PETROPHYSICAL ASSESSMENT OF LITHOLOGY AND KEY PHYSICAL PROPERTIES OF MUDSTONE CAPROCKS

Andrew C. Aplin, Yunlai Yang, Steve R. Larter and Julian K.S. Moore
(University of Newcastle, UK)

Introduction

Compaction, absolute and relative permeability, pore pressure and seal capacity are the inextricably linked properties of mudstone caprocks which must be accurately described in two phase fluid flow models of petroleum systems. Three key relationships are those between (a) porosity (or void ratio, e) and effective stress (σ'), (b) flow rate and hydraulic gradient (Darcy's law) and (c) permeability and porosity:

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

where e_{100} is the void ratio at 100kPa effective stress; e_{100} and β are compression coefficients;

$$q = K\frac{\rho}{\eta}\frac{\Delta h}{L} \qquad (2)$$

where q = flow rate, K = absolute permeability (L^2), $\Delta h/L$ = hydraulic gradient, ρ and η are respectively the unit weight and coefficient of dynamic viscosity of the fluid;

$$K = f(e) \qquad (3)$$

Also, we can anticipate a general relationship between permeability and capillary seal capacity, because both are reduced by the collapse of pore systems during compaction (Borst, 1982; Yang and Aplin, 1998; Dewhurst et al., 1998).

Lithological Control of Key Relationships

Over the past few years we have tried to quantify the way in which the relationships between (a) porosity and effective stress and (b) porosity and permeability in mudstones are influenced by lithology, defined here in terms of clay content (% particles smaller than 2μm). We have constructed a relationship between porosity and effective stress with a 3000 strong data set comprising clay content, effective stress and void ratio. We are confident that equation 1 accurately describes the compaction of natural mudstones and the compression coefficients e_{100} and β are strongly correlated with clay content. Equation 1 can thus be used to estimate the pore pressure of a mudstone from its porosity, if the clay content of the mudstone can be established.

We have also constructed a relationship between the permeability and void ratio of homogeneous mudstones using a database of 362 permeability values, some of which are measured and some of which which are calculated from pore size data using a calibrated permeability model (Yang and Aplin, 1998). Regression of the data shows that the relationship between absolute vertical permeability (K_z in m^2) and void ratio (e) is strongly dependent on clay content (clay):

$\ln(K_z) = a_K + b_K \cdot e + c_K \cdot e^2$ $r^2 = 0.95$ (4)

where a_K, b_K and c_K are permeability constants. The relationship appears to be quite robust for a wide range of clastic mudstones which have porosities greater than 10%.

To date, we have not constructed a quantitative relationship describing the critical capillary entry pressure of a mudstone as a function of porosity and lithology. However, it is clear from the work of Dewhurst et al. (1998) that at a given porosity, the critical capillary entry pressure of coarser mudstones will be lower than those of finer grained mudstones.

Evaluation of Clay Content from Wireline Logs using Artificial Neural Networks

The work outlined above shows that establishing the clay content of a mudstone is central to the rapid assessment of key caprock parameters such as compressibility, permeability and critical capillary entry pressure. Our pragmatic approach to this problem has been to construct Artificial Neural Network (ANN) models to estimate the clay content of mudstones from wireline log data. The models were trained using 400 samples from the Gulf of Mexico and the North Sea, from depths ranging from 550 to 5200m. Resistivity, sonic, gamma ray and density logs were used as inputs to the ANNs, along with burial depth and the difference between the calliper and drilling bit size. Since we are interested in the solid phases of the mudstones, log data were transformed in standard ways in order to remove the effects of porosity on the log values. The ANN models have been coded into the computer program "ShaleQuant", allowing the very rapid assessment of mudstone clay contents (Figure 1).

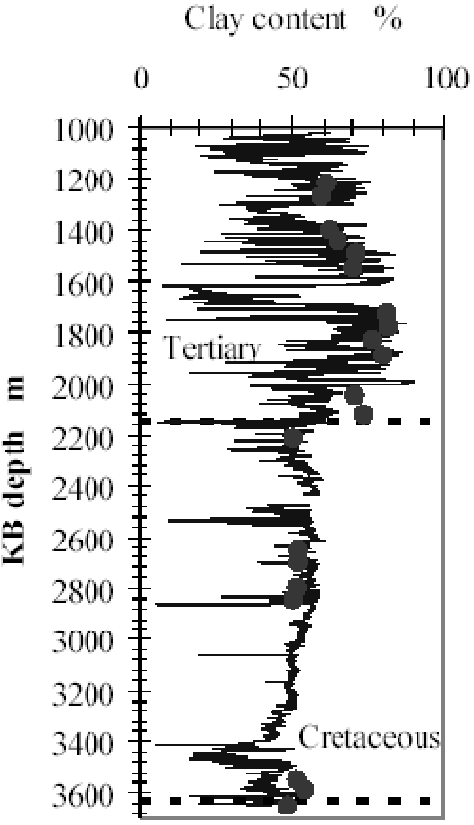

Figure 1. Comparison of ANN model output and measured clay content (circles) for a North Sea well.

