Application of Magnetic Resonance Sounding to the characterization of Hard Rock Aquifers: example of Benin

Application de la Résonance Magnétique Protonique à la caractérisation des aquifères de socle : exemple du Bénin

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I. INTRODUCTION

Hard rock aquifers are generally poor, i.e. they can produce few hundreds to few thousand liters per hour (MacDonald et al., 2012). In Africa, boreholes producing less than 700 l per hour (i.e. the minimum usually required for supplying a hand pump) are considered as negative and are quite common (e.g. Courtois et al., 2010; Vouillamoz et al., this volume).
Geophysical methods are commonly used for sitting boreholes and most of the drilling campaigns in hard rock aquifers of Africa are still based on common Electromagnetic and/or Direct Current resistivity methods (e.g. Dutta et al., 2006; Allé et al., this volume). As compared to the other non-invasive geophysical methods, Magnetic Resonance Sounding (MRS) has the potential for quantifying before drilling both the productivity (i.e. the transmissivity *T*) and the storage (i.e. *Sy* x *e* where *Sy* is the specific yield and *e* is the saturated thickness) of aquifers. However, uncertainty on the estimate of transmissivity when using MRS results is unclear and no quantitative relationships between MRS parameters and *Sy* have been proposed in most of the published works (e.g. Baltassat et al., 2005; Legchenko et al., 2006; Wyns et al., 2004). Recently, Vouillamoz et al. (2014) proposed equations for estimating *Sy* and *T* from MRS results based on field experiments conducted in 6 different geological units of hard rocks in Benin. However, their approach considered the hard rock aquifer as an equivalent single layer although weathering process of hard rocks results in a heterogeneous reservoir which is fissured at depth and unconsolidated on top. This groundwater reservoir is conceptually described by hydrogeologists as a two layer reservoir where the fissured layer is located just below the unconsolidated saprolite layer (Lachassagne et al., 2011). In this study, we extend the results of Vouillamoz et al. (2014; 2015) by considering the hard rock aquifers as a two-layer reservoir and we improve the understanding of uncertainty on the estimate of *T* and *storage* when using MRS results.

II. MATERIEL AND METHOD

We first compare *T* and *Sy* obtained from the interpretation of pumping test to *T* and *Sy* derived from the interpretation of MRS carried out using a single layer model (Vouillamoz et al., 2014). Then, we interpret the MRS using a two-layer model and we compare the two-layer to the single layer results. Finally, we conduct numerical modeling (1) to improve the understanding of uncertainty on the estimate of *T* and storage when using MRS results, and (2) to assess the conditions when the estimate of aquifer transmissivity and storage is improved by the use of a two-layer model.

II. 1 MRS measurements

Magnetic Resonance Sounding is one of the geophysical methods which is applied for groundwater survey (e.g. Vouillamoz et al. 2005; 2012). It has the advantage over the common methods (e.g. resistivity methods) to measure a signal that is directly linked to the presence of groundwater (for a detailed description of the method see Legchenko and Valla, 2002). To carry out a MRS, the nuclei of the hydrogen atoms of water molecules in the subsurface (i.e. protons) are energized with an electromagnetic pulse, and the signal response of the hydrogen nuclei is measured after the energizing pulse is switched off. This signal is characterized by two main output parameters: its initial amplitude which is linked to the water content (θ_{MRS}) and its decay time (T_2^*) which is linked to the mean size of the pore that contains water (Schirov et al., 1991).
We carried out 39 MRS distributed in various types of hard rocks in Benin (Figure 1). Then we selected six experimental sites where MRS parameters have a broad range of values, each site being located in a different hard rock group. MRS measurements have been carried out with the NumisPlus® apparatus from Iris Instruments. We selected the shape of the MRS loop (square or eight square) according to the electromagnetic noise (EM) noise conditions encountered in the field. The size of the loop was chosen as large as possible (side length of 125 or 150m for the square loop, and 62.5 or 75m for the eight square loop) for increasing the amplitude of the MRS signal, and the number of stacks (300 in average) was chosen to maximize the signal to noise ratio which varies from 2.2 to 6.2. The encountered larmor frequencies range between 1,411 and 1,424 Hz.
MRS Free Induction Decay (FID) measurements are interpreted with Samovar V11 software (Legchenko et al., 2008). We first interpret the MRS records using a single layer-solution, and then using a two-layer solution. The geometry of the two-layer is defined from borehole reports.

