

INTERNAL FIELD GRADIENTS IN POROUS MEDIA

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Abstract

A requirement for certain cases in NMR well logging is the evaluation of the effect of internal field gradients on nuclear magnetic resonance (NMR) spin-spin relaxation (T_2). Systematic methods are developed to calculate the induced magnetic fields and gradients for three types of porous media: spheres, cylinders, and rectangular flakes. Strong internal field gradients were observed on North Burbank (N. B.) sandstones and chlorite/fluid slurries. The experimental observations are compared with calculations.

For pores lined with clay flakes, field gradients are concentrated around the sharp corners of the clay flakes regardless of their orientations. The radius of curvature of an object determines the maximum value of the field gradients. Pores lined with clay flakes have the dimensional gradient scaled to the width of the clay flake, whereas for cylinder or sphere systems the dimensional gradient is scaled to the cylinder or sphere radius. Consequently, thin chlorite clay flakes will have much stronger gradients than larger spherical siderite particles.

Both N. B. sandstone and chlorite slurry are simulated as a square pore lined with rectangular chlorite clay flakes with the fraction of micropores matching that of real systems. The field gradients in the micropores of N. B. sandstone and chlorite slurry are similar. The mean gradient value of the macropore in the chlorite slurry is much higher

than in the N. B. sandstone. Both N. B. sandstone and chlorite slurry have much higher gradients than the field gradients generated by the permanent magnet of logging tools.

T_1 and T_2 measurements at different echo spacings were performed on N. B. sandstones at various saturation conditions. Gradient values for the whole pore, micropore, and macropore are determined from the slope of the first several data points on the plot of $1/T_2$ vs. τ^2 . Gradient values from simulations using a 0.2- μm clay width were found to be close to the experiment results for the whole pore and micropore. For macropores, the simulation results match the mean value of the experiments while individual experiments have a larger variation. For chlorite/fluid slurries, the simulation results with a 0.2- μm clay width match well with the mean gradient value of the experiments.

Introduction

A chlorite-coated sandstone, North Burbank, showed significant departures from the default assumptions about the sandstone response in the interpretation of NMR logs (Zhang et al., 1998, 2001). These included a strong echo spacing dependent shortening of NMR T_2 relaxation time distributions, large T_1/T_2 ratio, and small T_2 cutoff for S_{wir} . These departures are due to spins diffusing in the strong internal field gradients induced by the pore lining chlorite flakes that have a much higher magnetic susceptibility than the surrounding pore fluids. Also, much stronger internal field gradients were observed in the chlorite/fluid slurries than the kaolinite/fluid slurries (Zhang et al., 2001). Development of systematic methods to determine the magnetic fields and gradient distributions for

complex porous media is essential to evaluate this diffusion effect in formation evaluation.

The historical development of internal field gradient models is reviewed in the Appendix. The geometric models were usually spherical or cylindrical. These models illustrate the relation between the particle dimensions and the gradient magnitude. Chlorite clay flakes are better described as rectangular objects with a magnetic susceptibility different from that of the surrounding fluid. The induced magnetic field gradient is infinite at the corners of the rectangular objects. Thus, the dominant geometric parameter in chlorite containing systems is the proximity of the fluid in the pore space to the corners.

Recently, other investigators have measured internal gradients of reservoir rocks (Hurlimann, 1998; Appel et al., 1999; Appel et al., 2000; Shafer et al., 1999; Dunn et al., 2001; Sun and Dunn 2002). Hurlimann (1998) estimated a distribution of internal gradients for C9 and Berea sandstones. Both have significant gradients greater than 100 gauss/cm. Shafer et al. (1999) estimated the internal gradients of iron and clay-rich Vicksburg sandstone by using the bulk fluid diffusivity and the shortest two echo spacings. The internal gradients ranged from 25 to 100 gauss/cm. Appel et al. (1999, 2000) assumed that the diffusivity would change from that for free diffusion to restricted diffusion with increasing diffusion time. Their estimated internal gradients ranged from 38 to 110 gauss/cm when measured with a 2 MHz NMR spectrometer and 12 to 28 gauss/cm when measured with a 1 MHz spectrometer, demonstrating the dependence of the internal gradient on the applied magnetic field. Dunn et al. (2001) assumed that all pores have the same internal field gradient distribution. Their internal gradient

distributions had a mode that ranged from 20 to 100 gauss/cm. The tails of distribution were sometimes as large as 1,000 gauss/cm. Sun and Dunn (2002) used a two dimensional representation to display the relaxation time and internal gradient joint distribution of rocks. They show significant internal gradients that are greater than 100 gauss/cm.

A new method of pore structure characterization called magnetization decay due to diffusion in the internal field (DDIF) has been introduced to take advantage of the internal gradients (Chen and Song, 1999, Song, 2001, 2002).

For fluid in a porous medium, the total spin-lattice relaxation rate, $\frac{1}{T_{1t}}$, is the sum of two terms:

$$\frac{1}{T_{1t}} = \frac{1}{T_{1B}} + \frac{1}{T_{1S}}$$

where T_{1B} is the T_1 relaxation time of bulk fluid. T_{1S} is the surface relaxation time.

Like the T_1 relaxation rate, the T_2 relaxation rate also has contributions from bulk relaxation and surface relaxation. However, it has an additional term due to the effect of spin diffusion in magnetic field inhomogeneity. This diffusion term is expressed as

$$\frac{1}{T_{2D}} = \frac{1}{3}(\tau\gamma G)^2 D$$

where τ is half echo spacing; γ , the gyromagnetic ratio; G , the magnetic field gradient, either internally induced or externally applied; and D , the molecular self diffusion coefficient of the fluid. This equation applies to the simple case of a uniform gradient, G ,

and unbounded diffusion, i.e., where pore walls do not restrict molecular diffusion (Kleinberg and Horsfield, 1990).

Therefore, the observed T_2 relaxation rate is expressed as the summation of three mechanisms:

$$\frac{1}{T_{2t}} = \frac{1}{T_{2B}} + \frac{1}{T_{2S}} + \frac{1}{3}(\gamma G)^2 D$$

where T_{2B} is the T_2 relaxation time of bulk fluid, and T_{2S} is the surface relaxation time.

In this paper, we will first develop the theory and calculate the magnetic fields and gradient distributions for three types of porous media: array of cylinders, array of spheres, and a square pore lined with clay flakes. Then, we will simulate the pore space of chlorite coated North Burbank sandstone and chlorite/fluid slurry. Finally, we will compare the simulation results with experiment results.

Comparison of three types of porous media

Theory: Porous media are usually modeled as an array of cylindrical or spherical particles. For an infinitely long cylinder or a sphere put in a homogeneous magnetic field (Figure 1a), a magnetic dipole theory can be used to model the fields induced by these objects. In the case of the cylinder, the induced fields can be viewed as those generated by two lines of current along the center of the cylinder, one flowing out and one in, with a distance, l , apart. For the sphere, the induced fields arise as if from a ring of current at the center of the sphere (Figure 1b).

