AN INVESTIGATION OF THE EXPONENT IN ARCHIE'S EQUATION: COMPARING NUMERICAL MODELING WITH LABORATORY DATA: TOWARDS CHARACTERISING DISTURBED SAMPLES FROM THE CASCADIA MARGIN:- IODP Expedition 311

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ABSTRACT

Archie's equation is used routinely in estimating the water saturation of reservoirs, or for estimating a value for the reservoir water resistivity in the water leg. We consider experimental results from the laboratory for a range of samples exhibiting various grain-shapes, and mixtures of differently-shaped grains. These are combined with a numerical modeling approach, considering 3D flow of electric current around 'typical' grain shapes and is extended and applied to spheres and ellipsoids.

Numerical modelling, considering a single, spherical grain, led to values of Archie's '***m***' parameter in excellent agreement with those obtained for large numbers of sand-sized glass spheres deposited and compacted in the laboratory. Similarly, for platy grains their orientation relative to the direction of flow of electric current is shown to be critical, in line with the efficiency concept proposed by Herrick and Kennedy (1993).

Existing results for two-component mixtures of differently-shaped grains, namely: quartz sands, glass spheres and shell fragments are considered. Predictions made of Archie's 'm' parameter for such mixtures, on the basis of their proportion and laboratory-determined values of 'm' for each component, matched laboratory derived values, suggesting the prospect of predicting Archie's 'm' parameter on the basis of grain properties (e.g. shape) alone. Each individual sample, including these mixtures, obeyed Archie's equation. Samples having differently shaped grains, however, when plotted together were better-described by Winsauer's equation, although the values of 'm' derived from Archie and Winsauer's equations were quite different.

Our approach is applied to estimating ***m*** from a knowledge of the grains themselves, even though a sample may be highly disturbed. Improving the possibilities for reservoir characterization in running sands and sediment hosted methane hydrates.

INTRODUCTION

The first downhole log was an electrical log recorded by H G Doll on September 5, 1927, in the Pechelbronn field, Alsace, France. This was initially applied as a stratigraphic correlation tool between wells until Archie (1942) derived an empirical relationship between the electrical resistivity and porosity, thus enabling the first downhole assessment of porosity *in situ*. Since then alternative measurements have been developed for determining the porosity *in situ*, thus enabling the electrical resistivity to be used to determine the water saturation in the reservoir, and hence the hydrocarbon saturation. Consequently Archie's equation underpins the use of electrical resistivity in determining the hydrocarbon saturation, but requires a series of empirical parameters to be determined. While Archie dealt solely with clean formations, later studies demonstrated a need for including a non-unitary value for the multiplier "a" (Winsauer et al 1952). For clean formations exhibiting intergranular porosity these parameters may be well defined and the parameters constant, while for heterogeneous formations or formations containing conductive matrix (e.g. "shales") alternative strategies may be required (e.g. Ragland, 2001; Worthington, 1982).

Through his laboratory results, Archie demonstrated the electrical resistivity of sandy rocks was related to porosity as follows:

$$F=1/(\text{porosity})^{m} \qquad (1)$$

where: $F = Ro/Rw$,

and Ro is the resistivity of the water-saturated formation, Rw is the resistivity of the water fullysaturating the pore-space, and ***m*** is a formation dependent parameter; Archie showed ***m*** increased with the degree of cementation of his sand samples, being lowest for loose sands. Relationships for selected porous media and Archie's ***m*** parameter are shown in Table 1.

A more general relationship, was proposed by Winsauer et al., (1952):

$$F = a / \text{porosity}^{m} \qquad (2)$$

While Winsauer's equation has been applied to sets of downhole data, it does not satisfy the boundary condition: F=1.0 when porosity=1.0

Archie (1942) extended these relationships to include water saturation, Sw:

$$Sw=(Ro/Rt)^{1/n} \qquad (3)$$

where Rt is the resistivity of the partially saturated formation, 'Sw' is the water saturation, and 'n' is an empirically derived saturation exponent, typically taken to be 2.0, on the basis of laboratory studies of core (e.g. Archie 1942).

Porous Medium	Value of Archie's 'm'
Straight cylinders	1.0 (Herrick et al 1993)
Inclined cylinders	>1.0 (Wyllie et al, 1952)
Change in diameter	>1.0 (Jackson, 1975)
Cemented sandstones	1.8-2.0 (Archie, 1942)
Loose sands	1.3 (Archie, 1942) 1.4-1.7 (Jackson et al., 1978)
Loose quartz spheres	1.25 (Atkins et al., 1961) 1.25 (Jackson et al., 1978) 1.3 (Wyllie et al., 1953)
Shell fragments	1.9 (Jackson et al., 1978)
Spheres and shell fragments	1.25-1.9 (Jackson et al., 1978)
Vuggy dolomite	2.0-5.0 (Focke et al., 1987)

