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Characterization of crystalline basement aquifers with MRS: comparison with boreholes and pumping tests data in Burkina Faso

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ABSTRACT

In the Sahelian region of Burkina Faso (Western Africa), groundwater resources are scarce. The hydrogeological context is mainly crystalline basement aquifers that often present a challenge to hydrogeologists when investigating their exploration and management. A magnetic resonance sounding (MRS) survey was conducted to evaluate the ability of the method to answer the following main questions encountered by hydrogeologists in this hard-rock context:
• Where is the groundwater? • How deep and how thick are the water-bearing formations?
• What are the reserves of groundwater? • What is the productivity of the aquifer?

MRS measurements were implemented around recent boreholes drilled both in the weathered and in the fissured-fractured units of the reservoirs. In order to evaluate the MRS method, MRS results are compared with borehole and pumping test data. The depths and thicknesses of the saturated aquifers encountered by the boreholes are compared with those estimated by MRS. The T_1 decay-time constant of the magnetic resonance signal is used for calculating the storativity and transmissivity estimators from geophysical data. These MRS hydrogeological estimators are compared with the local transmissivity and storativity of the aquifer, estimated from pumping test results.

The main conclusions of the comparison between the 13 MRS results and the borehole data are:
• The depths and thicknesses of the saturated alterites are accurately described by the MRS results, and the mean differences with the borehole data are ±12% and ±17%, respectively.
• The storativity estimated from MRS data is not reliable. The proposed estimators need to be confirmed with larger data sets, and further research needs to be conducted on this matter.
• The transmissivity can be accurately estimated from MRS data after calibration with pumping test results. The mean difference between MRS and pumping test results is ±41%.
• The main limiting factors of MRS applied in hard-rock areas are the 1D approximation in a highly heterogeneous context, the screen effect that causes deep weathered-fissured reservoirs to be poorly resolved when topped by shallow alterites reservoirs, and the suppression principle that causes deep narrow fractures to be undetectable.

MRS is a useful tool to characterize the saturated alterites and the weathered-fissured zones of aquifers in a crystalline rock context. With knowledge of its limitations, its use within the framework of hydrogeological strategy is promising, both for borehole implementation and for groundwater reserve evaluation.

INTRODUCTION

Crystalline rock aquifers are of particular importance in tropical regions because of their widespread extent and because there is often no readily available alternative source of water supply. Even in more humid regions, water quality considerations can favour their use (Wright and Burgess 1992).

Crystalline basement aquifers are developed within the weathered overburden and fractured bedrock of plutonic and metamorphic rocks. The usual conceptual model of the basement aquifer describes several zones that together form the reservoir

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illustrated in Fig. 1 (Lachassagne *et al.* 2001):
• The alterites (regolith) consist of weathered and decayed rocks of clayey-sandy composition. Their hydraulic conductivity (permeability coefficient) is usually low, but their water-retention capacity can be significant and they perform the major part of the storativity in aquifer functioning.
• The underlying weathered-fissured zone (cap rock) is characterized by almost horizontal fractures that decrease in density with depth, and often by vertical fractures and fissures that enhance the flow relationship with the fractures in the bedrock. This zone has interesting hydrogeological properties, regarding both its transmissivity and its storativity.
• The deeper zone is represented by fractured bedrock; it is highly permeable only locally where it is affected by tectonic fracturing and it has a very limited storativity.

There are a number of important constraints to the development of basement aquifers. The failure rate of low-yield boreholes for rural water supplies is high in the drier regions (typically in the range 40–50%), and the implementation of high-yield boreholes for urban or irrigation purposes is always a challenge for hydrogeologists. Furthermore, the common low storativity of basement aquifers often leads to an unsustainable borehole yield.

Therefore, it is important both to improve the current methodology for high-yield borehole implementation and to evaluate more accurately the overall resources and aquifer occurrence. This can greatly assist in the efficiency and long-term sustained control of development programs.

This paper assesses the contribution of magnetic resonance sounding (MRS) (also known as surface nuclear magnetic resonance (SNMR) and proton magnetic resonance (PMR)) to the characterization of crystalline basement aquifers in Burkina Faso.

BACKGROUND

Survey objectives

Crystalline rock aquifers are of significant extent in Burkina Faso (more than 80% of the country’s total surface area). The development of these aquifers involves technical difficulties and also economic constraints. The implementation of high-yield boreholes and the evaluation of the sustainability of the reserves are complex (Compaore 1997; Wyns *et al.* 2004), and the overall costs of the studies have to be kept as low as possible due to the financial capacities of a developing country.

The MRS method has the advantage over other geophysical methods as is sensitive only to groundwater; this can be of use to hydrogeologists (Legchenko *et al.* 2002; Vouillamoz 2003). To assess the contribution of MRS to the characterization of crystalline rock aquifers, a survey was conducted from November 2002 to January 2003 on granite and the associated rocks of Precambrian age in Burkina Faso. The objectives were to check in what way MRS can provide answers to some of the main hydrogeological questions regarding the saturated zone of this geological context:

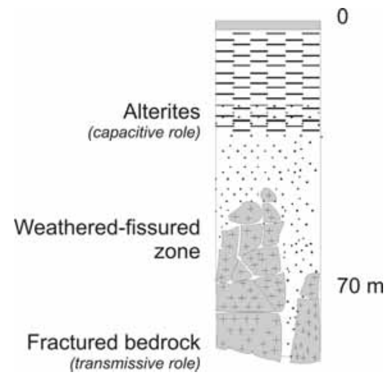

FIGURE 1
Conceptual model of crystalline basement aquifers.

