Field and laboratory investigation in support of the application of the magnetic resonance sounding method in granular aquifers in the Grenville Province

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ABSTRACT
Previous attempts to apply the MRS method in the Grenville geological Province has not yielded expected results and it has been suggested that disseminated fine-grain magnetite inhibits the generation of coherent response. Modified equipment and a new MRS protocol were used in field test carried out in 2008 in granular aquifers in the Grenville Province. Samples have been collected at the test sites and have been analyzed. Our results indicate that magnetite constitutes about 4-6% of the mineral content of the samples and that the magnetite presence is an important factor for obtaining a signal that is coherent or not with the MRS method.

RÉSUMÉ
Des essais antérieurs pour appliquer la méthode SRM dans la Province géologique du Grenville n'ont pas donnés les résultats escomptés et il a alors été suggéré que des grains de magnétites disséminés sont la cause d'un signal incohérent. Avec un équipement et un protocole modifié, des sondages ont été effectués sur le terrain en 2008, dans des aquifères granulaires de la Province du Grenville où des échantillons ont aussi été récoltés. Nos résultats indiquent que la magnétite constitue environ 4-6% des échantillons et que la présence de magnétite est donc un facteur important pour l'obtention d'un signal cohérent ou non avec la méthode SRM.

1 INTRODUCTION

The magnetic resonance sounding (MRS) technique has been tested in many countries, and its capacity to estimate proprieties and boundaries of aquifers is well established (Roy and Lubczynski, 2003). In 2003, a number of soundings have been carried out in Eastern Canada, more precisely in the Grenville Geological Province and its southern boundary. Unfortunately, most of these soundings did not yield coherent results, indicating that the existing MRS technique was not adapted to this geological environment (Roy et al., 2008). Because the MRS is based on environmental magnetic proprieties, it has been proposed that the presence of magnetic minerals in the sandy aquifer material may interfere with the results of the MRS method.

This paper reports on new field tests carried out in the southern Grenville in 2008 using a modified MRS procedure, as well as laboratory tests on the presence of magnetic minerals in the material from the investigated granular aquifers.

2 THE MRS TECHNIQUE

The magnetic resonance sounding (MRS) technique is based on quantum physic at the atomic scale. At equilibrium, the hydrogen nucleus has a weak magnetic moment that acts like a tiny magnet with a vector oriented in the direction of the magnetic field (B_0). Since most of the hydrogen present underground is in water, this propriety can be used to detect directly the quantity of H_2O molecules.

In summary, the MRS consists in transmitting an excitation field from the ground surface with a wire loop energized by an alternating current and producing a field with a component perpendicular to the earth's magnetic field. The frequency of the transmitted current must be equal to the Larmor frequency, which is a function of the amplitude of the Earth magnetic field (B_0) and a gyromagnetic factor (γ), a constant for hydrogen:

$$f = \gamma B_0 / 2\pi. \qquad [1]$$

During the excitation, there is a nutation (a rotation) of the angular moment axe of the hydrogen nucleus. As a result of the excitation field, the hydrogen nuclei get oriented away from the earth's field direction. When the excitation field is stopped, the nutated hydrogen nuclei gradually return to their original orientation; but, because of their angular momentum, they precess around the earth's field direction while coming back to that orientation.

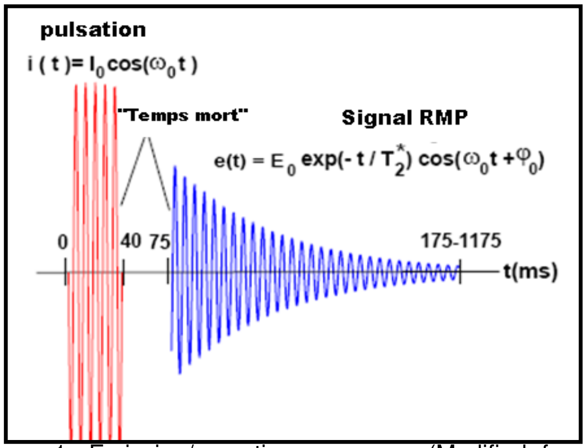


Figure 1: Emission/reception sequence (Modified from Legchenko, 2008).

Figure 1 shows an example of alternating current impulse $i(t)$ transmitted in the loop, corresponding to $i(t)=I_0\cos(\omega_0 t)$, $0<t\leq\tau$. The parameter I_0 is the amplitude of the transmitted impulse, t is the time during the impulse and τ is the impulse duration. The frequency of the current, ω_0, is equal to the Larmor frequency.

