NEW REAL-TIME APPLICATIONS OF ACOUSTIC LWD MEASUREMENTS IN HORIZONTAL WELLS TO OPTIMIZE WELL PLACEMENT

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ABSTRACT

Usually density/neutron porosity services are used for porosity estimations and fluid contact detections. Gas-oil contacts are often easily established from LWD logs by using the change in density/neutron porosity separation from gas-to-oil based on the difference in the hydrogen index.

This paper describes a case study where density/neutron porosity could not be run due to operational reasons. Identification of different fluid levels in the landing phase of a horizontal well was vital to optimise reservoir mechanisms during production and injection of gas. To mitigate a potential drilling hazard, advanced LWD acoustic services were run for fluid typing and fluid contact identification.

Acoustic measurements were used in the 12¼" landing section. The 12¼" section was drilled from the overburden and into the reservoir where well inclination was built to horizontal prior to set casing. In this phase of drilling, it was critical to determine the gas-oil contact (GOC) correctly.

Injection of gas determines the initial level of horizontal well placement to avoid early gas breakthrough. This case shows a successful real-time verification of the contact based on acoustic measurement and optimum placement of the heel of the horizontal producer. Cross-plotting of memory compressional and shear data (Vp, Vs) confirm hydrocarbon identification based on real-time data.

Further data analysis in the horizontal section shows the benefit from optimum landing of the well in real time.

INTRODUCTION

Acoustic LWD technology has matured with development of array tools capable of full waveform recording. It has for quite some years been possible to acquire compressional data in real time, and shear data from post-processed memory data from monopole and multipole measurements. LWD acoustic data sets were recently acquired in several different hole sections on the Grane Field.

Figure 1: Grane Field location in the Norwegian North Sea

Acquisition of high quality velocity data, both compressional and shear, was critical for all hole sections penetrating any part of the reservoir and the caprock–reservoir interface. Real-time compression was planned to be used for GOC detection in the 12¼" section, prior to landing the well horizontally, and continuing with the drainage section. LWD was considered the most cost-effective method to firmly determine GOC.

Acoustic porosity was also calculated from data acquired during drilling of the 8 1/2" horizontal section.

Grane Field is located in the Norwegian North Sea (**Figure 1**). The reservoir consists of massive, predominantly fine- to medium-grained, moderate-to-well sorted, turbidite sandstones of the Heimdal Formation of Paleocene age, encased in the Lista Formation claystones located approximately 1,700 m below sea level.

These sandstones are very friable; slightly quartz cemented in parts, and show excellent reservoir properties with permeabilities commonly in the 5-10

Darcy range and average porosity of 33 p.u. However, due to the small difference between oil (0.894 g/cc) and formation water (1.018 g/cc), a long transition zone exists above the oil-water contact (OWC), as shown in **Figure 2**.

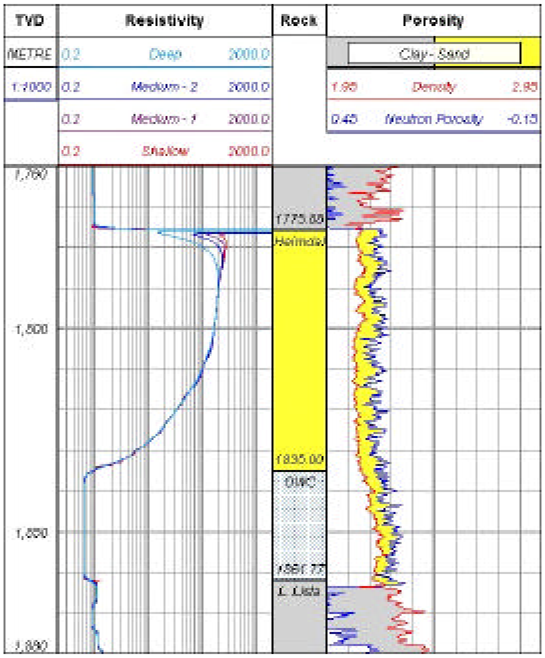

Figure 2: Saturation transition zone in the virgin Grane Field described by the gradual decrease in resistivity, showing a transition zone in the magnitude of 50 m TVD.

Hydro discovered the field in 1991, which came onstream in September 2003 as the first heavy crude oil field on the Norwegian continental shelf.

