Hydrogeophysical characterization of bedrock aquifers: the case of the White Bandama upstream watershed (northern Ivory Coast)
Caractérisation hydrogéophysique des aquifères de socle : exemple du bassin amont du Bandama Blanc (nord de la Côte d'Ivoire)

OUEDRAOGO Moussa[1,2], PESSEL Marc[1], DURAND Véronique[1], MARLIN Christelle[1], SAVANE Issiaka[2]
(1) UMR 8148 GEOPS, CNRS, Université Paris-Sud,
91405 Orsay, France
(2) Laboratoire de Géosciences et Environnement (LGE), Université NANGUI ABROGOUA,
02 BP 801 Abidjan 02, Côte d'Ivoire
Email address : moussa.ouedraogo@u-psud.fr

I. INTRODUCTION

The use of hard rock aquifers as the only reliable source of drinking water for people, especially those from rural Africa, has grown considerably. But because of the intrinsic low hydraulic conductivity and low porosity of the basement, hard rock aquifers are complex in many levels, difficult for hydrogeological exploration, different from other types of aquifers, and require technical knowledge to detect and extract significant quantities of water. The lack of sufficient knowledge on this type of aquifers, the flow and the recharge of the groundwater base environment has greatly contributed to irrational use of this resource (Chilton and Foster, 1995). Significant progress has been made recently in the geological and hydrogeological characterization of these complex aquifers (Lachassagne et al., 2001, 2011; Wyns et al., 2004; Dewandel et al., 2006; Durand et al., 2006; and Vouillamoz et al., 2014).

Independent or related factors such as lithology and tectonics play an important role in the mode of occurrence of underground water in the base medium, because together they control (1) the nature and thickness of the weathering, (2) the development of fractures, fault zones of vein structures and geological contacts, (3) the presence of highly porous medium (Holland and Witthüser, 2011). The search for these characteristics under the rock weathering appears therefore very important. The importance of these aquifers for water supply makes imperative the need to characterize, to identify these reservoirs hydrogeologically able of high productivity. Indeed, they can be targets, well fields for drinking water to supply the regions of high population densities with little or no alternative water sources.

Geophysical methods are commonly used for the installation of boreholes in rock aquifers, and most of hydraulic campaigns are always based on common methods of electromagnetic (EM) and / or direct current resistivity (DC) (Yadav and Singh, 2007; Dutta et al., 2006). Among geophysical methods, electromagnetic methods are ideally suited for hydrogeological investigations (Mcneill, 1990). Excellent resolution of the conductive targets make them a very attractive geophysical tool, with large depth of investigation, rapid deployment at the sounding sites while yielding a complete set of parameters useful in determining the electrical resistivity distribution in the ground. The objective of this study is to develop a new methodology to describe the hard-rock aquifers geometry in sub-saharian context. Extensive electromagnetic soundings were combined with the local knowledge of borehole logs to characterize the aquifer in presence.

II. STUDY AREA

The watershed upstream of White Bandama, in northern Côte d'Ivoire, covers an area of 2100 km^2 extending between 5°40' and 6°15' W longitude and 9°15' and 9°50' N latitude (Figure 1). Its climate which

exerts a predominant influence on the different aspects of the basin natural environment is of Sudanese type and is characterized by a dry season (November to May) and a rainy season (June to October), with annual averages rainfall and temperature, respectively 1332 mm and 26.7°C at Korhogo weather station.
The geology of the study area is mainly represented by a succession of bands of Proterozoic crystalline rocks oriented NE-SW, whose ranges are dominated by granitoids, volcano-sedimentary of Birimian age (gabbros, shale, etc.). The observed geomorphic units are plateaus defining a peneplain altitude ranging from 200 to 400 m, and inselbergs up to 800 m.

