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Improving Estimation of NMR Log $T_{2cutoff}$ Value with Core NMR and Capillary Pressure Measurements

Songhua Chen, Gary Ostroff, and Daniel T. Georgi
Western Atlas Logging Service, Houston, Texas, USA

Abstract

Accurate determination of $T_{2cutoff}$ values is a vital step for the estimation of bulk volume irreducible water and permeability from NMR logs. The generalized $T_{2cutoff}$ values used for clastics (33 ms) and carbonates (90 ms) are frequently found to be unrealistic for log interpretation, due to mineralogy-dependent surface relaxivity effects which shift the T_2 spectra. Thus, it is often desirable to calibrate $T_{2cutoff}$ values with core NMR measurements.

We assessed the various differences between the NMR log and core data and their effects on the $T_{2cutoff}$ estimation. The signal-to-noise level and the regularization strength can affect T_2 spectral resolvability and, consequently, the estimates of $T_{2cutoff}$ values. In addition, differences in the echo time and number of echoes, N, can not be ignored. Thus, it is necessary to first account for these effects before we can derive core NMR-based $T_{2cutoff}$ values applicable to NMR log data. This is particularly important for log data acquired in low-porosity and high-noise environment reservoirs.

Two methods are developed to address this problem. The first method adds random noise to the core echo data to render the *SNR* comparable to that of the log data. Then, the $T_{2cutoff}$ is derived from these "noisy log-like" core data. The procedure is repeated with several noise realizations to reduce the "randomness" of the added noise. The second method involves using *BVI* values determined from capillary pressure measurements to calibrate NMR $T_{2cutoff}$ values. In this method, calculated from NMR log data, the $T_{2cutoff}$ value is chosen such that the cumulative porosity matches the core capillary-pressure-based *BVI*. This procedure is performed for NMR log data after careful core to log depth-matching. The advantage of the first approach is that there is no need to depth match core samples to log data. The advantage of the second approach is that the $T_{2cutoff}$ is calibrated from capillary pressure data, which conceptually is closely related to *BVI* and there is no need to match the *SNR* of the core and NMR log data. The application of either technique for calibrating the $T_{2cutoff}$ improves both *BVI* and permeability estimation.

Introduction

The standard approach of applying a cutoff T_2 value to partition the T_2 spectra has been routinely used for estimating bulk volume irreducible (*BVI*) water and movable fluids (*BVM*) from an NMR T_2 distribution. This approach is based on the assumption that irreducible water saturates the pores with T_2 less than a threshold relaxation time, $T_{2cutoff}$, whereas the fluids in pores with $T_2 > T_{2cutoff}$ are movable. The accuracy of the $T_{2cutoff}$ value not only plays a vital role in the estimation of *BVI* and *BVM* ($f_{eff} - BVI$), but it also affects the estimation of permeability with the Coates model (Coates et al, 1991),

$$k = \left(\frac{f_{eff}}{C}\right)^m \left(\frac{f_{eff} - BVI}{BVI}\right)^n . \tag{1}$$

In the fast diffusion limit, T_2 is given by (Brownstein and Tarr, 1979)

$$\frac{1}{T_2} = \frac{1}{T_{2B}} + r\,\frac{S_{pore}}{V_{pore}} \approx r\,\frac{S_{pore}}{V_{pore}} . \tag{2}$$

In this limit, T_2 is affected by two factors: (1) the surface relaxivity r and the characteristic pore body size $r_{pore} = V_{pore} / S_{pore}$, and (2) the bulk relaxation time T_{2B} which is much longer than the surface fluid relaxation time. Thus the effect of the first term in Eq. (2) is negligible and hence, $T_2 \approx r_{pore} / r$. If one further assumes that a linear correlation exists between the size of pore body (r_{pore}) and pore throat aperture, one can directly establish

$$r_{throat} = r_{pore} / \Gamma \approx T_2 \cdot r / \Gamma . \tag{3}$$

Thus, the $T_{2\mathrm{cutoff}}$ is proportional to a threshold pore throat aperture,

$$T_{2\mathrm{cutoff}} = r_{threshold} \cdot \Gamma / r . \tag{4}$$

The relaxivity, r, and the pore body-throat factor Γ, are the scaling variables responsible for the variation of $T_{2\mathrm{cutoff}}$ value controlled by mineralogy and pore geometry. Because of the large variations in surface properties (r) among different formation rocks and pore geometries (Γ), the well-known industrial standards of $T_{2\mathrm{cutoff}}$ values (33 ms for sandstone and 92 ms for carbonates) are not always applicable (Chen et al, 1998; Bunain et al, 1998; Coates et al, 1998; Zhang et al, 1998). Therefore, core NMR measurements are often desired to calibrate formation-specific $T_{2\mathrm{cutoff}}$ values.