The signal detected by the receptor shows an oscillation corresponding to the Larmor frequency, that decreases according to an exponential function characterised by the time constant T2*. The observed signal is called the Free Induction Decay Signal (FID), which can be modeled by the equation:

$$e(t) = E_0 \exp(-t/T2^*)\cos(\omega_0 t + \varphi_o), \qquad [2]$$

with E_0 corresponding to the initial amplitude, T2*, the transversal relaxation decay time and φ_o the MRS decay phase (Legchenko et al., 2008). The relaxation constant T1* (an approximation of T1, the longitudinal relaxation time), is obtained by injecting two consecutive pulses and measuring the response after those pulsations. The parameter T1 refers to the time taken by the magnetic moment to return to is initial state.

With this technique, it is theoretically possible to estimate:

- The water saturation; the initial amplitude of the relaxation field, $E_0(q)$, corresponding to the quantity of hydrogen nucleus;
- The depth and boundaries of the aquifer;
- The pore-size, leading to hydraulic conductivity estimators (Roy et al., 2008) by measuring the relaxation constant

The following section describes how a first attempt in 2003 to apply the MRS technique in sandy aquifers in the Grenville geological province did not yield the expected results. A second field campaign in 2008 is then described; it was carried out with a modified approach and supported by laboratory experiments.

3 PREVIOUS WORK

3.1 MRS in the Grenville Province in 2003

The MRS has been tested in 2003 for the first time in the geological Province of Grenville. Twelve different sites have been investigated in three different areas: in the Laurentides North-West of Montréal, in the Saguenay area and in the St-Lawrence Lowlands. This recent technology has then been tested in the Grenville Province for three main reasons: it had never been tested previously in this part of the world, the signal/noise ratio was supposedly good, and the ambient magnetic field was expected to be superior of 55 000nT.

However, no quantifiable groundwater response has been obtained at the twelve sites tested in 2003, eventhough the environmental conditions were favourable, i.e. saturated aquifers, with high porosity and near the ground surface. It was suggested that these poor results are due to an important contrast of magnetic susceptibility at the pore scale (Roy et al, 2008), a factor common to all of the tested sites in the Grenville Province and at its southern limit. This contrast could be related to the presence of disseminated fine-grained magnetite in the aquifer sand.

It then appeared necessary to document the presence of disseminated magnetite grains, which could cause an important local magnetic gradient. It was also suggested to adapt the current MRS method in order to make the measurements possible at sites with an important heterogeneity in magnetic susceptibility.

3.2 Modified MRS method

Between 2003 and 2008, a number of modifications were brought to the *NUMIS* equipment (IRIS-Instruments, France) and on the testing protocol. New soundings in the Grenville were then required to test those modifications. In the usual protocol, when an impulse is sent and stopped the hydrogen nucleus precesses at the Larmor frequency; the resulting field is recorded and interpreted to determine the aquifer parameters. Where grains with a high magnetic susceptibility are close to grains with a lower susceptibility (e.g. magnetic vs quartz), the hydrogen nucleus doesn't precess all at the same speed and only system noise is measured. In fact, the nucleuses have to precesss in phase (synchronised) all at the same frequency to generate a detectable field at the ground surface.

This problem is circumvented by sending two consecutive impulses within the system instead of only one. A first impulse (I_1) is sent for a duration Δt, and stopped. The hydrogen nucleuses located near mineral grains with different values of magnetic susceptibility precess at difference phases. A second and inverse impulse (I_2), two times longer than the first one (2Δt) is then sent. This makes the hydrogen nucleuses to precess in the opposite direction. The nucleuses then precess the inverse way and eventually return to their initial position; at which time they precess all in phase, making measurement possible. This procedure is called MRS with *spin echo*; this is the most important difference between the measurement protocol in 2003 and in 2008.

4 MRS IN THE GRENVILLE PROVINCE IN 2008

A number of field tests have been carried out with the modified equipment and the new MRS protocol, in August 2008, in granular aquifers in the Grenville Province and near it's southern boundary. Samples of the aquifer material have been collected at three of these sites: at Saint-Honoré, and at Saint-Fulgence in the Saguenay area, and at Sainte-Marthe, located west of Montréal (Fig. 2).

The aquifer material at these sites is derived mostly from the erosion of rock units of the Grenville geological Province. This geological province (1.2 Ga to 950Ma) includes many anorthositic and other igneous mafic complexes (Fig. 2; Perreault and Moukhsil, 2004), rock bodies with a high content of iron and magnesium. This high iron content in the bedrock is also reflected in the granular aquifer material derived from it.