Additionally, a rectangular clay flake is modeled. For such a system, the clay/fluid interfaces are either parallel or perpendicular to the homogeneous magnetic

field $\vec{B}_0$ (Figure 2a). Interfaces with other orientations can be decomposed into steps parallel and perpendicular to the applied field. The potential theory is developed as follows.

Start with Maxwell's equations for a static field in a non-conducting medium:

$$\nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{H} = 0$$

and the nonferromagnetic condition:

$$\vec{B} = \mu_0(1 + \chi)\vec{H}$$

where $\vec{B}$ is the magnetic flux density; $\vec{H}$, the magnetic field intensity; χ , the magnetic volume susceptibility; and μ_0 , the permeability of free space, $4\pi \times 10^{-7}$ Wb/(A*m).

Because $\nabla \cdot \vec{B} = 0$, we can introduce a vector potential $\vec{A}$, such that $\vec{B} = \nabla \times \vec{A}$.

With a series of steps and neglecting terms of $O(\chi^2)$, the following scalar partial differential equation is derived:

$$\frac{\partial^2 A_\delta}{\partial y^2} + \frac{\partial^2 A_\delta}{\partial z^2} = -B_0 \frac{\partial \chi}{\partial y} \quad (1)$$

where A_δ is the vector potential deviating from that of the homogeneous, applied magnetic field, $\vec{B}_0$. Equation (1) is derived with the assumption that $\vec{B}_0$ is parallel to the z-axis and there is no dependence on the x-coordinate, i.e., the system is 2-D. Also, it is assumed that the RF (radio-frequency) field applied in NMR measurements is small compared to the static field, $\vec{B}_0$.

Equation (1) states that A_δ satisfies the Laplace equation everywhere except at the places where there is a change of χ over y . These places are the clay/fluid interfaces parallel to $\vec{B}_0$.

The right-hand side of Equation (1) is a singularity at the interface parallel to $\vec{B}_0$. However, the singularity is integratable to $-B_0\Delta\chi$, where $\Delta\chi = \chi_{clay} - \chi_{fluid}$. Therefore, Equation (1) can be rewritten as

$$\frac{\partial^2 A_\delta}{\partial y^2} + \frac{\partial^2 A_\delta}{\partial z^2} = \begin{cases} \mp B_0\Delta\chi\delta(y-y_0) & z \in C_{||} \\ 0 & z \notin C_{||} \end{cases} \quad (2)$$

where y_0 is the y coordinate of the parallel interface. The '-' sign is for the left parallel interface of the clay flake, whereas the '+' sign is for the right parallel interface.

Because the 2-D Green's function, $G(y, z, y_0, z_0)$, satisfies the Laplace equation everywhere except at the singularity points, (y_0, z_0) , Green's function will give a solution to Equation (2). For a single singularity point along the interface (in the analog of magnetostatics, it corresponds to a line of current with an infinite length in the x direction.), the solution is

$$A_\delta^{line} = \frac{-B_0\Delta\chi}{4\pi} \ln[(y-y_0)^2 + (z-z_0)^2] \quad (3)$$

Then, for the interface parallel to $\vec{B}_0$ (viewed as a sheet of currents in magnetostatics, as shown in Figure 2b), the solution will be the integration of Equation (3):

$$\begin{aligned}
A_{\delta}^{sheet} = & (z_{0u} - z) \log[(y - y_0)^2 + (z - z_{0u})^2] \\
& - 2z_{0u} + 2|y - y_0| \tan^{-1} \left(\frac{z_{0u} - z}{|y - y_0|} \right) \\
& - (z_{0l} - z) \log[(y - y_0)^2 + (z - z_{0l})^2] \\
& + 2z_{0l} - 2|y - y_0| \tan^{-1} \left(\frac{z_{0l} - z}{|y - y_0|} \right)
\end{aligned} \tag{4}$$

where z_{0l} and z_{0u} are the z coordinates of the lower and upper ends of the parallel interface, respectively. A_{δ} is then just the summation of A_{δ}^{sheet} over all parallel interfaces.

Knowing A_{δ} , the magnetic field gradient can be solved analytically. The gradient, $\vec{\vec{G}} = \nabla \vec{B}$, is a second order tensor. We define the magnitude of the gradient, $|\vec{\vec{G}}|$, as the square root of the absolute value of the only non-zero invariant of this tensor (Aris, 1989), i.e.,

$$|\vec{\vec{G}}| = \sqrt{G_{yz}^2 + G_{zz}^2} \tag{5}$$

where $G_{yz} = -\frac{\partial^2 A_{\delta}}{\partial y^2}$ and $G_{zz} = -\frac{\partial^2 A_{\delta}}{\partial y \partial z}$. It can be proved that $|\vec{\vec{G}}| = |\nabla \vec{B}|$. The magnitude of the gradient is made dimensionless with respect to the characteristic length, strength of the homogeneous magnetic field, B_0 , and magnetic volume susceptibility.

Results and Discussions: Contour lines of the dimensionless gradients of the induced fields for a single cylinder, sphere, and clay flake are shown in Figure 3. For the sphere system, the vertical plane through the center of the sphere is displayed. The values of the contour lines differ by a factor of 2. The field gradients are higher near the surface of the sphere than those near the surface of the cylinder. However, for a clay flake, overall, the induced field has higher gradients. Most importantly, much higher gradients are around

the corners of the clay flake. The gradient at the corner will approach infinity as the resolution of the calculation grid is refined. Therefore, the radius of curvature of the particle determines the maximum value of gradients.

With superposition, an infinite cubic array of cylinders or spheres can be modeled. With 36 cylinders or 64 spheres, the resultant fields can well represent those of an infinite array. Contour lines of the dimensionless gradients are drawn for the central pore space of a cubic array of 36 cylinders and for the vertical plane passing the centers of spheres at the innermost of a cubic array of 64 spheres (Figure 4 a, b). Similarly, by superposition of Green's function, field gradients can be determined for a square pore lined with clay flakes. We modeled a system with two distinct pore sizes. One is the small pores in between clay flakes, referred to as micropores, the other is the central big pore, referred to as a macropore. It can be observed from Figure 4c that strong gradients are concentrated around the tips of clay flakes no matter the orientations of these clay flakes. Table 1 lists the mean, standard deviation, minimum, and maximum values of the gradients. For the sphere system, the values are for the whole central pore volume. It can be concluded that the infinite cubic array of spheres has higher gradient values than the infinite cubic array of cylinders. Even though the mean value of the gradients of the clay flake system is similar to that of the cylinder and sphere systems, the standard deviation is much higher because gradients are infinite at the corners of the clay flakes.