Although both NMR core and log data may be acquired with the same pulse sequence, the two measurements usually yield data with significant differences in the signal-to-noise ratio (*SNR*). It has often been overlooked that possible mismatches may occur between T_2 distributions derived from log and from core NMR data as the result of the different *SNR* in the data and the regularization used in inverting NMR echo trains. The differences between the T_2 distributions are most evident when the spectra contain abundant short T_2 porosities. The differences can affect the computation of *BVI*. In this paper, we present a method that address the noise-level discrepancy between core and log NMR data, and we describe methods to generate $T_{2\mathrm{cutoff}}$ values from either core NMR data or capillary pressure data that are more suitable for log interpretations.

Review of method of NMR core $T_{2\mathrm{cutoff}}$ estimation

Typical core NMR studies usually include two measurements corresponding to 100% brine saturated and core plugs desaturated to an irreducible water saturation (S_{wir}). The echo trains of the two measurements are inverted to obtain two T_2 spectra, respectively. Then, the cumulative porosity corresponding to the fully-saturated state,

$$\phi_{eff} = \int_{T_{2\min}}^{T_{2\max}} P_{S_w=1}(T_2)\,dT_2 \,, \tag{5}$$

where $P_{S_w=1}$ is the T_2 distribution corresponding to the fully-saturated state, and that corresponding to the desaturated state,

$$BVI = \int_{T_{2\min}}^{T_{2\max}} P_{S_w=S_{wir}}(T_2)\,dT_2 \,, \tag{6}$$

where $P_{S_w=S_{wir}}$ is the T_2 distribution corresponding to the desaturated state, are calculated. The $T_{2\text{cutoff}}$ value is determined to be the time which satisfies

$$\int_{T_{2\min}}^{T_{2\text{cutoff}}} P_{S_w=1}(T_2)\,dT_2 \equiv BVI \,. \tag{7}$$

Although it is commonplace for BVI values used in Eq. (7) to be determined from core NMR data, it is also valid to estimate BVI from other techniques such as the capillary pressure measurements. The latter approach is particularly useful when the core NMR data are not available; in which case $T_{2\text{cutoff}}$ may be derived directly from the NMR log data T_2 distributions and depth-matched core BVI. From Eq. (7), it is clear that errors occurring in BVI and $P_{S_w=1}$ could lead to the uncertainty of $T_{2\text{cutoff}}$ value in a nonlinear manner.

The process for determining the $T_{2\text{cutoff}}$ value from core NMR data is illustrated in Fig. 1. Plots (A) and (B) show the incremental and cumulative T_2 distributions for 100% brine saturation (S_w = 1) and at irreducible brine saturation, respectively. The $T_{2\text{cutoff}}$ is determined from the cumulative porosity distributions, where the maximum cumulative porosity (BVI) from $S_w = S_{wir}$ intercepts the cumulative porosity curve from $S_w = 1$.

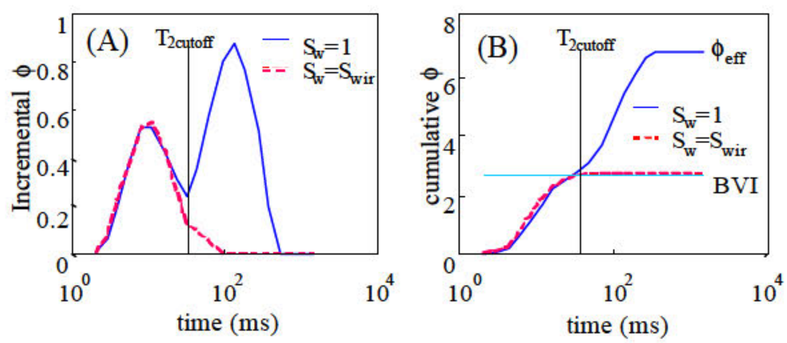

Fig. 1. Illustration of $T_{2\text{cutoff}}$ estimation process with NMR core measurements. (A) is the incremental distribution and (B) is the cumulative distribution.