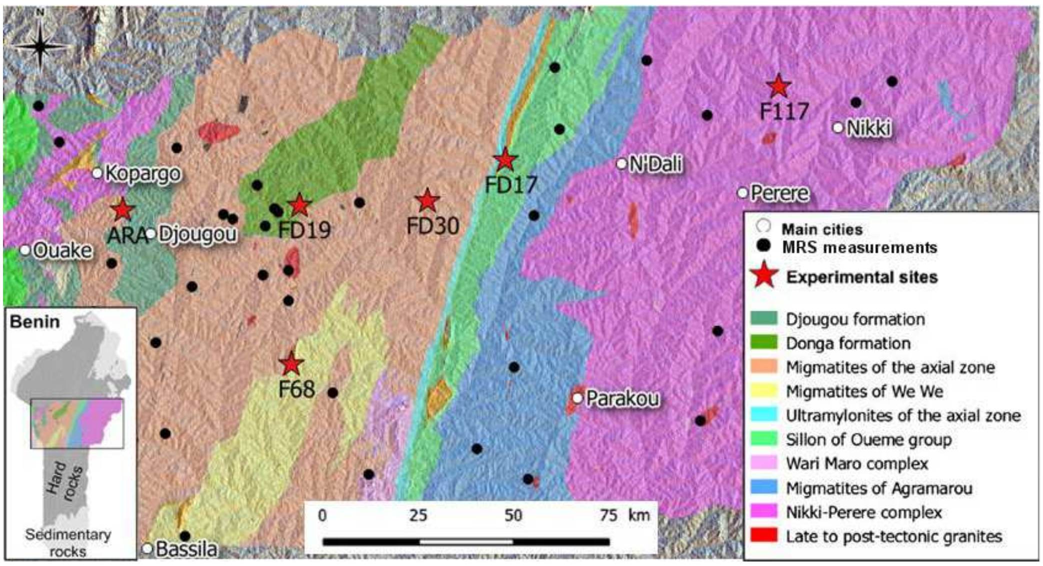

Figure 1 – Location of the investigated and experimental sites and simplified geological map (modified from Vouillamoz et al. 2015).

II. 2 MRS numerical modeling

The parameters of the two-layer initial models are chosen to describe the hydrogeological conceptual model, i.e. an unconsolidated saprolite that overlays a consolidated fissured zone (FZ). The values of θ_{MRS} and T_2^* are defined from the 39 MRS measurements carried out in Benin and from Baltassat et al. (2006) and Vouillamoz et al. (2005): respectively 6% and 190ms for the saprolite, and 1.5% and 300ms for the FZ. The thickness of both layers are obtained from a statistical work carried out on boreholes in Benin (Vouillamoz et al., this volume): the FZ thickness is fixed to 10, 30 and 60 metres (value of first quartile, median and third quartile respectively), and for every value of FZ thickness, the saprolite thickness is ranging from 2 to 55m (Figure 2-A). Examples of generated MRS models for a fixed FZ thickness of 30m are presented in Figure 2-B. The maximum signal amplitude is ranging in-between 90 and 325 nV and the signal to noise ratios varies from 2 to 7.
MRS signals are computed using the common field configuration encountered in Benin (i.e. square loop with a side length of 125m, generator frequency of 1,414 Hz). The signals are generated with Samovar modeling software and interpreted with Samovar inversion software V11 (Legchenko et al., 2008). A total of 42 MRS models are generated and a random noise of 10 nV on average is added to obtain signal to noise ratios which are equivalent to those encountered in the field in Benin. The computed signals are inverted using a single layer solution and then using a two-layer solution. Then, MRS storage and unparameterized transmissivity (*F*) are calculated as:

