NATURE OF SOLID ORGANIC MATTERS IN SHALE

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Abstract

Petroleum industry is always one of the major concerns in everyone’s daily life. In recent years, people paid even more attention to the field because human beings are faced with the severe problem of short in oil, or energy resource in general.

This paper discusses how to characterize solid organic matters in gas-producing shale plays and how its presence affects well log measurement. This paper contributes to a better understanding on how oil/gas is stored in shale layers. Analyzing logging, Archie’s equation and other formation evaluation methods are used. The goal is to establish how conventional log analysis applied and what limitations are in shale gas plays. Future research requirements will be carefully elaborated.
Contents
Acknowledgement ................................................................................................................. 3
Abstract ................................................................................................................................. 4
Introduction & background ................................................................................................... 6
  Part 1 conventional wells .................................................................................................... 6
    Core sampling and mud logging ....................................................................................... 7
    Electric logging ................................................................................................................ 7
    SP curve ............................................................................................................................ 8
    Induction logging ............................................................................................................ 9
    Nuclear logging ............................................................................................................... 9
    Gamma ray logging ....................................................................................................... 10
    Neutron logging ............................................................................................................. 10
    Formation density logging ............................................................................................ 11
    Sonic (acoustic) logging .................................................................................................. 11
  Part 2 horizontal wells ....................................................................................................... 12
  Natural Gamma Ray Spectrometry log .............................................................................. 15
  Conventional vs. unconventional oil and gas well logging measurements ...................... 17
  Conventional and unconventional models set up .............................................................. 19
    Model 1. Conventional model ......................................................................................... 19
    Model 2. Unconventional model ...................................................................................... 20
  Tortuosity and wettability explanation ............................................................................. 21
  Dual-water dual-porosity calculation ................................................................................. 23
  Prediction for future research ........................................................................................... 28
  Bibliography ....................................................................................................................... 31
  Appendix ............................................................................................................................. 34
**Introduction & background**

**Part 1 conventional wells**

Evaluation on an oil reservoir always based on several key factors: porosity, permeability, oil, gas or water saturation. Porosity, which is defined differently in distinct cases, is generally understood as the percentage of void spaces in a rock matrix. The higher the porosity, the higher the possibility for a rock matrix to contain oil or gas because fossil fuel only exists in the pore spaces of rock matrices. Permeability is defined as the ability to transmit fluids in the rock. Oil and gas are producible if and only if they could be transmitted to the well and then the surface. Imagine an underground tank with sufficient amount of oil but there is no technique to transmit it onto the surface. That tank of oil is of no significance to human beings as all. In other word, we do not care about it. So far it is understandable that the “target rock” will be rock with high porosity and permeability. After that oil/ gas and water saturation need to be take into consideration. Oil/ gas/ water saturation is referred to the ratio of a single fluid in the mixture of all fluid. It is pretty straightforward that a high oil or gas saturation is desired depending on what is the production. Least water is preferred but it actually does not happen in real world. Thus, from log interpretation, the potential intervals are those who showed high porosity, permeability and oil/gas saturation.

After the discussion on target intervals, the next step is to locate these intervals. Since 19th century more than 10 loggings were invented to accurately pursue the source rocks under the ground. Here 9 popular loggings are introduced.¹

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Core sampling and mud logging

In the relatively adventuring years in petroleum engineering field, the only way to measure and forecast a well was through the core sample taken out of the well inside the drill pipes. In early 20th century, core-barrel tool was invented which allowed people to collect the bottom-hole core samples and evaluate these stone cylinders using laboratory equipment. There is no doubt that core sampling provides the most accurate data of bottom-hole matrices but it is of comparably high expanse due to the requirement of continuous drilling.

After the drilling muds are used to circulate the cuttings, the core samplings from different depth could be compared. The process of comparing is treating the core sample with some chemical solution and then exposing them under ultraviolet. In that way a lot of data is collected therefore the deep wells could be described.

