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Quantification, Permeability and Compaction of Mudstones: Some Applications to Basin Modelling and Pore Pressure Estimation

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1. Introduction

Mechanical compression or compaction of fine grained sediments, which typically comprise 60 - 70% of basin fill, is a major process in the evolution of a sedimentary basin. Compaction and permeability is central to basin modelling and the estimate of fluid pressure in low permeability, fine-grained units. The three constitutive equations which describe mechanical compaction are (1) the relationship between void ratio and effective stress, (2) Darcy's law and (3) the relationship between permeability and void ratio.

The relationship between void ratio (or porosity) and effective stress is described in Soil Mechanics by the one dimensional compaction model:

$$e = e_{100} - \beta \cdot \ln\left(\frac{\sigma'}{100}\right) \qquad (1)$$

where e = void ratio; e_{100} = void ratio at 100 kPa effective stress compaction; σ' - effective stress kPa. e_{100} and β are termed *compression coefficients*.

Darcy's permeability law describe the rate of the fluid flow in a porous media:

$$q = kA\frac{\Delta h}{L} \qquad (2)$$

where q = flow rate (units of L^3T^{-1}); k = coefficient of permeability or hydraulic conductivity (LT^{-1}); A = cross section area (L^2); L = length along flow path (L) and Δh = fluid head (pressure) loss along the flow path (L). $\Delta h/L$ is the hydraulic gradient and is dimensionless.

In Darcy's law the permeability is a constant for a given medium and fluid. To separate the influence of fluid from the porous medium, the absolute or specific permeability K is defined which only describes the permeability of the porous medium (see Leonards (1962) for a review):

$$K = k\frac{\eta}{\rho} \qquad (3)$$

where *K* – absolute or specific permeability (L^2); η - coefficient of dynamic viscosity of the fluid (TFL^{-2}) and ρ - unit weight of the fluid (FL^{-3}).

The absolute permeability is a function of void ratio:

$$K = f(e) \qquad (4)$$

In contrast to Darcy's law, which is widely accepted, there are some unsolved questions in application of equations (1) and (4). Equation (1) is well established in soil mechanics from both laboratory experiments and in situ observation (Skempton, 1970; Burland, 1990). However, almost all the data sets are for sediments at stresses below 10 MPa, with most less than 0.5 MPa. One concern is therefore the extent to which the soil mechanics compaction equation is also applicable to the higher stress levels typical of sedimentary basins. A more serious problem is how to derive the compression coefficients e_{100} and β for extensive packages of fine grained sediments in a sediment basin.

The relationship between permeability and void ratio (equation 4) of mudstones is more poorly constrained, significantly reflecting the technical difficulty of measuring mudstone permeabilities, which are typically less than $10^{-18}m^2$. Published data suggest that mudstone permeabilities vary by three orders of magnitude at a single porosity. Such a wide range places real restrictions on the modelling of flow and pressure in basins.

Our research over the last few years has constrained the above equations. Data mainly from the soil mechanics literature suggest that compression coefficients and the relationship between permeability and void ratio are strongly lithology dependent (Skempton, 1970; Burland, 1990; Aplin et al 1995). Since mechanical compaction is lithology dependent, our general approach has been to:

1. Develop a mathematical model (artificial neural network models) to quantitatively evaluate lithology, represented by clay fraction (the fraction of particles with diameters below 2µm), from wireline logs.

2. Use clay fraction as the key descriptor defining the two constitutive equations.

The application of the work includes: (1) generating basic input in terms of permeability and compression coefficients for basin modelling from wireline logs. (2) Evaluating fluid pressure generated by local mechanical compaction from wireline logs or log wile drilling data (in real time while drilling).

2. Evaluation of clay content from wireline logs using artificial neural network (ANN) models

Clay content and correspondent wireline log data were collected for nearly 400 samples, artificial neural network models were constructed between clay content and the log values.

The 400 samples were collected from 19 North Sea and 9 Gulf of Mexico wells. The burial depth of North Sea samples is in the range of 550 – 4500 meters. The geological age of the North Sea samples ranges from Quaternary to Jurassic. The burial depth of the Gulf of Mexico samples is in the range of 1500 – 5200 meters. Most of the samples from Gulf of Mexico were from Tertiary section.