$$\text{MRS storage} = \theta_{MRS} \,.\Delta z \text{ (Lubczynski and Roy, 2003)} \quad (1)$$
$$F = (T_2^*)^2 \,.\theta_{MRS} \,.\Delta z \text{ (Plata and Rubio, 2008)} \quad (2)$$

where Δz is the saturated aquifer thickness. For the two-layer models, MRS storage is calculated as the sum and *F* as the weighted sum of the storage and *F* of the two layers respectively. Finally, we compare the MRS storage and *F* calculated from both single and two-layer solutions to values calculated from the initial model. We also compare the results of the single layer solutions to the results of the two-layer solutions in order to define the conditions when the estimate of aquifer transmissivity and storage is improved by the use of a two-layer MRS model.

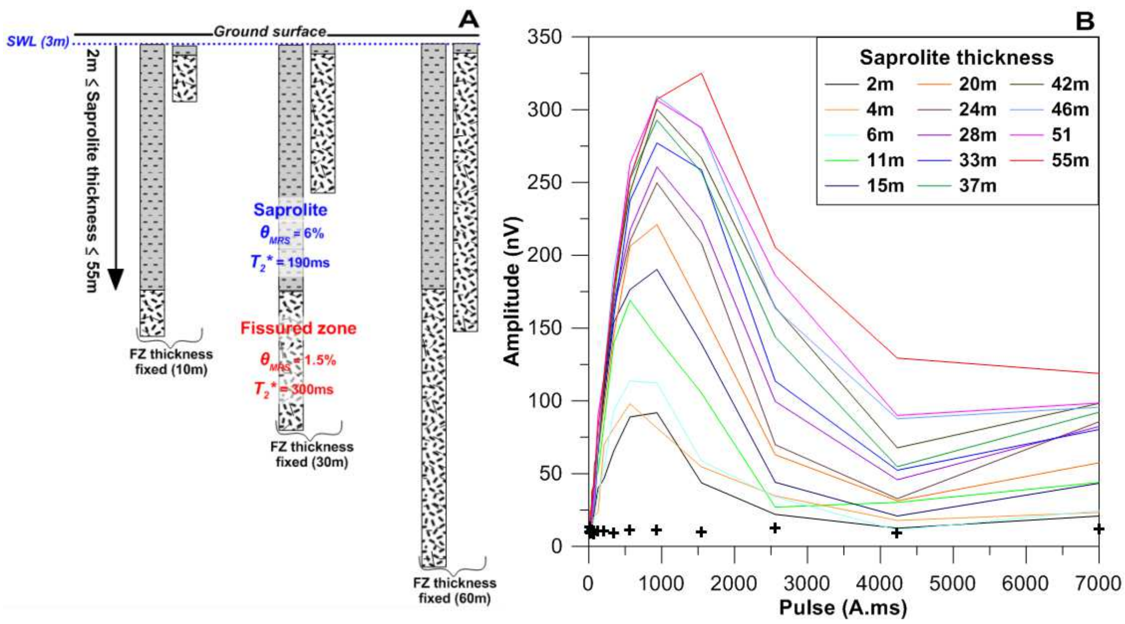

Figure 2 – Computed MRS models. A: Models geometry and input parameters (SWL is the static water level). B: Computed signals for a fixed FZ thickness of 30m. The crosses are the EM noise.