Electric logging

First run by Schlumberger, the initial intention of electric logging had little to do with formation evaluation. On the contrary, the primary purpose was to detect the underground rock layers to confirm the data with seismic phenomena. The principle of electric logging is quite simple, recording the conductivity (or resistivity) using a conductive metal core as it is dragging upward along the vertical well. Nonetheless, it was not very long after noticed the diverse in conductivity in distinct rocks. As it

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mentioned in the paper “Formation Evaluation: loggings and testing”, “Clays have a low resistivity. Porous sands are conductive if saturated with salt water, are moderately resistive if the water is fresh, and are very resistive if the impregnating fluid is oil.” So far it is pretty straightforward that on an electric logging record the basic judgment is the higher the resistivity, the better the oil or gas reservoir.

SP curve

Short for Spontaneous Potential logging, which deals with the fact that if one or more layers of rock matrices are permeable, the fluid exists in the center of bore hole will filtrate into the rocks. At the beginning when SP was being studied, only the electro capillarity was considered by the researchers. Later on MRJ Wyllie provided with a more comprehensive and convincing explanation for the SP phenomena. According to Wyllie, SP is the outcome of combining two effects, electromotive forces and concentration of sodium chloride solution. His comprehensive explanation greatly improved the reliability of SP in formation evaluation. Also, it is understandable why SP curve might be inverted sometimes due to the high concentration in drilling fluid. Thus, SP curve combined with resistivity logging provides a relatively accurate image of the characteristic on different rock matrices.

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Induction logging

From the working principle it is clear that electric, more concisely, resistivity, logging is the most reliable especially when combined with SP curve. But the one drawback makes resistivity log not able to run through every well. That is, resistivity logging does not collect the electrical information inside a cased hole where no drilling fluid occupies the spaces. The weakness of resistivity logging was covered by the introduction of induction logging. Intended to discover the hidden mines during WW II, induction devices add one extra magnetic field into the environment and measure the new magnetic field lines. If there was a hidden mine in the man-made magnetic field, it would disturb the oval shape of the field lines. In that way magnetic or conductive objects were found within a short time. Induction loggings worked based on the same theory of interrupted magnetic field lines without any impact from casing cement.

Nuclear logging

"By the early 1900’s, it became evident that all terrestrial materials contain measurable quantities of radioactive elements in extremely minute quantities." These radioactive elements, such as uranium, decay by their own half-life period ranging from several seconds up to hundreds of years. As the process of disintegrating and transforming, measurable amount of energy is emitted through different rays from the elements. By recording these rays, or radioactivity, the rock type could be determined. Gamma ray, for instance, will be discussed more in the next paragraph.

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7 Same as 6
**Gamma ray logging**

As the resistivity (electric) logging cannot read through casing, gamma ray logging was invented to replace the resistivity logging with basically the same function. As it mentioned in the last paragraph, gamma ray logging measures the natural gamma ray of rock matrices near the borehole. The trend of gamma ray logging coincide with SP logging, the difference is that when measuring the same “depth”, referred to the distance from borehole, in a vertical well, gamma ray logging provides more details of the rock.

**Neutron logging**

Inspired by the idea of measuring gamma ray in bore hole, R.E Fearton came up with the idea of neutron logging in borehole. Further improved by Bruno Pontecorvo in 1941, neutron loggings work by bombarding neutrons into formations and then collecting the data on “secondary gamma ray activity” in react to the neutrons. Because the “secondary gamma ray” is highly sensitive to the water component in rock matrices, neutron loggings are generally used in determining the porosity. Not until later, neutron logging was qualitative rather than quantitative measurement. The well-known Archie’s equation is also closely related to neutron logging.

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8 Same as 6
Formation density logging\textsuperscript{10}

Formation density logging is another significant data set determining porosity. The devices consist of a gamma ray emitter and a detector; measure the porosity using bulk density. Usually in the formation evaluation field, the porosity used for more detailed calculation is simply the average value of formation density logging and neutron logging.

Sonic (acoustic) logging\textsuperscript{11}

Based on the physical principle that acoustic (sound) waves travels at a higher velocity in heavier rocks than lighter rocks, here the term “heavier” and “lighter” could be restated as “more dense” and “more porous”. Similar to electric logging, the technology “uses transmitters and receivers” to document the time need for the acoustic waves reflection in distinct layers. Sonic logging interprets the porosity and fracture even more accurately than other loggings.