Effects of Noise, Regularization, and TE on Spectral Resolvability

The validity of the method described in the last section depends on the reliability of the T_2 spectra. Thus, it is important to shed some light on the sources of error that could affect T_2 distribution and the BVI estimation. NMR echo data, acquired in time domain, consist of N echo amplitudes recorded in a discrete series with time increment of TE for a total sampling time $T = N \cdot TE$. The capability of resolving the T_2 spectra with the echo data depends on the *SNR* and the sampling period. We define an effective dynamic time range, $DT(T_2)$, as the time interval within which a T_2 component decays from its full strength to the noise level. In general, $\Delta T(T_2)$ can be considered to extend up to $3T_2$ when the noise level is low. $\Delta T(T_2)$ is reduced to less than $3T_2$ when the noise level is larger than the signal strength at $3T_2$. The faster a T_2 component decays, the smaller the number of echoes that are available to resolve this T_2 component. Although the number of echo N acquired in a measurement may be large (a long sampling time T), the useful sampling time does not exceed $DT(T_2)$ for any T_2 component. Thus, we further define the number of effective echoes, $N_E(T_2) = \Delta T(T_2)/TE$. These are the echoes that effectively carry information of the corresponding T_2 component. The T_2 spectral resolvability can then be expressed by

$$\text{Resolvability} \propto \frac{SNR\sqrt{\Delta T(T_2)}}{\sqrt{TE}} = SNR \cdot \sqrt{N_E(T_2)} \,. \tag{8}$$

This equation illustrates two important facts: (1) the lower the *SNR*, the poorer the resolution, and (2) the fast decay (short T_2) components have poorer resolution compared to slowly decaying components. The later part is caused by the decrease of $N_E(T_2)$ with the decrease of T_2. In addition, acquisition with a shorter *TE* yields higher spectral resolution for a given T_2 component and *SNR*.

SNR is the most significant difference between NMR logs and core measurements. In favorable logging environments, log data quality may approach laboratory data quality. However, log quality may be degraded for various reasons. Conductive drilling mud and formation fluids cause the loss of the rf energy. For low porosity and/or shallow gas wells, the received NMR signal weakens, because of the reduced number of protons within the sensitive volume in the formation. Although the random noise can be reduced by increasing the number of levels averaged, consideration of vertical resolution and logging speed often prohibit aggressive averaging, particularly for thin-bed formations. In contrast, core NMR data can be collected with high *SNR* by merely increasing the averaging.

Inversion of time-domain echo data to T_2 spectra is known to be an ill-conditioned problem. Regularization is often used to stabilize solution. However, regularization can smear out distinctive peaks in T_2 distributions, particularly when the porosities are overwhelmingly concentrated in the short T_2 bins. In such cases, the regularization broadens the otherwise sharp (and narrow) *BVI* distribution. Theoretically, the broadening does not shift the T_2 spectra; however, if the multiexponential T_2 fitting function is kept for the same range, the broadening can not spread to T_2 bins shorter than the minimum T_2 of the fitting model. Thus, the estimated T_2 distribution is forced to shift to the longer T_2 bins. This effect is illustrated in Fig. 2.

Although the algorithm and strength of regularization may vary for different inversion techniques, the induced spectral broadening effects are commonly observed (Chen and Georgi, 1997; Chunh, 1996). Figure 3 shows the T_2 spectra of core plug measurements estimated when three levels of computer-generated random noise were added to the measured echo data. The inversion algorithm used is the SVD method implemented in MAP-II (Prammer, 1996) program. The T_2 spectra of the two samples are characteristically different in that, Sample A has most of its pore volumes narrowly distributed in the short T_2 bins, while Sample B has broad T_2 distribution peaked at 100 ms. As expected from Eq. (8), sample A is more sensitive to the noise increase while the broad monomodal distribution of long T_2 bins in Sample B are less vulnerable to noise increase. From these examples, we see that $T_{2cutoff}$ estimates based on high *SNR* (laboratory quality) NMR data may *not* be applicable to log data if the latter has considerably higher noise levels than the corresponding core data.

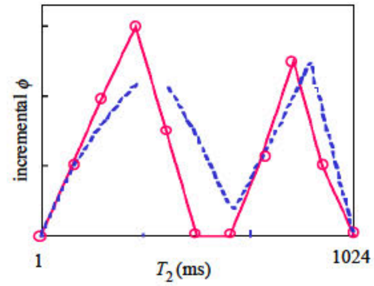

Fig. 2. Illustration of noise broadening effect on T_2 distribution. O: Synthetic model, solid line: fitting result without adding noise to the synthetic echo train, dash line: fitting result with noise-added synthetic echo train

Laboratory core NMR instruments often can acquire several thousand echoes and use a smaller minimum *TE* than that used by logging tools. For the latter, the shortest *TE* is generally limited by the available peak power delivered to the sensitive volume, whereas the number of echoes acquired depends on both the power availability as well as the ability to dissipate the rf generated heat. Thus the typical number of echoes acquired by the MRIL[a] C tool is 300-800. The difference in the number of echoes and *TE* values could also affect $T_{2cutoff}$ determination. For clay-rich core plugs, for example, 0.6 ms and 1.2 ms *TE* measurements may yield somewhat different spectra, particularly in the short T_2 bins.