Table 1. *Values of Archie's* ***m*** *parameter*

Typically, Archie's equations (1,2,3) are combined as follows:

$$Sw = (Ro/Rt)^{1/2}, \text{ and}$$

$$Sw = (F{*}Rw/Rt)^{1/2},$$

$$Sw=(\text{porosity}^{-m}Rw/Rt)^{1/n} \qquad (4)$$

have been found suitable for calculating water saturations in reservoir rocks, and have led to the resistivity approach becoming the method of choice for estimating oil in place. Typically the exponents 'm' and 'n' described above are determined from laboratory measurements on cylindrical core samples (e.g. 100mm long and 35mm diameter?) sub-sampled from larger whole-core samples (Archie, 1942).

More recently, effective medium models have successfully described resistivity porosity and saturation relationships, without the constraint of a non-conducting matrix which is inherent in traditional methods such as Archie's (Taylor et al., 2006; Berg, 1995; Berg, 2007).

For example: Taylor et al. (2006) suggested

$$F = \text{porosity}^{-m} \left((1-Rw/Rma)/(1-Ro/Rma)\right)^{-m} \qquad (5)$$

where Rma is the resistivity of the particle matrix., and ***m*** is 'Archie's '***m***' parameter.

Consequently predicting water saturation (and hence hydrocarbon and methane hydrate saturation) using these newer models, still requires an estimate of Archie's ***m*** parameter.

Predictions of water saturation are highly dependent on the value of ***m*** selected for conventional modeling (e.g. (4)), as shown in figure 1.

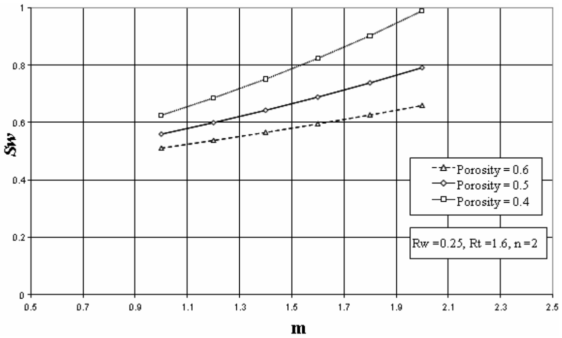

Fig. 1. *Water Saturation (Sw) is sensitive to the* ***m*** *parameter of Archie's equation*

Herrick et al., (1993) suggested, ***m*** is related to the efficiency of the flow of electric current through porous media, in the sense of having been 'normalized' for both the amount of fluid in the porous medium (porosity) and fluid resistivity.

Archie's '***m***' parameter has been shown to be controlled by particle shape (Wyllie et al., 1953; Atkins et al., 1961), while Jackson et al., (1978) explored individual, loose, unconsolidated sand samples in the laboratory, each having a different particle-shape; compacted in a controlled manner; they demonstrated these sands followed Archie's original relationship with ***m*** strongly related to grain-shape, as illustrated in Fig. 2. Jackson et al. deposited each individual sample underwater, as a means of producing the highest porosity (Kolbuszewski, 1948) and subsequently compacted in stages using a sieve shaker, providing independent porosity relationships for each sample of differently shaped grains (Jackson et al., 1978). Mixing spheres and shells (1:1 by dry weight) resulted in an intermediate value of ***m***, the data following Archie's equation as shown in figure 2.

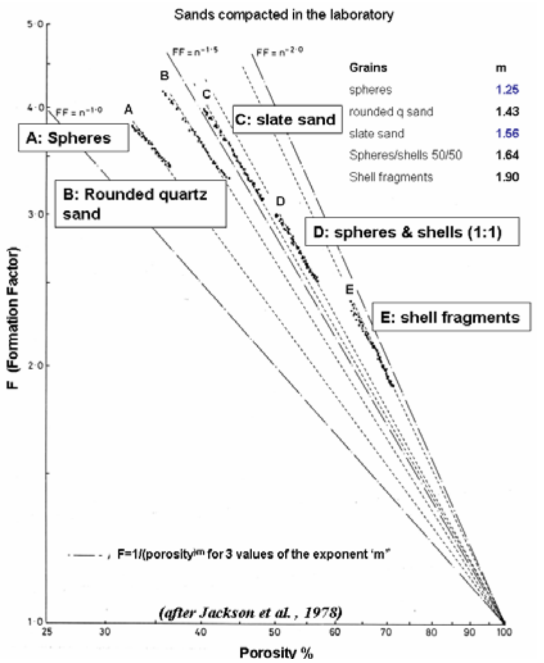

Fig. 2. *Individual sand samples compacted in the laboratory (after Jackson et al., 1978)*

GRAIN MIXTURES

Mixing differently-shaped grains was also investigated by Jackson et al., they used two-component mixtures of differing proportions of glass spheres, quartz sand grains, and platy shell fragments as shown in Figs 2 & 3, their data followed Archie's equation, with the values of ***m*** increasing smoothly as the grains became less spherical.