All nine loggings are frequently-used in formation evaluation area but each one or combination of two loggings focuses on different properties. While searching for a potential pay zone, formation evaluation advisory always suggests the zones with high resistivity and porosity. Resistivity logging itself or combined with SP logging merging right (higher value) indicates that there is a potential of oil or gas. The range of SP logging reveals the permeability in formation. The porosity is determined by taking the average value of neutron and density loggings.

\textsuperscript{10} Same as 9
\textsuperscript{11} Same as 9
In either conventional wells or horizontal wells for shale gases, the loggings always provide reliable information because they measure the lithology or the nature of rock matrices. Lithology would not change no matter how the well is drilled.

**Part 2 horizontal wells**

Despite the relatively low price of natural gas compare to oil, the exploration and improvement in shale gas is no doubt one of the most exciting news in the energy field. People consider the 21 century a “new resources century”, and shale gas is likely to be the “new resource” or at least a significant step to the more efficient or environmentally friendlier energy resource.

In the past several decades, shale played a role of cap rock in the oil and gas reservoirs. Nonetheless, the story changed completely due to the re-exploration of Marcellus Shale, which extent from Ohio all the way north east to New York. Based on Dr. Terry Englander and Gary Lash’s research result, “Marcellus Natural Gas Shale Field could potentially hold up to 500 trillion cubic feet of Natural Gas with 10 percent recoverable reserves.”¹² Currently the daily usage of natural gas in United States is about 390 million gallons (52.14 million cubic feet), and

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the potential production of Marcellus Shale would support the gas usage for next couple centuries if the energy structure stays the same.\textsuperscript{13}

Because of the huge and healthy potential of shale gas (Marcellus is only one of the shale gas plays), production became a major concern in shale-gas research. Without the technologies of horizontal drilling and hydraulic fracture people may not able to start production.\textsuperscript{14}

Horizontal drilling allows the further production technology such as hydraulic fracture to be finished in shale gas plays. Figure 1 shows the simplified diagram for a horizontal drilling.

![Horizontal Drilling Diagram](image)

Figure 1\textsuperscript{15}

After the horizontal well is drilled, the formation is ready for hydraulic fractures. By increasing the pressure in deep well, rock formations open several different paths from wellbore to the outside rock matrices. Such technology keeps the rock formation inside elastic zone and the after decreasing the pressure to the original state, man-made fractures will close and cause no damage to the underground rock depositions. Some formations contain natural fractures which in most cases benefit the production. However, the optimum production rate requires an

\textsuperscript{13} Same as 12

\textsuperscript{14} Same as 12


accurate number of fractures in a certain interval but not as much as possible. Figure 2 showed the horizontal drilling and hydraulic fractures in a target zone.

![Figure 2](image)

Figure 216

Oil and gas wells cannot reach their maximal production rate without hydraulic fractures especially in shale gas plays because the rock matrices are more compacted than sandstone or limestone. Compare to linear flow, radial flow is not efficient due to the decreasing flow area from outside toward the wellbore while the flow area in linear flow does not change. Figure 3 gives a clear comparison on these two types of flow.

![Figure 3](image)

Figure 317

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Besides, fractures help reduce the flow distance of oil and gas in target zone, which contribute to the maximum flow rate. (maximal production rate refers to the maximum a well could reach in real world, but not the theoretic data) \textsuperscript{18}

\textbf{Natural Gamma Ray Spectrometry log}

Gamma ray log is actually a composition of three types of radiation: potassium, thorium and uranium. In conventional vertical log interpretations, gamma ray logging measurements were rarely taken apart because by measuring the total gamma ray radiation, we get enough


\textsuperscript{18} Same as 17
information on whether the rock layer would be pay-zone or not. If the rock matrix is young and contain $^{14}\text{C}$, decisions could be made simply by comparing the radioactivity of carbon and it of rock. Nonetheless, the fact is that almost all $^{14}\text{C}$ decay to $^{12}\text{C}$ during the process of forming carbon matters. $^{12}\text{C}$ does not have any gamma ray radioactivity, which make it hard to identify from gamma ray logging measurements. Uranium and thorium, which are two portions of gamma ray, adsorb to carbon because of the cation exchange capacity. The cation exchange capacity refers to the maximum cation that rock matrix could hold. The fact leads us to explore more about spectrometry log, especially uranium and thorium since these two logging measurements are key parts to the analysis of carbon matters in the rock matrix. Figure 4 is a typical graph for spectrometry logging.