Normalized cumulative distributions of dimensionless gradients are shown for an infinite cubic array of cylinders or spheres with different porosities (by varying the distance between the centers of the particles), or a square pore lined with clay flakes with different fractions of micropores (by varying the number of clay flakes on each side of

the pore) in Figure 5. Two dotted horizontal lines mark the median value and the gradient when it reaches the 95 percentile. The median value of the gradient is similar in all three systems. However, comparing the gradient values at the 95% line clearly indicates that values double from the cylinder system to the sphere system and then again double to the clay flake system. The significant point is that a small fraction of the clay flake system has gradients much larger than the maximum gradients in the cylinder or sphere system while all three systems have similar median gradients. Thus, a clay flake system cannot be described by an average gradient value but will have different values of gradients near the clay flakes (micropore) compared to the large pores (macropore).

The following three equations convert the dimensionless gradient to the dimensional gradient for the cylinder, sphere, and clay flake system, respectively:

$$\left| \bar{\bar{G}} \right| = \frac{k-1}{k+1} \frac{B_0}{a} \left| \bar{\bar{G}}^* \right| \quad \text{for cylinder system}$$

$$\left| \bar{\bar{G}} \right| = \frac{k-1}{k+2} \frac{B_0}{a} \left| \bar{\bar{G}}^* \right| \quad \text{for sphere system}$$

$$\left| \bar{\bar{G}} \right| = \frac{\Delta\chi}{4\pi} \frac{B_0}{w} \left| \bar{\bar{G}}^* \right| \quad \text{for clay flake system}$$

where $k = \frac{1 + \chi_{particle}}{1 + \chi_{fluid}}$, a is the radius of the cylinder or sphere, and w is the width of the

clay flake. For the cylinder and sphere systems, $\frac{k-1}{k+1}$ and $\frac{k-1}{k+2}$ are all in the order of $\Delta\chi$.

The dimensional gradients are scaled to the radius of the cylinder or sphere, whereas for the clay flake system they are scaled to the width of the clay flake. This is very important because for the clay flake system, like pointedly shaped chlorite clays, the width is in the order of 0.1 μm . For a spherical system like siderite crystals, their dimensions are in the order of 10 μm . So even though there is a factor of three between the χ values of siderite and chlorite, the difference due to dimensions is 100 times. Therefore, thin chlorite clay flakes will have much stronger gradients than larger spherical siderite particles. Also, chlorite pervasively coats quartz grains while siderite crystals are usually isolated.

Magnetic field simulation for N. B. sandstone and chlorite slurry

The magnetic fields of N. B. sandstone and chlorite slurry are simulated using the model of a square pore lined with clay flakes. First, we need to determine the typical shape and spacing of the chlorite clay flakes. Based on the photomicrograph shown in Figure 6, we set the height of the clay flake as seven times the width and the fluid gap between two clay flakes as the clay width.

The size of the macropore relative to the micropore is modeled by the number of clay flakes on each side of the square pore. Figure 7 illustrates the models used for the N. B. sandstone and the chlorite slurry. The S_{wir} of 0.32 for N. B. sandstone was modeled with 15 clay flakes on each side of the square pore. The chlorite slurry was modeled as a small macropore with only 3 clay flakes on each side of the square pore. This resulted in a microporosity that is 69% of the total porosity. In the calculations, we will not consider the four corners.

The contour lines of dimensionless gradients for the whole pore of the N. B. sandstone and chlorite slurry are shown in Figure 7. The values of the contour lines differ by a factor of 2. For both systems, high gradients occur around the clay tips. Lower gradients are in the middle portion of the micropores and macropore. Contour lines of very weak gradients are closed and appear in between the clay flakes near the tips. These arise from the symmetry in the calculation. We are cautious not to let them mislead us as high gradients, which are actually at the corners.

Figure 8 shows the contour lines of dimensionless gradients for the micropores of N. B. sandstone and chlorite slurry. By observing the positions of the two contour lines, 20.5 and 0.32, and comparing the maximum, mean, and standard deviation values, we can conclude that the gradient distributions are similar in these two systems.

Figure 9 shows the contour lines of dimensionless gradients for the macropores of N. B. sandstone and chlorite slurry. Due to the relatively large fraction of the macropore (0.68) in the N. B. sandstone, a large portion of the macropore has relatively small gradients compared to the regions near the clay tips. For the chlorite slurry, however, the decay from high gradients to low gradients spans the macropore. Therefore, although very similar maximum values are achieved at the corners of the clay flakes for both systems, the mean value for chlorite slurry is much higher than that of N. B. sandstone, and the standard deviation is about twice as high. Dimensional gradient values in gauss/cm units can be easily determined from dimensionless values through the width of clay flakes. Using a clay width of $0.2\ \mu\text{m}$, the contour line of 0.01 is approximately 2 gauss/cm and the 0.16 contour line is roughly 32 gauss/cm, close to the applied field

gradients of logging tools. So, the magnetic field in the macropore of N. B. sandstone is not homogeneous, and gradients in the macropore still have considerable strength.

Comparison of simulations with experiments

For a square pore lined with chlorite clay flakes, dimensionless gradients for the whole pore, micropores, and macropores are plotted as a function of the fraction of micropores in Figure 10. The solid line is the mean value and the dashed line is mean plus standard deviation. As the fraction of micropores increases, the mean and standard deviation of dimensionless gradients remain almost unchanged for the micropores, while they increase substantially for the macropore. The effect on the whole pore is in between. The simulation of N. B. sandstone is at the left end of the curves with the fraction of micropores being 0.32 and the simulation of chlorite slurry is at the right end with the fraction of micropores being 0.69. The mean values of the dimensionless gradients for the whole pore, micropore and macropore of N. B. sandstone are shown in Figure 10. However, only the whole pore is considered for the chlorite slurry since the micropore and macropore cannot be experimentally distinguished with the chlorite slurry. For other porous systems, the dimensionless gradient values can be determined from these curves using a value of the fraction of micropores determined from S_{wir} . Table 2 lists the dimensional gradient values using a clay width of 0.2 μm . The gradient value for the whole pore of N. B. sandstone is in between the values for micropore and macropore, and they are all much higher than the applied field gradients of logging tools. The gradient in the whole pore of the chlorite slurry is about twice as high as that of N. B. sandstone. This is consistent with the experimental data.

