Protonic Magnetic Resonance Properties of the Hard Rocks Fracture Zones in the Department of Donga

Euloge N. Yalo, Bertrand H. Akokponhoué and Marc Youan Ta

Abstract—The Donga Department is located in the northwest of Benin in an area made up of crystalline and crystallophyllic basement rocks where most of the groundwater resources are found in the area of weathered and conductive fractures. The carrying out of drilling campaigns in this department are often crowned with a significant number of negative boreholes (<0.7 m³/h) due to the poor choice of sites for drilling. This leads to situations of difficulties in supplying drinking water, or even more frequent shortages during the dry season. The objective of this study is to use geophysical methods to characterize the fractured basement areas, with a view to improving the implantations and the sustainable management of the aquifers they contain. The application of the Protonic Magnetic Resonance (PMR) method made it possible to determine the hydrogeological properties of the fracture zones. As a result, the determination of the hydrodynamic properties shows that the $W_{PMR}$, $T₁$ and $S_y$ values in 5 different localities of the study area are between 4 and 13% respectively, between 150 and 212.5 ms and between 2.3 and 8.2%. The minimum height of the water slide is 820 mm and the maximum height is estimated at 3672 mm for a water reserve of up to 2313 mm in the Donga gneisses. It emerges from this study that in the department of Donga the PMR water content is also a function of the particle size, $T₂$ of the fractured zone.

Index Terms—Weathered Zone (WZ), Fractured Zone (FZ), Benin, Geophysics, Protonic Magnetic Resonance (PMR).

I. INTRODUCTION

In the middle of the basement rocks, discontinuous aquifers are affected by tectonic dislocations which generate zones of fractures and weathered layers. The detection of tectonic dislocations contributes to the understanding of the functioning of the underground system [1].

Most of the groundwater resources in the Donga department are contained in basement fracture reservoirs. The work of [2], [3], [4] under the same conditions in West Africa, [5], [6] in Greece and [7], [8] in India have proposed a hydrogeological prospecting approach. This approach makes it possible to combine geology, hydrogeology and geophysics on the one hand. The combination of these methods has made it possible to characterize fractured zones favorable to the establishment of boreholes in Ivory Coast ([9], [10], in India [8], in Burkina Faso, [11] and in Benin [12], [13], [14]. Then, the present study aims to identify the hydrogeological properties of fracture zones favorable to the establishment of boreholes in the department of Donga. This study will contribute to improving prospecting of basement fracture aquifers for access to water for populations in Africa.

II. GEOGRAPHIC, GEOLOGICAL AND HYDROGEOLOGICAL CONTEXT OF THE DONGA DEPARTMENT

The department of Donga is located in the northwest of Benin, between 08°28’ and 10°02’ north latitude and between 1°20’ and 2°14’ east longitude. It covers an area of 11.126 km² with a population of approximately 543 130 inhabitants. It has a very dense hydrographic network with a total length of the drains estimated at 7870 km, i.e. a drainage density of 1.66 km/km² (Fig. 1a). The relief of the Donga department is represented by the digital terrain model (Fig. 1b). This model shows the different elevation levels of the Donga department. There are essentially two types of relief. A rugged terrain, located in the northwest and central part, especially northwest of the village of Alfa-kpara and Tanéka Koko (Couffé Mount, Tanéka Mount, d’Alédjo-Koura Mount). It is the domain of the high peaks of the Donga department where the altitudes generally exceed 660 meters. A monotonous relief, located particularly in the South-East, North-East parts, where the altitudes vary from 177 to 382 m. It is a vast, slightly inclined peneplain sharing the runoff from the Donga watersheds in the northeast and that of the Oueme watershed in the southeast. Small rivers criss-cross the peneplain in a disorderly fashion, sculpting its surface and giving it a bas-relief character.

Geologically, the study area is comprised between the outer and inner zone of the Pan-African Dahomeyides chain, comprising the structural unit of the Atacora and the structural unit of the Benin plain (Fig. 2). In lithological terms, these units are respectively made up of three large ensembles (quartzites, schists and sandstones) and four large ensembles: migmatites, granulites, matasediments, gneisses with a high degree of metamorphism [15], [16]. Structurally, the department of Donga has been affected by several phases of tectonic deformation, the most important of which are: The Eburnean and Pan-African orogeny (650-600 M.a.).

