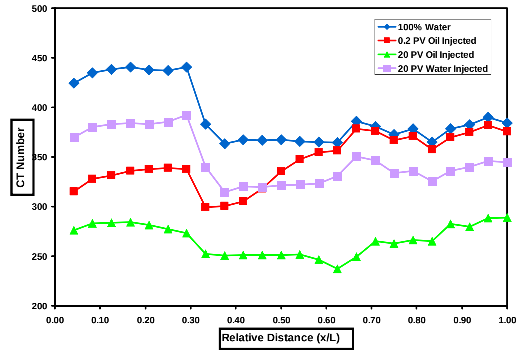
Calibrated CT-scans offer more than a simple visualization of the issue, and ***can in fact quantify the respective time lapse saturations*** (Figure 17).

Time Lapse Saturation from CT Scan

Figure 17

• Mass Balance yields Swir = 34.2 %

• ***Intermediate core flood saturations may be determined*** by ratio between the two baselines (green & blue)



Courtesy Shameem Siddiqui, Texas Tech

Finally, we should note that ***the absence, or change, of an invasion profile may indicate the presence of immobile oil***. Proper oil-in-place calculations and / or reservoir management protocols require one distinguish between the mobile and immobile oil (Figure 18), and an examination of the invasion profile may offer that option (the Sadlerochit, at Prudhoe Bay, comes to mind, and there are many other examples).

Why perforate a tar interval? Why inject water below a tar mat, if the pressure support does not benefit the light oil production?

Sxo > Sw indicates that oil has moved. S_{xo} ~ S_w indicates little or no movement. This logic applies in a general, qualitative sense, and in a locally specific quantitative sense (Chapter V. Combining Water Saturation by Ratio Method, Moveable Hydrocarbon Index, Bulk Volume Water and Archie Water Saturation. Located with Google, Author, date and publication n/a.).

Lack of Invasion and Immobile Oil

Figure 18

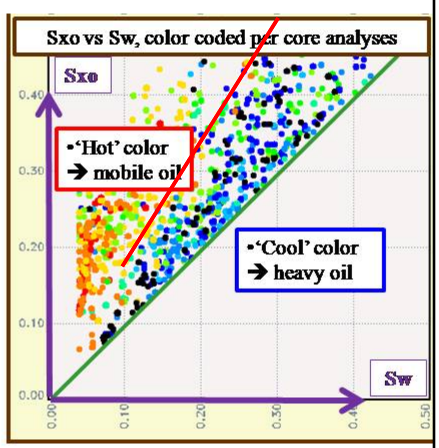
•The ***absence, or change, of an invasion profile may indicate the presence of immobile oil***.

•Why perforate a tar interval? Why inject water below a tar mat, if the pressure support does not benefit the light oil production?

• When $S_w / S_{xo} < 0.7$ for sandstones or $S_w / S_{xo} < 0.6$ for limestone, moveable hydrocarbons are indicated.

$$S_{xo} > S_w / 0.6 \sim 1.67 * S_w$$

•Locally specific calibration will enhance the utility of the concept: Hamada (2004)



Chapter V. Combining Water Saturation by Ratio Method, Moveable Hydrocarbon Index, Bulk Volume Water and Archie Water Saturation. Located with Google, Author, date and publication n/a

- Define the Moveable Hydrocarbon Index as

$$S_w / S_{xo} = [(R_w / R_{mf}) * (R_{xo} / R_{deep})] \wedge (1/2)$$

- Whenever $S_w / S_{xo} < 0.7$ for sandstones or $S_w / S_{xo} < 0.6$ for limestone, moveable hydrocarbons are indicated.

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$$S_{xo} > S_w / 0.6 \sim 1.67 * S_w$$

- If a carbonate reservoir has a Moveable Hydrocarbon Index < 0.6, you can conclude
  - hydrocarbons are present (although not necessarily in commercial quantities),
  - the reservoir has enough permeability so that hydrocarbons have been moved during the invasion process by mud filtrate.

Locally specific calibrations are possible, and will enhance the utility of the concept: Hamada (2004)

Invasion Revisited by David Allen et al (Oilfield Review. July 1991.) and ***Chenevert & Dewan (2001) are 'must reads'*** for those interested in issues and illustrations. Additional calculations and details may be found with the articles tabulated in the References.

Permeability and Fractional Flow Estimates

Invasion, and associated effects, is like so many things that we do in formation evaluation, in that ***the more questions asked, the more issues that arise***. That does not mean, however, that it's an insurmountable problem or even necessarily all bad news.

Ramakrishnan et al (1995) take that approach that 'when life hands you a lemon, make lemonade', and proceed to ***regard invasion as an uncontrolled experiment, which may possibly be inverted to yield an indication of fractional flow***.