• Can MRS differentiate between the reservoir units, i.e. the alterites, the weathered-fissured zone and the fractured bedrock?
• Is MRS able to resolve the depths and thicknesses of these reservoirs?
• How can the storativity of the saturated reservoir be estimated from MRS signal?
• Can the hydraulic conductivity and the transmissivity be estimated from MRS signal?

Survey method

The method applied consists of comparing the saturated aquifer characteristics with MRS results at different locations where boreholes were drilled.

The local aquifer characteristics were obtained from 13 boreholes. The geometry of the aquifers was deduced from borehole reports, and the static water level (SWL) was measured in boreholes while implementing the MRS. Step-test pumping tests (total pumping duration: 4 hours per test) were carried out in all of the 13 boreholes, and 6 of the boreholes were used to conduct aquifer tests with observation wells (pumping duration: 72 hours). The hydraulic parameters of the aquifers were obtained using Theis and Jacob methods (Kruseman and de Ridder 2000).The local transmissivities were calculated from the recovery period of tests (13 locations), and the storativities were calculated from the observation well records (6 locations).

The MRS surveys were implemented around the boreholes. NumisPlus® equipment was used with a square loop of side 125 m, and an adapted saturation recovery method was used to measure the longitudinal relaxation time T_1 of the signal (Legchenko *et al.* 2004). To compare the borehole characterization of a saturated aquifer with the geophysical data, we used MRS hydrogeological estimators calculated from MRS recorded signals.

MRS HYDROGEOLOGICAL ESTIMATORS

MRS signal

The MRS aims to energize the nuclei of the hydrogen of the groundwater molecules and to measure the magnetic resonance signal which is sent out by protons after the stimulation signal is cut off. This signal oscillates at the Larmor frequency and has an exponential envelope that decays with time, given by

$$e(t,q) = E_{0\_1}(q \exp\left(\frac{-t}{T_2^*(q)}\right)\cos\left(\omega_0 t + \varphi_0(q)\right), \tag{1}$$

where $q=I_o\tau$ is the energizing pulse parameter (I_o is the pulse amplitude and τ is the pulse duration), φ_o is the phase, T_2^* is the signal decay-time constant, referred to as the transverse relaxation time in the usual terminology, and $E_{0\_1}(q)$ is the initial signal amplitude given by

$$E_{0\_1}(q) = \frac{\omega_0 M_0}{I_0}\int_V B_{1\perp}(\mathbf{r})\mathrm{e}^{\mathrm{j}(2\varphi_0(\mathbf{r}))}\sin\left(\theta(\mathbf{r},q)\right)w(\mathbf{r})\mathrm{d}V(\mathbf{r}), \tag{2}$$

where M_o is the equilibrium nuclear magnetization for the protons, $B_{1\perp}$ is the transmitting magnetic field component perpendicular to the static field B_0, φ_o is the phase shift caused by the electrical conductivity of the rock, $\theta = {}^1/_2\,\gamma B_{1\perp}\tau$ is the flip angle of the spin magnetization of the dV sample, **r** is the coordinate vector and $w(\mathbf{r})$ is the water content.

From (1) and (2), it can be shown that

- The initial amplitude of the signal E_{0_1} is related to the water content $w(\mathbf{r})$. Resolving (2) leads to the estimation of the water content of the investigated volume. The maximum investigated volume of a sounding can be approximated by an area 1.5 times the loop size for a depth corresponding to the loop diameter (Vouillamoz *et al.* 2003). In Burkina Faso, this maximum volume was about $(1{,}5 \times 125)^2 \times 125 \approx 4\,000\,000$ m^3
- The signal decays with time according to the T_2^* constant. This constant is linked to the mean pore size containing water (Schirov *et al.* 1991), but it is also influenced by the local inhomogeneities of the static field that is often induced by the magnetic properties of rocks (Legchenko and Valla 2002).

To obtain a more reliable parameter linked to the pore size, an excitation sequence of two pulses, known as saturation recovery, can be used (Dunn *et al.* 2002). A modified form of this sequence was proposed by Legchenko *et al.* (2004), in which the initial amplitude of the signal after the second pulse is given by

$$E_{0\_2}(q,\tau_\mathrm{d}) = \frac{\omega_0 M_0}{I_0}\int_V\left(1-\exp\left(\frac{-\tau_\mathrm{d}}{T_1(\mathbf{r})}\right)\right)B_{1\perp}(\mathbf{r})\mathrm{e}^{\mathrm{j}(2\varphi_0(\mathbf{r})+\pi)}\sin \tag{3}$$

$$\left(\theta(\mathbf{r},q)\right)w(\mathbf{r})\mathrm{d}V(\mathbf{r}),$$

where τ_d is the delay time separating the two pulses. The constant T_1, called the longitudinal relaxation time, is linked to the mean pore size of the saturated aquifer as follows (Kenyon 1997):

$$T_1 \approx \frac{V_\mathrm{p}}{\rho_{\mathrm{s}\_1}S_\mathrm{p}}, \tag{4}$$

where V_p and S_p are the volume and the surface area of the pores containing water, and ρ_{s_1} is the longitudinal surface relaxivity of the rocks.