Figure 4

In figure 4, the dashed line on left-hand side shows the total gamma ray, which is the gamma ray logging we always refer to in conventional wells. On the right-hand side, the left solid line is thorium logging, dashed line in middle is uranium and solid line on right is

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potassium logging. So far it is very clear that the goal is to find a zone where total gamma ray is relatively high especially that uranium and thorium are high.

**Conventional vs. unconventional oil and gas well logging measurements**

Because the logging tools in conventional and unconventional wells are the same, it is helpful to analyze the log reading starting with conventional logging measurements, which are the what people familiar with, and then move to unconventional oil and gas logging measurements, which are the information being examined in this paper. Table 1(a) is how logging measurements behave in conventional wells.

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Fluid</th>
<th>Gamma ray</th>
<th>Density g/cc</th>
<th>Potassium</th>
<th>Uranium</th>
<th>Thorium</th>
<th>Neutron Porosity</th>
<th>Resistivity (Rt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>sandstone</td>
<td>Gas</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Oil</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Moderate</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Water</td>
<td>Low</td>
<td>high</td>
<td>low</td>
<td>Low</td>
<td>Low</td>
<td>moderate</td>
<td>low</td>
</tr>
<tr>
<td>limestone</td>
<td>Gas</td>
<td>Low</td>
<td>Moderate</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>low</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Oil</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>low</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Water</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>low</td>
<td>low</td>
</tr>
<tr>
<td>shale</td>
<td>high</td>
<td>High</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1(a)

It is clearly shown in table 1(a) that gamma ray is the primary logging measurement to distinguish different lithology and is not affected by the existence of fluids. Other logging measurements, such as SP, Density, Neutron and Resistivity are all affected by different fluids. Here Sonic is not considered because when gas exists, the logging measurement is not stable.
Also enough information provided by other logging measurements made it possible to accurately predict the well without considering Sonic. According to Archie’s equation, total resistivity could be calculated with a corresponding $R_t$. Thus in unconventional wells, gamma ray and resistivity are the two logging measurement we chose for further research. Table 1(b) is a rough expression of unconventional oil and gas reservoir. As we discussed, uranium and thorium are expected to be high because of the existence of carbon. Resistivity is supposed to be moderate since it is a combination of gas/oil and shale.

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Fluid</th>
<th>Gamma Ray</th>
<th>Density (g/cc)</th>
<th>Potassium</th>
<th>Uranium</th>
<th>Thorium</th>
<th>Neutron Porosity</th>
<th>Resistivity (Rt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shale</td>
<td>Gas</td>
<td>Low</td>
<td>Moderate</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>Oil</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>Water</td>
<td>Low</td>
<td>high</td>
<td>low</td>
<td>Low</td>
<td>Low</td>
<td>moderate</td>
<td>low</td>
</tr>
</tbody>
</table>

Table 1(b)

In table 1(b), the resistivity logging differs from it in table 1(a) because the huge percentage of shale in lithology will lower the resistivity reading even when the fluids are oil and gas. Nonetheless, describing the distinction using the words “high” and “moderate” are definitely not convincing enough. More digital information is required to show the diverse of resistivity in sandstone and shale. To be more specific, the resistivity is lowered by how many $\Omega$m. Uranium and Thorium logging measurements changed by the presence of oil and gas. Due to the property that uranium and thorium are attached to carbon, the increase of these two logging measurements implied the fact that there are oil and gas in shale layer.
Conventional and unconventional models set up

To provide a quantity difference of resistivity in conventional and unconventional wells, Archie’s equation and an ideal reservoir model need to be set up.