Grane has been described as a challenging field, mainly because of heaviness of the oil and low pressure in the reservoir. Natural gas is pumped into the reservoir to make efficient sweep of the oil. In the production wells it is paramount to log GOC to interpret the lateral extent and thickness of the injected gas column. This gas will be produced back at the field's tail end when it will be converted to a gas field.

DATA ACQUISITION

The obvious method to determine GOC is by density/neutron separation, which is seen in **Figure 3**. The gas interval stands out very clearly and is easily determined from this log. For all practical purposes, the gas interval is logged in the 12¼" section when landing the well in the reservoir.

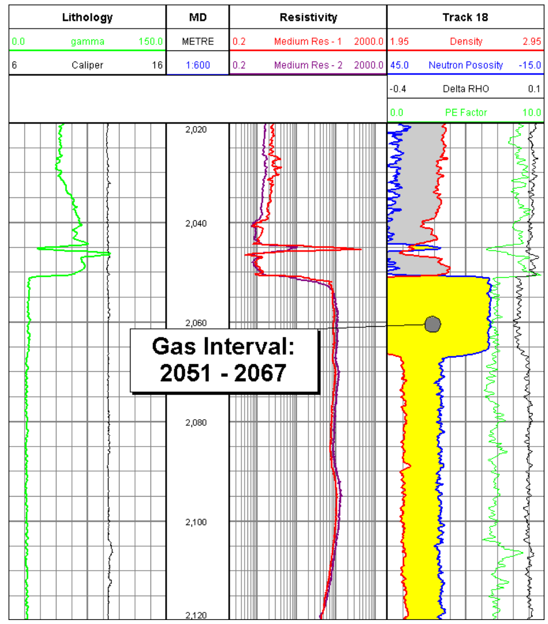

Figure 3: Gas interval from density/neutron separation

However, operational constraints indicated that density/neutron was not favourable in the 12¼" section in one well, and hence other LWD measurements were pursued to maintain the level of information needed to understand the injection/production profile in the Grane reservoir.

The 12¼" well profile is illustrated in **Figure 4**. After the well was landed in the reservoir, the entire drainage section was drilled at 90° to maintain a set distance above OWC for maximum production.

The aim was to determine GOC by using acoustic measurements. Based on the rather large difference in the acoustic response in a gas zone, opposed to an oil zone, confidence was given to the expectation that GOC could be determined by use of acoustic measurements. Gamma and resistivity were also part of the logging string in the 12¼" hole, but none of these measurements would give rise to GOC determination.

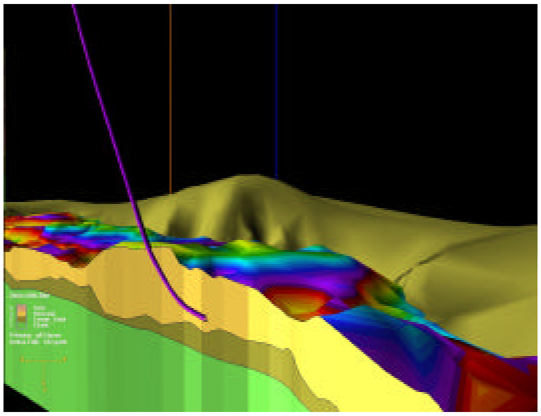

Figure 4: The 12¼" section is drilled into the reservoir: yellow represents the main HC-bearing sand. Anticipated gas is in the uppermost part of the reservoir.

The 8½" horizontal section utilized full quad combo service including gamma ray, resistivity (conventional propagation resistivity, directional and extra deep resistivity, depth of detection of up to 12 m), density, neutron and acoustic (both compressional and shear). Porosity calculations based on the different physical measurements were then made and compared.

The 8½" section is not penetrating any interval with gas breakthrough, hence it is only in the 12¼" section where gas detection is deemed necessary.

This paper focuses on data acquisition to determine GOC, although the major goal in this demanding reservoir is to maintain desired position within the reservoir, in addition to gaining maximum understanding of both the drainage mechanisms over time and the overall reservoir geometry and quality while drilling.

ACOUSTIC TOOL DESCRIPTION

The same type of LWD array acoustic tool was run in both hole sections.