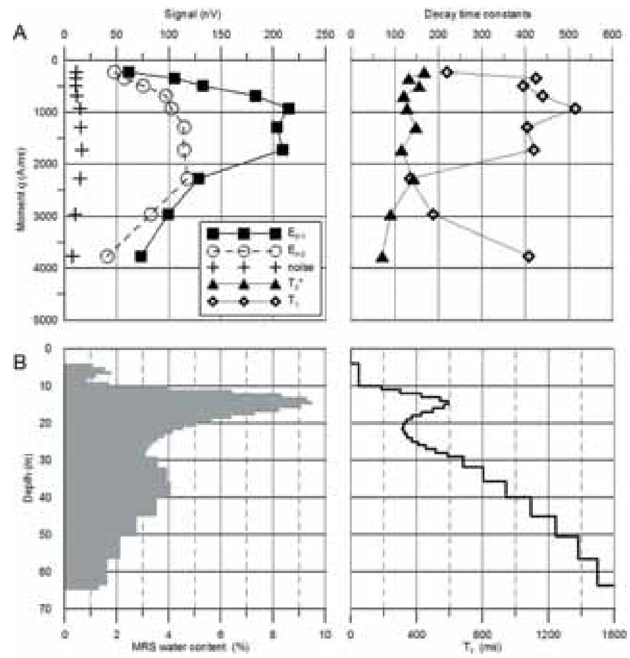

FIGURE 2

Example of MRS data, Sanon S1 borehole. (a) Recorded signal; (b) output parameters. (Square Tx/Rx loop of side 125m; Larmor frequency 1412 Hz; signal-to-noise ratio 7.5 on average).

Assuming horizontal stratification, modified forms of (1), (2) and (3) are used to derive, from the recorded signals $E_{1,2}\,(t, q, \tau_\mathrm{d})$, the output parameters versus depth (z) (Legchenko and Shushakov 1998; Legchenko *et al.* 2004), i.e. water content $w(z)$ and decay times $T_2^*(z)$ and $T_1(z)$ (Fig. 2).

The MRS output parameters provide two types of hydrogeological estimator: storage-related parameters and flow-related parameters.

MRS storativity estimator

In comparison with the total porosity, the MRS water content is defined as (Legchenko *et al.* 2002)

$$w_\mathrm{MRS} = \frac{V_\mathrm{long}}{V_\mathrm{total}}100, \tag{5}$$

where V_long is the volume of water with sufficiently long T_2^* that can be measured with the actual instrumentation (>30 ms) and V_total is the total volume of the sample. Equation (5) shows that the MRS water content differs from the total porosity of saturated media because the relaxation effect can make the MRS signal shorter than that which the equipment is able to detect. Because the relaxation time is longer for free water (some tens to some thousands of ms) than for bound water (some units to some tens of ms), the MRS water content is a rough estimation of the kinematic porosity (often called the effective porosity) of the saturated zone if the porosities of the dead-end and unconnected pores are neglected (see Lubczynski and Roy 2003, and Fig. 3), thus

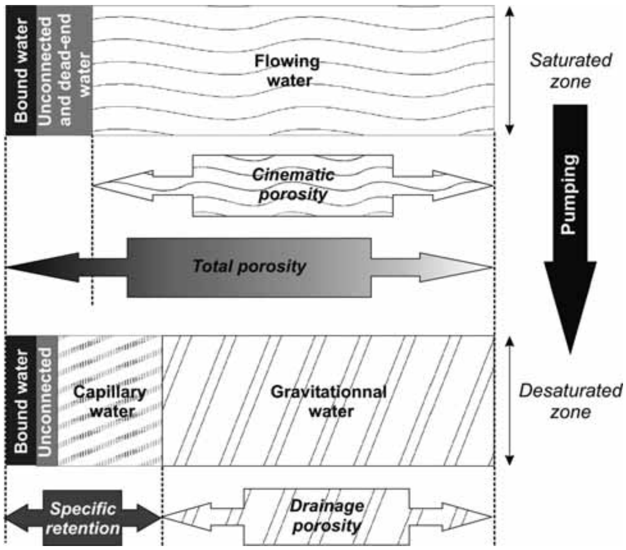

FIGURE 3
Aquifer storativity concept (modified from de Marsily 1986).

$$w_{\mathrm{MRS}} \approx n_c, \tag{6}$$

where n_c is the kinematic porosity.

To quantify the volume of water that is stored and is usable by pumping in saturated aquifers, hydrogeologists use the concept of storativity.

• In confined aquifers, the amount of water released from the reservoir by well abstraction depends on the elastic properties of the matrix and the water (de Marsily 1986). The water is released because the pressure of the system changes, due to the water drawdown created by pumping. In this context, the aquifer storativity is measured by the so-called storage coefficient given by

$$S_e = \rho g(\alpha/_n + \beta)en, \tag{7}$$

where ρ is the mass per unit volume of water, g is the gravitational constant, α and β are the compressibility coefficients of the aquifer skeleton and water respectively, e is the saturated thickness and n is the total porosity. The MRS water content w_{MRS} is thus linked to the storage coefficient through the total porosity of the medium.