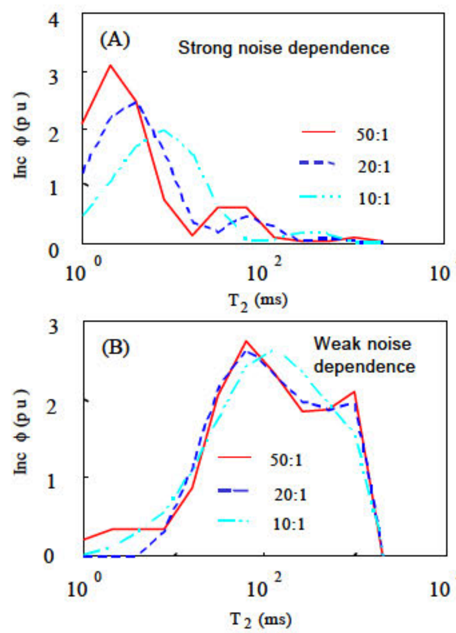

Fig. 3. Noise effect on two plug T_2 distributions. Weak noise dependence for T_2 distribution peaked at long T_2 and strong dependence for peaked at a very short T_2.

To illustrate the regularization and noise effect on the *BVI* determination, a set of synthetic log data, provided by Shell International Co. in the Hague, Netherlands, was used. Figure 4 plots the *BVI* values ($T_{2cutoff}$ = 33 ms) computed from T_2 distributions estimate with various *SNR* and regularization conditions. The solid line is the result based on low noise level

[a] MRIL is a registered trade mark of Numar Corp.

data; the dash lines are the results based on high noise level data with different strength of regularization being used. The estimate with high regularization is shown with the short-dash, light line and that based on using half of the regularization strength is shown with the long-dash line. We see that increase noised levels can result in noticeable difference in *BVI*. In particular, when the regularization is high, the underestimation is more obvious.

New procedure for $T_{2cutoff}$ estimation based on core NMR

Because $T_{2cutoff}$ is derived from T_2 spectra, the noise-induced T_2 spectrum uncertainty degrades the accuracy of $T_{2cutoff}$ estimates. Therefore, $T_{2cutoff}$ should be derived from echo trains that have similar *SNR* as well as *TE* and echo number *N*. Based on these considerations, we modified the core NMR analysis procedures as follows:

1. The core NMR measurement procedures are unchanged. That is, measurements are carried out with brine saturations at $S_w = 1$ and $S_w = S_{wir}$. *TE* of the experiments should be the same as that used in the log acquisitions.
2. Zero-mean Gaussian noise is added to the $S_w = 1$ echo data. T_2 spectra are obtained with and without adding the noise. The number of echoes used in the inversion is the same as that acquired by logging tools.
3. The analysis in step 2 is repeated with different noise realizations. Then the averaged spectra with different noise realizations are computed to reduce the effects of the random errors due to any particular noise realization. When regularization is adequately used in the inversion, we find that typically 3-4 realizations are sufficient.
4. Steps 2 and 3 are repeated with several noise strengths that are comparable to what is seen in the NMR log data.
5. Accurate *BVI* is obtained from the sum of the T_2 bin distribution estimated from the *original* $S_w = S_{wir}$ echo data without adding noise. Noise should not be added to these echoes to avoid the introduction of errors in the core *BVI* estimation.
6. For each level of noise strength, the corresponding $T_{2cutoff}$ value is estimated with Eq. (7), except that the distribution function used here is $P_{S_w=1}(SNR)$ which corresponds to specified *SNR*.

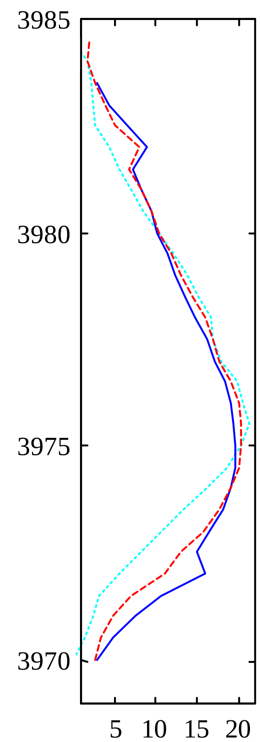

Fig. 4. Comparison of BVI estimates from low noise data (——), high-noise, high regularization (·········), and high-noise, ½ of the regularization (– – –).

