REVIEW OF THE WINLAND R35 METHOD FOR NET PAY DEFINITION AND ITS APPLICATION IN LOW PERMEABILITY SANDS

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INTRODUCTION

The definition of "net sand" for use in hydrocarbon volumetric calculations or reservoir simulations is particularly difficult in low permeability gas reservoirs, since sands which are typically excluded as being "tight" may, in fact, contribute significantly to gas movement. An under-estimation of the gas reserves could lead to the production facilities being designed for too short a lifetime, with possible consequent loss in gas reserves. A main factor which might contribute to this under estimation, is the definition of net-to-gross (which can be rather arbitrary).

Permeability is determined by the dimensions of the connected pores, and many workers have used capillary pressure curves, obtained experimentally by mercury injection, to determine pore throat sizes. Dale Winland of Amoco established an empirical relationship between porosity, permeability and pore throat radius from mercury intrusion tests, using the data to obtain net pay cut-off values in some clastic reservoirs. Although Winland never published his equation, it was later published by Kolodzie (1980) as

$$\log r_{35} = 0.732 + 0.588 \log K_{air} - 0.864 \log \varphi_{core} \qquad [1]$$

where r_{35} is the pore aperture radius corresponding to the 35^{th} percentile of mercury saturation, K_{air} is the uncorrected air permeability (mD), and φ is porosity (%).

In Winland's empirical relationship the highest statistical correlation was at the pore throat size corresponding to the 35th percentile of the cumulative mercury saturation curve, and this pore throat radius was named R35. R35 has been interpreted to approximate the point where the modal pore aperture occurs and is taken to be the point where the pore network becomes interconnected, forming a continuous fluid path through the sample. More accurately, the above is only true at the pore throat size corresponding to the point of inflexion of the pore throat size versus mercury saturation plot (Katz, 1986).

This method has been used as a useful evaluative tool by petrophysicists since the early 1970's and has also be used as a somewhat arbitrary "net pay cut-off". This is often done as a working guide to exclude very low porosity-permeability, using a slightly more scientific approach than simply selecting a certain porosity or permeability.

Estimation of net pay cut-off essentially involves calculation of R35 from poro/perm data using the above equation, and then plotting R35 against permeability and porosity. Cut off poro/perm values are then read off at an R35 value of 0.5µm. The use of 0.5µm stems

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from Winland who observed that in the Terry Sandstone at Spindle Field, Colorado, there was an updip trap caused by a reduction in the pore throat size below a certain value, which he estimated to be 0.5µm. This was later confirmed by Pittman (1992) using some of the same wells as Winland. The 0.5µm pore throat size cut-off has since been used arbitrarily for net pay determination in other reservoirs.

This study was performed for the UK Department of Trade and Industry (DTI) to investigate some key concerns with the Winland method, in relation to tight gas sands:-

- The R35 parameter may be inappropriate in low permeability sands as this class of samples may not have a dominant modal pore aperture, leading to an essentially straight mercury injection curve when plotted on semilog axes (Pittman 1992).
- R35 values are *calculated* from a correlation rather than *measured* on the particular rock type in question. We consider the correlation could change markedly for different rock types, therefore giving different cut-off points.

EXPERIMENTAL DESCRIPTION

Forty samples were selected from a Sherwood Sandstone reservoir in Morecambe Bay. The samples were collected from two wells whose petrographic analyses were also available. The sedimentological core descriptions, together with the wireline logs, were used to identify the facies associations of the forty samples, these being fluvial, aeolian and sheet-flood. Routine porosity and permeability data were also available which allowed the samples to be sub-divided into low permeability (<5mD) and higher permeability (>5mD).

Mercury intrusion tests were carried out on all 40 samples up to 60,000psi. The pressure at 35% mercury saturation (R35) and hence the throat size, was read off for each sample as shown in Figure 1. All of the 40 samples tested showed this sigmoid shape. The pore throat size corresponding to the point of inflexion was calculated by plotting δ(Pc)/δ(Hg sat) versus Hg saturation and pore throat radius versus Hg saturation on the same graph, Figure 2. In most cases the mercury saturation corresponding to R(inflex) did not equal 35%.

LINEAR REGRESSION

For samples of a given sub-group a linear regression correlation was made of measured pore throat radius against calculated pore throat radius to derive the coefficients of the Winland type equation: $\log R(x) = a + b \log K - c \log \varphi$ where R is the pore throat radius and x is the mercury saturation. Correlations were derived at x = 35% for all sub-groups and x = saturation of the inflexion point, for a selection of sub-groups. The quality of the fit was found to be poor for all sub-groups studied, with the best r^2 correlation coefficient being 0.853 for the aeolian subgroup. The other sub-groups showed correlation coefficients of around 0.6. This is in contrast to the fits obtained by Pitmann (1992), where r^2 values of greater 0.9 were obtained for all mercury saturations up to 55%. It is believed that the reason for this is that in the Pittman study over 200 samples were used, whereas the largest sub-group in this study contained only 25 samples, and the smallest sub-group (aeolian) contained just 6 samples. Thus, the statistical validity of the new equations calculated for each facies sub-group is somewhat reduced. A plot of measured pore throat radius versus calculated pore throat radius for one of the wells is shown in Figure 3. The scatter in the data is a reflection of the poor correlation coefficients.

