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NMR STUDIES OF AN IRON-RICH SANDSTONE OIL RESERVOIR

Håkon Rueslåtten, Terje Eidesmo, Statoil R&D
Carsten Slot-Petersen, Statoil E&P
Jim White, Schlumberger

Abstract: A special NMR study is performed on a sandstone oil reservoir in the North Sea that is characterised by high contents of glauconite and abundant chlorite. Tar zones complicate the reservoir characterisation further.

Standard logs indicate porosities of 25 to 35 PU throughout the reservoir column, but core analyses (and well tests) show a very poor relation between porosity and permeability, expected to be caused mainly by the chlorite content. A high proportion of intra-particle micro-porosity confined in the glauconite grains creates an additional uncertainty with respect to fluid saturation and distribution. In order to obtain more information about the productivity of the individual reservoir zones a specially designed programme was set up including NMR logging, special core analyses and laboratory NMR measurements.

Several interesting aspects regarding the NMR log responses were revealed; (i) by applying the normally used 33 ms cut-off value for BVI, substantial deviations from the measured Swirr values were found; (ii) the T1/T2 ratios range from 2 to 10 for oil saturated core plugs (at irreducible water saturation); and (iii) the difference between NMR log derived porosity and total porosity is a function of the chlorite content rather than the glauconite content. The suggested interpretation of the latter observations is that the fine-grained chlorite is inducing magnetic gradients on the pore level causing the T2 relaxation times to be shortened dramatically. The sand-grain-sized glauconite, in contrast, affects a much smaller fluid interface and is therefore less detrimental to the T2 relaxation. This knowledge is essential to the understanding and interpretation of NMR logs and in particular for the parameter input to the permeability model.

Introduction

The connection between NMR measurements and petrophysical parameters such as permeability and wettability stems from the strong effect that the rock surface has on promoting magnetic decay of the wetting fluid phase. The longitudinal relaxation time (T1) is the parameter of greatest interest for the estimation of petrophysical parameters, but the NMR well logging tools only measures the transverse relaxation time (T2) which is influenced by other rock properties that are more difficult to interpret. An important factor influencing the T2 measurements is that paramagnetic minerals in the reservoir rock influence the magnetic gradient. LaTorraca *et al.* (1995) suggested that magnetic susceptibility contrasts between iron-bearing rock minerals and pore fluids induce magnetic gradients promoting diffusional movements of oil and water molecules out of the frequency domain, resulting in faster T2 decay. The faster T2 decay may lead to an underestimation of the porosity of the formation and also to difficulties in the determination of "bound" and "free" fluids. The understanding of these processes are therefore a critical factor for the interpretation of NMR log data.

Reservoir characteristics
A Late Paleocene/Early Eocene sandstone oil reservoir in the North Sea is characterised by standard log and core porosities ranging from 25 to 35 PU and permeabilities ranging from <1 to 1000 mD. The reservoir sands are fine to very fine grained, well sorted and contain abundant glauconite and chlorite. The reservoir quality is controlled by sedimentary facies variations, primary sand quality and diagenesis. Low intergranular macro-porosity is due to the compaction of an abundance of ductile grains; i.e. glauconite pellets, mica and detrital clay clasts. Carbonate cement has also reduced intergranular porosity locally.

The reservoir is further characterised by high proportions of micro-porosity (> 50%) associated with the micro-porous glauconite and dispersed pore-filling and pore-lining chloritic clay, causing a poor correlation between porosity and permeability. The water-wet micro-porosity is also causing high immobile water saturations, resulting in low electric resistivities (1-5 ohm-m) of the pay zones. For these reasons it was decided to log two of the wells with Schlumberger's NMR logging tool (CMR) and to use core analysis for calibration.

Data acquisition procedures

Drilling, Coring and Log data acquisition
The entire gross reservoir interval of Well-A and Well-B were cored using a low invasion core bit and a tracer-doped synthetic oil-based mud for the purpose of providing core NMR and core water saturation data for log calibration. Upon retrieval at the rig floor, centre core plugs were drilled every metre and heat sealed before shipment to the lab for reference measurement of the formation water volumes. The CMR logging in both wells was carried out using the following CPMG (Carr-Purcell-Meiboom-Gill) pulse-sequence parameters; (1) 6 sec wait time, (2) 1800 spin echoes, and (3) inter-echo spacing of 0.32 ms. Total measurement cycle time was 13.2 sec giving a vertical resolution of 6 in at the maximum logging speed of some 137 ft/hr (42 m/hr).