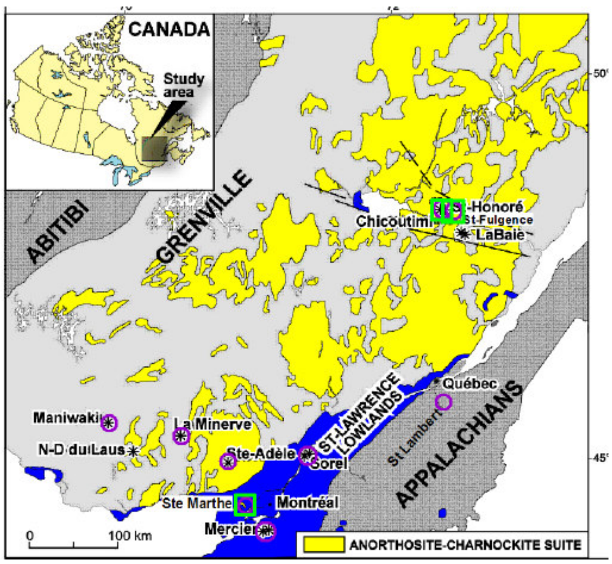


Figure 2: MRS investigated sites in 2008. The purple circles correspond to investigated aquifers and the green squares show the aquifers considered in this paper (adapted from Roy and al., 2008).

Measurements of the earth magnetic field had to be carried out first, using a field magnetometer, as the Larmor frequency is a function of this magnetic field. Measurements of the electromagnetic noise have also been taken at all of the sites before the MRS. Because the noise was about ten times higher at St-Honoré than at St-Fulgence, most of the soundings have been carried out at Saint-Fulgence. The soundings at both Saint-Honoré and Saint-Fulgence have been conducted in spin echo mode. As opposed to the 2003 data, the 2008 data present coherent results; the signal that is generated by the hydrogen precession has higher amplitude than the ambient noise. The inversion of these spin echo data requires a method that is still under development. This inversion would provide estimates of the water content in the aquifer, and an indirect estimate of the porosity; the later could then be compared with estimates obtained from more direct field and laboratory methods.

The sounding at Sainte-Marthe has been carried out in both the free precession and the spin echo modes. The inversion results are available at the moment only for data obtained with the former mode.

5 LABORATORY TESTING

Samples of the aquifer material have been collected for laboratory measurements.. Those samples represent the different facies observed at the ground surface near the sounding sites; they are also considered representative of the aquifer material below the surface. Grain-size separation during sieve analysis has allowed a number of laboratory tests to be carried out on the different classes of grain size, including magnetic separation, observation with binocular magnifier, and microfluorescence-X analysis. Moreover, measurements of the magnetic susceptibility has been realised *in situ* on the samples. The results of two of these measurements will be discussed: one conducted on the more important facies at Saint-Fulgence and the other one at Sainte-Marthe.

5.1 Sieving

All samples were dried and sieved following the BNQ standard 2501-025 (BNQ, 1987). The material is classified as medium sand with gravel for the Saint-Fulgence aquifer, and medium to fine sand for Sainte-Marthe.

5.2 Magnetic separation

Magnetic separation has been carried out with a hand magnet on every one of the sub-samples corresponding to the different classes of grain size. Every sub-sample was then divided in two parts: the magnetic grains and the other grains. After magnetic separation, observation with a binocular magnifier indicated that most of the grains are actually polymineralic. So most of the grains in the magnetic part contain a magnetic mineral for one part, but also other mineral such as quartz, feldspar, amphibole, etc. It was also observed that the percentage of magnetic minerals in the fine-grain sub-samples is closer to the total percentage than it is in the coarse grain sub-samples. So, the degree of liberation of the magnetite grains appears to depend on the grain size. The grain angularity has also been determined on the magnetic fraction following the ASTM D2488-00 (ASTM, 2000) standard. In average, the mineral grains attracted to the magnet were sub-angular in all samples.

Binocular observation of the non-magnetic fraction indicated that those grains were also polymineralics and that some of those grains contain a part of magnetite. This later observation indicated that another method should be used to better establish the magnetite percentage. It was then decided to conduct a microfluorescence-X analysis of selected samples.