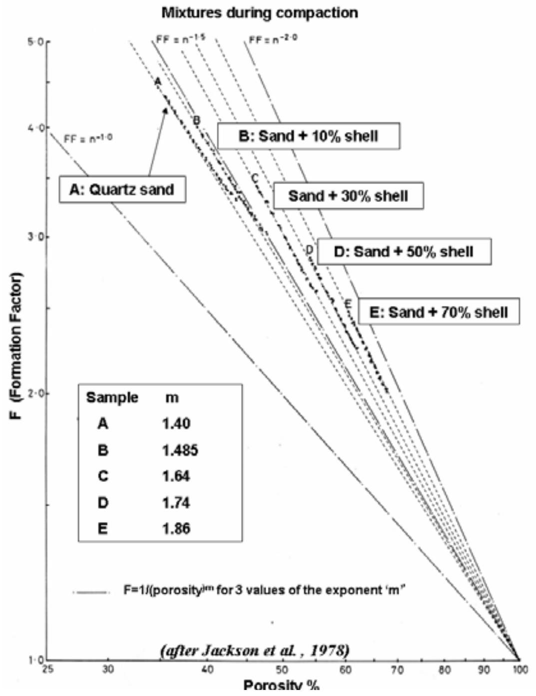

Fig. 3. *Mixtures of quartz sand and shell fragments compacted in the laboratory (after Jackson et al., 1978).*

An empirical 'mixing' equation (6) was developed relating the value of ***m*** for each mixture, to the value of ***m*** of each component and its relative abundance (ie ***m***sand, ***m***sphere, ***m***shell), the value of ***m*** having been derived experimentally for each component shown in Fig. 2, as follows:.

For spheres *OR* sand *PLUS* shell fragments:

$$mp = 1.0 + (1.0.p1.m1^{*} + 1.15\,p2.m2^{*}) \qquad \ldots\ldots \qquad (6)$$

where: ***m***p is the predicted value of ***m***
m1* = (***m***sphere – 1.0) OR (***m***sand – 1.0)
m2* = (***m***shell-1.0)
p1 and ***p2*** are the proportions by wt. of each grain type constituting each mixture.

Shell %	Sand %	Sphere %	Laboratory derived '***m***'	Predicted '***m***'
10	90	0	1.485	1.49
30	70	0	1.64	1.61
50	50	0	1.74	1.73
70	30	0	1.86	1.85
0	100	0	1.43	1.43
50	0	50	1.64	1.64
100	0	0	1.90	2.04

Table 2. *Laboratory derived and predicted **m** values*

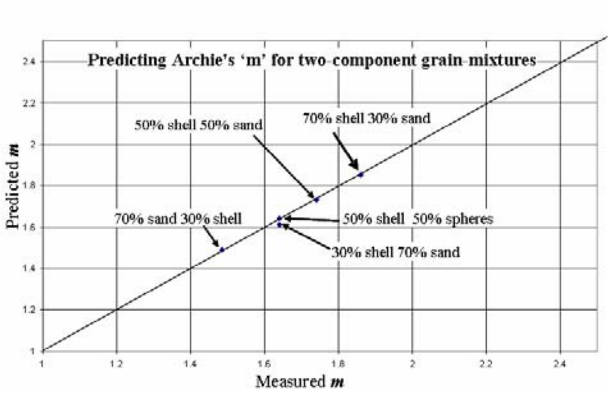

Fig. 4. *Predicted values of* ***m*** *for the two-component mixtures of sand-sized particles shown in Fig. 3.*

This empirical relationship (6) successfully predicts the value of ***m*** for the two-component mixtures of differently shaped grains as shown in Table 2 and Fig. 4, 30% shell and 70% quartz sand, for example; interestingly, the associated value of ***m*** (1.64) is almost identical to that obtained for 50% shell and 50% spheres. However, the relationship (6) does not apply to shells alone, as the 'shell' coefficient is greater than 1.0, indicating the proportion of shell fragments, by weight, underestimates their contributions to predicted values of ***m*** for mixtures containing shell fragments. The authors suggest this is likely due to the very thin platy nature of the shell fragments, giving them a far larger 'diameter' than either spheres or quartz sand grains of similar mass. Consequently, shell fragments, orientated normal to the direction of the flow of electric current, would influence the flow of that current far more than a similar weight of spheres (Jackson, 1971).

The median points of each of the five experimental datasets, shown in Fig. 3 are plotted in Fig. 5, and can be seen to follow Winsauer's equation (Winsauer et al., 1952), although each individual mixture has been shown to follow Archie's equation (Fig. 3).