Ordinarily, multiple core plugs are measured for calibrating $T_{2cutoff}$ values so that the sample variation is averaged out. In our procedures, the average $T_{2cutoff}$ is computed from the weighted or non-weighted sample-averaged echo train, $\bar{E}(k \cdot TE)$,

$$\overline{E}(k \cdot TE) = \sum_{j=1}^{N_S} W_j \cdot E_j(k \cdot TE) \Big/ \sum_{j=1}^{N_S} W_j \, , \tag{9}$$

where j and k are the sample and echo indices, respectively. The weights, W_j, could be chosen to reflect bed thickness ($W_j = H_j$), porosity ($W_j = f_j$), reserves ($W_j = H_j f_j$), producibility ($W_j = H_j k_j$) or reservoir quality ($W_j = H_j \cdot \sqrt{k_j / f_j}$). If core plug samples are taken from equal depth intervals, $W_j = 1$, $\overline{E}$ simply represents the formation average.

Figure 5 shows the $T_{2\text{cutoff}}$ values for 13 core samples analyzed with the new procedure. These samples were selected among several sets of NMR core plugs from clastic reservoirs in North and South America, and exhibit significant discrepancies in $T_{2\text{cutoff}}$ due to noise level differences. Five hundred echoes were used in the analysis. Our inversion method automatically adjusts regularization for *SNR*. The original core study (*SNR*>100, without adding noise) found that the $T_{2\text{cutoff}}$ values, on the average, are below 10 ms. By adding noise to render SNR = 10, the $T_{2\text{cutoff}}$ values noticeably increase. Note that the samples we show in Fig. 5 appear to all have their $T_{2\text{cutoff}}$ values shifted to larger values. We have also observed cases where the shifts occur in the opposite direction. However, in a study with a large number of core data samples and synthetic echoes, we observe that statistically the $T_{2\text{cutoff}}$ shift occurs more frequently to the right than to the left, which explains why some $T_{2\text{cutoff}}$ values derived from core-NMR do not give satisfactory interpretation of the corresponding logs. For the same set of data when *SNR* level is 20, the discrepancy of $T_{2\text{cutoff}}$ estimates was reduced greatly (see the right hand side plot of Fig. 5). For the MRIL tool, a typical low conductivity borehole environment results in 1 p.u. of noise. With 20-30 p.u. of porosity, the *SNR* should be sufficiently good to avoid the problem. However, for a high conductivity environment, the typical noise may be more than 2 p.u. This noise, when coupled with low formation porosity, could be a significant problem.

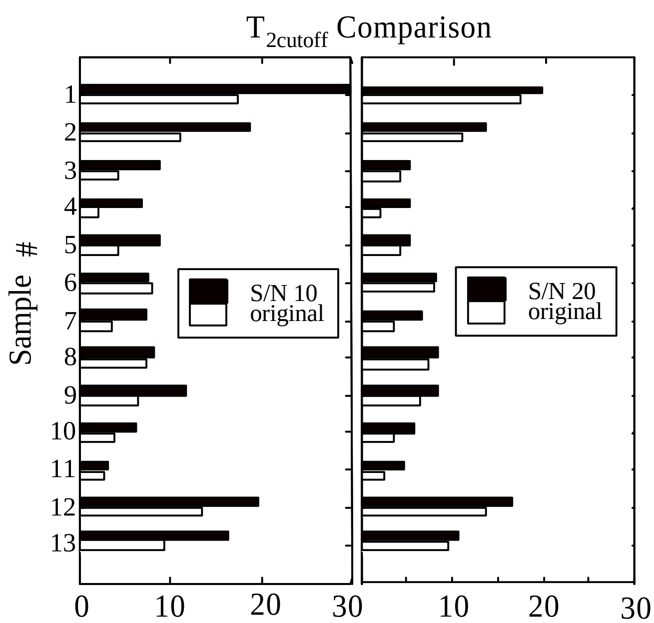

Fig. 5. Comparison of the core-based $T_{2\text{cutoff}}$ estimates from original core data and core data + noise (SNR=10 and 20).

Because the noise effect on the $T_{2\text{cutoff}}$ depends not only on the *SNR* but also on the structure of the T_2 spectra and the degree of regularization, the adjustment of the $T_{2\text{cutoff}}$

value is specific to each core data set and a simple generalized correction factor is not appropriate.

$T_{2cutoff}$ estimation based on core BVI and NMR Log data

The sole use of the $S_w = S_{wir}$ core NMR data is to obtain *BVI*. However, the *BVI* information can be obtained from other measurements: core capillary pressure (P_c) and porosity (f_{core}) data is a good alternative source:

$$BVI_{core} = S_{wir\ core} \cdot f_{core} . \tag{10}$$

If f_{core} is determined after humidity drying, BVI_{core} can be considered as $BVI_{effective}$. If oven drying is employed, BVI_{core} is BVI_{total} = $BVI_{effective}$ + Clay Bound Water (*CBW*). For NMR logs acquired with *TE* = 1.2 ms, $BVI_{effective}$ should be used in the calculation, since it is equivalent to the *BVI* determined from NMR log data.