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These different events affected the territory by numerous fractures generally structured N00°-20° and N20°-30°, the most important of which is the Kandi fault, which is a transcontinental lithospheric fracture crossing the whole territory of Benin. The work of [15], [17] has shown the complexity of this zone, both locally and regionally. In addition to tectonics, other processes such as weathering, surface decompression, seismicity, etc... may favor the establishment of fracturing [18], [19], [20], [21]. Hydrologically, there are two types of aquifers: weathered aquifer and fractured aquifer. The first hydrogeological studies in the basement zone in Benin were carried out by [22], [23], [24] with a view to a better knowledge of the hydrogeological characteristics of this very complex environment and the possibilities of setting up wells for the water supply of the populations. During the last century, several works have increased the knowledge of the hydrogeology of the Precambrian basement rocks of West Africa and many authors [23], [25], [26], [27], [28] have shown that this environment contains a stock of groundwater resources likely to supply populations. Consequently, the work of [21] on groundwater has classically made it possible to establish different conceptual models of underground aquifers that have evolved over time. These models of aquifer structures show three main zones constituting potential reservoirs, controlled by the type of fracturing encountered: the weathered layer, the fissured horizon and the hard rock (Fig. 3) locally affected.
by geological discontinuities and deep fracturing. In this study we refer to Wyns' model and our fracture zones are located in the fissured layer just below the base of laminated layer (Fig. 3).

III. METHODOLOGY

A. PMR surveys

The PMR soundings were conducted with NUMIS plus RGT equipment. Generally, to implement an PMR sounding, a transmitting loop is deployed on the ground surface from which an alternating electrical current is injected. This alternating electrical current injected into the loop creates an excitation field that varies according to the Larmor frequency. This frequency is calculated after measuring the field amplitude. In fact, the implementation of an PMR survey is always conditioned by two activities. Firstly, it consists of measuring the electromagnetic noise of the site to be studied. Then, using a proton magnetometer, the ambient H₀ geomagnetic field of the site is measured. This makes it possible to determine the resonance frequency of the protons and to construct the inversion matrix of the acquired data. The size and type of loop to be deployed at a site is related to the depth to be investigated and the resistivity of the ground. Different antenna geometries (square or "8") can be used. But on a noisy site, it is advisable to use a loop in the form of an "8". This often significantly improves the signal-to-noise ratio [29], [11].

Depending on the amplitude of the electromagnetic noise, the square loop was used at two sites and the figure-of-eight loop at the other three sites (Table I). The precise location of these five boreholes is shown in Fig. 6. The characteristics of the acquisition parameters of the PMR measurements used in the Department of Donga are shown in Table I.

| TABLE I: CHARACTERISTICS OF MRS SURVEYS |
| Survey | Loop shape and size | Larmor frequency | Average number of stacks |
| S1 (Tanëka Koko) | Eight 125 m | 1418 Hz | 550 |
| S2 (Donga) | Square 125 m | 1413.5 Hz | 130 |
| S3 (Ara) | Eight 75 m | 1412 Hz | 400 |
| S4 (Séméré) | Eight 125 m | 1416.8 Hz | 600 |
| S5 (Daranga) | Square 125 m | 1411 Hz | 250 |

The NumRun acquisition software is usually used to invert PMR surveys. All the soundings in this study were conducted with fourteen pulses. Several authors [29], [30] deemed it necessary to specify before any treatment that the water content (W₉₀) and the time constant decay T₂* are not hydrogeological parameters. The inversion of E₀(q) data provides the depth, thickness and water content of each water-containing layer. The W₉₀ water content can be defined as follows (Equation 1):

\[ W_{PMR} = \frac{V_0}{V} \times 100 \]  

With V₀ – water subjected to a homogeneous magnetic field called open water.

This equation implies that PMR water content is less than total porosity [31]. The two borderline cases are W₉₀ = 0 for dry rock and W₉₀=100% for lake water.

In the end, S₀ < W₀ < Φ₀; the PMR water content is therefore a quantity between the drainage porosity and the total porosity. The signal decay time constant, T₂*, is related to the environment in which the protons are located. The main factors that will influence this time T₂* are the average pore size and the inhomogeneity of the static field [32]. Table II gives indicative T₂* values for a few rocks:

| TABLE II: T₂*: DECAY TIME CONSTANT [32] |
| Types of aquifer formation | Decay time T₂* (ms) |
| Sandy clay | <30 |
| Clayey sands, very fine sand | 30-60 |
| Fine sand | 60-120 |
| Medium sands | 120-180 |
| Coarse-grained and gravelly sands | 180-300 |
| Gravel | 300-600 |
| Surface water | 600-1500 |

In this study, the modelling software Samovar V11.5 [33] was used to invert the data. It offers the possibility of at least qualitative interpretation of the phase of the PMR signal.