Acoustic LWD Tools

Acoustic LWD tools operate in a noisy drilling environment. To ensure an adequate signal to noise (S/N) ratio, early tools used a short distance between the transmitter and receivers. This, however, had a negative effect on measurement accuracy as the measurement was more affected by borehole conditions, such as washouts and near wellbore alterations. Earlier acoustic LWD tools also suffered from lack of downhole processing and memory capacity for waveform analyses and storage.

The SoundTrak™, run in these hole sections, enhances the S/N ratio through acquisition of multiple sets of waveform data, which minimizes tool decentralization effects and the use of advanced signal processing techniques (Tang et al., 2003). Formation slowness values and associated quality control indicators are derived and processed downhole while drilling and pulsed to the surface. Raw waveform data are stored in downhole memory for post-processing and analysis.

The LWD acoustic tool consists of three primary components: a segmented omni-directional acoustic transmitter, an omni-directional receiver array, and an isolator section (**Figure 5**). The design of each of these components is optimised to ensure measurement quality and is closely based on the WL equivalent, a full waveform, multi-mode array acoustic tool (Gravem et al., 2003)

In WL environment, dipole mode is predominantly employed to acquire shear slowness. In LWD environment, the added presence of the drill collar significantly interferes with flexural wave propagation.

Fortunately, a quadrupole mode creates guided wave that will not excite a collar mode when operated below the cutoff, frequency allowing it to be used for the determination of the formation shear slowness.

In this study, the tool was programmed to acquire combination monopole and quadrupole modes.
For further description of quadrupole mode in LWD environments, the reader is referred to Tang et al. (2002, 2003), Leggett et al. (2001), and Page et al. (2002).

REAL-TIME DATA QUALITY CONTROL

Real-time quality control of LWD acoustic data is paramount, as is the subsequent comparison of real-time downhole processed and post-processed LWD data.

Pulsed up real-time data from the LWD acoustic tool consists of only a compressional slowness (DTC) and a quality control semblance value derived from the downhole processed data. This is due to bandwidth limitations of the telemetry system, which exclude pulsing full waveforms to the surface, and therefore real-time downhole processing in the acoustic LWD tool is performed. Processing is based on the n-th root semblance technique (Smith et al., 1991). This technique is used in the LWD tool to derive formation slowness values in real time, which involves a waveform correlation process. The resulting correlogram is used to identify the most dominant events and their associated semblance or correlation values between 0 and 1 (the higher the value, the better the correlation).

The semblance values for these two wells were generally in the range from 0.9 to 1.0, except for areas with beds too thin for the array to fully resolve.

Shear slowness (DTS) is only available after downloading the full waveform memory data from quadrupole processing in the computing center.

FLUID CONTACT DETECTION

When drilling the 12¼" section, a drop in the compressional slowness was measured, as expected, when going from the gas zone to the oil zone of the reservoir (**Figure 6**). The GOC was later confirmed by post-processing of shear slowness data (**Figure 7 and 8**). As shear slowness is not affected by fluid in the pore space, this shows that the reduction in compressional slowness is because of fluid effects, and not lithology effects. The shear slowness of the rock, a function of the stiffness of the rock framework alone, is unchanged during the course of fluid changes.

GOC was thereby identified, and the horizontal was safely placed below the gas zone.

POROSITY CALCULATIONS IN THE HORIZONTAL SECTION

Porosity was calculated from density, compressional slowness, and shear slowness and compared.

Density porosity in the 8½" section was calculated using the standard equation:

$$\Phi = (r_{matrix} - r_b)/(r_{matrix} - r_{fluid})$$

Matrix density is 2.65 g/cc, and the fluid density was set to oil density 0.894 g/cc.

Acoustic compressional porosity was done by using the standard Wylie formula:

$$\Phi = (DTC - DTC_{matrix})/(DTC_{fluid} - DTC_{matrix})$$

Matrix compressional slowness was set to 55 us/ft, and fluid slowness was set to 240 us/ft.

As the Grane Field is a clean turbidite sandstone reservoir, porosity calculated from shear was based on the empirical equation from Medlin et. al. (1990):

$$\Phi = (DTS - 92.9)/319$$

Figure 9 shows comparison of the two acoustic porosities. As seen on the frequency plot, the average difference between shear and compressional is less than 1%.