5.3 Microfluorescence-X

The microfluorescence-X is a non-destructive technique providing grade images of major and trace elements in the analysed grains. So, iron images have been obtained for selected soil samples. Sample preparation consists in sticking grains from the sample on polished glass slides. The microfluorescence-X then produces an image showing the presence of iron (fig. 3).

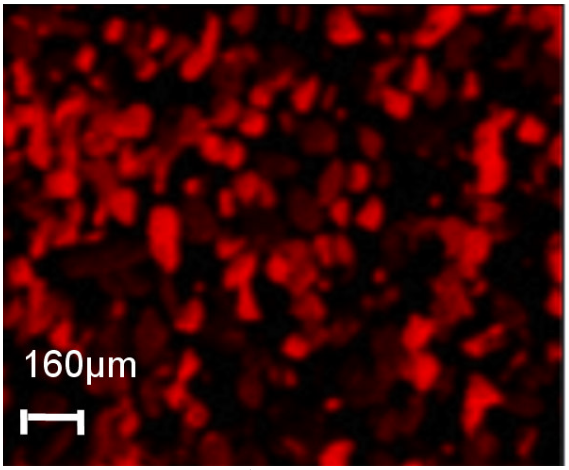
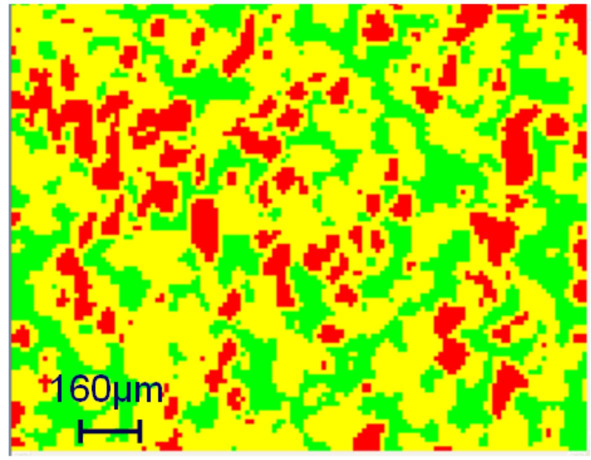


Figure 3 : Example of an iron image obtained with the microfluorescence-X. The red represent iron and the black represent all the other elements (Menier, 2008).

The image analysis software *Image-Pro Plus* (Media Cybernetics) was then used for further class separation using three different colors. The red colour has been assigned to iron grains and yellow to the other grains; green corresponds to empty space, i.e. where no grain is present on the slide.

The void percentage is required to obtain the actual iron percentage as explained below. The total sample area occupied by grains is equal to iron percentage plus the percentage of the other grains. In the case shown in Figure 4, this yields 72.3% (i.e. 15.3%+57.0%) for the grains. The iron percentage is then obtained by:

$$\frac{15,3\%}{72,3\%}\times 100\% = 21,2\% \quad [3]$$



	Pourcentage
Iron	15,3
Other grains	57,0
Voids	27,7

Figure 4: Calculation of the iron occupied superficies with *Image-Pro Plus* (Menier, 2008).

The percentage of magnetite for all of the investigated grain-size classes is obtained with this method. By summation the total magnetite percentage is estimated for the Saint-Fulgence and the Sainte-Marthe sites (Table 1). As the hematite percentage has been observed to be very low, all of the iron has been attributed to the magnetite.

Table 1 : Characteristics of aquifer material

	Saint-Fulgence	**Sainte-Marthe**
Aquifer material	Medium sand with some gravel	Medium to fine sand
Magnetic susceptibility	3.01×10^{-3} to 5.14×10^{-3}	1.06×10^{-3} to 1.16×10^{-3}
MRS mode	Spin echo	Free precession and spin echo
Magnetite content	5.47%	4.83 %

The sub-samples with grain-size lower than 2.00mm in the case of the Saint-Fulgence sample, and lower than 1,25mm in the case of the Sainte-Marthe sample, have been analysed by the microfluorescence-X method, while the magnetite percentage have been determined visually for the coarser grain size sub-samples. For each grain-size class that has been analysed by microfluorescence-X, two slides have been used: one slide with the material attracted by the magnet and the other slide with the non-attracted material.

6 ESTIMATION OF WATER CONTENT IN THE SAINTE-MARTHE AQUIFER

It has been possible to estimate the water content in the Sainte-Marthe aquifer by inverting the MRS free precession results. This has been compared with porosity estimates based on the bulk density.

6.1 Estimation of water content with MRS result inversion

The estimation of the water content in the Sainte-Marthe aquifer has been possible using existing inversion method for free precession MRS sounding. Figure 5 shows that the estimated water content values varies from 8% to 12% with respect to depth.