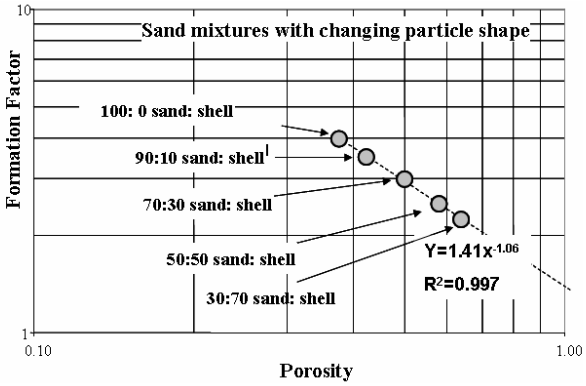

Fig. 5. *Median points of the datasets in Fig. 3*

The value of ***m*** obtained via Winsauer's equation was 1.06, (Fig. 5) whereas the values of ***m*** attributed to each of the five individual mixtures of quartz sand and shell fragments, fell in the range 1.4 to 1.7. Very different water saturations would be predicted by such differences in ***m***, (see Fig. 1).

Therefore, considering down-hole measurements, we suggest unrepresentative estimates of ***m*** may arise from downhole logging data alone, in formations where ***m*** is changing with depth, in response to a systematic change in grain-shape, for example; while individual sandy samples, from different depth intervals, might follow Archie's equation, with ***m*** varying between each depth interval, for example.

Consequently, assuming Archie's equation to be applicable and predicting ***m*** from a knowledge of resistivity and porosity derived from downhole logs, is attractive for clean sandy formations.

Although methods of assessing ***m*** from grain fabric data alone, are not established, such an approach would be attractive, particularly in the presence of significant disturbance, such as in cores containing sediment-hosted methane hydrate or friable sands. Such an approach inspired us to seek a method of estimating ***m*** from knowledge of the constituents of core samples. To investigate the feasibility of this approach we report, below, numerical experiments using known grain shapes, and compare the results with the laboratory data discussed above. Thus, testing the hypothesis: 'modeling resistance measurements using the flow of electric current in 3D around typical grain shapes is representative of macroscopic core samples, underpinning a suitable method for estimating ***m***'.

MODELING ELECTRIC CURRENT FLOW IN 3D AROUND INDIVIDUAL GRAIN-SHAPES

An existing approach to modeling electric current flow in 3D through rectilinear pore channels (Jackson et al., 2002) has been extended to include spheres, ellipsoids and cylinders, using a standard finite element modeling (FEM) scheme (e.g. Zimmerman, 2006). Our approach is summarized in Figure 6, where electric current Jo (current density) is set to flow uniformly inwards from side 1 into our model (from high to low values of X), inside a cuboid whose four long sides are set to be insulating, as shown in Figure 6, simulating electric

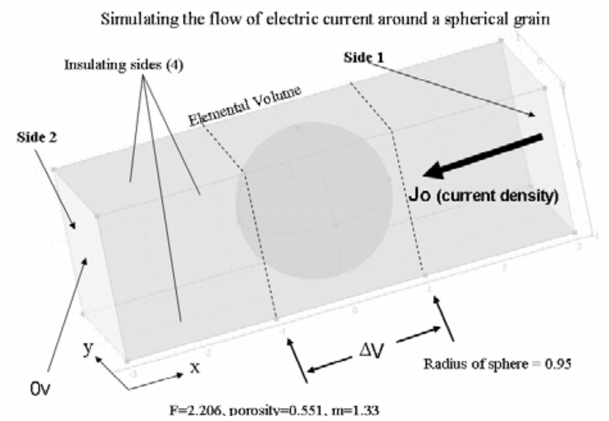

Fig. 6. *Modeling electric current flow (Jo) in 3D around a spherical grain (after, Jackson, et al., 2002).*

current flow in an elemental volume, being inspired by the definition of resistivity: ‘uniform current flow through a unit cube parallel to one edge’ (e.g. Grant et al., 1965). In this way current flows uniformly inward from side 1, and then flows uniformly through the central elemental volume (2x2x2) finishing at ‘side 2’, which is held at 0v.

The porosity of each experiment was calculated as:

Porosity = (elemental volume-grain volume)/(elemental volume)

where the elemental volume shown in Fig. 6 is 2x2x2 (i.e. 8 units).

The example in Fig. 6, shows a single, insulating, spherical grain of radius 0.95, set inside the 2 x 2 x 2 elemental conducting volume. Applying Archie’s equation to the associated numerical data, resulted in a Formation Factor (F) of 2.206, a porosity of 0.551, and a corresponding value of ***m*** of 1.33. Similarly, spheres of radii in the range 0.95 to 0.5 were modeled, the results in Fig. 7 show all the values of ***m*** to be close to 1.3, although the porosity varied from 0.55 to 0.95, respectively, being almost independent of the size of the sphere and hence the porosity associated with the elemental volume containing it, demonstrating the robustness of this approach.