Model 1. Conventional model

In this model, the ideal data are used for calculation with the assumption that neither uranium nor thorium exists. For the case where: $\Phi=20\%$, $R_w=0.1 \, \Omega m$, percentage $V_{sh}=20$ $Sw=0.2$.

$$R_t = \frac{R_w}{\Phi^m \cdot Sw^n}$$

In Archie’s equation, $m$ represents the tortuosity of the path and $n$ represents the wettability of rock matrix. In conventional wells, it is common to assume these two numbers to be 2.

$$R_t = \frac{0.1}{0.2^2 \cdot 0.2^2} = 62.5 \, \Omega m$$

Since it is an inverse relationship, lower measured resistivities would represent higher water saturations (the water saturation is never significantly less than 20%).
Model 2. Unconventional model

The case is much more complicated in unconventional wells than in conventional wells, because we cannot assume that m and n are both 2. Again m=f(tortuosity), n=f(wettability). The basic process of determining the m, n and Rt are divided into three steps. The physical significance of tortuosity and wettability, as well as their effects on the measurements is explained later.

1). Measure Rt in a mixed saturation of oil, gas and water.

The first step is a simulation of rock matrix located underground with generally the same ratio of oil, gas and water.

2). Measure Rt in a 100% water saturated environment.

Here Sw=1, so that the wettability of rock matrix (n) does not have any impact on other values in Archie’s equation. We can simply state that Sw^{n} = 1 in step 2.

\[ \phi^{m} \frac{R_{w}}{R_{t}} \] Therefore we have \( m=\log_{\phi} \left( \frac{R_{w}}{R_{t}} \right) \), call it eq(*).

3). Substitute m with the solution of eq(*) in Archie’s equation.

\[ Sw^{n} = \frac{R_{w}}{\phi^{m}R_{t}} \] and n could be calculated.

After running the calculation of m and n we need to use Archie’s equation again and calculate Rt at various values of water saturation.

These three steps are run based on the assumption that Rt, Rw and \( \phi \) could be measured by laboratory equipment and core samples of the target zone are available. After
gaining m and n, Rt in shale plays could be obtained by using new m and n. Rt in shale plays should be lower than 62.5 Ωm if still using Φ= 20%, Rw=0.1 Ωm, Sw=0.2. The outcomes should confirm the table 1(a) and 1(b).

**Tortuosity and wettability explanation**

As noted by Ransom in his book, “the geometry and degree of interconnection of interstitial-water volumes control the resistivity of reservoir rock. Electrically conductive paths provided by interstitial-water solutions will have different resistances when the same quantity of the same interstitial-water solution has different distributions and geometrical shapes within different insulating rock frameworks.” That is to say, m is directly related to Rt because “interstitial water behaves as a network of conductive path.” An equation provided by Ransom relates resistance to resistivity, as a function of path length and cross-sectional area.

\[ r = R \cdot \frac{L}{A} \]

\( r = \text{resistance (Ω)} \)

\( R = \text{resistivity of the substance making up the conductive network (Ω-m}^2/\text{m}) \)

\( L = \text{effective length of the network (m)} \)

\( A = \text{effective cross-sectional area of the network (m}^2) \)

---

By applying the equation in a cubic model could help us understand the scenario of how tortuosity works to change resistivity.

Figure 5

Figure 5 is a cubic rock matrix with 20% solid material removed in the middle. A liquid flow is forced to flow through the fracture inside the cubic matrix. From the equation, \( r = R \frac{L}{A} \), we get the resistivity in this specific situation.

\[
r_{\text{water}} = Rw \frac{L}{A} = Rw \frac{S}{0.2S^2} = Rw \frac{1}{0.2S}
\]

It is clearly interpreted in the equation that resistivity is inversely proportional to the area of the fracture.

Big chunks of organic matters will decrease the flow area more significantly than small chunks. Thus the value of \( m \) will increase more when big chunks show up in pore spaces of rock matrices.

---

The inverse happened in wettability, that is reflected in the value of \( n \). According to the definition of wettability, it is “the measurement of wetting phase currently in a formation. Wetting is driven by fluids or the surfactants in the fluid in contact with the surface.” For the same volume of the organic matter, the smaller the chunk, the higher the surface area in contact with fluid resulting in a larger value in wettability (\( n \)).