• In unconfined aquifers, the amount of water released from the reservoir by well abstraction depends mainly on gravity forces (the elastic component is neglected). The storativity is quantified by the drainage porosity parameter (often called specific yield S_y). The drainage porosity differs from the kinematic porosity that measures the quantity of water flowing in a saturated reservoir as follows: $S_y \approx n_c - S_r$, where S_r is the water that cannot be released by gravity, known as the specific retention capacity. consists of bound water and a portion of water retained against gravity by capillary forces (if we neglect the unconnected pore porosity, Fig. 3). Then, the drainage porosity is linked to the MRS water content w_{MRS} as follows:

$$S_y \approx w_{\mathrm{MRS}} - S_r. \tag{8}$$

• While pumping, a confined aquifer can become locally unconfined if the water level is drawn down below the confining layer. In this case, the storativity is linked both to the storage coefficient and to the drainage porosity. The drainage porosity of such a confined aquifer is called the specific drainage by Lubczynski and Roy (2003).

The complexity of the hydrogeological storativity parameter does not yield a unique link with the MRS water content. As for the hydrogeological storativity, two MRS estimators can be proposed (Vouillamoz 2003):

$$\begin{aligned} S_{\mathrm{e\_MRS}} &= \left(w_{\mathrm{MRS}}\Delta z\right)C_1, \\ S_{\mathrm{y\_MRS}} &= w_{\mathrm{MRS}}C_2, \end{aligned} \tag{9}$$

where $S_{\mathrm{e\_MRS}}$ is the MRS estimator of storativity in a confined aquifer (the storage coefficient where Δz is the saturated thickness derived from MRS) and $S_{\mathrm{y\_MRS}}$ is the MRS estimator of specific yield in an unconfined aquifer (the drainage porosity). C_1[L^{-1}] and C_2 [no units] are parametrization factors that need to be calculated by comparing MRS estimators with hydrogeological storativities obtained from pumping test results.

MRS transmissivity estimator

Field experiments indicate a good relationship between the average size of rock pores and the MRS decay-time constant, as expressed by (4). This link led Kenyon (1997) to go further and to propose an empirical formula of the intrinsic permeability of rocks:

$$k_{\mathrm{MRS}} = C_p w^a T^b, \tag{10}$$

where C_p, *a* and *b* are parametrization factors that are site specific. Since the intrinsic permeability is linked to the hydraulic conductivity, Legchenko *et al.* (2002) proposed using the water content and the relaxation time as derived from MRS to estimate the hydraulic conductivity *K*. Various experiments were carried out to check the appropriate value of the factors *a* and *b* and the formula chosen for this survey in Burkina Faso is

$$\begin{aligned} K_{\mathrm{MRS}} &= C_p w(z)T_1^2(z), \\ T_{\mathrm{MRS}} &= K_{\mathrm{MRS}}\Delta z, \end{aligned} \tag{11}$$

with a=1, b=2; Δz is the saturated thickness, C_p[LT^{-3}] is a parametrization factor that must be calibrated from pumping test data, and K_{MRS} and T_{MRS} are respectively the MRS hydraulic conductivity and transmissivity estimators.

FIELD RESULTS

Reservoir geometry

In an unconfined aquifer, the static water level (SWL) corresponds to the top of the saturated zone and it should be estimat-

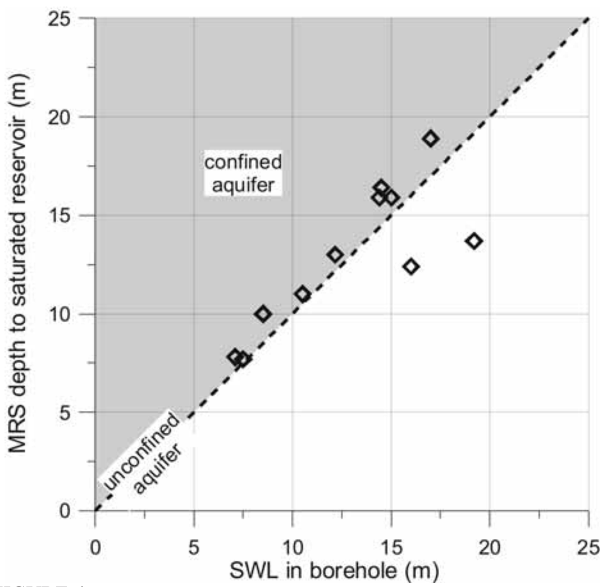

FIGURE 4
MRS depth to saturated aquifer against SWL in borehole. Dashed line: SWL for unconfined aquifers; grey area: area of possible SWL of confined aquifers.