> Mud filtrate invasion is usually regarded as a process that corrupts the true logs. In reality, the multiphase flow characteristics that influence filtrate flow also determine the subsequent reservoir performance. ***We propose the notion that invasion is an experiment, albeit uncontrolled, that may be used to invert for multiphase flow properties.***
>
> The forward model for filtrate invasion is based on two-phase (aqueous and oleic), three-component (oil, water and salt) radial transport. Hysteretic behavior of oil and water relative permeability functions is included. Porosity, fluid properties, and cementation/saturation exponents are assumed known from other logs or independent data. The radial conductivity profiles calculated from the flow model are converted to induction logs using radial response functions.
>
> Based on the inverted parameters, presentations for several output logs have been developed: ***a reserves estimate that partitions porosity into residual and movable saturations, initial water cut in the production stream, the fractional flow curve as a function of saturation, filtrate loss per unit depth, and a quality indicator. A field example of the processing, and its comparison with production data is also discussed***.

C. Y. Yao (1996) recognized that time lapse log responses are related to permeability, and proceeded to an estimation, which was compared against core and production.

Jesus Salazar of the University of Texas (download his Power Point file from the University of Texas Site) estimates permeability from core calibrated, mud filtrate based, simulations and compares that to a Winland estimate, while Sigal and Salazar (2005) publish a similar study in the Petrophysics journal.

Salazar et al (2006) describe an inversion technique for permeability estimation.

- Tight gas sand subject to water base mud filtrate invasion
- Incorporates the physics of two phase immiscible displacement and salt mixing between the invading water base mud filtrate and connate water
- Honors the physics of mud cake growth, as well as the petrophysical properties that govern the process of two phase three component flow

Additional material is tabulated in the References.

Good News, Bad News, No News and a **Good Friend**

Mud filtrate ***invasion signals the presence of permeability***.

Radioactive reservoirs (potassium feldspar, uranium effects on the GR, etc) may not be apparent on the GR, and yet display SP development and / or the presence of mud cake. In such a case, ***it can be invasion that allows one to recognize the presence of a potential reservoir, that otherwise may have gone unnoticed***.

Ratio's of Archie's equation, in the flushed and uninvaded zones, ***allow an estimate of saturation that is independent of both porosity and cementation exponent***. Not only does this facilitate a QC cross-check on routine (with porosity log) saturations, but ***can in the case of vuggy porosity, alert one to changes in the cementation exponent***.

Invasion and permeability (plus other attributes) are related, so that ***the invasion profile can allow an estimation of permeability, and fractional flow***.

Not all the news is good, however, in that ***at the simplest level, variable depths of invasion - tool radii of investigation, can confuse an interpretation***. And ***if a salinity annulus has been formed, intervals of pay may even be missed***.

Finally, there are times when ***an invasion profile does not develop***. ***No News may signal the presence of immobile oil***. Why perforate a tar interval? Why inject water below a tar mat, if the pressure support does not benefit the light oil production?

Each time I look at an invasion profile, my memory goes back in time. As an Aramco petrophysicist, I receipted, QC'ed and evaluated newly acquired log data. Once satisfied with the results, they were then presented to Geology and Reservoir Management, and I remember as if it were yesterday, reviewing an analyses with my friend ***Yahya Shinawi*** (Aramco Reservoir Management). While I was discussing the porosity and saturation per routine calculations, he quickly noticed, and inquired about, an apparent resistivity annulus signature. From that I

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gained a lesson that I remind myself of before every presentation: Never Underestimate Your Audience. I've lost contact with Yahya over the years, but I wish him well, where ever he is.

Acknowledgement

It is a pleasure to acknowledgement the following individuals, for kindly looking over this material. Omissions, typos etc remain, of course, my responsibility.

- Allen, David
- Ramakrishnan, Rama
- Siddiqui, Shameem
- Torres-Verdin, Carlos

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Biography

R. E. (Gene) Ballay's 32 years in petrophysics include research and operations assignments in Houston (Shell Research), Texas; Anchorage (ARCO), Alaska; Dallas (Arco Research), Texas; Jakarta (Huffco), Indonesia; Bakersfield (ARCO), California; and Dhahran, Saudi Arabia. His carbonate experience ranges from individual Niagaran reefs in Michigan to the Lisburne in Alaska to Ghawar, Saudi Arabia (the largest oilfield in the world).

He holds a PhD in Theoretical Physics with double minors in Electrical Engineering & Mathematics, has taught physics in two universities, mentored Nationals in Indonesia and Saudi Arabia, published numerous technical articles and been designated co-inventor on both American and European patents.

At retirement from the Saudi Arabian Oil Company he was the senior technical petrophysicist in the Reservoir Description Division and had represented petrophysics in three multi-discipline teams bringing on-line three (one clastic, two carbonate) multi-billion barrel increments. Subsequent to retirement from Saudi Aramco he established Robert E Ballay LLC, which provides physics - petrophysics consulting services.

He served in the U.S. Army as a Microwave Repairman and in the U.S. Navy as an Electronics Technician, and he is a USPA Parachutist and a PADI Dive Master.

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