Once *BVI* is determined, either from core P_c or core NMR measurements, it can be applied directly to the NMR log data, in the same way *BVI* was employed to determine the $T_{2cutoff}$ from the NMR core data of fully saturated cores, as described in the previous section. Figure 6 illustrates the method using *BVI* derived from P_c. By using this approach, one avoids the necessity of taking into account the effects of mismatch between the *SNR* of NMR log and cores. However, this approach does require careful depth matching between core and log data. P_c measurements are performed on core plugs of about 1 inch physical length while the vertical resolution of MRIL logging tool is more than 2 feet. Therefore, the application of core data to NMR log data is more valid when the cores are taken from homogeneous intervals, and is less valid for very thin-beds or irregularly vuggy samples.

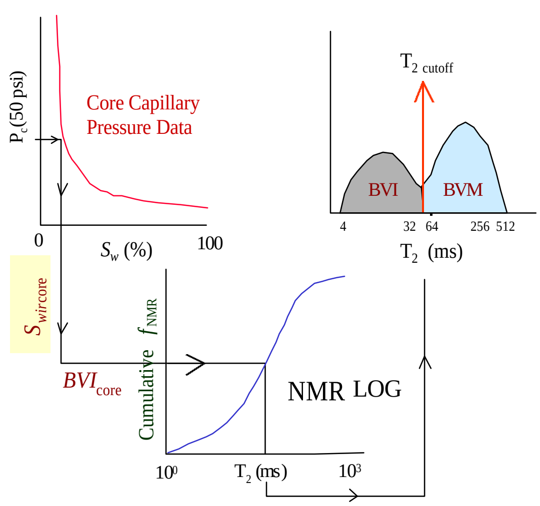

Fig. 6. Illustration of $T_{2cutoff}$ determination with core P_c data and NMR log T_2 distribution.

We applied this approach to calibrate $T_{2cutoff}$ for a clastic reservoir in the North Sea. Nine *BVI* values were determined from core plug capillary pressure measurements. This *BVI* data was then carefully depth matched to the NMR log data. $T_{2cutoff}$ values were determined at each of the nine sample levels as the time values where the cumulative NMR log porosity corresponded to the capillary pressure-derived *BVI* value. The geometric mean of the nine $T_{2cutoff}$ values was then computed to be 80 ms. An iterative approach was employed to solve for $T_{2cutoff}$. This involved determination of multiple *BVI* values from NMR log data over a range of assumed $T_{2cutoff}$ values, which were incremented from 33 ms to 150 ms. The cumulative absolute error between the nine depth-matched capillary pressure-derived *BVI* values (BVI_{core}) and the NMR log-derived *BVI* values (BVI_{MRIL}) computed at each of the incremental $T_{2cutoff}$ values was then computed as:

$$\varepsilon = \sum_{j=1}^{9} \left| BVI_{core} - BVI_{MRIL} \right| \quad (11)$$

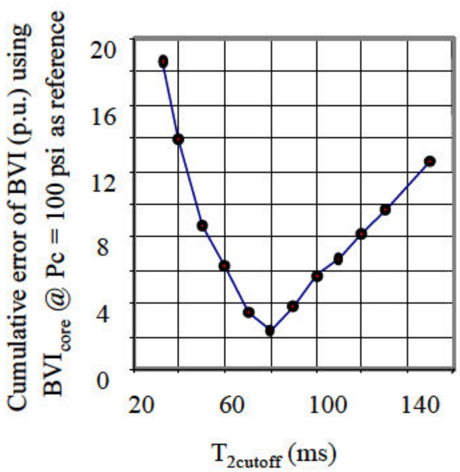

Fig. 7. $T_{2cutoff}$ vs cumulative error of *BVI*.

The optimal $T_{2cutoff}$ value of 80 ms was determined from the minimum ε, as shown in Fig. 7. The *BVI* cross plot of Fig 8 shows that the BVI_{MRIL} estimated using this $T_{2cutoff}$ value has an excellent 1:1 correlation to BVI_{core}, which justifies the use of a single $T_{2cutoff}$ for the interpretation of the entire log. This $T_{2cutoff}$ value was then used to process the NMR log data for the determination of *BVI* and *BVM*. Reservoir permeability was then computed using Eq. (1) with optimized model parameters (C = 10.91, m = 4, and n = 1.73) which were determined from regression analysis.

Figure 9 displays the core-calibrated log NMR data processing results with an overlay of core data for validation. The track to the far right in Fig 9 displays the NMR log porosity and the subdivision of the *BVI* and *BVM* components. All core data (ϕ, k, S_{wir}) are in good agreement with that derived from NMR log data.