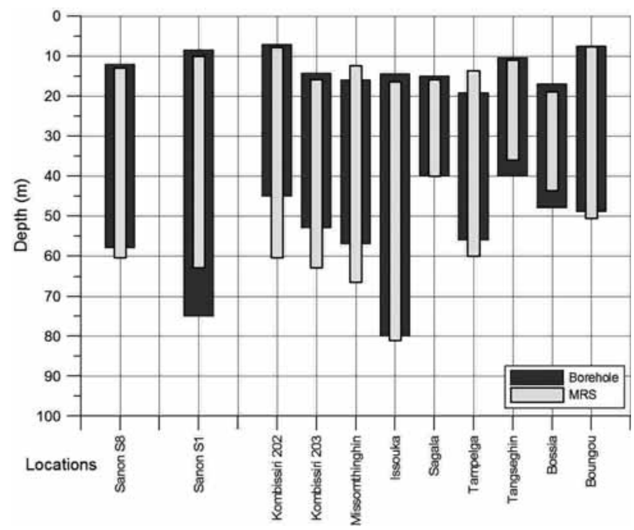

FIGURE 5
Reservoir geometry estimated by MRS and boreholes.

ed by MRS. However, when the depth of saturated media indicated by MRS corresponds to the top of a confined aquifer, the SWL that is measured in the borehole is obviously higher (see aquifer characteristics, Fetter 1994).

Figure 4 shows that most of the surveyed sites are unconfined or slightly confined, which can also be deduced from the lithology in the borehole reports. The reservoir geometry is described by MRS using a 1D assumption with a relative average difference from the borehole data of ±12% for the depth to the top of the saturated reservoir (if we consider that all the sites are unconfined) and ±17% for the depth to the fresh bedrock (if we consider that it is the bottom of the aquifer) (Fig. 5).

Reservoir storativity

On the one hand, the borehole lithology and the good correlation obtained between the SWL and the top of saturated layers indicate that most of the sites are unconfined, but on the other hand the low values of storativity obtained by the pumping tests for half of the sites (less than 10^{-2}) indicate that some aquifers can be confined. As a consequence, MRS storativity estimators for both confined and unconfined aquifers are tested using (9).

The best fits are obtained with C_1=4e^{-3} m^{-1} and C_2=0,28 (Fig. 6). The relative differences between the pumping test storativities and the MRS estimators are ± 79% for the drainage porosity and ± 93% for the storage coefficient, on average, which means that the difference between these MRS estimators is not significant and that storativity is poorly derived from MRS. It could be explained by the simplifications used to calculate MRS estimators (see section 2.2) and by the parameter uncertainty (Table 1).

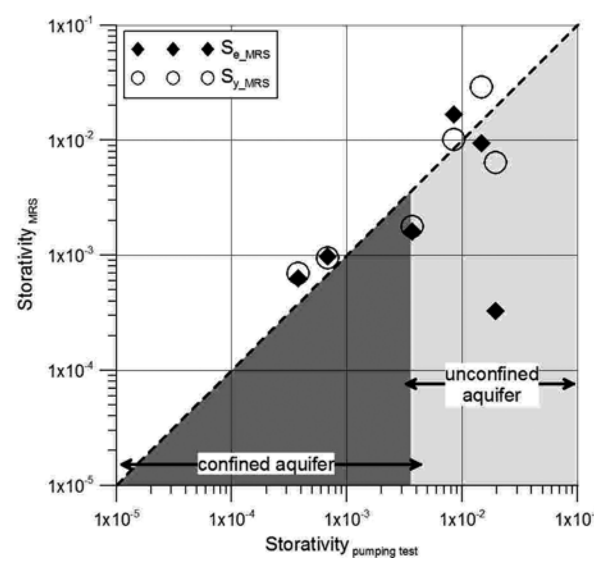

FIGURE 6
Aquifer local storativity. Dark grey: area of common confined aquifers; light grey: area of common unconfined aquifers.

Parameter	Interval	Average difference
Top of saturated zone	From 7.5 to 19.2 m	± 12%
Bottom of saturated zone	From 40 to 80 m	± 17%
Storativity	From 3.7×10^{-4} to 1.95×10^{-2}	± 79% or ± 93% *
Transmissivity	From 5×10^{-6} to 6.8×10^{-4}	± 41%

TABLE 1
Difference between MRS and borehole characterization (* see section 3.2)

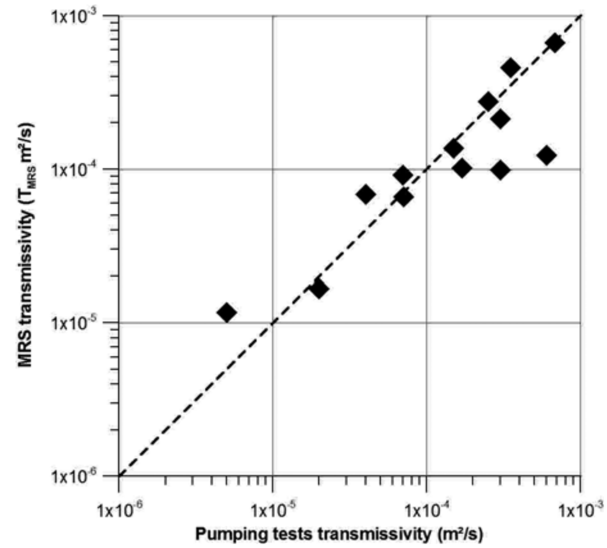

FIGURE 7
Local transmissivity of aquifers.