Core selection and analyses
In the cored interval of Well-A and Well-B six twin sets of seal peal core plugs were selected for this special NMR laboratory study to complement and calibrate the downhole CMR log measurements; sampled within zones exhibiting significant differences in the CMR log characteristics. The core plugs measuring 38 mm in diameter and 70 mm long,

were drilled out and run through a comprehensive experimental programme including petrographical, petrophysical and NMR measurements. The NMR laboratory program was carried out in the following sequence:

- Cleaning of the freshly received core plugs with brine;
- NMR T1 and T2 measurements of the water saturated core plugs;
- Desaturation of the plugs by air in a centrifuge (4.0 bar equivalent air-brine capillary pressure for plug A13 and A14 and 5.7 bar for the other plugs);
- NMR T1 and T2 measurements at Swirr (air/brine) (not discussed here);
- Saturation of the plugs with decane at irreducible water saturation (Swirr);
- NMR T1 and T2 measurement at Swirr (decane/ brine);
- Karl Fischer titration for measuring irreducible water saturation.

Further characterisation of the core plugs included standard petrophysical measurements of helium porosity, brine permeability, Co/Cw, and Pc/RI. Petrographical analyses included point counting of thin sections, SEM and XRD analyses.

Results

Petrographic analyses

The petroghraphic analyses revealed a complex mineralogy with quartz being the dominant mineral, but also large volumes of glauconite (18-38 vol%) in addition to abundant chlorite varying from 4 to 26 wt% (Table 1). The continuity of the pore system is apparently good, but the fine-textured dispersed pore-lining and pore-filling chloritic clay is detrimental to permeability. The glauconite is found as rounded sand-sized grains containing in the order of 30 vol% micro-porosity. SEM analyses show a zonation of the glauconite grains, with more micro-porosity in the outer part of the grains. It is evident from the XRD analysis that the glauconite shows various degrees of low expandability when saturated with ethylene-glycol.

Core Petrophysical and NMR analyses

The He-porosities of the twelve core plugs range from 22.6 to 35.3 PU, and the brine permeabilities range from 4.9 mD to 567 mD. Irreducible water saturations vary between 27 and 55% of the total core porosity. Some data pertinent to this paper are given in Table 1 and 2. These include log mean T1 and T2 data for various states of core plug saturations as well as petrophysical and mineralogical data.

Laboratory NMR measurements were performed using a Resonance - MARAN-2 NMR Spectrometer at a proton resonance frequency of 2.04 MHz. The T2 relaxation curves were measured using a Repetition Time (RT) of 10sec, number of echoes 8100, and CPMG inter echo spacing (τ) 350μs. Spin lattice relaxation curves (T1) were measured using a (π - τ - $\pi/2$) inversion recovery sequence. The π and $\pi/2$ pulses were approximately 34μs and 17μs, respectively, (tuned according to core susceptibility). Thirty data points were recorded in order to cover the entire T1 relaxation curve. The temperature of the sample holder was controlled at 30 ^{0}C.

Discussion

NMR relaxation processes and chlorite

NMR longitudinal relaxation (T1) of fluids confined in a porous rock is affected by both surface and bulk relaxation processes expressed by

$$1/T1=1/T1_{Bulk} + \rho S/V \qquad \text{(Eq. 1)}$$

while transverse relaxation (T2) is additionally affected by dephasing in case of molecular diffusion and magnetic gradients in the system, expressed by the last part of equation 2:

$$1/T2=1/T2_{Bulk} + \rho S/V + 1/3D(\delta B\gamma\tau)^2 \qquad \text{(Eq. 2)}$$

Where: ρ = Surface relaxation strength; D = Diffusion coefficient; δB = Magnetic gradient;
S/V = Surface to Volume ratio; γ = Gyromagnetic constant; and τ = Inter-echo spacing.