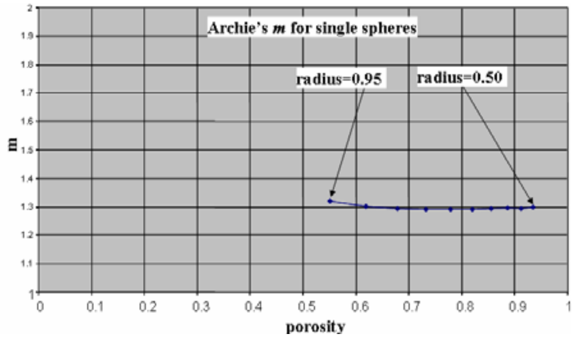

Fig. 7. *Modeling electric current flow in 3D around single spheres, assuming Archie’s equation*

Similarly, multiple spherical grains were modeled as illustrated in Fig. 8, where the value of ***m*** can be seen to be little changed from that derived for a single sphere. These values of ***m*** derived for various numbers of spherical grains are essentially the same, being 1.30 +- 0.05, and are indistinguishable from those derived experimentally from laboratory samples containing many millions of grains (***m*** = 1.20-1.50).

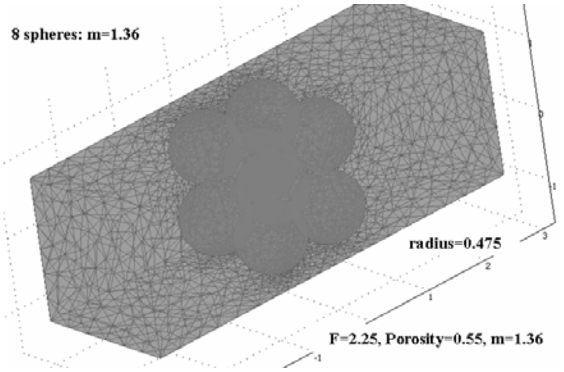

Fig. 8. *3D FEM modeling of electric current flow past 8 spherical grains assuming Archie’s equation.*

Similarly, to study the effect of changing grain-shape and orientation an ellipsoidal particle was modeled as shown in Figure 9, the value of ***m*** was calculated to be 2.56 when the maximum cross-sectional area was offered normal to the direction of the flow of electric current. Conversely, rotating the ellipsoidal grain by 90 degrees, presenting the least cross-sectional area normal to the direction of flow of electric current, the value of ***m*** was calculated to be a minimum 1.06 (see Fig. 10).

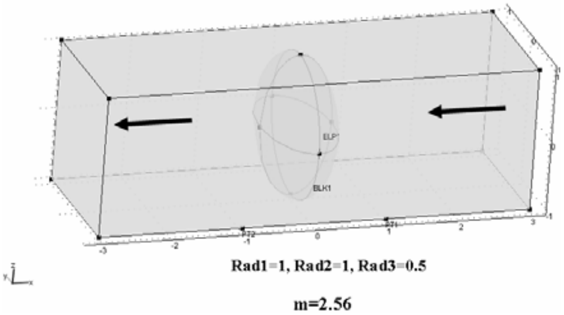

Fig. 9. *3D FEM modeling of electric current flow past an ellipsoidal grain, assuming Archie’s equation*

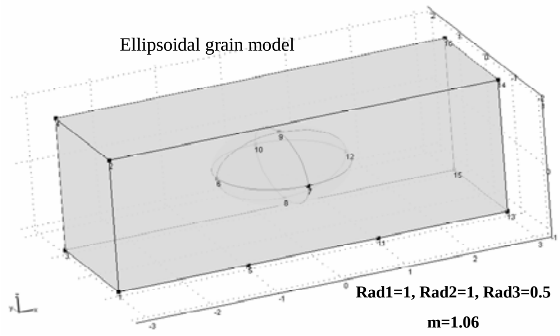

Fig. 10. *3D FEM modeling of electric current flow past an ellipsoidal grain orientated parallel to the direction of the flow of electric current, assuming Archie's equation*

Modeling a cubic grain is shown in Fig. 11, where the value of ***m*** was calculated to be 1.37, similarly, modeling close, regularly-spaced rectangular columns provided a slightly smaller value of ***m*** of 1.25 as shown in Fig. 12.