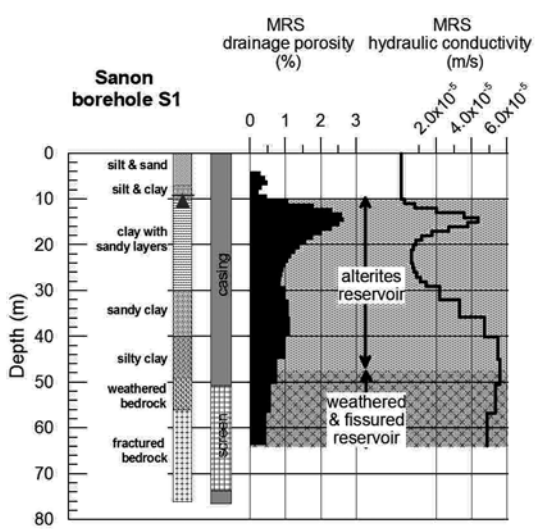

FIGURE 8
Sanon borehole. Description of reservoir units with MRS estimators.

Reservoir	Water content (%)			T^*_1 (ms)		
	Max.	Average	Min.	Max.	Average	Min.
Alterites	6	3	1	600	400	180
Fissured-fractured rock	2.5	1	0.2	1500	650	350

TABLE 2
MRS parameters and reservoir units

The data set is small (6 sites) compared to the sets used for the geometry and transmissivity estimations (respectively 11 and 13 sites). Only a few sites were selected to calculate the storativity from pumping tests because their accurate estimation needs two boreholes at the same location (a pumping well and an observation well).

Because of this small data set, it is not possible to conclude either that these storativity estimators are valid or that one is more appropriate than the other. In order to establish a quantitative correspondence between the water content derived from MRS data and the storativity used in hydrogeology, further research is required.

Reservoir transmissivity

The MRS transmissivities are calculated using (11) and the best fit is obtained with the calibration constant C_p=1.3e^{-9} ms^{-3} (Fig. 7). C_p is calculated so as to reduce the mean difference between MRS and pumping test transmissivities for the whole data set. This mean difference is ±41%, which means that the MRS estimation is sufficiently accurate compared to the data uncertainty (Table 1).

Characterization of reservoir units

For water in alterite reservoirs, the average value of the water content *w* is higher and the average value of the longitudinal relaxation time T_1 is shorter than for water in fissured-fractured reservoirs (Table 2). According to (9) and (11), the storativity is higher and the transmissivity is less for the alterites than for the fissured-fractured zones. This is in accordance with the hydrogeological conceptual model as illustrated for the Sanon borehole in Fig. 8.

However, the observed dispersion of the reservoir parameters is large and an ambiguity still remains when interpreting the MRS data alone. Because the reservoir units can also partly be identified using common rock resistivity measurement methods, a joint interpretation of both MRS parameters and electrical resistivity can be conducted. Figure 9 shows the MRS transmissivity, calculated using (11), against the interpreted rock resistivity obtained from Schlumberger soundings. The reservoir units can be clearly identified in all the geophysical information.

DISCUSSION

Data uncertainty

The average differences between the reference parameters obtained from boreholes and the MRS estimations need to be analysed according to the uncertainty of the parameters (Table 1).

When analysing experimental data, there are almost always several possible values of the surveyed parameter that fit the observed data. Whatever the parameter is, a spread of the parameter values around the selected value is observed. The uncertainty is calculated as ,

$$\iota = \frac{X_{max\_min} - X_{selected}}{X_{selected}}, \text{ with } X_{max\_min}$$

being the value of the parameters that differs most from the selected value $X_{selected}$. The selected value is chosen from the whole experimental data set analysis. It is considered as representative because either it is best fit to the experimental data or it is simply the average of possible values.

The uncertainties in MRS parameters and estimators are due to the raw data quality, the inversion process and the equivalence problem (Legchenko *et al.* 2002; Vouillamoz 2003). However, there are also uncertainties in the aquifer characterization obtained from borehole data because it also depends on the quality of the records and the interpretation assumptions (Vouillamoz 2003). For example, the reservoir geometry is obtained from the analysis of the drilling cuttings under field conditions and is not always very accurate, while the interpretation of pumping tests is conducted with several assumptions (simplification of the model compared to the real situation). Finally, geometry, storativity and transmissivity values that are obtained from hydrogeological surveys also lie within an uncertainty interval (Table 3).

MRS 1D assumption and volume integration

MRS is currently an integrating method with a 1D measurement set-up. The measured data are average values for the whole investigated volume that can be approximated to a maximum of 4 000 000 m^3 for this survey. The MRS records are interpreted with a 1D assumption that considers the subsurface as a succession of horizontal homogeneous layers. In heterogeneous contexts such as crystalline bedrock aquifers, this 1D assumption is not always valid. For example, the geometry of the saturated zone estimated from MRS is not strictly comparable with the one revealed by the borehole that is site specific. Hydraulic conductivity and storativity can also vary laterally according to the degree of weathering and fracturing of the reservoir.