NMR relaxation measurements were made on the N. B. sandstones at various saturation conditions with a 2 MHz MARAN spectrometer using a homogeneous magnetic field. T_1 was measured with the inversion recovery sequence and T_2 was measured with the CPMG sequence. T_1 and T_2 at 100% brine saturation are shown in Figure 11. The latter are measured with echo spacings from 0.2 ms to 2 ms. All distributions are bi-modal, with distinct peaks for brine responses in micropores and macropores. The mode of the distribution for the micropores does not become shorter for the three longest echo spacings because the measured data is truncated by the absence of data before the first echo. To quantify the shifting of the distributions, we used log mean values for the whole pore and mode values from the quadratic fitting for the micropores and macropores. $1/T_2$ vs. τ^2 are shown for the whole pore, micropore, and macropore in Figure 12. $1/T_1$ is marked by a solid square at zero echo spacing. On each plot, results of three samples are shown for comparison. For the micropores, $1/T_2$ decreases at larger echo spacings because more fast-relaxing components are lost before the acquisition of the first echo. However, for the whole pore, $1/T_2$ also decreases at larger echo spacings. And for the macropore, $1/T_2$ first increases, levels off, then increases again. If the gradient is constant and there is no effect of restricted diffusion, the data would be expected to fall along a straight line. The departure from a straight line is expected to result from a combination of a distribution of gradients and the restricted diffusion. The first 2 to 5 points are fitted to a straight line and the gradient is estimated from the slope.

Mean values of the dimensional gradients from simulations are compared with experiment results for the whole pore, micropores, and macropores of N. B. sandstones in Figure 13. The gray shaded bar represents simulation results. Four hashed bars show the

experiment results from the following conditions: 100% brine saturation, SMY crude oil with brine at S_{wir} before aging, after aging, and after forced imbibition of brine, respectively. Error bars show the standard deviation among three N. B. sandstone samples. For the whole pore, brine diffusivity is used to calculate the gradient from the slope for the 100% brine saturated condition. A diffusivity value that is an average between that of brine and SMY crude oil according to the saturation is used for the other three conditions. For the micropores, since they are always filled with brine, brine diffusivity is used for all four saturation conditions. The free diffusion value is appropriate for micropores only for a very short period before restricted diffusion reduces the value of the effective diffusivity. Thus, the free diffusion value of diffusivity was used only for the early time (short echo spacing) linear portion of the response to estimate the value of the internal gradient. For the macropores, brine diffusivity is used for the 100% brine saturated condition and after forced imbibition, while crude oil diffusivity is used for before aging and after aging conditions. It can be observed that the simulation results are close to the experiment results for the whole pore and micropore. For the macropore, the simulation results give a good approximation to the mean value of the experiment results, which show a larger variation among different saturation conditions.

T_1 and T_2 measurements at different echo spacings were performed on four chlorite/fluid slurries. Figure 14 shows the relaxation time distributions with hexane as the fluid. The bold solid curve is T_1 for bulk hexane and the regular solid curve is T_1 for chlorite/hexane slurry. The shift between these two distributions indicates a surface relaxation for hexane in the chlorite/hexane slurry. The dashed curve is T_2 at a 0.2-ms echo spacing and the dotted curve is T_2 at a 2-ms echo spacing. The T_2 values for the

hexane slurry are shorter than the T_1 value and dependent on echo spacings. Because all the relaxation times would have been the same without a field gradient, we conclude that there must be a significant internal field gradient. Mode values from quadratic fitting are used to quantify the distribution shift. Figure 15 plots $1/T_2$ vs. τ^2 for chlorite/brine, hexane, soltrol, and SMY crude oil slurries. Again, $1/T_1$ is shown as a solid square at zero echo spacing. The first 4 to 7 points are approximately linear. The data with longer echo spacings have decreasing slope, similar to that seen for N. B. sandstones in Figure 12. The decrease in slope for the longer echo spacings may be due to restricted diffusion and/or the gradient decreasing in larger pores. Thus, the gradient is estimated from the linear portion of the data.

The experimentally observed gradients are compared with the modeled gradient in Figure 16. The error bar for the experimental observations represents the range of values seen for the different fluids. The modeled gradient agrees with the experimental observations. They are in the range of 300–400 gauss/cm. These results for the chlorite slurries are similar to the value of the gradient observed in the micropores of N. B. sandstone, Figure 13. This is an order of magnitude larger than the gradient of well logging tools.

Implications for core analysis and well logging

Formations containing chlorite are usually suspected for internal gradients because chlorite usually contains iron in its crystal structure. The theoretical analysis presented here indicates that the internal gradient is a function of the difference in magnetic susceptibility between the minerals and the pore fluid and the proximity of the

pore fluids to sharp edges where the gradient is singular. Paramagnetic chlorite has a larger magnetic susceptibility than diamagnetic kaolinite (Zhang et al., 2001). However, if the formation has soluble iron minerals like pyrite and high surface area clays such as illite or smectite, the iron adsorbed on the surfaces of the clay may give the clay a large magnetic susceptibility. Also, if the clay has a high surface area and is pore-lining then the pore fluids may be in close proximity to the clay edges lining the pore walls and internal gradients may be important.

The results shown here for the N. B. sandstones are not typical for most sandstones. Therefore, if it is recognized that the formation of interest has pore lining chlorite or if T_2 is a function of echo spacings with a homogeneous applied magnetic field, special precautions must be taken. T_2 cut-off should be determined with the formation material rather than using the default 33 ms correlation for sandstones. Also, the internal gradients may be larger than the applied gradient of the logging tool. If the NMR logging plan includes diffusion type measurements, it may be necessary to interpret the logs with the greater of the applied or internal gradient. A method to estimate the magnitude of the internal gradient from core samples was described here. A possible means to estimate the degree of internal gradients by logging is to acquire T_1 logs at several depths and compare with the T_2 log at the same depth. The effective gradient could be estimated by calculating the gradient value required to match the log measured T_2 when the diffusion-free surface relaxation is given by the T_1 distribution (with appropriate correction for diffusion-free T_1/T_2 of approximately 1.6).

Conclusions

Magnetic dipole theory can be used to model cylindrical and spherical systems, while potential theory can be used to model more complex pore structures. For pores lined with clay flakes, the deviation of the vector potential from that of the homogeneous field satisfies the Laplace equation everywhere except along the clay/fluid interfaces parallel to the homogeneous magnetic field. Thus, this induced magnetic field can be solved analytically by means of the superposition of Green's function.

Dimensionless magnetic field gradients are higher in the sphere system than the cylinder system. For pores lined with clay flakes, field gradients are much higher at sharp corners (singularity points). Therefore, the radius of curvature of the object determines the maximum value of gradients.

Both N. B. sandstones and chlorite slurries are simulated by matching the fraction of micropores with that of real systems. The simulation results using a 0.2- μm clay width match well to the experiment results for both N. B. sandstones and chlorite slurries. The simulated and measured gradients of about 200 gauss/cm for the chlorite coated N. B. sandstone and about 400 gauss/cm for the chlorite slurry are much larger than the gradient of logging tools.