Thanks to the SamovarMod subroutine the determination of W₉₀ and Δz is possible from numerical modelling. The aim is to find a model that fits well with the data collected in the field. The fit is considered acceptable if the difference between the field data and the "computed" data is less than the average noise contained in the data [11].

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B. Estimation of $S_y$ and the $R_{PMR}$ reserve from $W_{PMR}$ and $\Delta Z_{PMR}$

Using the $W_{PMR}$ water content, and the saturated thickness PMR ($\Delta Z_{PMR}$), the drainage porosity ($S_y_{PMR}$) and $R_{PMR}$ reserve of the fracture zone can be determined. The equations (Equations II and III) below allow the calculation of the following parameters:

$$S_y = W_{PMR} \times b_i$$  

(2)

$$R_{PMR} = S_{yPMR} \times \Delta Z_{PMR}$$  

(3)

With: $W_{PMR}$ the average water content of the aquifer; $\Delta Z$ the thickness of the aquifer; $b_i$ – Calibration factor. These were estimated with the value 0.63 [34].

IV. RESULTS AND DISCUSSIONS

The results of the five PMR surveys carried out are generally of good quality as the signal-to-noise ratios are all above 2. The lowest ratio was found in the S5DR survey with 2.2 and the highest in the S4SE survey with 12.

An example of a signal-to-noise ratio of 8.3 for the PMR survey at the Ara site is shown in Fig. 5.

Fig. 5. Signal to Noise Ratio (125/15) on the PMR sounding of the Ara site

A. Water content, decay time and PMR water column

1) SITN survey

The analysis of this survey reveals that for all the pulses, the signal is clearly free of noise. The signal amplitude at this site has the highest signal-to-noise ratio of all the soundings with 6.5. The model fits the signal well for an average noise of 11.43 nV (Fig. 6). The inverted data indicate a $W_{PMR}$ of 6.5%, a $T_2^*$ of 176 ms and a saturated thickness of 23.4 m. In addition, the depths of the reservoir roof and impermeable bedrock are estimated as a function of static levels and bedrock depths revealed by drilling [35]. Thus, the depth of the roof is underestimated by 2.6 m by the PMR and that of the bedrock is overestimated by 1.2 m.

Fig. 6. Presentation of PMR SITN survey. a) Survey log b) Lithologs in the vicinity of the survey and c) Inversion results

2) S4SE Survey

The model fits well with the data set from this survey, which has a signal-to-noise ratio of 5.16. For the other pulses, the signal is well separated from the noise. Thus, the inversion of the data indicates 7.5% $W_{PMR}$ and 171.7 ms for $T_2^*$ for a saturated thickness of 50 m. The average noise for this borehole is 18.28 nV, concerning, the depth of the bedrock we note that it is overestimated by 1.4 m by the borehole and that of the static level is underestimated at 2.6 m (Fig. 7).

Fig. 7. Presentation of PMR S4SE. a) Logs b) Lithologs in the vicinity of the borehole and c) Results of the inversion

3) SCBA S3 Survey

The model fits well with the data set from this survey, which has a signal-to-noise ratio of 5.6. For the other pulses, the signal is well separated from the noise. Thus, the inversion of the data indicates 3.9% $W_{PMR}$ and 150 ms for $T_2^*$ for a saturated thickness of 20.5 m. The average noise for this borehole is 8 nV, concerning, the depth of the bedrock we note that it is overestimated by 3 m by the borehole and that of the static level is underestimated at 2 m (Fig. 8).

Fig. 8. Presentation of the S3ARA PMR borehole. a) Borehole log b) Lithologs in the vicinity of the borehole and c) Inversion results

Table III summarizes the overall results of the five PMR surveys. Indeed, these results reveal that the PMR water content ($W_{PMR}$) in the department of Donga varies according to the investigated sites and the geological formations in place. This variation is between 4 and 13%. The decay time is between 150 and 210ms. The water content in the weathering of the Donga is a function of the grain size governed by the pore size ($T_2^*$). This correlation is 0.9 (Fig. 9). The weathering with coarse sand granulometry ($T_2^* = 210$ ms) has a water content twice as high as that of medium sand granulometry ($T_2^* = 176$ ms).
TABLE III: SUMMARY OF SOME PARAMETERS FROM THE RESULTS OF THE PMR INVERSIONS

| Surveys | \( W_{PMR} \) (%) | \( T_2^* \) (ms) | Water-bearing roof (m) | Saturated thickness (m) | \( (W_{PMR} \Delta x) \) (mm) |
|---------|-------------------|-----------------|------------------------|------------------------|---------------------------|
| S1TN    | 6.5               | 176             | 4.6                    | 23.4                   | 1521                      |
| S2DG    | 9                 | 175             | 4.2                    | 40.8                   | 3672                      |
| S3ARA   | 4                 | 150             | 1.5                    | 20.5                   | 820                       |
| S4SE    | 7.5               | 171.7           | 3.8                    | 22.2                   | 1665                      |
| S5DN    | 13                | 210             | 5.4                    | 24.6                   | 3198                      |