However, the integral character of MRS could be an advantage for hydrogeological purposes as it can define averaged values comparable to those obtained from pumping tests: indeed, the hydraulic properties of rocks estimated by MRS concern a volume of rock that can be compare to that estimated from short-time pumping tests (Vouillamoz 2003).

MRS limiting factor

The difference between hydrogeological and MRS characterization of saturated aquifers is partly explained by the uncertainty of the parameters and by the 1D assumption, but is also due to the limiting factors of the MRS method in a bedrock context.

According to the hydrogeological conceptual model, the deep fractured bedrock can be very hydraulic-conductive if the fractures are open, but it does not contain a large volume of water. Consequently, the amplitude of the relaxation signal produced by hydrogen nuclei present in these fractures is small. It is generally impossible to detect this signal with the current equipment if it comes from a depth greater than half the diameter of the transmitter/receiver (Tx/Rx) loop under low noise conditions (a non-noisy area or noise reduced by the stacking process). This phenomenon, called the principle of suppression, is explained by the decrease in both the MRS signal amplitude and the resolution of inversion with depth (Legchenko and Shushakov 1998). Forward modelling indicates that the minimum detectable water content at a depth of half the loop size is currently 0.5% under normal conditions (stacked noise of about 5 nV) or 0.3% in a very low noise area (stacked noise less than 2–3 nV).

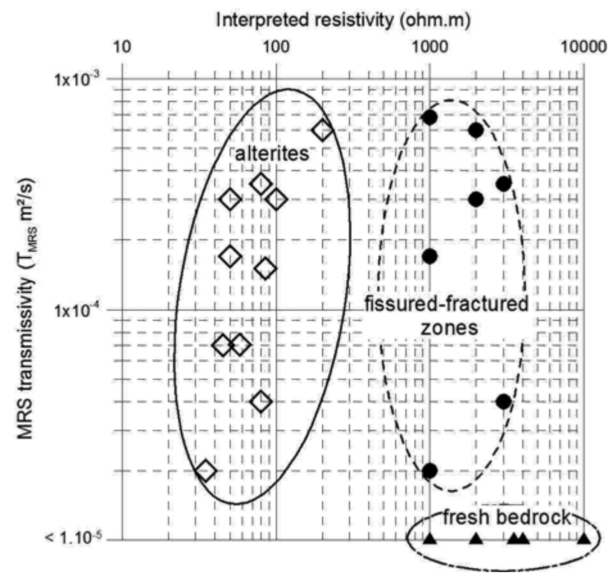

FIGURE 9
Reservoir characterization with MRS estimator and electrical resistivity obtained with Schlumberger soundings.

Hydrogeological characterization				MRS characterization			
Static water level*	Thickness of saturated zone*	Storativity	Transmissivity	Depth to saturated zone	Thickness of saturated zone	Water content	Transmissivity
1%	15%	65%	89%	84%	41%	49%	65%

TABLE 3
Average uncertainties of hydrogeological and MRS estimators (*estimated from field experience but not calculated).

The screen effect is also an important limiting factor of MRS. It consists of reducing the interpreted MRS water content of a deep reservoir when it is topped by a shallower one. This configuration can be common in bedrock aquifers that are describe as multireservoirs aquifers (Fig. 1).

An example of combined screen and suppression principles is shown in Fig. 10: the MRS measurements were carried out with a square loop of side 125 m and signal-to-noise ratio of 1.6. The water content and T_1 decay-time constant values are coherent for the alterites and weathered-fissured units, but almost no signal is detected below 40 m. An electrical logging conducted in this borehole indicates water-productive fractures in the bedrock. These fractures were also identified while drilling but they are not detected by MRS. Thus, the MRS transmissivity estimator does not consider them and is three times lower than the pumping test transmissivity.

Economic analysis and field feasibility

The economic analysis aims to measure the financial impact of MRS on a drilling program. The calculations are carried out by considering the costs of a local private company (for year 2002).

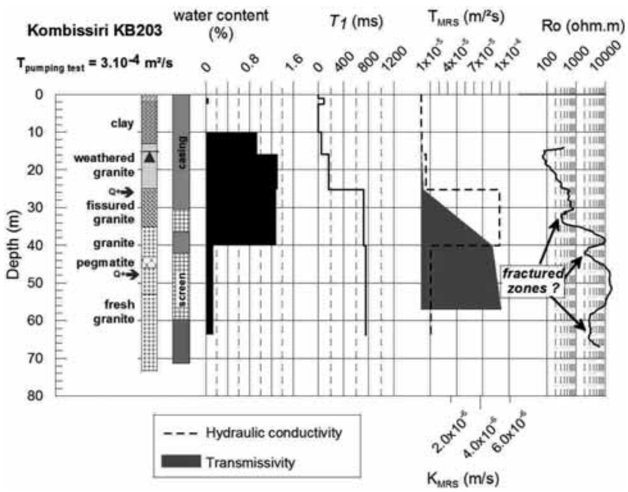

FIGURE 10
Kombissiri borehole. Principle of suppression and the screen effect in MRS. T: transmissivity; K: hydraulic conductivity; Ro: apparent electrical resistivity measured with borehole logging; Q+: water intake measured while drilling.