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Appendix

Historically, much research has been done to evaluate field inhomogeneities in heterogeneous systems. Menzel (1955) determined the distribution of magnetic field intensity for a sphere in a uniform external field. Durand (1968) gave the analytical solution of the magnetic field induced by an isolated infinite diamagnetic cylinder placed

in a medium of differing susceptibility. Roschach et al. (1973) estimated the field inhomogeneity in muscle samples that is derived for a sphere in a uniform field. Glasel and Lee (1974) expressed the analytical form for the induced fields due to a single spherical inclusion. The volume average of one field gradient component is determined. Eyges (1975) improved the integral equation method, previously derived by Phillips (1934) and exploited by Edwards and van Bladel (1961,1964), for solving the problem of a homogeneous permeable body of arbitrary shapes in an external magnetostatic field by reducing it to the dielectric problem. Majumdar et al. (1988) developed a physical model for a suspension of spherical magnetized particles by considering the magnetostatic superposition of the fields induced by many microspheres randomly distributed in a medium of differing susceptibility. They also derived a relationship between the number density, composition, and size of the particles and the variance of the resultant gradient field distribution. Bendel (1990) regarded the magnetic field of a saturated sand/water mixture as a superposition of many identical spherical particles. Zhong et al. (1991a, 1991b) modeled internal gradient distribution as Gaussian distribution to study the effects of susceptibility variations on NMR diffusion measurements. Brown et al. (1993) used a magnetic dipole method to list the induced fields in a few idealized geometric shapes, for example, cone, wedge, cylinder, crack and sphere. Holt et al. (1994) verified the superposition of fields created by individual objects for a model of two spheres with reasonable accuracy. Bobroff et al. (1996) modeled the inhomogeneous magnetic field of the fluid surrounding infinite parallel cylinders in a regular square array. Hürlimann (1998) estimated effective field gradients, which relate to the field variations over the local dephasing length, for water-saturated sedimentary rocks. Clark et al. (1999)

modeled the local magnetic susceptibility-induced gradients in the human brain as a Gaussian distribution. Dunn (2002) modeled the internal field gradient of a periodic cubic array of touching spheres.

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Dr. Gigi Qian Zhang: Dr. Gigi Qian Zhang works in the NMR program of Baker Hughes Incorporated as a scientist. She is actively involved in developing interpretive techniques and software for processing NMR wireline data. Her lab research focuses on the well logging applications of NMR, especially the high temperature and high pressure NMR properties of reservoir fluids. Dr. Zhang obtained a B.S. degree from Tsinghua University in 1996 and a Ph.D. degree from Rice University in 2001, both in Chemical Engineering. Her Ph.D. thesis focused on fluid-rock characterization and interactions in NMR well logging, particularly on hydrogen index, internal field gradient, and wettability.

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Table 1. Comparison of the mean, standard deviation, minimum, and maximum values of dimensionless gradients for an infinite cubic array of cylinders (The distance between the centers of two cylinders is $3a$, with $\phi = 65.1\%$), spheres (same, except $\phi = 84.5\%$), and a square pore with 15 clay flakes on each side ($f_{micro} = 0.32$).

$\left \vec{G}^* \right $	mean	std. dev.	min	max
array of cylinders	0.62	0.45	0	1.85
array of spheres	0.89	0.91	0	5.59
pore lined with clay flakes	0.81	2.28	0	81.26

Table 2. Dimensional gradient values for the simulation of N. B. sandstone and chlorite slurry.

$\left \vec{G} \right $ (gauss/cm)	whole pore	micro-pores	macro-pores
N. B. sandstone	168	248	134
chlorite slurry	390	—	—

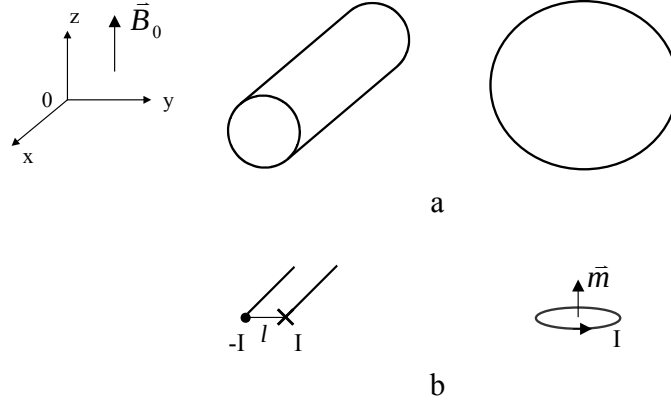


FIG. 1 An infinitely long cylinder or a sphere in a homogeneous magnetic field (a). Magnetic dipole theory for modeling the induced fields (b).

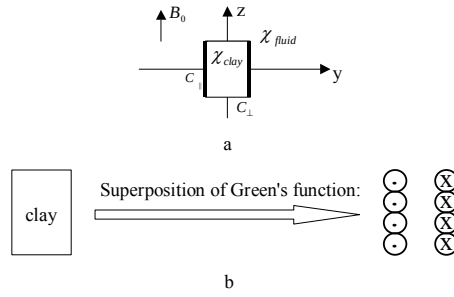
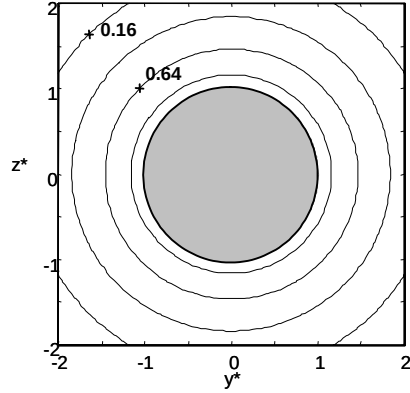
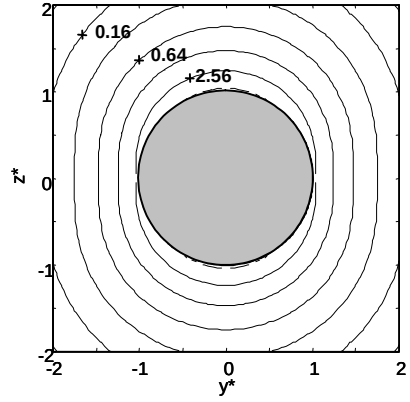


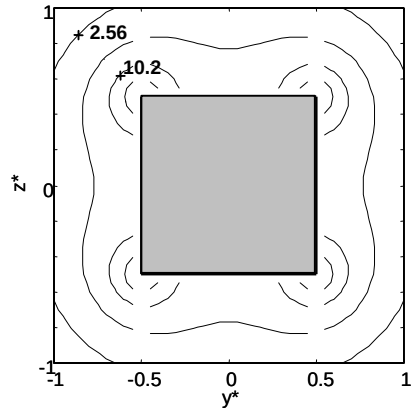
FIG. 2 A rectangular clay particle in a fluid with interfaces either parallel or perpendicular to the homogeneous magnetic field (a). Green's function solves A_δ for a clay flake in a fluid, which in analog of magnetostatics, corresponds to two sheets of current flowing in opposite directions (b).