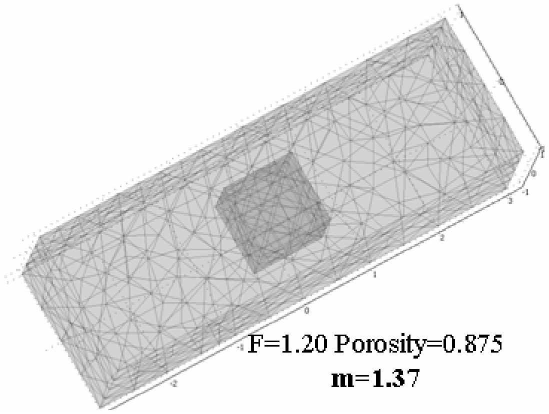

Fig. 11. *3D FEM modeling of electric current flow past a cubic grain, assuming Archie's equation.*

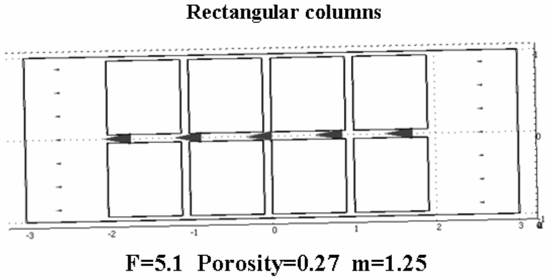

Fig. 12. *3D FEM modeling of electric current flow past closely-spaced rectangular columns.*

An open pore channel within a porous rock was modeled as a straight cylindrical channel set in a porous medium: F = 4, porosity = 0.5, ***m*** = 2.0, as shown in Fig. 13; the results in Table 3, show ***m*** moving smoothly from 2.0 towards 1.0 as the radius of the channel was increased. The porous rock was defined with an ***m*** value of 2.0, while a straight, cylindrical pore channel has been shown to have an ***m*** value of 1.0 (Herrick et al., 1993; see also Table 1).

Radius	Porosity	F	m
0.0	0.5	4	2
0.25	0.525	3.49	1.94
0.5	0.598	2.52	1.80
0.75	0.721	1.72	1.66
0.95	0.854	1.57	1.28

Table 3. *Numerical modeling results for a single cylindrical channel set in a porous rock (F=4, porosity=0.5,* ***m****=2.0).*

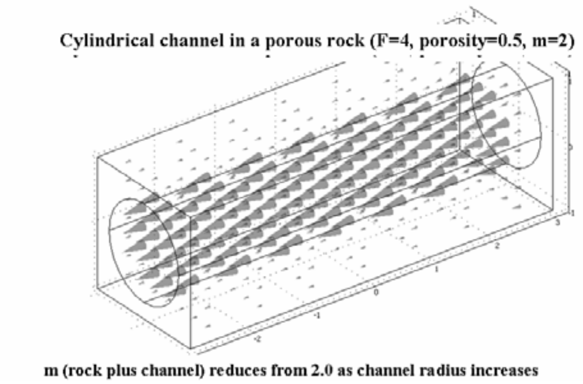

Fig. 13. *3D FEM modelling of electric current flow through a single cylindrical pore channel in a porous rock, assuming Archie's equation showing greater current flowing in the pore channel.*

ASSESSING DISTURBED SAMPLES: EXAMPLE FROM THE CASCADIA MARGIN: IODP EXPEDITION 311

Methane hydrates occur on continental slopes around the world, and have been attributed with being the greatest source of carbon in the earth's crust. Unless in-situ pressures are maintained during coring, methane hydrate contained within sediment cores tends to melt, liberating methane gas and fresh water (e.g. Reidel et al., 2006), often rendering the core useless for assessing sediment properties such as porosity.

A cryogenically preserved sediment-hosted methane hydrate sample obtained at a vent site on the Cascadia Margin, during Leg 311 of the International Drilling Program (Reidel et al., 2006), has been studied using a scanning electron microscope (SEM), as described by Camps et al., (2008). Following sublimation, a 3D salt fabric, defining where brine once existed between euhedral crystals of methane hydrate, was seen in a deeply frozen core (U1328B 2H1 40-60), as shown in Fig. 14. To assess the impact of electric current flowing within such material, a 2D simulation was undertaken on the basis the salt fabric defined where brines existed immediately prior to core recovery; the results in Fig. 15 show the value of ***m*** calculated from our model of these channels to be 1.78, similar to that associated with unconsolidated sands and muds (e.g. Jackson et al., 1978). Further SEM studies of the sample revealed the presence of an unobstructed channel (Fig. 16) passing through the salt fabric, which Camps et al., (2008) suggest acted as a conduit, transporting methane laden sea-water to sites where hydrate crystals were growing. Considering Fig 13, our modeling suggests the presence of such channels would reduce the value of ***m***.