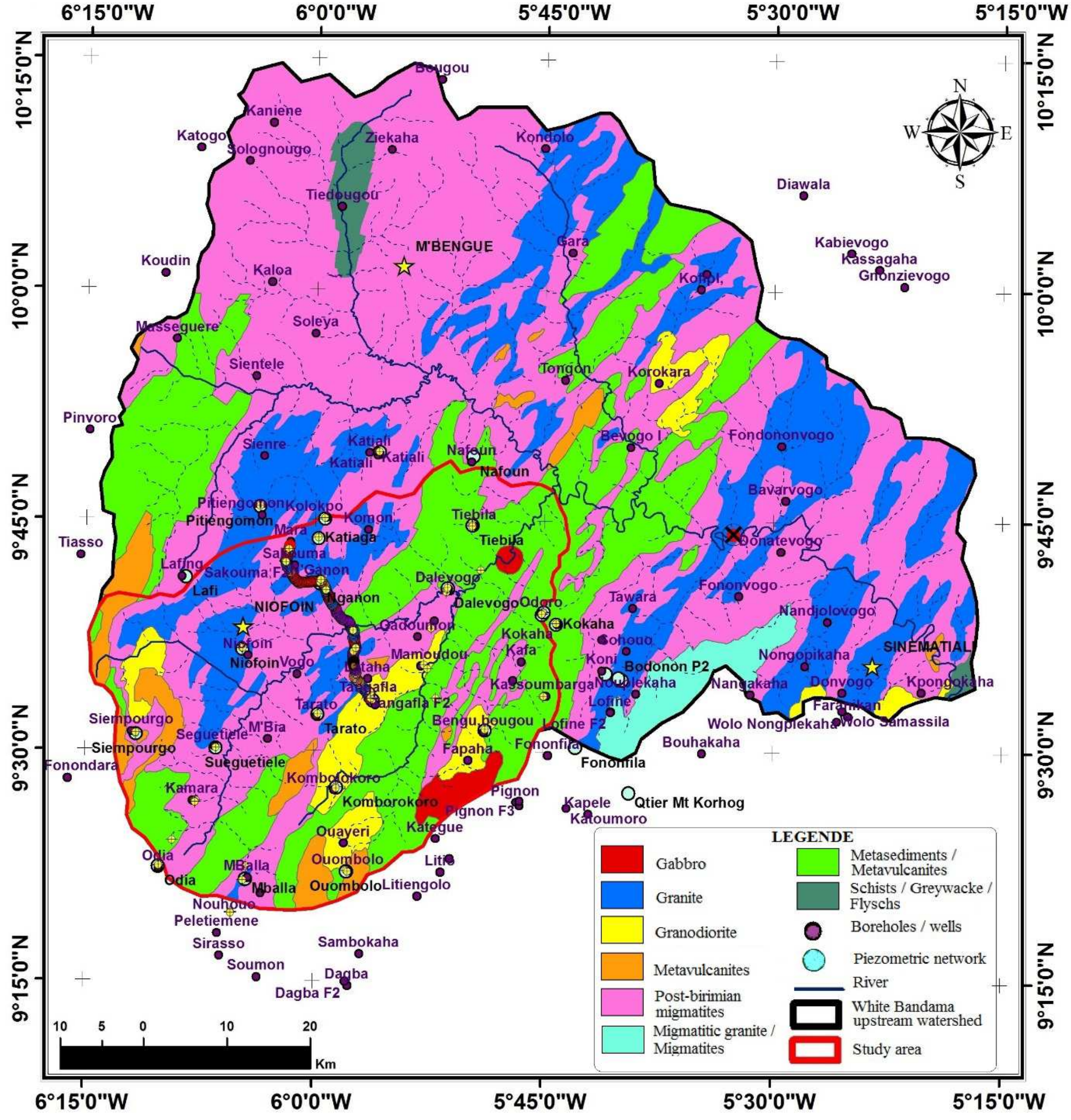

Figure 1 - Geological map of the White Bandama upstream watershed (simplified from Geomines, 1982) with location of survey area, observation wells, electromagnetic (EM) profile.

III. MATERIAL AND METHODS

The method in conjunction profiling / electromagnetic soundings is deployed in the study field, in order to optimize the efficiency of the electromagnetic method in the detection of structures of hydrogeology interest. Electromagnetic induction methods are widely used to determine the distribution of electrical conductivity (or its inverse, resistivity) and are well suited to the delineation of aquifers and clay layers because the electromagnetic field is strongly sensitive to conductive matrices. Electromagnetic sensors are suitable for the detection of conductive targets and have been commonly used to image geological and hydrogeological backgrounds (Shamper et al., 2012).

For field investigations, we used the PROMIS® (Iris Instruments) which is a type of Slingram geophysical measurement equipment, with 10 multifrequency frequency doubling from 110 to 56,320 Hz and separation distance (transceiver) from 20 to 400 m. We used for this study, based on the depth of the target structures of the area investigated, a 100 m cable to connect the transmitter to the receiver. HCP mode (horizontal coplanar) and an approximate height of 1 m coils, this configuration is investigating a depth of 50 m, depth depending on the separation distance, frequency of the electromagnetic field emitted and the electrical conductivity of the medium in which it spread :

$$h = 503.8(\sigma \cdot f)^{-1/2} \qquad (1)$$

where h is the depth in meters, σ the conductivity in $S.m^{-1}$ and f the frequency in Hz.

In EM soundings surveys, the in-phase and quadrature normalized to the primary field and expressed as a percentage, are measured for the frequency range and allows to account for the deep basement structures. This is the same principle as the survey by vertical electrical sounding. A succession of vertical soundings stations on a profile at a constant offset, allows to obtain an image of the subsurface resistivity in profile cross-section.