Figure 10 shows shear porosity versus density porosity. Average difference between density porosity and shear porosity is less than 1.6%, well within the uncertainty of the different physical measurements. In addition, some of the variation can be attributed to differences in depth of investigation between the acoustic shear measurements and density measurements when logging a horizontal well.

Shear measurements also gave accurate porosities in the gas zone. Generally both density and, compressional and neutron porosity are affected by the gas effect to different degrees, making it more challenging to calculate porosity from these measurements.

CONCLUSIONS

Sound waves have multiple applications, especially if both compressional and shear are acquired.

- The combination of real-time compressional and post-processed shear proved to be a robust way to pick GOC.

- In clean turbidite sands like the Grane reservoir, porosity from density, compressional and shear are very comparable.
- Porosity from shear measurements can provide porosities in gas zones in clean sands.

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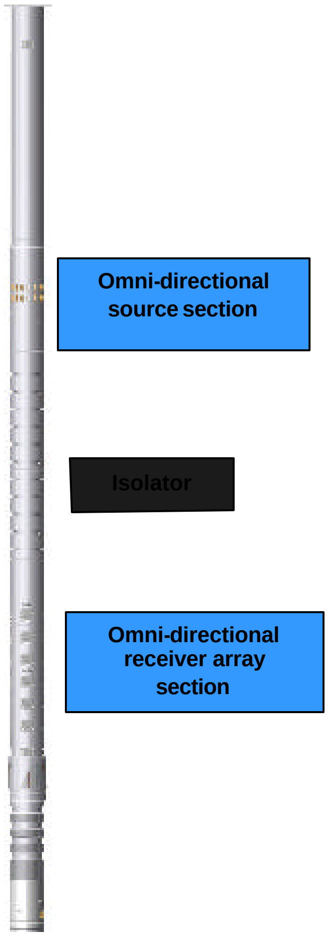