The commonly used logs: Resistivity (deep), Gamma Ray, Sonic transit time (Δt), and Density logs were used as inputs to the ANNs, and also used as inputs are burial depth and the difference between calliper log value and drilling bit size.

There are differences in the log response to petrophysical properties between North Sea and Gulf of Mexico sediments. To capture the difference in the log response in the ANN models, we introduced an input, "Location factor". The location factor for North Sea was assigned as 0.8 and Gulf of Mexico as 0.2. We hoped that the constructed ANN models could also be applied to a new region by choose a suitable location factor between 0 - 1.

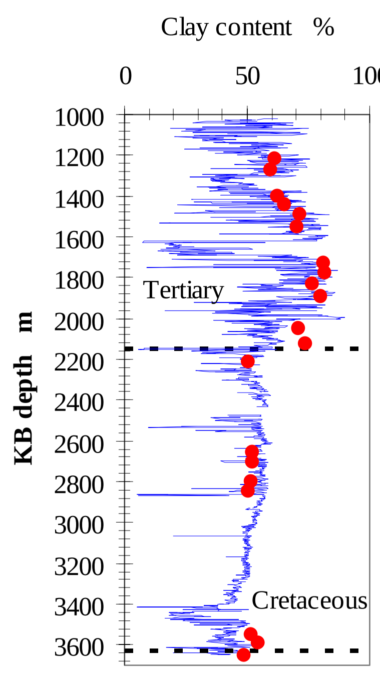

Figure 1, comparison between ANN model output (blue line) and measured clay content (red dots) for a North Sea Well

The ANN model was constructed using the data set. The ANN model were trained and tested well. Figure 1, as an example, shows the comparison between ANN output and laboratory measured clay content. The clay content model was also run on several wells of two very different regions, from which NO data were used in the training our ANN model. It was found the trained ANN model worked well in these two different regions by choosing suitable location factors. We also constructed ANN models for evaluating grain density, which is used together with density log to evaluate porosity. We have developed the ANN models into a computer program "*ShaleQuant*". Now the clay content and grain density can be quickly evaluated from wirelogs using “ShaleQuant”.

3. Void ratio - effective stress relationship

We collected a data set with over 3000 data points to check the compression equation (equation 1) and to construct the relationships between compression coefficients and clay content, Figure 2. The data set enclose clay content, void ratio and effective stress. The maximum effective stress is 40 Mpa. The clay content and void ratio of most data points were evaluated from wireline logs using ShaleQuant, of the rest were measured in laboratory. The effective stress was evaluated from total stress (=lithostatic stress = overburden) and RFT data. We have found that the well established compression equation in soil mechanics (equation 1) describe the natural sediments compaction very well for our data set and the compression coefficients are correlated well with clay content:

$$Compression\,coefficients = f\,(clay\,content) \qquad (5)$$

The correlation between the true void ratio or porosity and that modelled using the equations (1) and (5) is 0.96 (Figure 3).

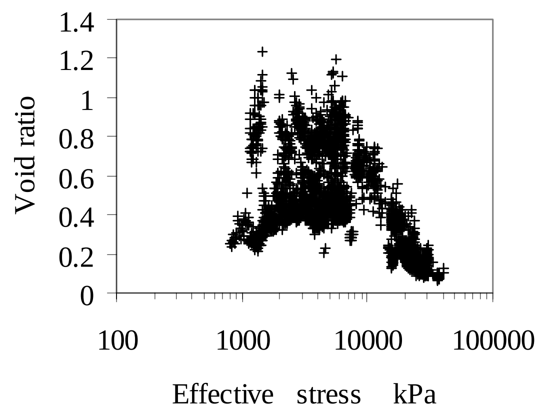

Figure 2 Data set used in the construction of the relationships between clay content and compression coefficients for gravitationally compacted sediments

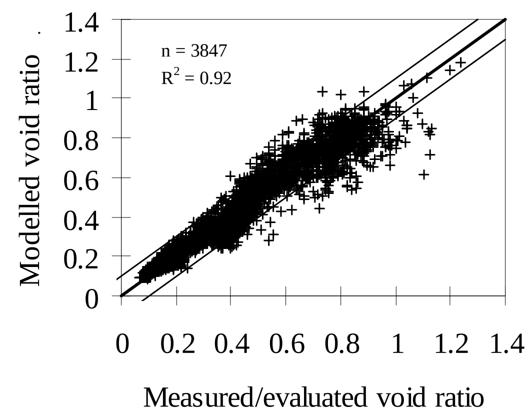

Figure 3 Comparison between evaluated void ratios and those modelled using the equations derived in this work.