**Dual-water dual-porosity calculation**

The principle of dual-water dual-porosity method is Archie’s three “empirical equations” listed below:

\[
F = \frac{1}{\varphi^m} \quad (1)
\]

\[
R_0 = F \cdot R_w \quad (2)
\]

\[
S_w = n \frac{R_o}{R_t} \quad (3)
\]

After three decades’ trial and error on determining the most practical method in qualifying these three equations, dual-water dual-porosity stood out as the most effective one, according to Ransom, Ebenhack and others. It has the advantage over some competing methods of not requiring costly and time-consuming laboratory measurements to evaluate each well. As discussed, \( R_o \), known as the total resistivity, is a measurement of all electrical resistivity in the investigation range of the tool. This includes the water-influenced resistivity “found in all electrically effective pore spaces, whether they are hydrodynamically effective or

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22 Same as 20
ineffective”. This observation is significant in shaly sand or shale reservoirs where “electrically effective porosity is almost always greater than the hydrodynamically effective porosity (φe).” also in Archie’s three equations, Rt includes the resistivity of conductive paths in both effective and non-effective pore spaces, using φe in shaly sands or shale to calculate water saturation is not appropriate. In Eq(1), using φe results in a higher F value. Then plugging the calculated F into Eq(2) leads to a higher Rø than the real one. And finally in Eq(3), the calculated Sw is much larger than the real value because the wrong porosity at the very beginning. Nonetheless, φe does not contribute to an unacceptable higher Sw in conventional reservoir since most porosity in sand reservoirs are all effective. But in shaly sand or shale layers, φt, the total porosity, must be used instead of φe.

It is pretty straightforward that

$$\Phi_t = \phi_e + \phi_{ne} \quad (4)$$

And then replacing φ with φt in Eq(1) we have:

$$F = \frac{1}{\phi t^m} \quad (5)$$

Ransom claimed that “Effective porosity is the pore space associated with reservoir rock. Non-effective porosity is defined as the porosity associated with clay shales.” If there exists two pore spaces, it is very likely to have two waters with different resistivity. In effective pore volumes, call the resistivity R_w for water. In non-effective pore volumes, call the resistivity R_{wb} for the fact that in non-effective pore spaces, conductivity is a combination of “surface conductance and electrical conductivity”. However, the resistivity logging measurement cannot
distinguish \( R_w \) from \( R_{wb} \). Figure 6 showed the relationship of everything that has been discussed.

By relating to the value of \( R_w \) and \( R_{wb} \), an equation for composite \( R_{wz} \) could be obtained:

\[
\frac{1}{R_{wz}} = \frac{\phi_e}{\phi_t R_w} + \frac{\phi_{ne}}{\phi_t R_{wb}} \quad (6)
\]

Equation (6) showed that “the conductivity of a solution is equal to the sum of the conductivities of its components”. Plug that into original Archie’s equations we get a set of revised Archie’s equations which applied to all rocks:

\[
F = \frac{1}{\phi m^c} \quad (7)
\]

\[
R_o = F \cdot R_{wz} \quad (8)
\]

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\[ S_{\text{wt}} = \frac{R_o}{R_t} \quad \text{(9)} \]

Assuming that all producable oil and gas reside in effective pore spaces (which is, in turn, a part of total pore space), a new equation for material balance could be written as:

\[ (1-S_{\text{we}}) \phi_e = (1-S_{\text{wt}}) \phi_t \quad \text{(10)} \]

So far we are done with the introduction of methodology of dual-water dual-porosity and are ready for the graph analysis of a real example. Figure 7 is a standard graph of percentage clay verses Rw. In this figure, Rwa and Rwb represent the water resistivity at 0 or 100 percent clay respectively. The red line is the bound line of Rw in this example.

![Figure 7(a)](image_url)

We can see from the graph that Rwa= 0.4 and Rwb=0.07, the numbers are made up so that the idea could be addressed better, the difference between Rwa and Rwb is typically

\[ ^{25} \text{Ransom, Robert.} \text{ Practical Formation Evaluation.} \text{ 1st ed. New York: Wiley Custom, 2011. 282. Print.} \]
smaller in practice. Referring back to Archie’s equation, a new equation which is the most powerful one in dual-water dual-porosity model could be obtained:

\[
Sw^* = \frac{1}{\frac{1}{\mr^*m} + \frac{(Rwz)\nu_{clay}}{\nu}}
\]

(12)

The data points are more likely to gather on “top right” area, compared to other data points because of its high clay content and high organic content, the yellow dots in figure 7(b) show the approximate position of organic-rich shale formation.