The enhancement of surface relaxation strength (ρ) by paramagnetic minerals is assumed to influence equally on T1 and T2 measurements. The problem addressed here is the impact of paramagnetic minerals on the magnetic gradient δB which would affect T2 only (Eq. 2). The reservoir discussed here is characterised by large amounts of paramagnetic glauconite and chlorite; glauconite being more abundant than chlorite. SEM analyses indicate that the percentage weight Fe_2O_3 in the two minerals varies between 15 and 21 %, and that the microporosity of glauconite is approximately 30 vol-%. XRD analyses show a larger variation in the chlorite content compared to glauconite (Table 1 and 2). In order to study the effects of these two mineral species on the NMR relaxation behaviour the T1/T2 ratios are plotted versus the chlorite contents (Fig.1). It is evident from Fig.1 that a good correlation exists between chlorite and the T1/T2 ratios, and that this correlation may be expressed by Eq.3:

$$T1/T2 = a + b(\text{Chlorite})^c \qquad \text{(Eq.3)}$$

Based on Fig.1 it is found that a=-3.6; b=3.0 and c=0.5, for decane saturated rocks at Swirr. For brine saturated rocks at Sor it is found that a = -3.6; b=3.3 and c=0.2. The T1/T2 ratio represents Eq.2 divided by Eq.1, and consequently the effect of δB is included in the ratio. By assuming that ρ is equal for T1 and T2, irrespective of the chlorite content, it is suggested that the correlation expressed by Eq.3 is caused by the chlorite inducing magnetic gradients on the pore scale that reduces the T2 relaxation time dramatically, and that the impact on T1 is negligible. The much stronger effect of chlorite to promote T2 decay compared to the micro-porous sand-sized glauconite is explained by the larger surface area of the chlorite being exposed to the fluids confined in the intergranular pore space.

Polarisation compensation

Kleinberg et al. (1993) studied a large suite of water saturated rock samples and found a mean value of 1.65 for the T1/T2 ratios. The T1/T2 ratios for the water saturated core plugs studied here vary from 1.4 to 3.5 (Table 2) and fall within a "normal" range of 1 - 3. Polarisation compensation of NMR logging tools is based on using a fixed T1/T2 ratio of 2.5. However, the T1/T2 ratios for decane saturated core plugs (at Swirr) are found to range from 2.0 to 10.9; demonstrating that the use of a fixed T1/T2 ratio for polarisation compensation may be erroneous for oil/water saturated rocks. As described above, this is particularly the case for chlorite bearing rocks due to their strong influence on the T2 decay. It should also be mentioned that the T1/T2 ratios used here are mean values, and that the longest relaxation components (which are important) may have even higher ratios.

Porosity estimations

It is evident that standard CMR "effective" porosity estimation using an inter-echo spacing of 3 ms underestimates the total porosity in a number of formations and that some of the observed porosity deficit is recovered by using CMR "total" porosity which operates with an inter-echo spacing of 0.3 ms (Freedman *et al.*, 1997). In the present CMR logging case an inter-echo spacing of 0.3 ms was applied, and still a variable but significant underestimation of CMR porosity ranging from approximately 2 to 15 PU was observed throughout the hydrocarbon reservoir. The porosity of each of the core samples will be discussed in terms of their composition, and compared with the respective CMR and density log derived porosity from the well logging.

Core plugs A13 and A14: The tar zone:

Core plugs A13 and A14 are from a tar filled reservoir zone. Missing porosity, poor free fluid signal and very short T2 decays are characteristic signatures on the CMR log from this zone. The largest underestimation of CMR porosity compared to the density derived porosity is encountered here; -15 PU (Slot-Petersen, 1998). The missing porosity is due to several factors; (1) the T2 relaxation of tar being faster than the resolution of the CMR tool (0.3 ms); (2) the hydrogen index of tar is lower than unity due to its higher content of aromatic components; (3) the tar is causing a more oil-wet situation resulting in a shorter relaxation time of the oil phase; and (4) the chlorite content (some 10 wt%) is also contributing to shorten the T2 relaxation times.

Core plugs A3 and A4: Water zone; low chlorite content:

This zone is characterised by a reasonably good match between CMR and core helium porosities (Table 2). Petrographically this zone is characterised by chlorite contents less than 5% while the glauconite content is approximately 20 vol%.

Core plugs A5 and A6: Water zone; high chlorite content:
A significant porosity underestimation is observed by both the CMR and the core NMR derived porosity compared to the standard density log derived porosity. The core plug investigations indicate that the zone contains more than 20 wt% chlorite and more than 20 vol% glauconite (Table 2). It is suggested that the faster T2 decay induced by chlorite leads to a loss of the fastest decaying signal, resulting in an underestimation of the CMR derived porosity of approximately 12 PU.