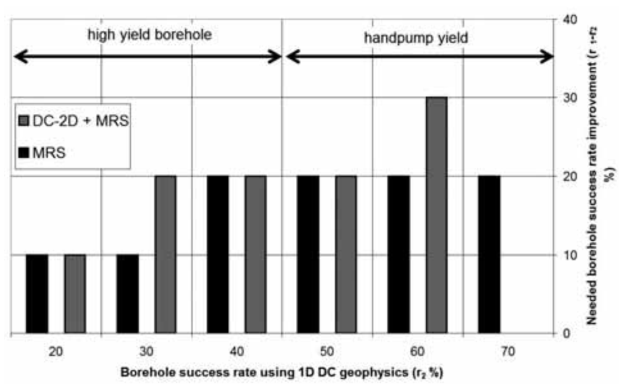

FIGURE 11
Economic boundaries of the use of MRS in drilling programs. 1D DC geophysical methods are electrical resistivity profiling and vertical electrical sounding; DC-2D is 2D electrical resistivity imaging.

These costs include the staff, the logistics and the geophysical equipment (buying, maintenance and depreciation). Eight working months and 100 borehole implementations per year are assumed. The local average cost is € 5350 for a successful borehole and € 3810 for an unsuccessful one.

Calculations show that a geophysical survey saves money on a drilling program when (Vouillamoz *et al.* 2002)

$$G \le bh^- \left[\frac{r_2}{r_1} - 1 \right], \tag{12}$$

where r_2 is the actual borehole success rate, r_1 is the success rate using the new geophysical methods, bh^- is the average cost of an unsuccessful borehole and G is the average cost of the geophysical surveys, per borehole.

Figure 11 shows the economic boundaries, computed with (12), for saving money when using the new geophysical methods. Starting from the local borehole success rate, using common 1D methods, in Burkina Faso (electrical resistivity profiling and Schlumberger sounding), Fig. 11 shows the minimum improvement in the success rate which must be reached to save money by using the new geophysical methods. For example, in some parts of the Burkina Faso crystalline bedrock region, the success rate of drilling programs that aim to install handpumps (yield of about 1 m^3/h) is about 70%: the use of MRS saves money if the borehole success rate is improved by 20% and reaches 70+20=90%, which does not appear to be realistic. However, as soon as the objective is to implement a high-yield borehole (yield > 5 m^3/h), the common success rates are lower than 50% for any crystalline bedrock area of the country. In this situation, the use of MRS or even the joint use of MRS and 2D resistivity imaging can reasonably improve the success rate by 10–20% and saves money on the drilling program. This is the case for all the areas in the country where the success rates are low (it can be as low as 30%, even when looking for a handpump yield) because of the complex geology.

For the MRS set-up in Burkina Faso, we used a square Tx/Rx loop of side 125–150 m. Such a large loop enables enhancing of the amplitude of the relaxation signal, which is quite low in this geological context (the amplitude ranges from 60 to 300 nV). To improve the signal-to-noise ratio, a large number of stacks were necessary (100–500).

This configuration achieves good quality data (the signal-to-noise ratio ranges between 1.6 and 12 with an average of 4.4) but it requires a fairly long acquisition period. Between 6 and 24 hours were needed to conduct a complete sounding of 14 excitation moments in Burkina Faso. Apart from the time-consuming drawbacks, this long acquisition period could lead to the problem of geomagnetic field instability because of its strong natural daily variations. Expressed as a Larmor frequency, a daily variation of 5 Hz was commonly observed during a sounding. This may complicate the interpretation of raw data, especially for the higher excitation moments (q>5000 A.ms) that are mainly concerned. However, a newly developed mathematical model which allows interpretation of MRS data in a time-varying geomagnetic field may help to solve this problem (Legchenko 2004).

CONCLUSION

The MRS method can be used for efficient improvement of the characterization of saturated zones of crystalline basement aquifers in Burkina Faso. On average, one sounding could be completed daily. It can deliver the following information:

- The depths to the top and to the bottom of a saturated reservoir are determined by MRS with mean differences with the borehole data of ±12% and ±17%, respectively. Eleven sites were used to obtain this result, from a shallow SWL at 7.5 m depth to an aquifer bottom at 80 m depth.
- The transmissivity is estimated by the MRS estimator with a

mean difference with the pumping test interpretations of ±41%. Thirteen locations were used to calibrate the MRS estimator, for a domain ranging from a semi-permeable medium ($T<10^{-5}$ m^2/s) to a highly productive aquifer ($T>5.10^{-4}$ m^2/s).

Nowadays, the storativity cannot be estimated from MRS with high accuracy. The proposed MRS storativity estimators need to be confirmed with larger data sets, and further research needs to be carried out.

The main limitations of MRS applied in hard-rock areas are the 1D assumption in highly heterogeneous contexts, the screen and the suppression problems, when looking for multireservoir aquifers and narrow fractures deeper than about half the side of the Tx/Rx loop.

Our overall estimation suggests that MRS is a useful tool to characterize the saturated zone of aquifers in crystalline rocks. It has to be used within the framework of a hydrogeological strategy, and its joint use with 1D electrical sounding and 2D electrical resistivity imaging promises support to hydrogeologists for both borehole implementation and groundwater reserves evaluation.

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