In order to explore and map the potential aquifer, a long profile / soundings EM survey (about 25 km, 2 measurement points every 100 m) was carried out in 2014 across the watershed and along the NW-SE direction, perpendicular to the direction of the geological structures and cross-checked all along the river, passing by known drilling. In total, in addition to the profile, 30 standard electromagnetic soundings were conducted on known drillings, evenly distributed over the study area and various geological formations.

The data obtained were analyzed and interpreted using the IX1D v3 software (Interpex).

IV. RESULTS, INTERPRETATIONS AND DISCUSSION

Data from the PROMIS sounding S71 are displayed in Figure 2. The geophysical field data fit is acquired with RMS error that varies between 2.11 % and 13 %. We have decided to ignore the two highest frequencies for the inversion of the EM data, as they are noisy. To analyze the EM data, we first apply a smooth inversion to all the PROMIS soundings.

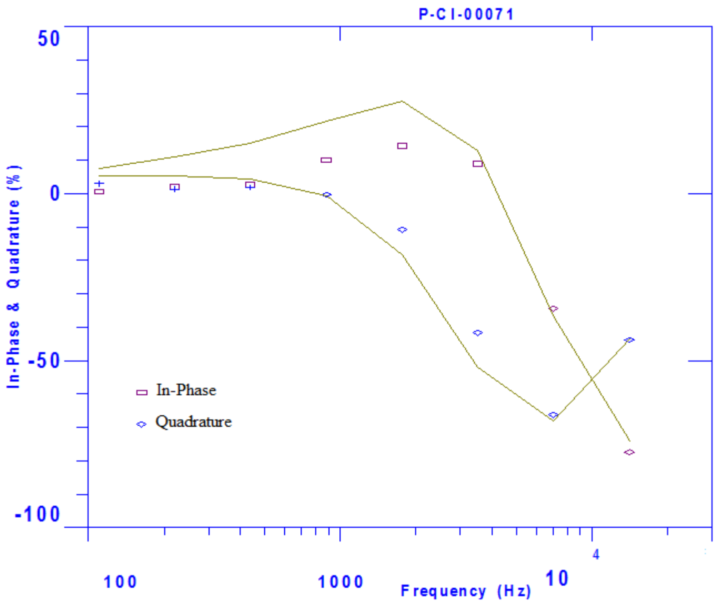

Figure 2 - Sounding S71 data (Ip, quadrature) acquired in Issoukaha

IV. 1 1D layer model typical models and weathering profile

A simple synthetic four-layer model (M1 model), consistent with the geologic context of the Sakouma site (Figure 3), is considered. The conductive first layer (with a resistivity of $\rho1= 10\ \Omega.m$ and a thickness of e1= 2 m) corresponds to a sand soil, the resistive second layer ($\rho2= 100\ \Omega.m$, e2= 24 m) is associated with a granitic sand, the third conductive layer ($\rho3= 10\ \Omega.m$, e2= 14 m) corresponds to a saturated fractured granite, and the resistive last, with a resistivity set to $\rho4= 60\ \Omega.m$, represents the upper component of a granite layer.

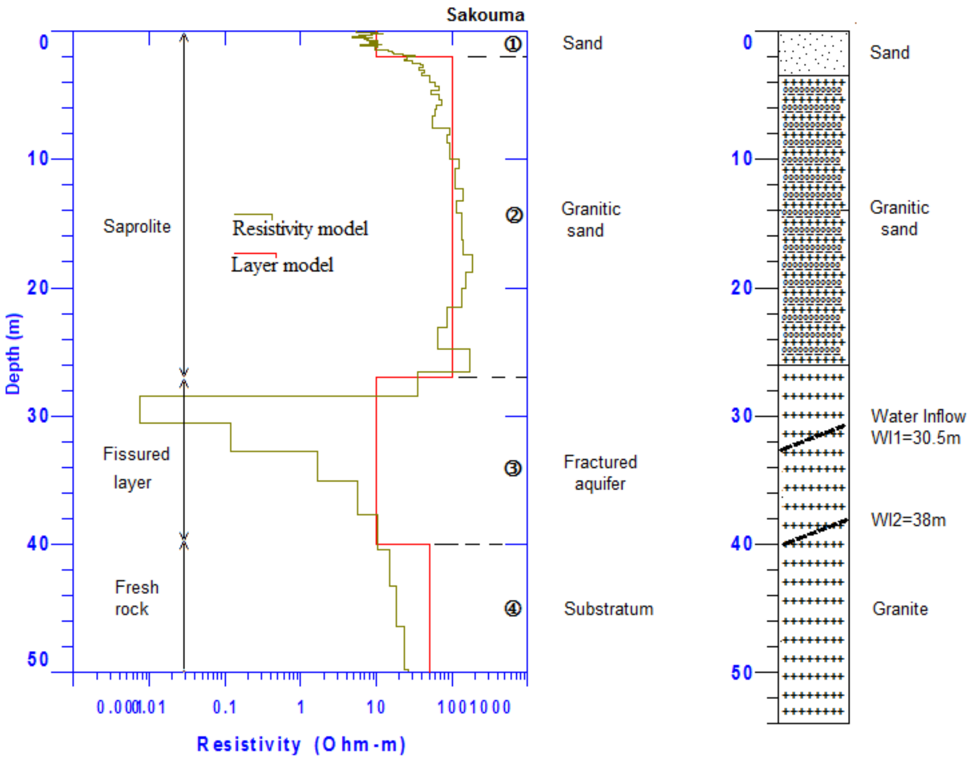

Figure 3 - 1D four-layer inversion model (resistivity/depth) from Sakouma site, with well log