Core plugs B7 and B8 (oil zone); and B9, B10, B11 and B12 (water zone):
Zones of intermediate chlorite contents and high glauconite contents:
The CMR porosity underestimation in the zones represented by these core plugs is ranging from approximately 10 to 12 PU compared to the density log derived porosity. The chlorite content is ranging from 9 to 15 wt% and with a high and relatively uniform glauconite content of 36 to 38 vol%.

The porosity of the brine and decane saturated core plugs were calculated based on the NMR T2 measurements, and as can be seen from Table 1 and 2 the laboratory derived NMR porosities are in rather good agreement with the He-porosities. The largest discrepancies (approx. 7.5 PU) are found for the samples A5 and A6 which are characterised by the largest chlorite content. The influence of chlorite and glauconite on the difference between He-porosities and NMR T2 derived porosities (ΔPorosity) is illustrated in Fig. 2. A broad positive correlation between increasing ΔPorosity with increasing chlorite is observed, while no correlation is seen with glauconite. This demonstrates the detrimental effect of chlorite on porosity estimation by NMR T2.

However, the large underestimations observed for the CMR derived porosities are not seen on the laboratory NMR measurements, indicating that other factors are of importance; two of which are the hydrogen index deviation from unity and the noise in the CMR log data; both of which may contribute to the observed underestimations. It is also evident that the multi-component relaxation behaviour of crude oil having shorter relaxation times than the decane (used in the laboratory experiments) may give rise to a higher loss of the crude oil signal compared to decane under the influence of chlorite (Rueslåtten *et al.*, 1998).

BVI comparison and T2 cut-off values
Based on the assumption that the short T2 components are associated with bound fluid a cut-off value of 33 ms is commonly used to quantify "bound fluid" (BVI) and "free fluid" (FFI). By applying this cut-off value for the decane saturated core plug NMR T2 data, some significant mismatch with the "Karl Fischer" measured Swirr data was observed for

the chlorite rich samples (Fig. 3). A good match is found between the titrated Swirr data and the T1 data (which is not effected by chlorite) using a cut-off value of 150 ms (Fig. 3). This cut-off value of 150 ms is chosen because it is close to the product of 33 ms (cut-off value for T2) and the average T1/T2 ratio.

In order to further study the measured Swirr in relation to the relaxation behaviour, the T2 spectra for all twelve decane saturated core plugs were plotted, and the "cut-off value" corresponding to the titrated Swirr value was indicated on each curve, respectively. This is illustrated in Fig. 4 where plots of one of the "twin" sets from Well-A is shown. It is evident from the plots that the cut-off value for the majority of the samples is ranging from 3.3 to 10.5 ms, and only the two samples low in chlorite (A3 and A4) have higher cut-off values. An interpretation of the data shown in Fig. 4 may be that some of the decane is relaxing faster than 10 ms in the chlorite rich rocks due to much faster diffusion in the local magnetic gradients (Eq.2).

Permeability

The permeability estimations from NMR core data are based on the standard Timur/Coates equation (Eq. 4):

$$K_{NMR} = C \times (MPHI)^{A} \times (FFI/BVI)^{B} \qquad \text{(Eq. 4)}$$

Where $C = 1 \times 10^{-4}$; $A = 4$; and $B = 2$.

From Eq. 4 it is evident that to obtain good permeability estimates it is of crucial importance to have correct values for the porosity and the FFI/BVI ratio. The comparison of Swirr data with NMR core plug measurements indicate that the BVI cut-off values should be below 10 ms for the chlorite rich rock samples (Fig. 5). By applying a BVI equal to Swirr one should expect an optimal permeability model. This is not the case for these samples, and the best-fit permeability model is obtained by using a 33 ms cut-off value. The need for a higher cut-off value in these rocks might be due to the fact that Swirr is strongly influenced by both chlorite and glauconite, while only the chlorite is detrimental to permeability. The even distribution of chlorite in all pore size classes has a strong influence on both permeability and T2 relaxation rate.

The CMR permeability estimations are also improved by using a 33 ms cut-off value. Due to the strong impact of chlorite on the CMR porosity estimations the density derived porosity is used in the permeability calculations.