(a)



(b)



(c)

FIG. 3 Contour lines of dimensionless gradients for a single cylinder (a), sphere (b) and clay flake (c). For the clay flake system, dimensional lengths are normalized to the width, rather than the half width, of the clay flake. Therefore, the clay flake system has a different scale from that of the cylinder and sphere systems.

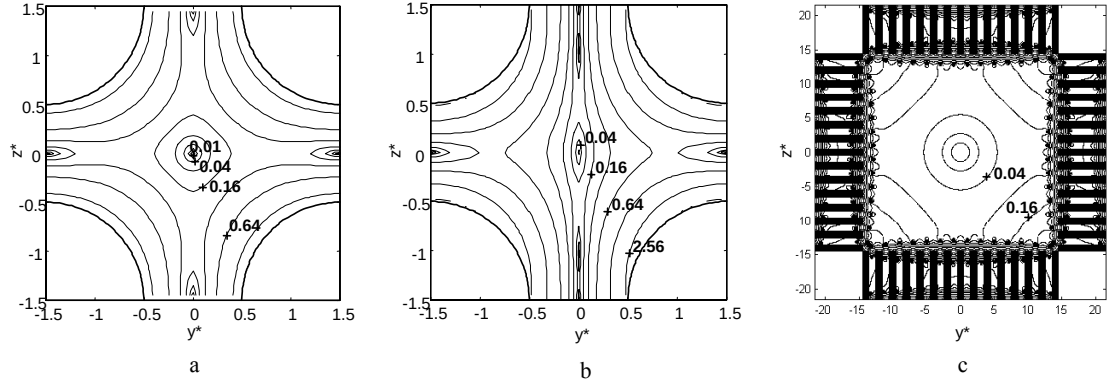


FIG. 4 Contour lines of the dimensionless gradients for the central pore space of a cubic array of 36 cylinders (a); for the vertical plane passing the centers of spheres at the innermost of a cubic array of 64 spheres (b), same scale as in (a); for a square pore lined with 15 clay flakes on each side (c), different scales from those of (a) and (b).

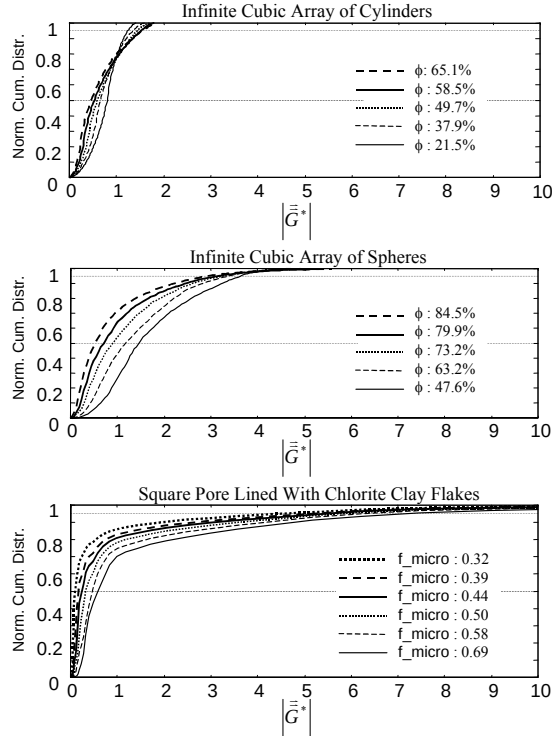


FIG. 5 Normalized cumulative distributions of dimensionless gradients for an infinite cubic array of cylinders or spheres with different porosities (by varying the distance between the centers of the particles), or a square pore lined with clay flakes with different fractions of micropores (by varying the number of the clay flakes on each side of the pore). The two dotted horizontal lines shown on each plot represent when gradients reach 50 percentile (i.e., median value) and 95 percentile.



FIG. 6 Photomicrograph (at 10,000 magnification) of North Burbank sand grain showing chlorite coating (adapted from Trantham and Clampitt, 1977).

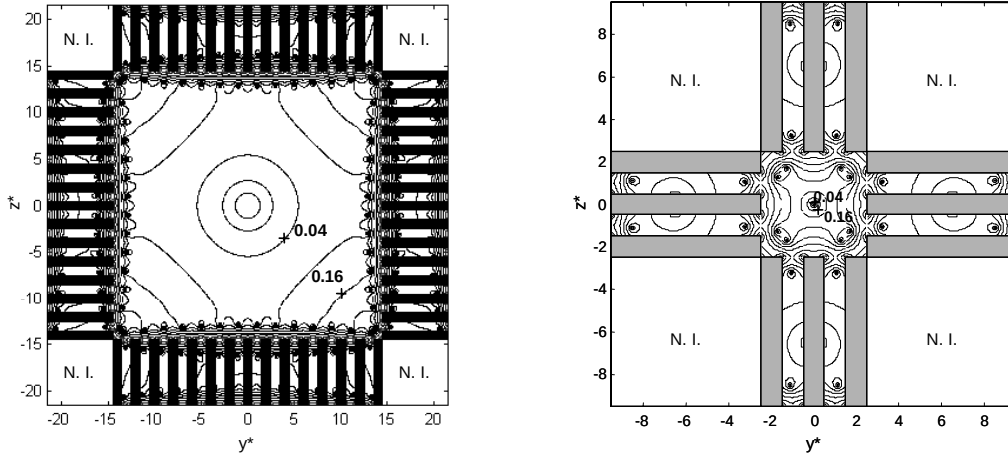


FIG. 7 Contour lines of the dimensionless gradients for the whole pore for the simulation of N. B. sandstone (left) and chlorite slurry (right). The corners are not included as part of the system. N. I. stands for Not Included.

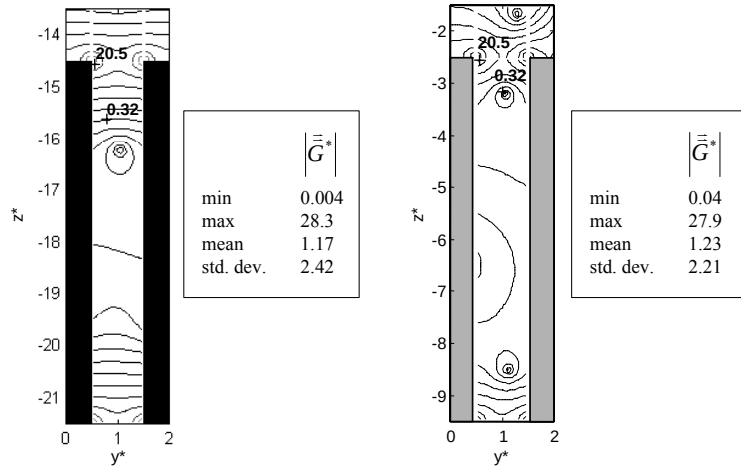


FIG. 8 Contour lines of the dimensionless gradients for the micropore of N. B. sandstone (left) and those in between the clay flakes of chlorite slurry (right).