Figure 7(b)\(^26\)

Pick a random point from those points and get the distance between the data point and the bound line, which is the real Rw value. Using the corresponding bound line data provided the more a specific data value. The value drew by the yellow line is the Rwz value goes into equation (12). Before the justification, Rwz value is the vertical difference between the dot and

\(^{26}\) Same as 25
Rwa, which in this example is about zero, and we know immediately that the value is wrong. Nonetheless, the bound line in real life is much flatter than the one we have here so that it does not make that much difference if the wrong one was used for the sake of this example.

After the Rw justification, Rwz could be plugged into eq (12) and Swt could be calculated from that equation. After that, plug Swt into eq (10). It is followed by a Swe value, which is the effective water saturation and the goal in the whole process of analyzing dual-water dual-porosity model. This is the water that occupies pore spaces that oil or gas could occupy. Since the conductive clay surfaces offer an additional path for electrical conduction, the resistivity is likely to be reduced due to the presence of the clay content, which would make the water saturation appear higher, without the use of a model such as the dual water dual porosity model.

The organic rich shales offer an extension of this model, a new type of porosity will be defined in next section of this paper.

**Prediction for future research**

Based on the result of Natural Gamma Ray Spectrometry log, high thorium and uranium value indicates the existence of carbon. If the potassium is low at the same point, it indicates relatively low clay content, and thus higher productive potential, the potassium content is not really related to the organic content.

It is pretty straight forward that solid organic matter cannot contribute to porosity because they occupy a certain amount of pore space. Research need to be done following the
process this paper discussed to determine other characteristics. The next step after researching on everything discussed could be defining a new idea of porosity other than the dual-water dual-porosity model which could be called dual-water triple porosity. The table below provides the basic idea of dual-water triple-porosity model.

One of the remaining questions is how to build a model that recognizes the presence of the organic matter in the shales. The table shows that the organic matter contributes to high resistivities. We don’t know yet exactly how it affects the continuity of the electrical current. If it tends to block pore channels, it may increase resistivity more than if it just occurs with the larger pore spaces. If this is the case, might we expect to see an increased ‘m’ exponent, because it is making the conductive path more tortuous.

<table>
<thead>
<tr>
<th>Rock Solid</th>
<th>Rock Solid</th>
<th>Rock Solid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swe (Swf+Swirr)</td>
<td>Effective porosity</td>
<td>Swirr</td>
</tr>
<tr>
<td>Swf</td>
<td>Swf</td>
<td>Organic porosity</td>
</tr>
<tr>
<td>Swb</td>
<td>Non-effective porosity</td>
<td>HC fluid</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Organic Solid (to be determined)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Swb</td>
</tr>
<tr>
<td>Clay</td>
<td>Clay</td>
<td></td>
</tr>
</tbody>
</table>

In this table, HC fluid could be categorized in either effective porosity or organic porosity.

Compare to the left hand side of the table, the right hand side contains three types of porosity: effective, organic and non-effective. Future research could be done on constructing this dual-
water triple porosity model. The effective porosity contains fluids that can contribute to flow, while the ineffective porosity contains water electrochemically bound to the clays, at the same time the solid organic matter cannot flow, but is not bound. It is not rock, but it is not fluid. So, we need to understand better its occurrence and distribution in the pores. In order to characterize the potential productivity of the shale plays, it is necessary to understand if and how the occurrence of the organic matter affects production and how it is seen on the measurements. This paper suggests some of the characteristics we can expect and speculates on how those may be reflected.