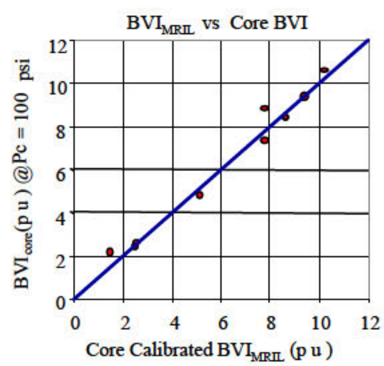

Fig. 8. *BVI* crossplot where NMR Log *BVI* is determined using $T_{2cutoff}$=80 ms, which is estimated from the plot shown in Fig. 7.

Discussion

1. Noise and inversion regularization of log T_2 spectra can contribute to the underestimation of NMR log-based *BVI* when core calibrated $T_{2cutoff}$ values are employed. Although errors in *BVI* estimation may have many sources, the indiscriminate use of $T_{2cutoff}$ values estimated from core data without noise calibration is one of these sources. The following steps can be used to identify whether re-calibration of the core-based $T_{2cutoff}$ is desired to account for noise effects.
    - Using the routine $T_{2cutoff}$ value from the core measurements, determine the log *BVI*. Calculate the average *BVI* for the entire log or individual zones which show similar T_2 distribution characteristics. We denote these average T_2-spectra based *BVI* as *BVIX* and the corresponding T_2 spectra as T_{2X}.

