Sandstone reservoirs, unlike Carbonate Reservoirs, are normally transported and deposited away from their final depositional environment. This dynamic transportation of sediment introduces a large complex lithology with shale volume and shale type, silt, sand and other sediments. The shale and silt fractions have a large influence on values of effective porosity, water saturation and permeability.
Overview

Sandstone reservoirs also provide a serious interpretation challenge because of the complex lithology structure:

- **Volume of Shale (Vsh):** Vsh will always be a challenge. Shale is a mixture of a specific clay type (50-70%) and the rest is a cocktail of other minerals. The shale parameters are likely to be variables at every point.

- **Shale depositional environment:** Two major depositional frameworks: *laminated* and *dispersed shales*. A small volume of *dispersed* shale (15%) is likely to wipe out the effective porosity and hence the permeability. Thin laminated shaly-sand would require high resolution imaging tools to quantify.

- **Silt:** Silt contents will reduce the permeability and increase the water saturation (Sw). It is difficult to quantify the silt volume from standard logging tools.

- **Water Saturation (Sw):** There are a whole range of empirically derived shaly-sand Sw equations. These tend to apply on a regional level where the cores were obtained. There are also few “excess conductivity” equations such as the Waxman-Smits and Dual-Water equations which have more universal applications.

- **High Technology Tools:** The introduction of high technology tools (MRI, Dielectric, electrical-imaging) improved the quality of interpretations in sandstone reservoirs. Neutron derived spectroscopy made it also possible to evaluate the complex lithology formations.

The course deals in details on evaluating these parameters so that values of water saturation, permeability, pore radius and rock typing can be more accurately characterized.
This course addresses very important aspects of clastics evaluations

**Porosities**: Total Porosity ($\phi_t$) and the components comprising that, namely: Effective Porosity ($\phi_e$), silt porosity ($\phi_{silt}$), and shale porosity ($\phi_{shale}$). These values are obtained directly from standard logging suites. Total Porosity ($\phi_t$) is critical if the excess conductivity equations (Waxman-Smits, Dual-Water) are used.

**Shale structure**: it is also very important to know the shale type, mainly to distinguish between dispersed and laminated shale. The shale depositional distribution is also obtained automatically from standard logging data. This evaluation is also very important to interpret for thin bed shaly-sand sequence. Imaging tools can be used to quantify that.

**High new technology tools** are contributing a lot to the evaluations of clastics formations. Dielectric measurements, Nuclear Magnetic Resonance (NMR) and neutron derived spectroscopy are used routinely to evaluate for Cation Exchange Capacity (CEC), bonded and free fluid and complex clastics lithology.

**The shaly-sand saturation equations** have mystified many an interpreter. The derivation of the two excess conductivity equations will be presented in details and the interpretation parameters obtained and quality controlled. This facilitates a very easy process to use these equations.

**Permeabilities (K)**: The course will cover in details permeability evaluations in shaly-sand. Ideally, using the NMR will provide the best means of estimating K. The bonded fluid can be obtained form standard logs and can be used to obtain K by emulating the NMR data.
Data Quality Control:
Quick-Look to identify the following zones: water/ transition/oil/tar zones.

New High Technology Tools:
The applications of new family of high technology tools to sandstone reservoir interpretations: Nuclear magnetic resonance, dielectric, electrical imaging, pulsed neutron and neutron spectroscopy and acoustic logging. High resolution micro-resistivity imaging is also essential to quantify thin beds.

Shale Evaluations:
Estimating Vsh is the first step in sandstone interpretations. Essentially every data acquisition measurement is affected by Vsh. The challenge is to obtain the most accurate value from this web of data. **Shale disposition:** It is also critical to divide the shale volume into dispersed and laminated shales. Structural shale may also be present in small quantities, but this can be lumped with the laminated shale.

Saturation Equations:
There are many empirical Sw equations that are used in estimating Sw in shaly-sand formations. There is no definitive means of defining which is the most suitable equation to use for the various formations. **Excess Conductivity Equations:** This includes Waxman-Smits and Dual-Water equations. This is a mix of theory and empirical derivations of parameters. These equations are essentially are not confined to regional applications.

Estimating Permeability:
There are few equations and processes to estimate the formation permeabilities in sandstone reservoirs.
A whole range of quick-look interpretations can be made to identify:

- Hydrocarbon and water zones,
- Tar Zones
- Estimations of Rw and Rmf

The plot above the Rxo data on the right are shifted by the multiplier Rw/Rmf and constraint to values of Vsh<25%. Where Rt = Shifted Rxo in the water zone, and Rt>shifted-Rxo in the oil zone.
A new generation of upgraded high technology logging tools improved the quality of sandstone formation Evaluations:

- NMR: gives the pore distribution
- Spectroscopy: to define the lithology and Al contents
- Borehole Imaging: to identify fine shaly-sand laminations
- Dielectric: can be used to obtain direct measurements of CEC (Cations Exchange Capacity).
Sequential Analysis from FMI images

Formation MicrScanner Borehole imaging can help in identifying the sequence deposition and facies type. This in-turn can be used to define the zone parameters. Borehole imaging is also the best method to identify thin laminated-shaly sand sequences.
Density-Neutron Cross-Plots in Clastics

Standard Density-Neutron cross-plot to obtain Effective porosity ($\phi_e$) and Vsh.