4. Permeability – void ratio relationship

A relationship between the permeability and void ratio of homogeneous mudstones has been derived using 362 permeability values which are either measured or modelled from pore size data using a calibrated permeability model (Yang and Aplin 1998). Lithological data are available for all samples in the form of grain size distributions or liquid limit. Regression of the data shows that the relationship between vertical absolute permeability (K_z) and void ratio (e) is strongly dependent on clay fraction (clay):

$$\ln(K_z) = a_K + b_K \cdot e + c_K \cdot e^2 \qquad r^2 = 0.95 \qquad (6)$$

where, the unit of the vertical absolute permeability, K_z is m^2; a_K, b_K and c_K are dimensionless permeability constants for a given clay content:

$$Permeability\,constants = f\,(clay\,content) \qquad (7)$$

The relationship appears to be quite robust for a very wide range of clastic mudstones which have porosities greater than 10% and lower than values typical of burial depths of 30 metres.

5. Applications

The basic parameters, compression coefficients and permeability constants can now be evaluated along depth from wireline logs using “ShaleQuant” and equations 5 and 7. The basic parameters can then be used as the basic inputs for basin modelling and in the evaluation of overpressure.

5.1 Generating basic inputs for basin model gridblocks

If the clay content of a given layer of sediment is known, the basic inputs for the mechanical compaction can be evaluated using equations 5 and 7. However, the sediments within a typical gridblock of a basin model are heterogeneous. Clay contents within a gridblock vary, as do the compression coefficients and permeability constants. A technical was developed to find a single set of the compression coefficients and permeability constants (referred as *basic parameters* hereafter) for the grid of a basin model. The procedure is termed as “Homogenisation” which is

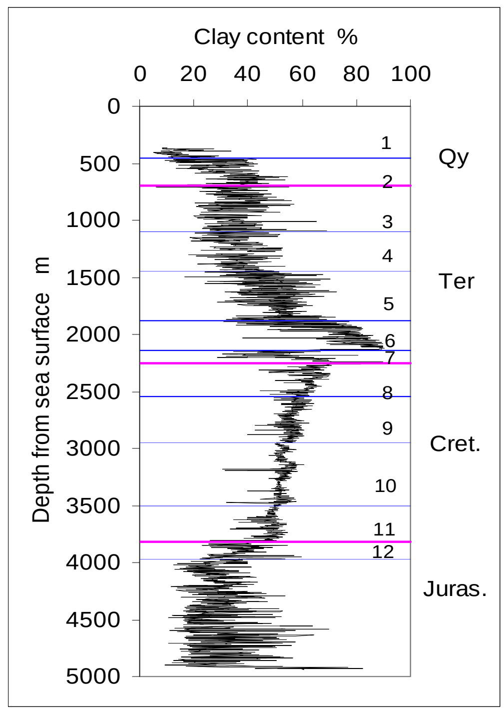

Figure 4. Evaluated clay content by “ShaleQuant” using wireline logs as input. The section is divided into grids based on similarity of clay content and geological periods. The pink lines are the boundaries of geological periods and the thin blue lines are the boundaries of the grids

conventionally known as "Up-scaling". The principles on which the techniques are based are that (1) the deformation of the equivalent, homogenised block is identical to that of the real gridblock composed of many individual layers; (2) the flow rate through the equivalent, homogenised gridblock is identical to that of all the real gridblock. The inputs to the homogenisation are the depth profiles of clay content and porosity.

Figure 4 shows the clay content profile of an example well evaluated by "ShaleQuant". In the example, the section has been divided into 12 blocks based major geological periods and units of generally similar clay content (Figure 4). The section below 3870 m is mainly sand and is not considered in the example since our models only apply to mudstone units. The homogenised compression and permeability – porosity relationships for some of the grids are shown graphically in Figures 5 and 6 respectively.