Conclusions

A North Sea sandstone oil reservoir is characterised by high contents of chlorite and micro-porous glauconite. These minerals are associated with large volumes of water-wet micro-porosity which causes difficulties in the formation evaluation process, and a study including NMR analysis of reservoir core plugs was initiated for calibration of CMR log data. From the study of the effect of chlorite and glauconite on the NMR responses during logging (CMR) and laboratory core plug investigations, it is concluded that the faster T2 magnetisation decay is associated with the chlorite content. The impact on T1 is negligible (compared to T2), and it is therefore suggested that the chlorite causes heterogeneities in the applied static magnetic field and induces internal magnetic field gradients on the pore scale. The T1/T2 ratios of the decane saturated rock samples (at Swirr) vary from 2 to 10.9 due to the mineralogical effects. The effect of glauconite is less pronounced due to its lower surface area. A correlation is also found between increasing T1/T2 ratio with increasing chlorite content which may be used to quantify (iron-bearing) chlorite in the formations; provided that no other minerals with a similar effect interfere. Despite the lower cut-off values needed for estimating "correct" irreducible water saturations, the cut-off value of 33 ms is found to be the best value for obtaining good permeability estimates in this oil field.

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Table 1. NMR, petrophysical and petrographical data for Well-A. "Porosity (water)" and "Porosity (decane)" is referring to the NMR T2 derived data. Sor = Brine/Crude oil. Swirr = Decane/Brine. (n.g.= not given)						
Plug	A3	A4	A5	A6	A13	A14
Depth	X127.4	X127.5	X152.38	X152.47	X106.82	X108.85
Mean T1 (Sor)	84.6	62.4	32	33.9	59.3	58.7
Mean T2 (Sor)	48.5	43.5	9.6	9.7	25	25
Mean T1 (Swirr)	262.1	273.3	131.9	109.9	276.7	256.7
Mean T2 (Swirr)	121.7	134.1	12.1	13.3	45.9	44.3
Porosity (helium)	34,6	36,6	30,1	30,3	33,4	33,4
Porosity (water)	35.3	34	22.6	24.1	n.g.	n.g.
Porosity (decane)	35.7	36.5	24.7	25.7	31.6	32.2
Permeability (mD)	494	567	26	27	292	289
Swirr (decane)	0.3	0.28	0.41	0.45	0.27	0.3
Chlorite (wt%)	4.5	n.g.	24.5	n.g.	9.4	n.g.
Glauconite (vol%)	20.7	n.g.	23.7	n.g.	17.7	n.g.

Table 2. NMR, petrophysical and petrographical data for Well-B. "Porosity (water)" and "Porosity (decane)" is referring to the NMR T2 derived data. Sor = Brine/Crude oil. Swirr = Decane/Brine. (n.g. = not given)						
Plug	B7	B8	B9	B10	B11	B12
Depth	X034.38	X034.48	X036.48	X036.58	X045.42	X045.48
Mean T1 (Sor)	39.9	45.6	21.3	21.9	25.2	28.4
Mean T2 (Sor)	17.8	19.2	9.5	8.8	7.7	7.7
Mean T1 (Swirr)	143.8	169.9	88.8	135.8	77.7	75.7
Mean T2 (Swirr)	25.2	24.2	12.2	13.3	9.6	9.5
Porosity (helium)	33,8	34,9	32,1	31,7	31,8	32
Porosity (water)	33.6	35.3	30.5	30.9	30.9	32
Porosity (decane)	34.6	37	33.2	31.8	33.1	33
Permeability (mD)	402	471	60	36	5	5
Swirr	0.4	0.37	0.45	0.35	0.49	0.55
Chlorite (wt%)	9.1	n.g.	12.4	n.g.	14.8	n.g.
Glauconite (vol%)	36	n.g.	37.7	n.g.	35.7	n.g.