III. RESULTS AND DISCUSSION

III. 1 Single layer interpretation

III. 1-1 Specific yield and storage

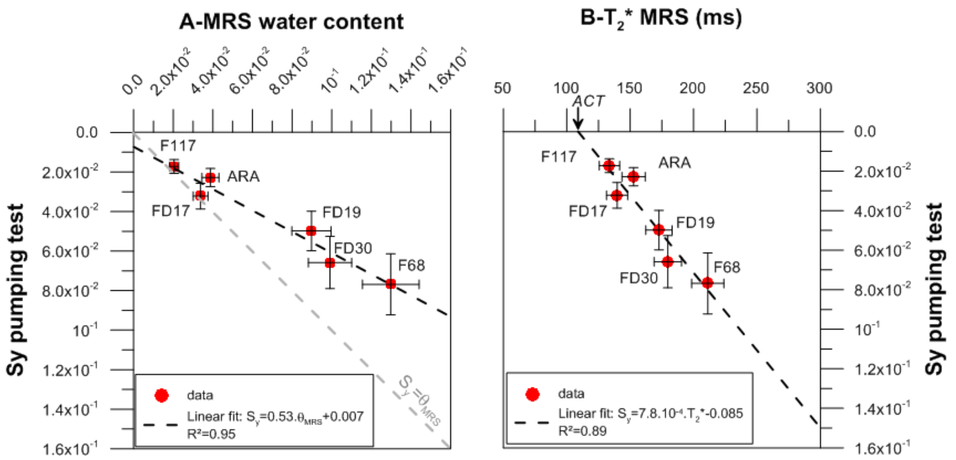

Figure 3 – Comparison of MRS parameters with specific yield. R^2 is the coefficient of determination. A: MRS water content. B: MRS decay T_2 (from Vouillamoz et al., 2014).*

As observed by Vouillamoz et al. (2005; 2012) θ_{MRS} is higher than *Sy* since about half of the MRS water content cannot be drained by gravity when pumping (i.e. mainly capillary water, Figure 3-A). Because the amount of capillary water is controlled by the size of the pores, a link between the decay T_2^* and *Sy* also exists (Figure 3-B). This observation is the basis of the so-named Apparent Cutoff Time (ACT) approach recently presented by Vouillamoz et al. (2012). The observed relationships between *Sy* and MRS parameters are (Vouillamoz et al., 2014):

$$Sy = 0.52\,.\theta_{MRS} + 0.007 \quad (3)$$
$$Sy = 7.8\,.10^{-4}\,.T_2^* - 0.085 \quad (4)$$

Equation (4) is the first experimental evidence that the specific yield of hard rock aquifers can be derived not only from θ_{MRS} but also from T_2^*. As compared to Equation (3), Equation (4) has the advantage to define an ACT value which is the boundary between non-drainable groundwater and gravitational groundwater. *Sy* values calculated from Equations (3) and (4) have respectively a mean difference with *Sy* obtained from pumping test of 12 and 18%. These differences are ranging within the uncertainty on *Sy* obtained from pumping test which was 20%.

To calculate groundwater storage in the different geological unit of Benin, we use *Sy* estimated from Equation (3) because of the known equivalence of the MRS output parameters $\theta_{MRS} \cdot \Delta z$ (Legchenko, 2013). We found that 80% of the groundwater storage values range from 230 mm to 1080 mm, with a median value of 590 mm (Figure 4-A). The overall groundwater storage in our study window is calculated as the sum of the storage of all geological units (Figure 4-B) and is 440 mm +/- 70 mm (Vouillamoz et al., 2015).

III. 1-2 Transmissivity

The transmissivity is calculated using the common approach which links the hydraulic conductivity to a power function of the average size of the pore (Plata and Roubio, 2008):

$$T_{MRS} = C_T \cdot F \quad (5)$$

where C_T is a parametric factor which is calculated comparing T_{MRS} with known transmissivity. The best fit between transmissivity derived from pumping tests and calculated using Equation (5) is obtained with $C_T = 3 \cdot 10^{-3}$ (m.s^{-3}), and the mean difference is 70% which is more than the uncertainty on the pumping test result (i.e. 40%).