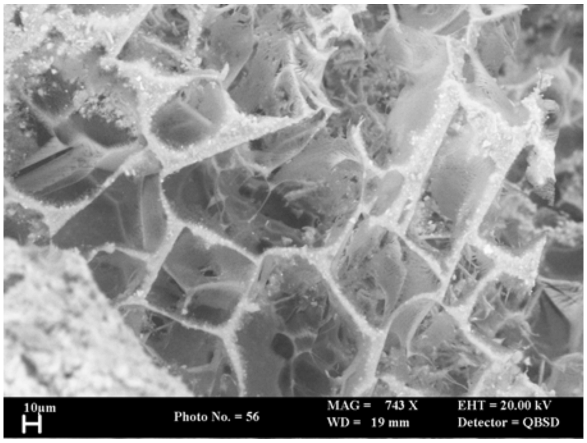

Fig.14. *SEM image of methane hydrate crystals following sublimation, show a 3D salt fabric which defines where brine once existed between euhedral crystals of hydrate as seen in a deeply frozen core (U1328B 2H1 40-60) obtained at shallow depth (9 mbsf) from a vent site on the Cascadia Margin (IODP Ex311).*

Estimating the value of ***m*** associated with sediment containing hydrate, such as that shown in Fig. 14, is essential for conventional assessments of hydrate saturation (Sh) using resistivity measurements and 'Archie' models. As such, hydrate saturation is sensitive to ***m***, as demonstrated in Fig. 1.

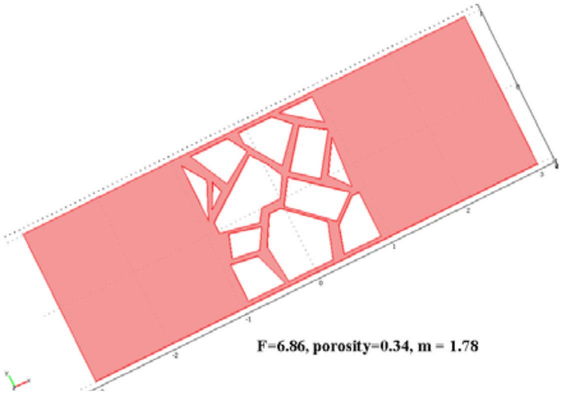

Fig. 15 *Modeling electric current flow in 'brine channels' inspired by Fig. 14.*

Typically, fast forming hydrate is associated with increased salinity, while dissociation has been observed to freshen pore-waters (e.g. Reidel et al., 2006). Typically, such salinity changes are taken to be ephemeral, because long-term diffusion is thought to prevail, consequently, hydrate is considered to act as an electrical insulator (as is crude oil) in conventional saturation assessments.

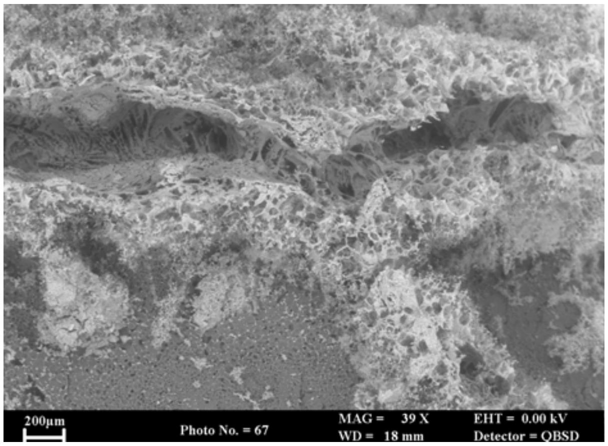

Fig.16. A possible pathway for methane-rich water was identified within the 3D salt fabric.

Considering, Figs 11-16, we conclude electrically conductive brines surrounded these insulating hydrate crystals when in situ, prior to sampling. Consequently, the presence of conductive brines would have tended to make such hydrate deposits electrically conductive, rather than insulating, although the individual crystals themselves remained non-conductive. Considering conventional resistivity-based saturation assessments, such conductive pathways would tend to reduce both measured resistances and predicted saturations.

This situation is explored in Fig. 17, where we postulate hydrate forming in the pore space of a porous medium such a sand as observed by Reidel et al. (2006); a salt audit reveals a doubling of salinity when hydrate fills half the pore-space, for example.

Applying this approach to ‘Archie’ saturation calculations, and taking ***m*** = 1.5 on the basis hydrate tended to be found in sandy sediments on the Cascadia Margin (e.g. Reidel et al., 2006). We modeled hydrate saturation as a function of porosity and pore-water salinity, assuming the formation of hydrate did not alter the value of ***m***, on the basis of the models in Figs 12 to 15 which show values of ***m*** less than 2.0 for the pore geometries characteristic of the SEM and grain modeling studies of core described above.