Figure 5: SoundTrak LWD acoustic tool elements

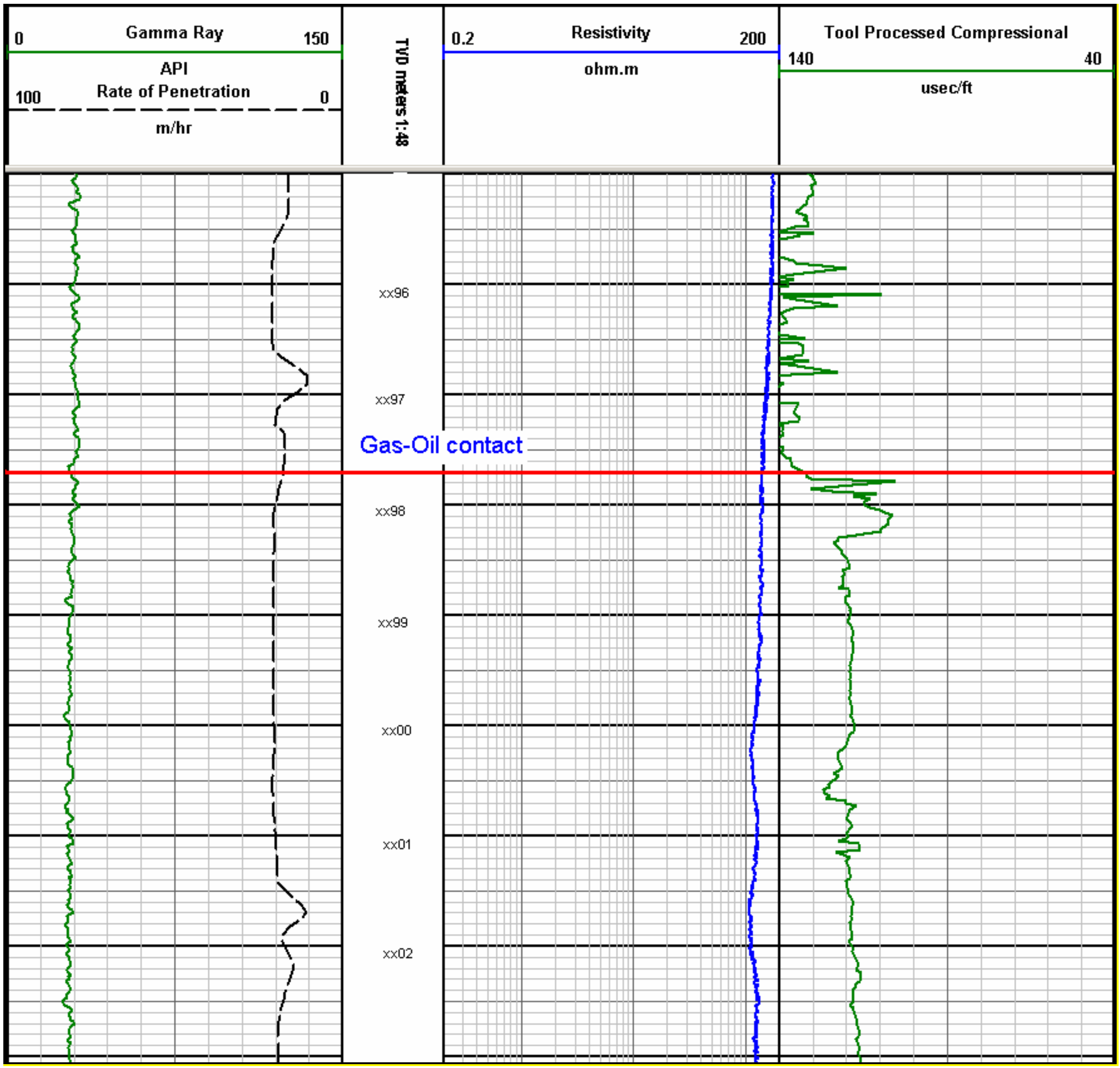

Figure 6: Tool-processed compressional slowness showing GOC.

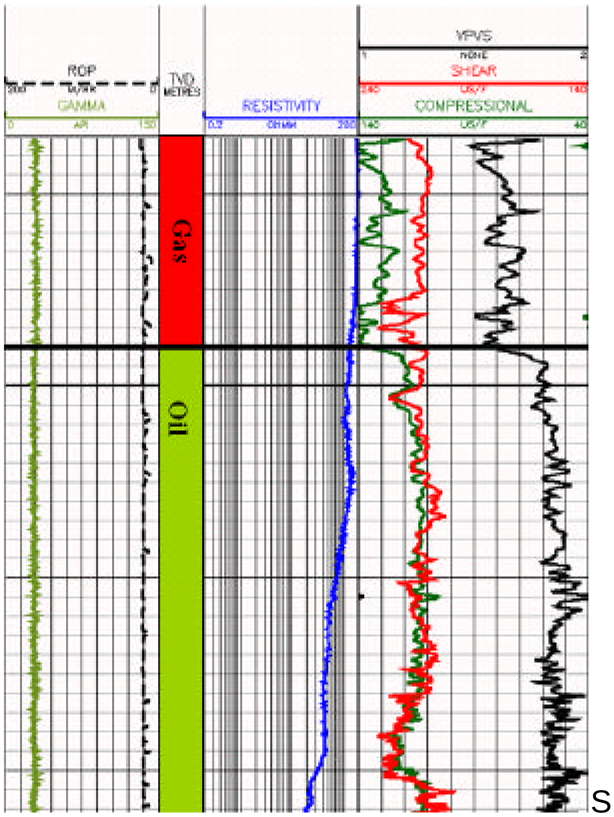

Figure 7: Post-processed compressional and shear slowness showing GOC.

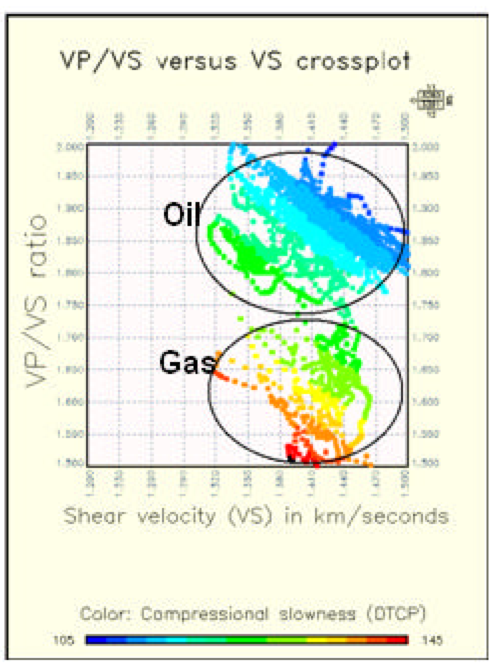

Figure 8: Compressional versus shear slowness ratio plot identifying the gas and oil zones.