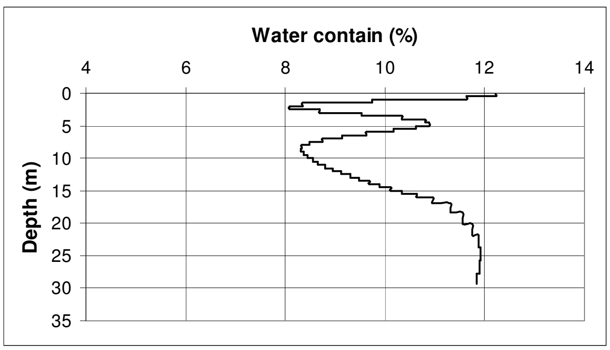


Figure 5 : Water content with respect to depth for a MRS done at Sainte-Marthe.

6.2 Estimation of porosity with the bulk density method

An estimate of porosity has been obtained in the laboratory using the bulk density method on samples collected in the Sainte-Marthe aquifer. Four small cylindrical samples (2.7cm radius, 3.55cm height) have been collected in the vertical wall of a trench hand dug at the MRS sounding site, paying special attention to obtain undisturbed samples. The samples have been dried out in the oven at 105°C during two days, and then weighted. The total porosity was then estimated by the relations (Black et al, 1965):

$$S_t = \frac{100(\rho_p - D_b)}{\rho_p} \quad [4]$$

With $D_b = \frac{P_s}{V_T}$ [5]

Where :

S_t : total porosity (%)
ρ_p : grain density (assumed equal to 2.65 g/cm^3)
D_b : bulk density (g/cm^3)
P_s : sample weight after drying (g)
V_t : bulk sample volume (cm^3)

Porosity estimates range from 43,2% to 45,6%, with a mean value of 44,2%. This value can be considered as an estimate of the total water content in the saturated part of this sandy aquifer.

7. DISCUSSION

In this section, comparisons are made between field data obtained at the Saint-Fulgence and the Sainte-Marthe sites. The water content estimates from MRS sounding at Sainte-Marthe are also compared to the total porosity estimated in the laboratory on aquifer samples. Further observations are presented on the grain-size and the mineralogy of the aquifer samples.

7.1 Field results

Differences were observed in MRS results from Sainte-Marthe and from Saint-Fulgence that could be related in part to a slight difference in magnetic susceptibility between the two sites.

Many geophysical soundings have been conducted in the spin echo mode at the Saint-Fulgence site and one in the free precession mode (without spin echo). No interpretable result has been obtained in the free precession mode, while the spin echo method yielded valid results. The later results could be interpreted when a data inversion method is available. Nevertheless, the fact that the spin echo mode yielded interpretable results at the Saint-Fulgence site, but not the free precession mode, indicates that the presence of magnetic mineral is indeed a limiting factor. The magnetic minerals that are present in the aquifer material prevent a coherent signal to be generated in free precession as explained above. Moreover, magnetic susceptibility measurements taken on samples of aquifer material indicate values between 3.01×10^{-3} and 5.14×10^{-3} for the Saint-Fulgence site. According to Bernard (2007), material with a magnetic susceptibility higher than 1×10^{-3} precludes valuable results to be obtained in free precession mode. Based on magnetic susceptibility, it was expected that sounding in free precession mode would not yield interpretable results at the Saint-Fulgence site.

At the Sainte-Marthe site, MRS yielded interpretable results both in free precession and in spin echo modes. This could imply that the magnetic mineral content is low enough not to affect the sounding methodology. Indeed, the magnetic susceptibility measured at this site varies from 1.06×10^{-3} to 1.26×10^{-3}; these values are lower than in Saint-Fulgence, but are still above the maximum value mentioned above for MRS in free precession mode.

The inversion of the MRS results in free precession mode obtained at the Sainte-Marthe site yielded water content estimate of about 8 to 12%. This value is very low in comparison with the expected porosity value for the aquifer material. Indeed, the grain-size distribution curve (Menier, 2008) indicates that the aquifer material sample is composed of a medium to fine grain, well-sorted sand; this type of material is generally caracterized by a relatively high porosity. Moreover, the total porosity value estimated in the laboratory using the bulk density approach is around 44%, as expected for a well-sorted sand as discussed above. These data suggest that the water content estimates obtained by MRS are probably biased toward low values. This could be due to the relaxation field being recorded for only part of the hydrogen nucleuses, i.e. those nucleuses that are not affected by the high magnetic gradient at the pore scale due to the magnetic mineral content at the Sainte-Marthe site.