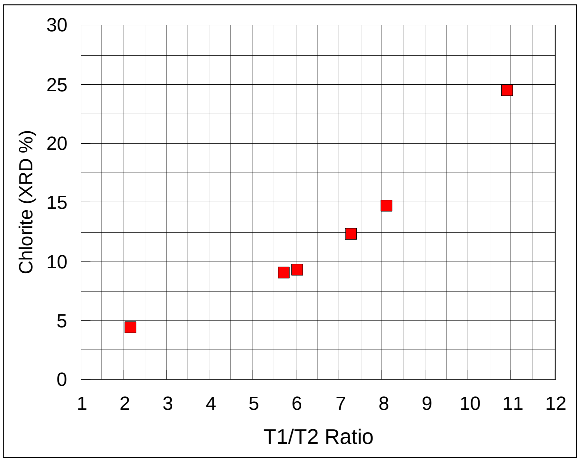

Figure 1. Chlorite content (XRD wt%) versus T1/T2 ratio

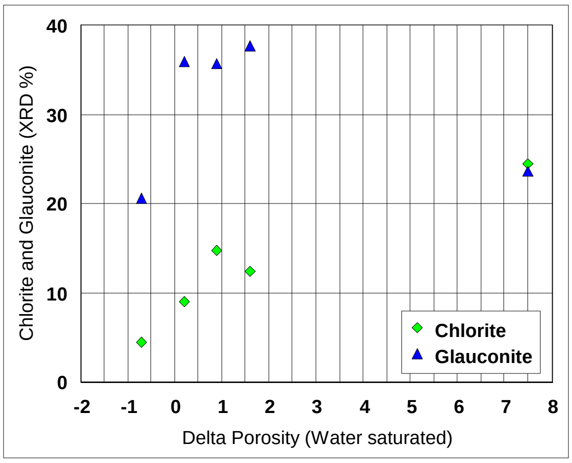

Figure 2. Chlorite and glauconite contents versus the difference between He- and NMR porosity (water).

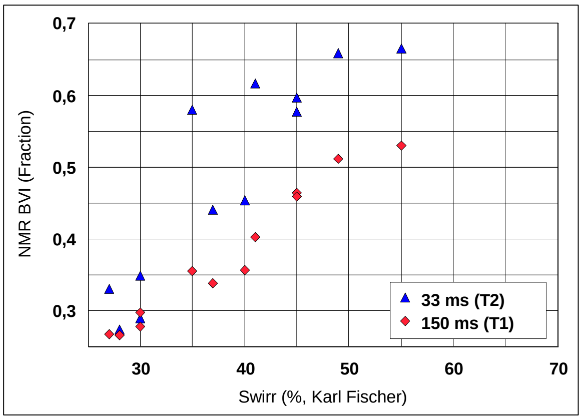

Figure 3. NMR BVI values from T1 and T2 versus irreducibel water saturation (Swirr).

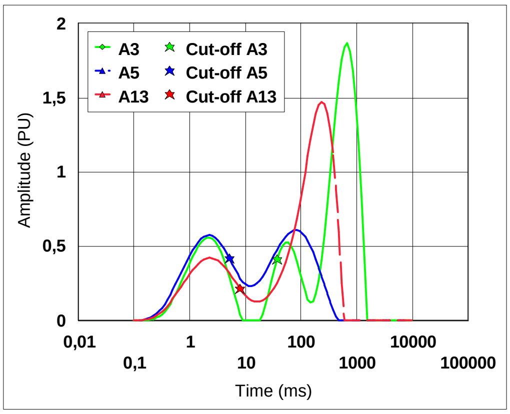

Figure 4. NMR T2 spectra for three Well-A core plugs. Swirr values are marked on the curves.

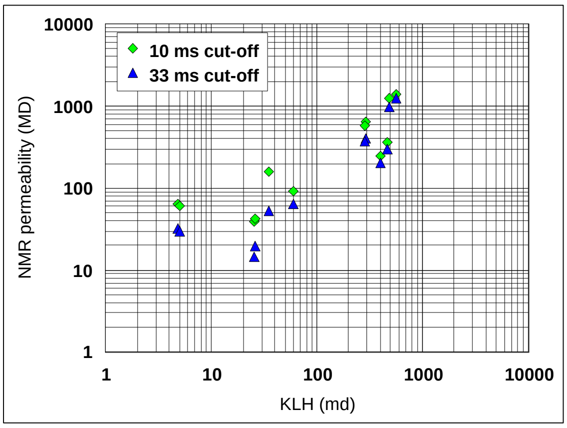

Figure 5. NMR permeability estimates using 10 and 33 ms cut-off value for BVI versus measured permeability.