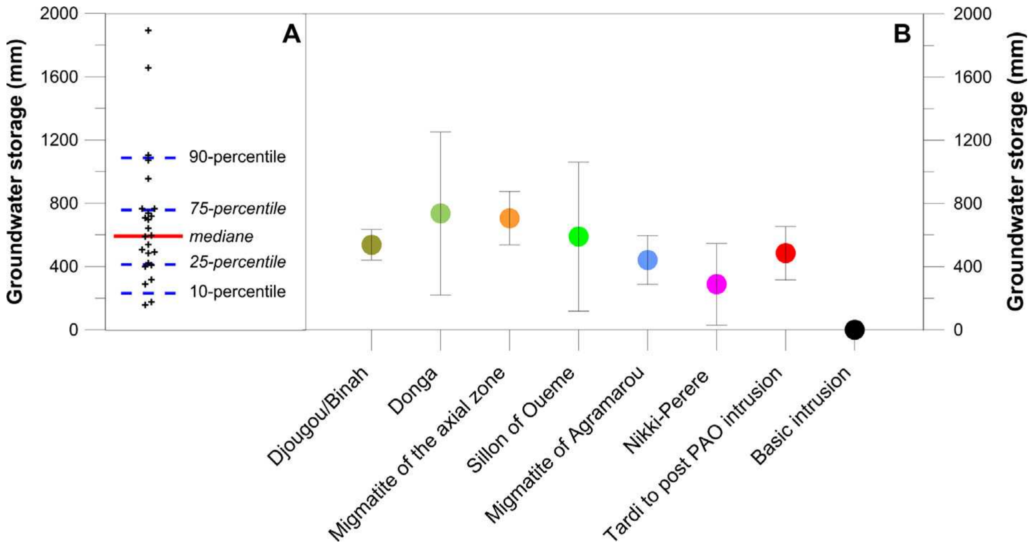

Figure 4 – Groundwater storage in hard rocks in the study window (from Vouillamoz et al., 2015). A: Percentile. B: Variation of storage among geological units (the point is the median value and the error bars are the mean difference to the median).

III. 2 Two-layer interpretation

The links observed previously between *Sy* and *T* obtained from pumping test and *Sy* and *T* calculated from the single layer MRS solutions are not as clear when using the two-layer MRS solutions (Table 1). Thus, considering our data set, we don't improve the characterization of hard rocks aquifer by the use of a two-layer solution.
The reason can be investigated by looking at an example of MRS results (Figure 5). The top layer of the two-layer solution (i.e. the saprolite) has higher values of θ_{MRS} and T_2^* as compare to the deeper layer (i.e. the FZ). This observation is quite surprising as the hydrogeological conceptual model suggests that the FZ layer should have a lower θ_{MRS} but a longer T_2^* (i.e. lower specific yield but higher hydraulic conductivity). Moreover, the top layer of the two-layer solution is quite similar to the equivalent layer of the single-layer solution (Figure 5-B), thus suggesting that both storage and transmissivity are mainly controlled by the saprolite. Note that a similar observation has been made by Vouillamoz et al. (this volume) when investigating the properties of several thousand of the boreholes in Benin: the authors found that the aquifers are mainly located in the unconsolidated weathered layer (i.e the saprolite) and only in the top first meters of the consolidated weathered layer (i.e. the FZ).

	T from Equation 5		*Sy* from Equation 3		*Sy* from Equation 4	
	Single layer	Two-layer	Single layer	Two-layer	Single layer	Two-layer
Mean difference with pumping test results	70%	111%	12%	30%	18%	138%

Table 1 – Differences between MRS results and pumping test results.