7.2 Laboratory results

Further observations on the samples of aquifer material provide valuable information that could explain some of the MRS results. The magnetite content is estimated at 5.7% in the Saint-Fulgence sample and 4.8% in the Sainte-Marthe sample. The difference between the two sites is only 0.5% which is surprising low considering that the MRS yielded a clear response in the free precession mode at the Sainte-Marthe site, but not at the Saint-Fulgence site. It was also observed by microfluorescence-X on the Sainte-Marthe sample that 73% of the total iron is contained in a single class of grain size (630µm to 1,25mm), and furthermore it is in grains that are non-attracted to the magnet. So this particular value prove that the information that we obtain with microfluorescence-X could not be translated into a precise estimate of magnetite content, due to the potentially low representatively of the small fraction of the sample that is analysed by microfluorescence-X.

It has been assumed that the iron content is all included in the magnetite mineral. Further analysis should be carried out to determine the content in other iron-rich minerals such as hematite, pyrite, ilmenite and pyrrhotite, in order to obtain a more accurate estimate of the magnetite content. The presence of other iron-rich minerals could explain the higher (3x) magnetic susceptibility at the Saint-Fulgence site than at Sainte-Marthe, while the estimated magnetite contents are actually similar.

As explained above, the percentage of magnetite attracted by the hand magnet is not indicative of the total magnetite content in the sample. Therefore, the accuracy of this method does not appear appropriate in the case of polymineralic grains.

Binocular observation indicates that the grains are generally polymineralic, as discussed above, and also sub-angular. These two characteristics are detrimental to the generation of a coherent RMS signal. Indeed, the hydrogen nucleuses are less homogeneously affected around angular grains than they are around well-rounded grains. Similarly, around polymineralic grains that contain magnetite, the hydrogen nucleuses near the magnetite will precess at a faster rate than those near another mineral in the same grain, such as quartz for example. As most of the magnet-attracted grains are both angular and polymineralic, these two factors combined constitute a likely explanation for the absence of coherent MRS response with the *NUMIS* system in free precession.

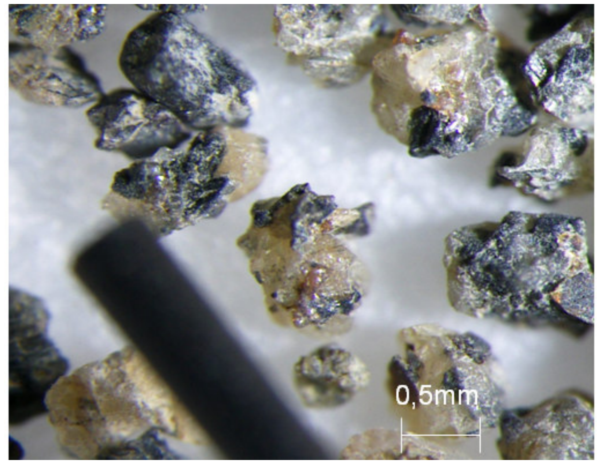


Figure 6: Example of polymineralic, sub-angular grains (Menier, 2008).

8. CONCLUSION

First estimates of the magnetite content have been obtained for granular aquifers in the Grenville geological Province. The significant presence of magnetite supports the hypothesis that this may be the cause of the absence of coherent response for the MRS carried out in 2003. It has been observed that the magnetite content varies significantly with grain size, and that most grains are actually polymineralic, including the grains that contain magnetite. Consequently, the magnetic separation method used in this study yields only partial results and should be complemented by other methods, such as a more systematic microfluorescence-X analysis. The spin echo MRS method yield coherent results at the tested sites, as opposed to the more conventional free precession method; this difference is comforting further the hypothesis that the free precession method is impeded by the presence of magnetite in the aquifer material. At the one site (Sainte-Marthe) where the free precession method has yielded coherent results, the value of water content obtained by MRS data inversion is considerably lower than expected. This suggests that a significant portion of the water does not precess in phase, presumably due the locally high magnetic gradient related to the presence of magnetite. All of these observations support the hypothesis that the absence of coherent response to MRS in granular aquifers in the Grenville Province is due to the significant presence of magnetite causing high magnetic gradient at the pore scale. These observations, as well as the development of the spin echo MRS method represent important steps in the adaptation of MRS method to the geological environment of the Grenville Province and its southern boundary.

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