Applications

We have used the ANNs to successfully predict the lithology of mudstones in many petroleum basins, including the North Sea, Gulf of Mexico, West Africa and the Caspian Sea. Although the clay content of mudstones is not of intrinsic interest, its importance is that it allows, through equations 1-3, the accurate appraisal of current pore pressure and permeability, and also the way in which permeability has evolved as a result of mudstone compaction. An example output, from the Gulf of Mexico, is shown in Figure 2. The prediction of both clay content and overpressure is good. However, there are facets of the pore pressure data which imply subtle, but important sedimentological variability which results in striking variations in fluid pressure and, by implication, sand connectivity. Overpressures in the upper section are similar, implying sand connectivity despite a high percentage of fine-grained mud in the section. In contrast, there is a sharp jump in overpressure around 14000ft, in a section which is sandier than the overlying section. The pressure jump cannot be explained by the occurrence of an especially fine-grained and thus low permeability mud section. It appears that muds in this section effectively separate sand units, acting both as pressure barriers and effective caprocks.

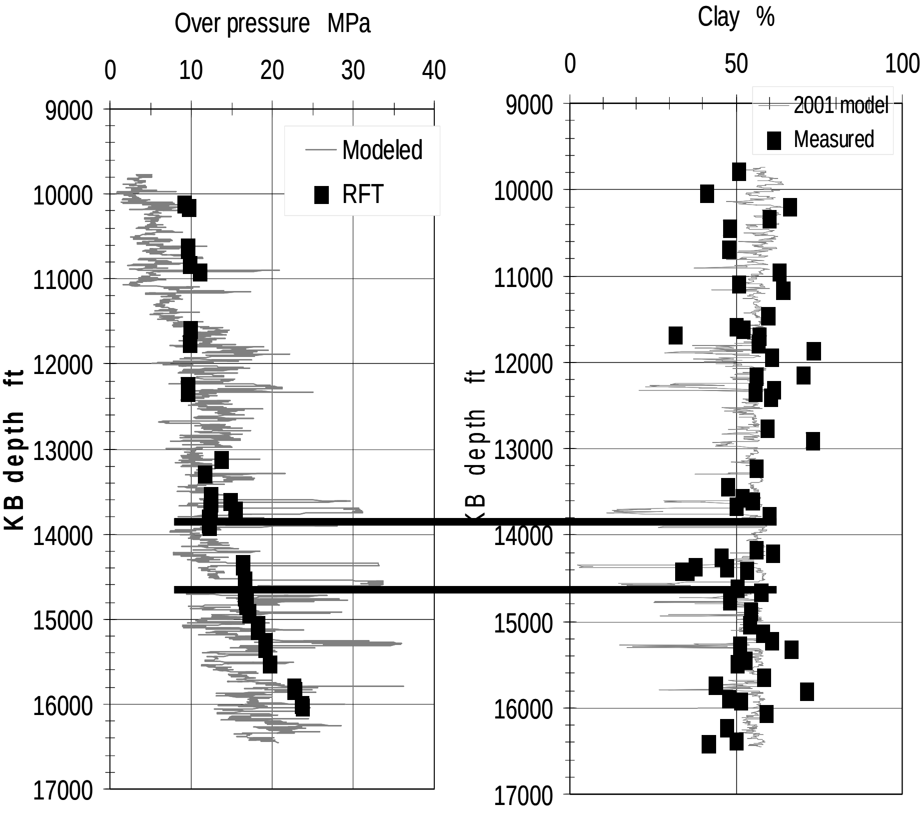

Figure 2. Left: Modelled overpressure based on mudstone porosity and compaction model, with RFT data, Gulf of Mexico well. Right; measured clay contents and clay contents modelled from ANN). Note that sands are shown as low clay spikes on the right hand plot. The corresponding pore pressures should be ignored, since neither the ANNs nor the porosity – effective stress models apply to sands.

Future Work

Our work to date has focused on establishing the basic physical properties of homogeneous mudstones. Although useful, mudstones are far from homogeneous on spatial scales ranging from millimetres to kilometres. As shown in Figure 2, this will of course affect their flow properties and thus their ability to act as petroleum seals and, conversely, migration pathways. Our work on the link between physical properties and grain size suggests that it is principle possible to predict the key properties of mudstones using sedimentological and sequence stratigraphic techniques. The difficulty is that sedimentological studies of mud-rich systems are much less well developed than those on sandstones (or carbonates). Limited work on modern environments has demonstrated simple links between grain size and sediment transport paths, but studies of ancient environments are essentially absent, not least because it is difficult and time-consuming to determine the grain size distributions of lithified mudstones.

Studies of mudstone sedimentology are still in its infancy. Key uncertainties remain, most importantly with respect to the sedimentological variability of mud-rich sequences. In order to populate fluid flow models and thus predict both petroleum column heights and likely migration pathways, what techniques can we use to define the 3D architecture of a cubic kilometre of mud-rich sediment? Whilst wireline techniques are a promising way of defining variability on a 0.1-1m scale, they do not pick out the mm-cm scale lamination which is common in mudstones and which must exert an important influence on their fluid flow characteristics. Equally, we need to develop ways of defining the connectivity of the more permeable sand-silt units within mud-rich sequences. These units define the weakest points in the petroleum system and it is their connectivity which define column heights and also the likelihood of forming steep pore pressure ramps across interbedded sand-mud units. These critical future exploration questions are fundamentally rooted in mudstone sedimentology.

References

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