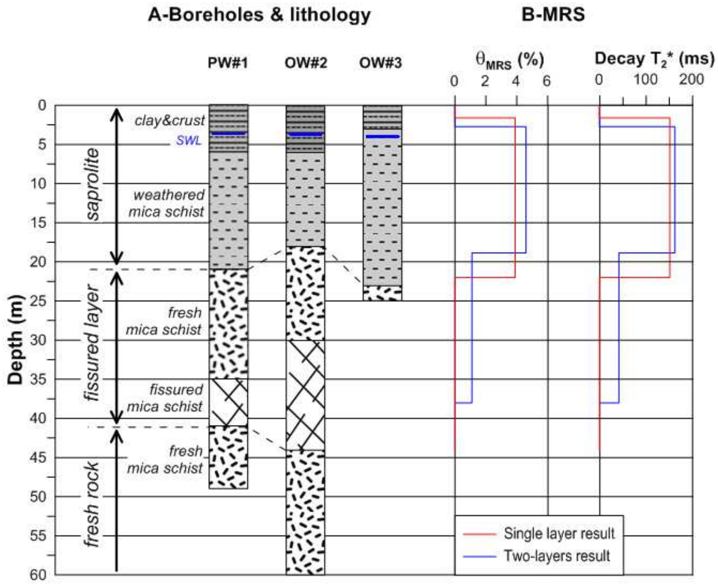

Figure 5 – Experiments at ARA site. A: Borehole lithology. SWL is the static water level. B: MRS results (modified from Vouillamoz et al., 2014).

III. 3 MRS numerical modelling

We compare the MRS storage and the unparameterized transmissivity recovered by the single and the two-layer solutions to the properties of the initial model. The single layer result recovers the storage with about the same difference whatever the thickness of the saprolite (Figure 6-A). The average difference of about -10% is caused by the signal processing used in the inversion software and can be corrected when the MRS results are parameterized (e.g. by using Equation 3, 4 and 5). Thus, the single layer solution recovers always well the initial storage. Concerning the two-layer solution, the initial storage is well recovered only when the FZ is thin (i.e. 10 m) or the saprolite thicker than the FZ (ratio higher than 1, Figure 6-B). When the FZ is thicker than the saprolite (ratio lower than 1), the storage in poorly resolved. These observation can be understood by the fact that the saprolite layer is better resolved than the FZ layer which has a low water content: thus (1) when the saprolite is thicker than the FZ, the storage which is mainly controlled by the saprolite is well resolved, and (2) when the saprolite is thinner than the FZ, the storage is mainly controlled by the FZ which is poorly resolved. The unparameterized transmissivity is well resolved only when the saprolite is thicker than the FZ for both the single and the two-layer solutions (Figure 6C&D).
Finally, when the properties of the aquifer are mainly controlled by the FZ (i.e. ratio lower than 1), the single layer solution recovers better the storage and the transmissivity, but single and two-layer results are about the same when the aquifer geometry is dominated by the saprolite (ratio higher than 1).
However the two-layer result has the advantage over the single layer result to define the properties of the saprolite and the FZ separately: when comparing the two-layer results to the initial model (for thickness ratios higher than 1) the saprolite is well resolved (i.e. mean difference of 6% and 9% on the storage and the unparameterized transmissivity respectively) but the FZ is poorly resolved (i.e. mean differences of 85% and 80% for the storage and the unparameterized transmissivity respectively). The reason why the FZ is not well resolved by the two-layer solution is probably due to the screening effect as observed by Baltassat et al., (2006).

IV. CONCLUSION

Vouillamoz et al. (2005) tried unsuccessfully to quantify the relationship between the specific yield and the MRS water content at the field scale in Hard rock aquifers. In this study, we propose two empirical relationships to estimate the specific yield from θ_{MRS} and T_2^* with an uncertainty of 12 and 18% respectively. We also estimate the transmissivity of hard rock aquifers with an accuracy of about 70%. Our

modelling works reveals that the MRS single layer inversion is more appropriate than the MRS two-layer inversion when considering the common geometry of the deep weathered hard rock aquifers in West Africa. Thus, the MRS method can efficiently be used for quantifying integrated properties of the aquifers, i.e. storage and transmissivity, but the method is not yet appropriate to define the variations of properties according to depth, i.e. Sy or hydraulic conductivity.
New developments in the MRS method which may improve the signal to noise ratio and the resolution with depth will be greatly useful for hydrogeological studies.