Extended Density-Neutron cross-plot to obtain the dry shale point (colloid) and total porosity ($\phi_t$).
Saturation Equations in Shaly-Sand

1- Empirical Equations

At the start few empirical equations were developed

These applied to specific regions, or even, specific environments.

They used effective porosity ($\phi_e$) and water saturation ($S_w$) in the matrix (sand, Dolomite, Limestone)

They used parameters for clay, such as $V_{cl}$ and $R_{cl}$
Saturation Equations in Shaly-Sand
1- Excess Conductivity Equations

- Three equations were developed independently by Shell and Schlumberger to account for the conductivity of the shale.
- These equations are based on theory and hence have more universal applications. This is where the concept of total porosity came into play.
Cation Exchange Capacity (CEC)

\[ Q_v = CEC \cdot \rho_g \cdot (1 - \phi_t)/(100 \cdot \phi_t) \]

CEC and QV relate to each other by the equation on the left.

Qv is obtained by measuring Ro in a core for different value of Rw. This is done for various cores with different value of \( \phi_t \).

Brine conductivity \((1/Rw)= C_w\n
There will be a correlation between Qv and \(1/ \phi_t\) of the form:

\[ Q_v = a/ \phi_t + b \]

This is then used in the W-S equation to obtain Sw.
Dispersed and Laminated Shale

- **Laminated Shale**: These run parallel to the sand layers. We can still have some effective porosity even when we have Vsh (Laminated) as high as 90%.

- **Dispersed Shale**: These are deposited at the same time as the sand and fills the pores. The maximum value of Vsh (dispersed) = maximum Clean effective porosity.

- **Structural shale**: This is deposited as grains, and essentially does not affect the effective porosity as much as the dispersed shale.

X-plots using Thomas-Steubabar or Poupon and Juhasz (shown on left) can be used to differentiate between dispersed and laminated shale. A common mistake is to have a cut-off at total Vsh>50% (yellow area). In fact the cut-off should be at Vsh-dispersed > 50% of the maximum Vsh-dispersed (red area).
Quantifying the Silt Volume (Vsilt)

The Nuclear Magnetic Resonance offers the best means of quantifying silt volume (Vsilt). This can be done as follows:

\[ Vsilt = Vb - Vsh \cdot \phi_{sh} \]

Where \( Vb \) is the bound water volume.

Another form of addressing Vsilt is to look at values of \( Sw \) above a given minimum (blue area) in a zone above the transition zone which is not depleted. If oil-based mud is used and a dielectric of pulsed neutron tool is used, \( Sxo \) can be used. Vsilt can be quantified as:

\[ Vsilt = (Sw - Sw-min) \cdot \phi_e \]

We can then obtain \( Vb \) as follows:

\[ Vb = Vsh \cdot \phi_{sh} + Vsilt \]
Estimating Permeability (K)

Many Equations were proposed to estimate permeability (K) in clastics reservoirs.

**Timur**

\[
k^{1/2} = \frac{100 \cdot \phi^{2.25}}{S_{\text{wir}}}
\]

**Coates**

\[
k^{1/2} = 70 \cdot \phi^{2} \cdot \frac{1 - S_{\text{wi}}}{S_{\text{wir}}}
\]

**Timur-Coats**

\[
K = a \cdot \phi_t^4 \cdot \left( \frac{\phi_t - V_b}{V_b} \right)^2
\]

The Timur and the Coats equations were obtained mainly from core analysis. However, they require having a value of Swir (irreducible water saturation).

The Timur-Coats Equation was based on having Vf (free fluid) and bonded fluid (Vb) values. These however can be obtained from logs as described earlier.
Agenda

Day-1:
• Geology of clastics reservoirs
• The Gamma Ray and Spontaneous Potential logs to obtain Vsh and Formation Water Salinity
• Defining the clay type
• Overview of standard logging tools
• Quick-Look data evaluation

Day: 2
• Applications of the density-neutron cross plot to determine effective porosity, total porosity, hydrocarbon effect and shale volume
• Hydrocarbon effects on density-neutron cross-plots.
• Acoustic measurements and the acoustic scanner to determine sand compaction and mechanical properties

Day-3:
Evaluation of Shales:
• Overview of shales and their depositional environments
• The various procedures to estimate Vsh.
• Estimating Vsh from spectroscopy from direct measurements of Al or obtaining an Al emulator.
• Defining the volumes of dispersed and laminated shales using Thomas Steubar and Popoun-Juasz.
• Evaluating the Cations Exchange Capacity (CEC) of shales
• Evaluating the silt volumes from standard logs.

Day-4:
Shaly sand equations:
• The family of empirically derived equations used
• Excess Conductivity shaly sand equations: Waxman-Smits (WS), Dual-Water, Modified W-S
• Comparison of the results from the various equations

Day-5
High Technology tools and their applications in shally sand-Sand formations. This includes:
Nuclear Magnetic Resonance, Dielectric Logs, Micro-resistivity Imaging
Permeability Estimations in Sandstone-Reservoirs

There will be daily practical workshops on each of the topics covered using field examples