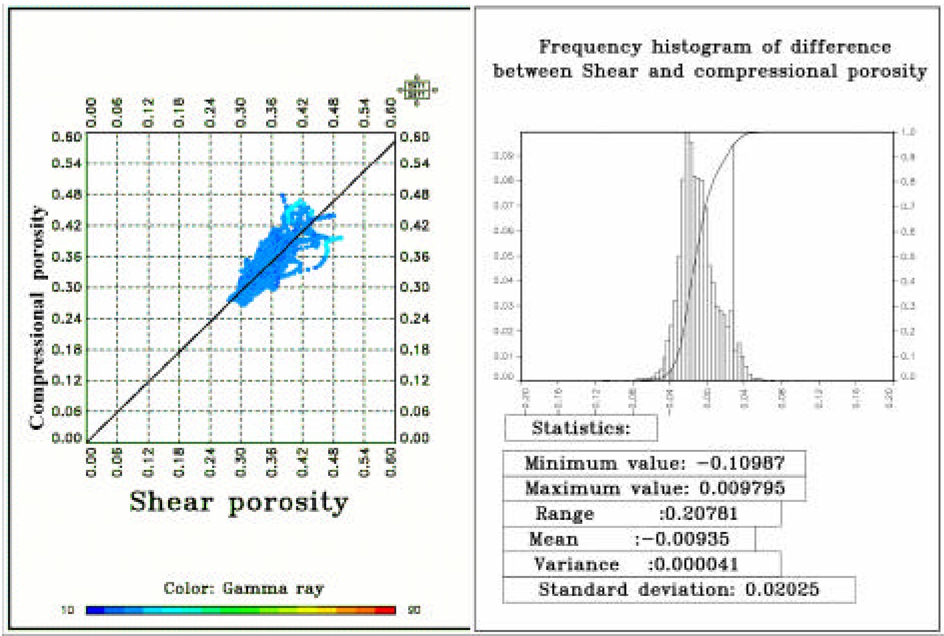

Figure 9: Comparison of shear versus compressional porosity.

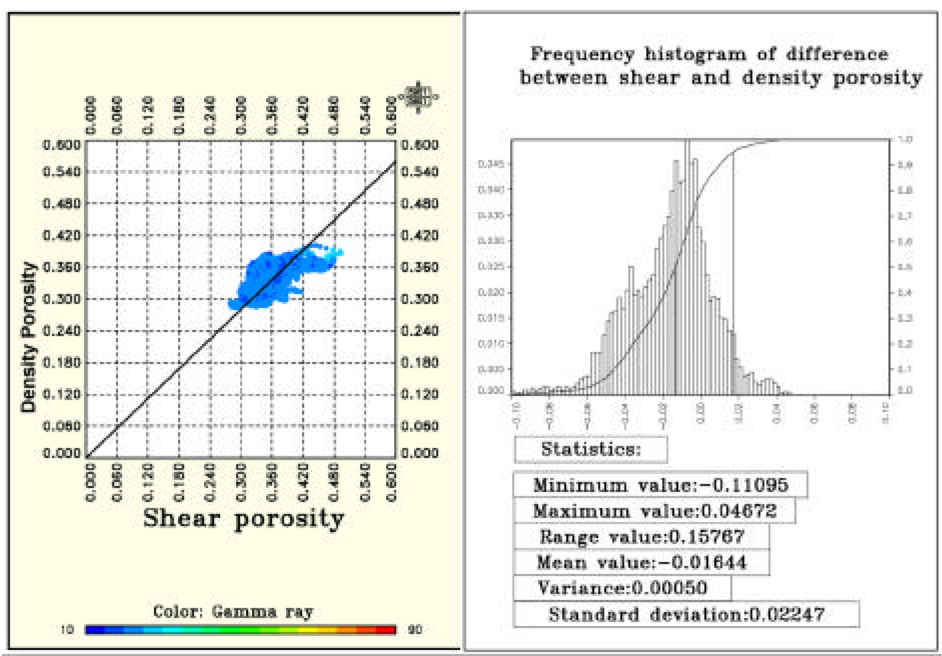

Figure 10: Comparison of shear versus density porosity.