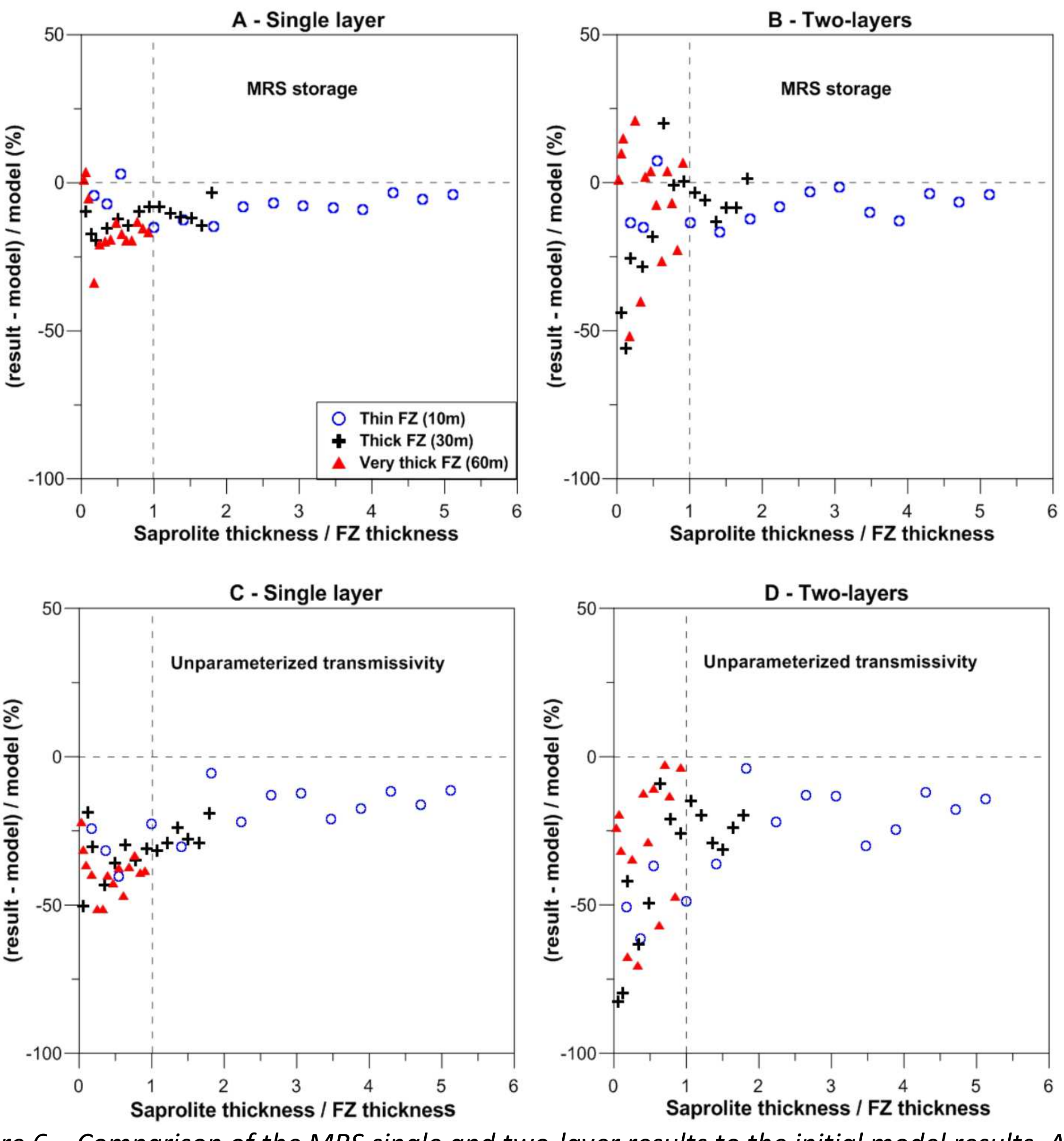

Figure 6 – Comparison of the MRS single and two-layer results to the initial model results. A&B: MRS storage. C&B: No-calibrated transmissivity.

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