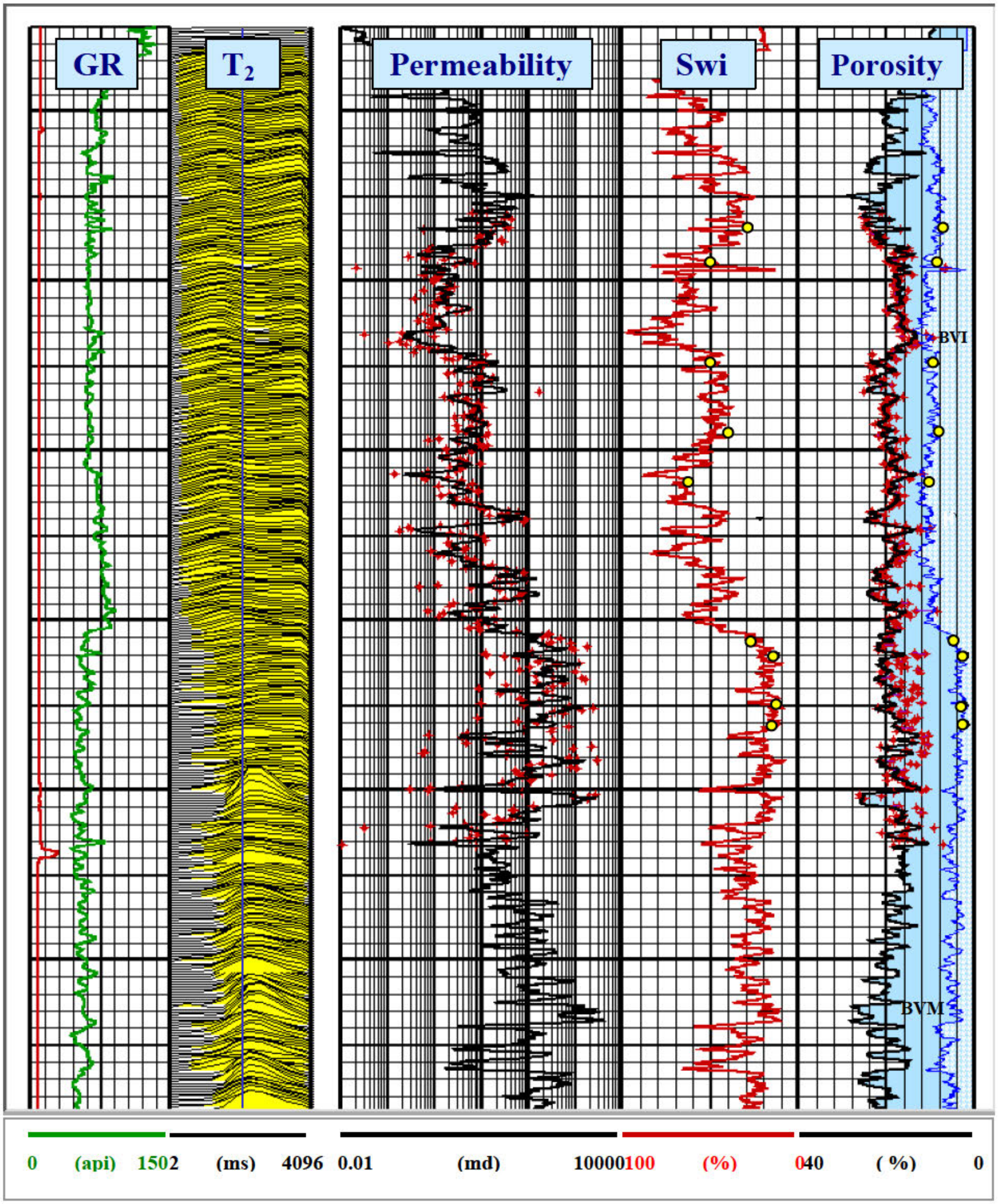

Fig. 9. Core and log data comparison. The discrete points on the figure are the core data. The porosity and BVI data are displayed on the far right track, The S_{wir} data are presented on the 2[nd] track from the right, and the permeability data are displayed on the 3[rd] track from the right. The BVI_{MRIL} data are estimated with $T_{2cutoff}$ = 80 ms, and the Coates permeability model employs the parameters m=4, n=1.73, and C=10.91, along with the core-calibrated BVI_{MRIL} as inputs.

- Next, average the echo trains *before* inversion. The averages are performed for the same intervals as defined in the last step. Then, calculate the average *BVI* of these intervals. These echo-averaging based *BVI* are denoted as *BVIY* and the T_2 spectra as T_{2Y}.
- For each zone where *BVIY* and *BVIX* are different, recalculate the $T_{2cutoff}$ value using the method described in this paper. Note that a fairly large interval for averaging may be required in order to improve *SNR* of log data to that of the core NMR data.

2. It should be noticed that high noise level in NMR log data can do more harm than affecting T_2 spectra accuracy. It may also increase the uncertainty in the effective porosity determination. Therefore, the best approach is to maximize the *SNR* in the data acquisition and enforce adequate requirements on the acceptable *SNR* range.

3. Heavy use of regularization may improve repeatability but does not guarantee the accuracy of the results. Large regularization can result in artificially broadened T_2 spectra and may require different $T_{2cutoff}$ values.

Conclusions

We have demonstrated that the core -based $T_{2cutoff}$ values should be estimated with comparable noise levels to that of NMR logs. We have developed two methods, which generate $T_{2cutoff}$ values more suitable for log interpretation. In the first method, random noise is added to the fully saturated core sample NMR echo data to render the signal-to-noise comparable to that of the logs before the estimation of T_2 spectra and $T_{2cutoff}$. In the second approach, *BVI* from core NMR or capillary pressure measurements is depth-matched to log T_2 spectra thus circumventing the problem of noise discrepancy between core and log data. Accurate *BVI* data is crucial for the estimation of permeability with the Coates equation.

References

Bunain, H. A., Latif, A. A., Altunbay M., and Georgi, D. T., 1998. “Derivation of variable T_2-partitioning coefficient when core NMR data are unavailable,” *GeoArabia Middle East Petroleum Geosciences*, **3**(1), pp. 76-77.

Brownstein, K. R. and Tarr, C. E., 1979. “Importance of classical diffusion in NMR studies of water in biological cells,” *Phys. Rev. A.*, **19**, pp. 2446-2453.

Chen, S., and Georgi, D. T., 1997. “Improving the accuracy of NMR relaxation distribution analysis in clay-rich reservoirs and core samples,” SCA paper 9702, *proceeding of 1997 SCA Symposium*, Calgory, Canada.

Chen, S., Roberto, A., Minetto, C., Georgi, D. T. and Liu, C., 1998. “Methods for estimating BVI and Swi from NMR logs,” paper HH, in *SPWLA 39th Annual Symposium Transactions*.

Chunh, T.-L., 1996. “Estimation of relaxation time distribution for NMR CPMG measurements,” M. S. Thesis, Rice University.

Coates, G. R., Marschall, D., Mardon, D., Galford, J., 1998. “A new characterization of bulk-volume irreducible using magnetic resonance,” *The Log Analysts*, **39**, pp. 51-63.

Coates, G.R., Miller, M., Gillen, M., Henderson, G., 1991. “An investigation of a new magnetic resonance imaging log.,” presented at *SPWLA conference in Midland*, Texas.

Prammer, M.G.: *Efficient Processing of NMR Echo Trains*, US Patent 5,517,115, 1996.

Whittall, K.P., Bronskill, M., and Henjelman, R.M., 1991. “Investigation of analysis techniques for complicated NMR relaxation data,” *J. Magn. Reson*., **95**, pp. 221-234.

Zhang, Q., Lo, S.-W., Huang, C. C., Hirasaki, G. J., Kobayashi, R., and House, W. V., 1998. “Some exceptions to default NMR rock and fluid properties, paper FF,” in *39th SPWLA Annual Symposium transactions*.

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