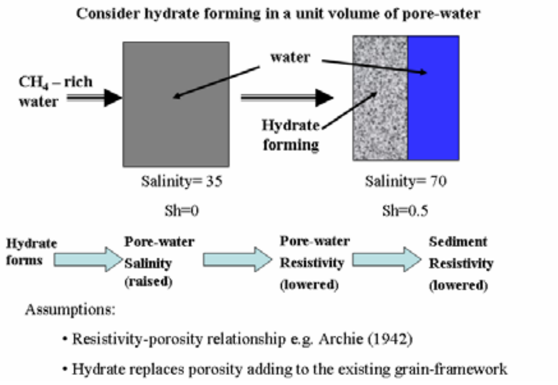

Fig.17. *A model of hydrate forming within pore-water reduces porosity but increases pore-water salinity.*

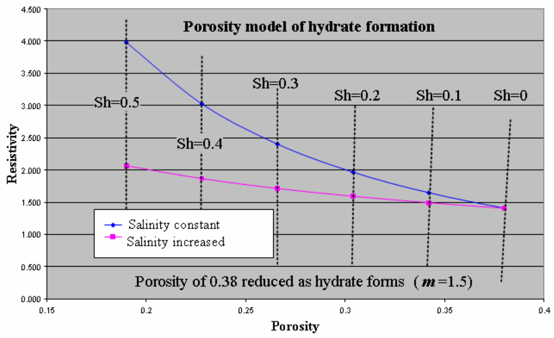

Fig. 18. *A resistivity model of sediment-hosted hydrate. As hydrate saturation (Sh) increases, the reduction in resistivity due to salinity increase, suggests greater hydrate saturations should be associated with lower values of resistivity, which, if typical, would significantly increase estimates of hydrates in place.*

The results in Fig. 18, model the effect of increased pore-water salinity, due to salt exclusion during hydrate formation. In this model 100% reduction in resistivity can be seen when hydrate fills 50% of the pore space. Calculated conventionally, such a reduction equates with resistivity values consistent with 20% hydrate saturation, rather than the 50% actually modeled. Consequently, a large, historical underestimation of hydrate saturation is likely if hydrate crystals surrounded by brine, as observed, in the sample studied, (Fig 14) are typical of sediment hosted hydrate.

CONCLUSIONS

While conventional estimates of water saturation are sensitive to changes in the value of ***m***; grain shapes are shown to control the value of ***m*** for sand-sized granular materials. Mixtures of differently-shaped grains exhibited values of ***m*** which varied smoothly between those of the individual components in proportion to their abundance, being more sensitive to platy grains than spherical ones.

Care is needed when predicting Archie’s ***m*** parameter using a Winsauer-type approach to ensure ***m*** (e.g. grain-shape) does not vary significantly over the depth interval concerned.

Modeling formation factor porosity relationships, via electric current the flow in 3D around ‘typical’ grains, is shown to be representative of samples having many millions of grains of similar shape. The orientation of platy-shaped grains is shown to be a significant control on the value of ***m***. Cubic grains and regularly arranged rectangular columns both exhibited values of ***m*** less than 1.5. The inclusion of a straight circular channel within a porous medium, orientated parallel to the direction of the flow of electric current, reduced ***m*** smoothly towards 1.0, as its diameter increased.

For spherical grains, 3D numerical modeling of single and small numbers of grains agree with laboratory derived values involving many millions of them, suggesting, this approach may lead to a method of estimating ***m*** from a knowledge of the grains themselves, even though a sample may be highly disturbed. Having the potential of improving reservoir characterization in running sands and sediment hosted methane hydrates, for example.

Mixing equations are an attractive approach to predicting ***m*** for mixtures containing a range of grain shapes. Consequently, predicting ***m*** for assemblages of grains, and hence geological facies, is within reach.

Considering a preserved but disturbed sample of sediment-hosted methane hydrate, and having identified brine pathways between hydrate crystals via SEM studies, modeling formation factor-porosity relationships for typical inter-crystalline brine channels, suggests ***m*** values (e.g. 1.7) close to that expected for un-cemented marine sediments (e.g. Jackson et al., 1978). In turn, this suggests a model in which hydrate formation leaves ***m*** relatively unchanged may be reasonable. Additionally, such a model, demonstrates accounting for conductive pore-waters is crucial when estimating water saturations where hydrates are forming fast and excluded salt is not removed by diffusion. Our model suggests a large underestimate of hydrate saturation (e.g. 20% rather than 50%) is likely in the presence of high salinity pore-water associated with fast hydrate formation (estimates of hydrate saturation would be too low by a factor of 2.5). The presence of salt fabrics, identified between euhedral hydrate crystals, suggests, for the purposes of estimating hydrate saturation, the possibility that sediment-hosted methane hydrate may behave as a conductive porous medium rather than an insulator. While evidence of brine pathways has been observed in one cryogenically preserved sample, additional work is required to establish the extent of sediment-hosted methane hydrate existing in this form. Consequently, the ephemeral nature of sediment-hosted methane hydrate, still poses a challenge to estimating the amount of methane hydrate sequestered in the subsurface.

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