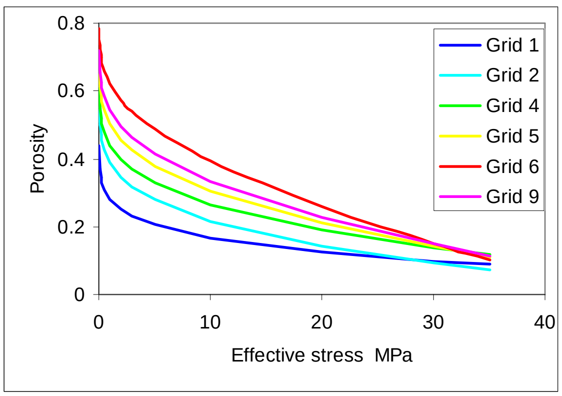

Figure 5 Single, effective compaction curves for some grids of the example well

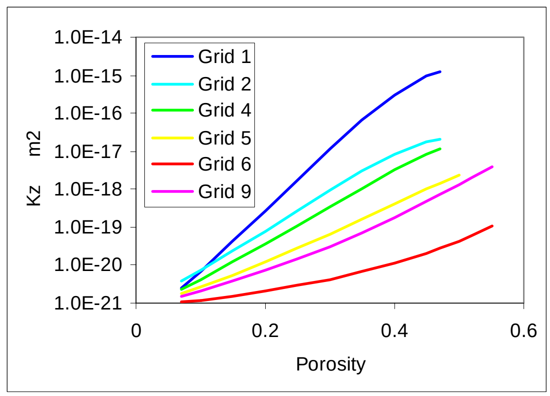

Figure 6 Single permeability – porosity curves for some grids of the example well

5.2. Estimation of formation pressure generated by local mechanical compaction

The input for evaluate formation pressure are wireline logs. Clay content and grain density are evaluated form wireline logs using "ShaleQuant". The compression coefficients and e_{100} can be calculated using equation (5). Porosity is evaluated from grain density and density log. Effective stress can then be calculated from compression coefficients and porosity using equation 1. The formation pressure is the difference between total stress and effective stress. The evaluated formation pressure is the one generated by mechanical compaction. If the formation pressure is inflated by other mechanisms, such as oil cracking into gas, the evaluated pressure in this way will be the minimum.

Figure 7 is an example of a Gulf of Mexico well. The data for the sand, which are indicated by extremely high evaluated pore pressure, are meaningless and should be ignored as our model does not apply to sandstones. The predicted pore pressures in the mudstones are consistent with the RFT data in interbedded sands. It shows that the pore pressure is purely as a result of mechanical compaction ("disequilibrium compaction").

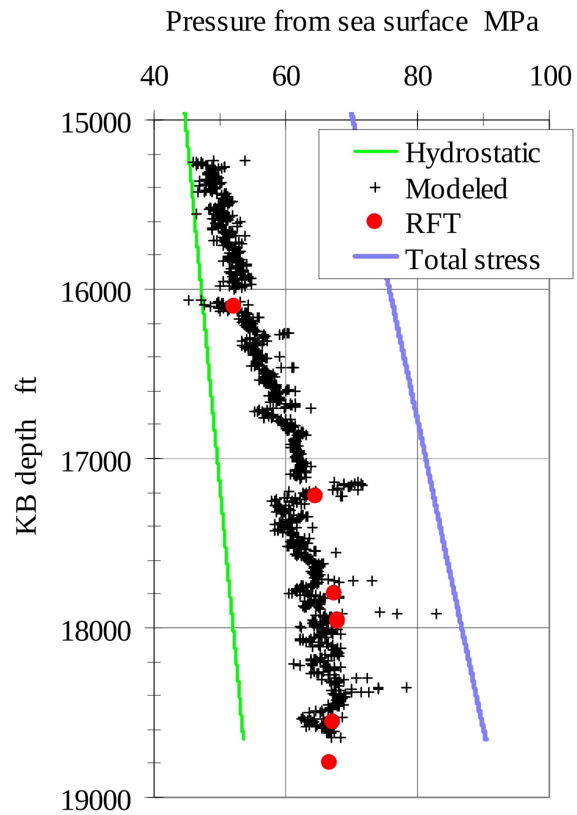

Figure 7. Gulf of Mexico well. The modelled pore pressure agrees with RFT measured values.

5. References

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