In summary, the spectrometry gamma ray measurements are expected to help identifying the presence the organic matter, especially when combined with higher resistivity measurements. This is what makes the new model important. The dual water model has shown the ability to evaluate the total amount of water filling pore space in face of complexity of ‘free’ water occupying effective pore space and water ‘bound’ to the clay surfaces. By combining this model with the understanding of the effects of presence of solid organic matter on other measurements (spectral gamma ray, density and neutron porosity), it should be feasible to characterize the shale potential more effectively from well logs.


<http://www.earthworksaction.org/issues/detail/directional_drilling>.


Print.

Appendix

Along with the process of researching, I presented my ideas of this project using powerpoint slides, which included the basic concepts in this paper.

Nature of Solid Organic Matters in Shale

—Xinyang Wu
Advisor: Dr. Ben Ebenhack
Dr. Matt Young

overview

- Goal & history
- Background information
- Analysis on shale
  - Natural gamma ray spectrometry log
  - Conventional vs. unconventional
  - Modeling
  - Calculation
  - Prediction
- Expect for future
The presentation started with introducing important definitions since the audience were not necessarily in petroleum engineering and related field.
Four out of nine logging tools were introduced due to the time limit.

One of the major topics nowadays in petroleum field is that if shale gas is really going to play an important role or not.
Marcellus shale is broadly distributed.
Background information

- Horizontal drilling

http://www.dec.ny.gov/energy/46331.html

Background information

- Fractured well

Unfractured Well Fractured Well

radial flow: Constricting Near-linear flow: More efficient
Analysis on shale

- Gamma ray
- $^{14}\text{C}$ and $^{12}\text{C}$
- Potassium, thorium and uranium
- Thorium and uranium adsorb to C
- Natural Gamma Ray Spectrometry log

Natural Gamma Ray Spectrometry log
Conventional vs. unconventional oil and gas well loggings

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Fluid</th>
<th>Gamma-ray</th>
<th>Density g/cc</th>
<th>Potassium</th>
<th>Uranium</th>
<th>Thorium</th>
<th>Neutron PORosity</th>
<th>Resistivity (RD)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>sandstone</em></td>
<td>Gas</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
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<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>Oil</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Moderate</td>
<td>High</td>
</tr>
<tr>
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<td>Water</td>
<td>Low</td>
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<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>moderate</td>
<td>low</td>
</tr>
<tr>
<td><em>shale</em></td>
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<td>Low</td>
<td>Moderate</td>
<td>Low</td>
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<td>Low</td>
<td>Low</td>
<td>moderate</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>
Conventional and unconventional models set up

1. conventional model
   - $\Phi = 20\%$, $R_w = 0.1 \ \Omega m$, percentage $V_{sh} = 20$
   - $S_w = 0.2$
   - $R_t = \frac{R_w}{\Phi^{m} S_w^n}$
   - $R_t = \frac{0.1}{0.2^2 \times 0.2^2} = 62.5 \ \Omega m$

2. unconventional model
   - 1). Measure $R_t$ in a mixed saturation of oil, gas and water
   - 2). Measure $R_t$ in a 100% water saturated environment.
   - Here $S_w = 1$, so that the wettability of rock matrix ($n$) does not have any impact on other values in Archie's equation. We can simply state that $S_w^n = 1$ in step 2
Conventional and unconventional models set up

- $\varphi^m = \frac{R_w}{R_t}$. Therefore $m = \log_\varphi (\frac{R_w}{R_t})$, call it eq(*)
- 3). Substitute $m$ with the solution of eq(*)
- $S_w^n = \frac{R_w}{\varphi^m R_t}$, and $n$ could be calculated
- After gaining $m$ and $n$, $R_t$ in shale plays could be obtained by using new $m$ and $n$

Dual-water dual-porosity calculation

- $(1 - S_w) \varphi_e = (1 - S_w) \varphi_t$
### Future?

<table>
<thead>
<tr>
<th>1940s</th>
<th>1950s</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock solids</td>
<td>Rock solids</td>
<td>Rock solids</td>
</tr>
<tr>
<td>Pore space</td>
<td>Swf+Swirr</td>
<td>Swirr</td>
</tr>
<tr>
<td>clay</td>
<td>Swb</td>
<td>Swf</td>
</tr>
<tr>
<td></td>
<td>Clay</td>
<td>HC fluid</td>
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### Works Cited