Fig. 9. Relation \( T_2^* \)- PMR water content

B. Drainage porosity (\( S_{y_{PMR}} \)) and water reserve (\( R_{PMR} \))

Determination of \( S_{y_{PMR}} \) and \( R_{PMR} \) values of aquifers in the department of Donga was made possible through the use of equations II and III and the work of [34]. The analysis in Table IV shows that the \( S_{y_{PMR}} \) values of the aquifers in the department of Donga vary from 2.52 and 8.19 per cent with an average value of 4.85 per cent. As for the \( R_{PMR} \) reserve of the studied reservoirs, it varies between 517 mm at the S3AA site and 2313 mm at the S2DG site.

TABLE IV: \( S_{y_{PMR}} \) and \( R_{PMR} \)

| Surveys | \( W_{PMR} \) (%) | Saturated thickness \( \Delta x \) (m) | \( S_{y_{PMR}} \) (%) | \( R_{PMR} \) (mm) |
|---------|-------------------|--------------------------------------|-------------------|------------------|
| S1TN    | 6.5               | 23.4                                 | 4.1               | 958              |
| S2DG    | 9                 | 40.8                                 | 5.67              | 2313             |
| S3AA    | 4                 | 20.5                                 | 2.52              | 517              |
| S4SE    | 7.5               | 22.2                                 | 4.72              | 839              |
| S5DN    | 13                | 24.6                                 | 8.19              | 2015             |

C. Analysis of PMR properties as a function of geological formations

The PMR hydrological properties of the weathering layers are intimately linked to the geological formations from which they are derived. Indeed, the analysis of the results from the PMR surveys shows that the low PMR (\( W_{PMR} \)) water contents (4%) are observed in the Djougou gneisses while the high \( W_{PMR} \) water contents (13%) were recorded in the granitoid migmatites (Table V). As for water levels (\( W_{PMR} \Delta x \)), the smallest (0.82 m) were also observed in the Djougou gneisses and the largest water column (3.67 m) was recorded in the Donga gneisses. The granitoid migmatites have a high drainage porosity (\( S_{y_{PMR}} = 8.19\% \)) compared to other formations in the study area. The weathering from the Donga gneisses and granitoid migmatites contain the largest groundwater stocks in the Donga Department with 2313 mm and 2015 mm respectively, i.e. double the stocks identified by [36] in the basement rocks area.

TABLE V: RELATIONSHIP OF PMR PROPERTIES TO GEOLOGICAL FORMATIONS

| Surveys | Geological Formations | \( W_{PMR} \) (%) | \( T_2^* \) (ms) | \( (W_{PMR} \Delta x) \) (mm) | \( S_{y_{PMR}} \) (%) | \( R_{PMR} \) (mm) |
|---------|-----------------------|------------------|-----------------|--------------------------|-------------------|------------------|
| S1TN    | Kara’s Orthogneiss    | 6.5              | 176             | 1.52                     | 4.1               | 958              |
| S2DG    | Gneiss of Donga       | 9                | 175             | 3.67                     | 5.67              | 2313             |
| S3AA    | Gneiss of Djougou     | 4                | 150             | 0.82                     | 2.52              | 517              |
| S4SE    | Granulite             | 7.5              | 171.7           | 1.33                     | 4.72              | 839              |
| S5DN    | Granitoid migmatites  | 13               | 210             | 3.19                     | 8.19              | 2015             |

V. CONCLUSION

The analysis of the PMR surveys carried out made it possible to estimate the \( W_{PMR} \) and \( T_2^* \) values in five different localities in the study area. Indeed, the amplitudes of \( W_{PMR} \), \( T_2^* \), \( S_{y_{PMR}} \) and \( R_{PMR} \) are between 4 and 13%, 150 and 212.5 ms and 2.3 and 8.2% respectively. The values of \( T_2^* \) amplitudes recorded during this study show that the weathering layers of Donga Department have a coarse to medium sand grain size. The calculation of the PMR water column indicates that the gneisses of Donga have the highest water column (3672 mm) and the granitoid migmatites have the highest \( W_{PMR} \) with 13%. The contribution of the ERT is mainly related to the detection of fracture zones with precision on their geometric properties. The contribution of the PMR is relative to the estimation of the hydrogeological properties of the fractured zones in different geological basement rocks context.

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