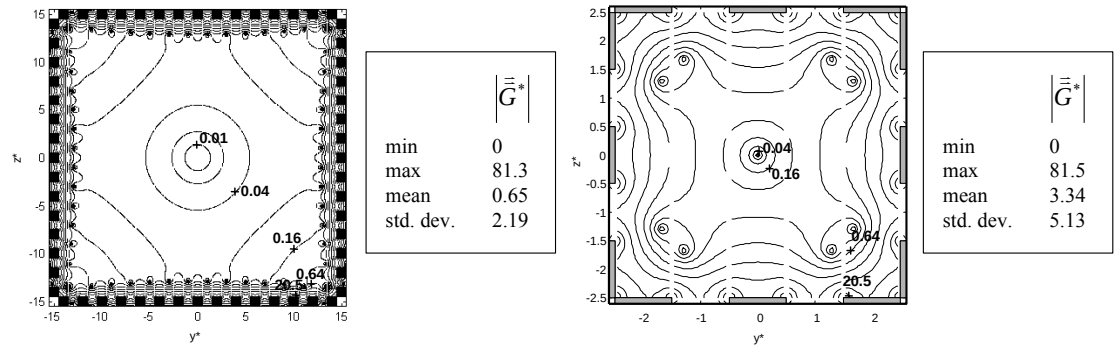


FIG. 9 Contour lines of the dimensionless gradients for the macropore of N. B. sandstone (left) and the big pore of chlorite slurry (right).

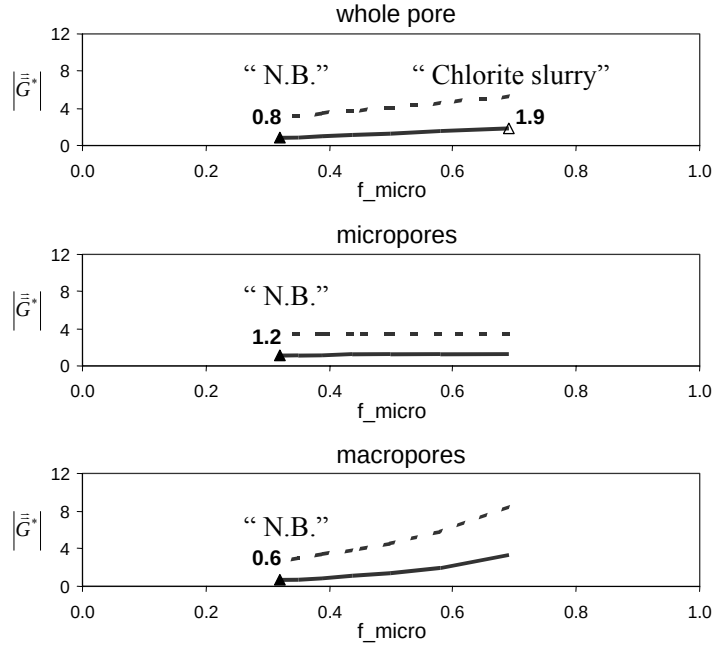


FIG. 10 Dimensionless gradients as a function of the fraction of micropores for the whole pore, micropore and macropore of a square pore lined with chlorite clay flakes. The simulation of N. B. sandstone is at the fraction of micropores of 0.32, while the simulation of chlorite slurry is at the fraction of micropores of 0.69. Only the whole pore is considered for the chlorite slurry since the micropore and macropore cannot be experimentally distinguished.

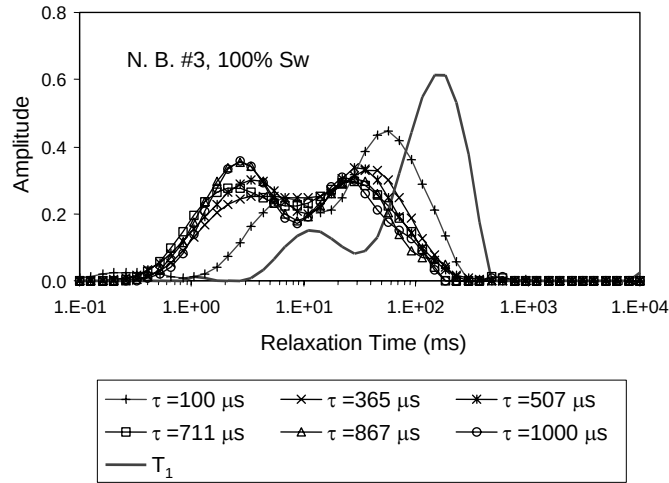


FIG. 11 The relaxation time distributions of T_1 and T_2 at different echo spacings for a N. B. sandstone at 100% brine saturated condition.

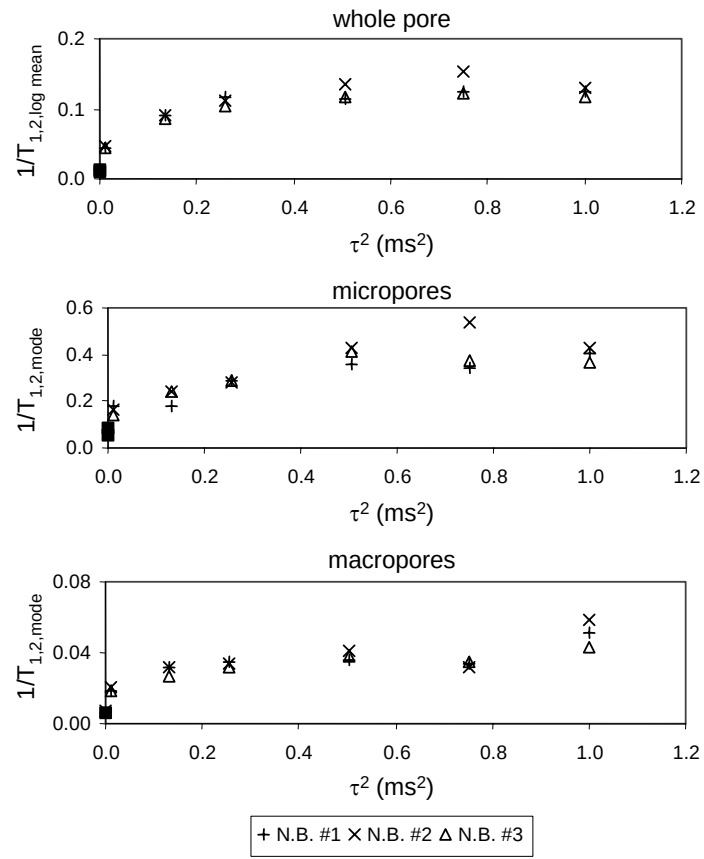


FIG. 12 $1/T_2$ vs. τ^2 for the whole pore, micropores and macropores of a N. B. sandstone at 100% brine saturated condition. $1/T_1$ is shown as a solid square at zero echo spacing.