NET PAY CUT OFF

The throat radii (R35 and R(inflex)) derived from the new correlations were plotted against porosity and permeability data for each sub-grouping. As an example, the permeability cut-off is shown in Figure 4 for the sheetflow sub-group. R35 is calculated by the new correlation and using Winland's Equation, and plotted together for comparative purposes. Net pay permeability cut-offs were then read-off these plots using the 0.5μm threshold. For this subgroup there was a significant difference in result depending on which correlation was used (0.5mD by Winland Equation and 1mD by the new correlation). The difference was not always so pronounced for each sub-group.

A second method of defining the cut-off porosity and permeability is via a cross-plot . By rearranging Winland's equation, permeability can be calculated for a given pore throat radius over a range of porosities. In this way a graph of porosity versus permeability can plotted showing lines of isopore-throat radius. This was performed with isopore-throat lines derived from both the Winland correlation and the new R35 correlation for a selection of subgroups. The actual poro/perm data was then super-imposed on both the cross-plots, with samples lying below the 0.5 micron line deemed non-pay and those above deemed to be pay. By way of example the two cross-plots for the <5mD sub-group are shown in Figures 5 and 6.

CONCLUSIONS

All of the 40 samples tested showed a sigmoid shape to the semilog mercury intrusion curve, confirming that the R35 method can at least be physically applied to low permeability gas sands, and that the concerns of Pittman (1992) are unfounded for the samples under test.

Measured values of porosity and permeability have been correlated with measured values of R35 for a number of rock type subsets, using the same linear form as the original Winland equation. The subsets investigated were aeolian, fluvial, sheetflow, <5mD, >5mD and <5mD with quartz cementing. Samples were also grouped by well. All correlations varied significantly from those of the Winland Equation.

Variations in r^2 values amongst facies groupings for x=35% in the Winland equation may have a qualitative basis in geological reality. The aeolian samples show the highest r^2 value of 0.8530. While the aeolian sample population was smaller in number than the other facies, this good correlation may reflect the greater tendency of aeolian sands to be better sorted through wind winnowing. This in turn may impact on the degree of diagenetic modification of these sands. The fluvial and sheetflow sands are likely to have greater initial heterogeneity, and are certainly observed to have more complex diagenetic cement histories, particularly with regard to clay minerals. The presence of clay minerals is likely to introduce a high degree of microporosity/porosity heterogeneity to the pore system, with linked effects on permeability variability.

Two methods of analysing the data have been investigated. The cross-plot analysis is the more informative in that the change in the isopore-throat line with porosity and permeability is seen. There are some small but possibly significant differences in the porosity and permeability cut-offs derived from the Winland correlation and new correlations respectively, both in percentage and absolute terms. In some cases the Winland equation is not applicable to the data as negative cut-offs are predicted.

It is debatable whether the expense of deriving a correlation for a particular rock type adds value, compared to the relatively small differences seen when using the original Winland Equation to identify pay flow units.

Although there would be differences in net pay determination depending on which correlation is used, these are relatively small compared to the differences that would occur if a completely different threshold value were chosen i.e. the 0.5 µm isopore-throat radius line is relatively insensitive to the correlation used. The more pertinent question is whether 0.5µm should be used as the cut-off threshold for tight gas reservoirs. The Winland analysis says little about flow potential and used in isolation from methods to quantify the relative permeability of tight gas sands (e.g. special core analysis laboratory measurements) may lead to erroneous estimates of net-to-gross.

FURTHER WORK

Previous studies for the DTI (Fishlock 1994, Cottrell 1996) have shown that low permeability core of just a few micro-darcies may produce gas, providing it is in reasonably close contact with higher permeability layers. This earlier work implied that permeability cut-offs in UKCS gas reservoirs were often too high. In most reservoirs there is a distribution of “good” and “poor” quality rock. Depending on the distribution of the different quality rocks, a significant contribution of the gas production may originate from the poor quality rock. This is possible as, in a depletion gas reservoir, gas can flow relatively easily from poor rock to good rock, from which it can flow to the well and be produced. This, together with the findings of the present study have prompted further work for the DTI to investigate guidelines for selecting permeability cut-offs in heterogeneous reservoir types where poor quality sand is connected to good quality sand.

Whilst the Winland method attempts to add some insight into the net pay cut-off concept when compared to the commonly used poro/perm cut-offs, none of the methods account for reservoir architecture effects, and so should be treated with caution.

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