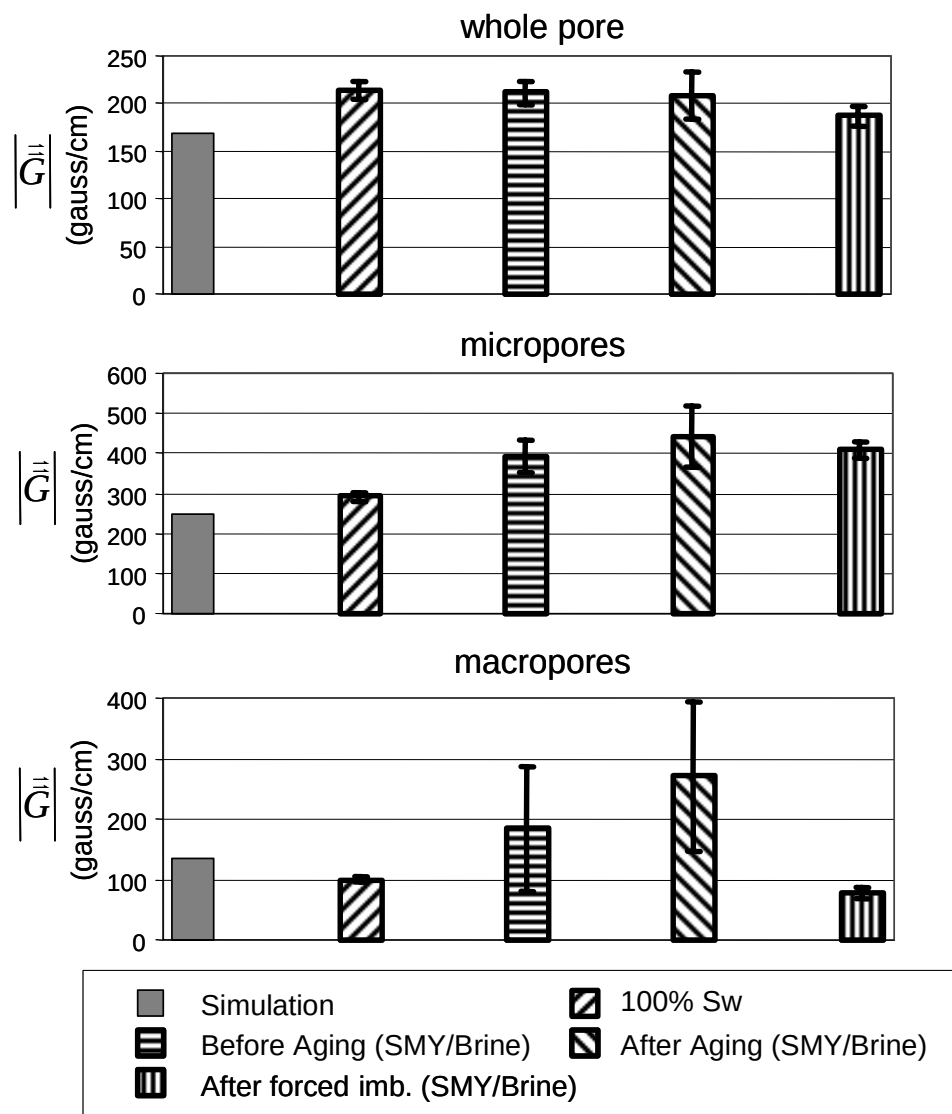


FIG. 13 Comparison of dimensional gradient values from simulations with experimental results for the whole pore, micropores and macropores of N. B. sandstones.

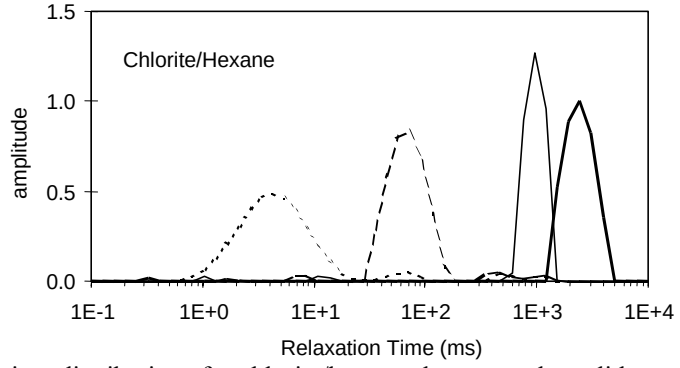


FIG. 14 Relaxation time distributions for chlorite/hexane slurry: regular solid curve corresponds to T_1 , dashed curve to T_2 at echo spacing of 0.2 ms, and dotted curve to T_2 at echo spacing of 2 ms. T_1 for bulk hexane is also shown as the bold solid curve.

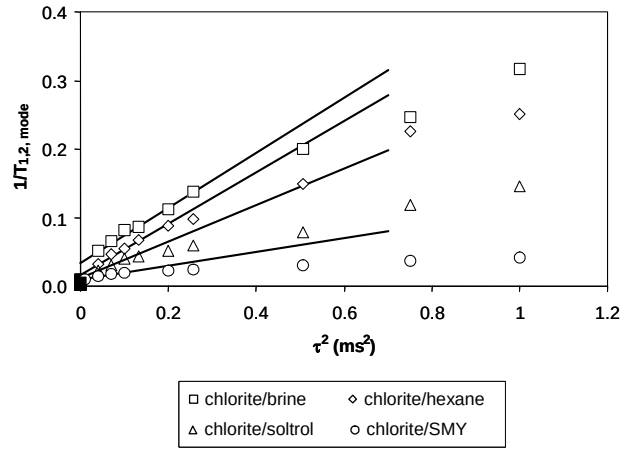


FIG. 15 $1/T_2$ vs. τ^2 for four chlorite/fluid slurries. $1/T_1$ is shown as a solid square at zero echo spacing.

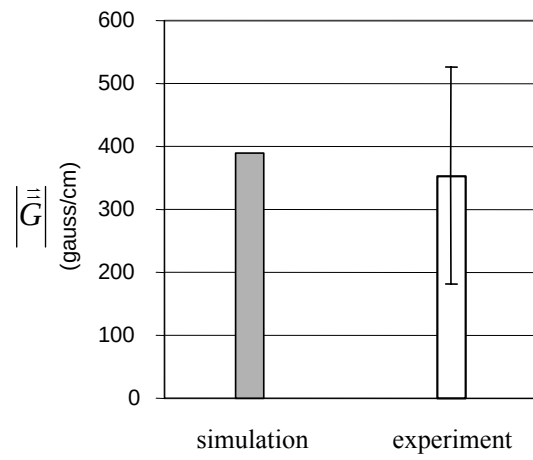


FIG. 16 Comparison of dimensional gradient values from the simulation results with the experiment results for the chlorite slurries.