This model worked well for four EM soundings (Siempurgo, Katiali, Kombolokoro and Ouombolo.
Two additional models M2 ($\rho5= 30\ \Omega.m$, e5= 13 m) and M3 ($\rho5= 10\ \Omega.m$, e5= 10 m) are considered to study the effect of a thicker and/or more conductive layer of Issoukaha and Gadoumon sites. All three models are summarized in Table 1.

Table 1 - Synthetic resistivity models with a conductive nearsurface layer

	Resistivity model (Ω.m)	Tickness (m)	Depth (m)
Four-layer model (M1) **Sakouma**	10	2	
	100	24	2
	10	14	26
	60	-	40
Five-layer model (M2) **Issoukaha**	40	2	
	90	10	2
	30	9	12
	70	16	21
	30	-	37
Six-layer model (M3) **Gadoumon**	30	2	
	90	7	2
	20	6	9
	80	15	15
	10	10	30
	150	-	40

The electromagnetic soundings data were interpreted with different models. The five-layer model (M5 Figure 4) is described as follows:
(1) the first layer under the surface, quite conductive (40 Ω.m) and very thin (0 to 2 m), is interpreted as laterite soil;
(2) the second layer (2 to 12 m), more resistive (90 Ω.m), can be interpreted as clayey soil;
(3) the third layer (12 to 21 m), more conductive (30 Ω.m) seem to be weathered rocks and can contain purched groundwater;
(4) the forth one from 21 to 37 m, is more resistive (30 Ω.m) than the previous one, and corresponds to granitic sand;
(5) the last observed layer (thickness unknown) has a resistivity around 30 Ω.m and corresponds to the saturated fractured bedrock.
This model worked well for EM soundings on Odoro and Benguebougou sites (Figure 1).

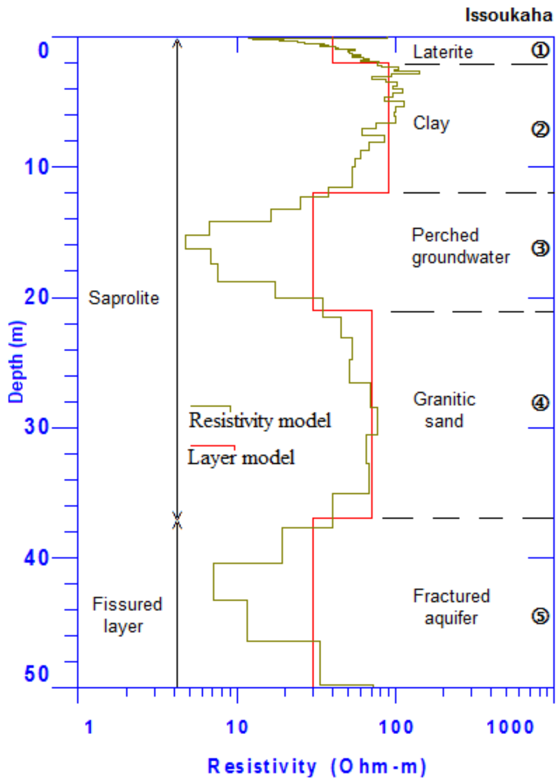

Figure 4 - 1D five-layer inversion model (resistivity/depth) from Issoukaha site

The third model (Figure 5), the six-layer model, from surface to bottom it consists of:
(1) A first layer of about 2 m, with resistivity of 30 Ω.m, associated with the laterite;
(2) A distinct resistive layer with a thickness of 7 m, located at a depth of 2 m below the stations. This layer corresponds to clayey layer;
(3) A thick, conductive (20 Ω.m) layer located at a depth of 9 m. This layer corresponds to the sandy clay sequence, saturated with water;
(4) A more resistive layer, with resistivity of 80 Ω.m at depths down to 15 m. This zone corresponds to a developed weathered schist and is associated with the upper part of the aquifer;
(5) A zone very conductive (10 Ω.m) is associated with the fresh water aquifer in the fractured schist. The thickness of this layer appears to be 10 m large;
(6) Finally, the highly resistive basement is associated with solid schist.

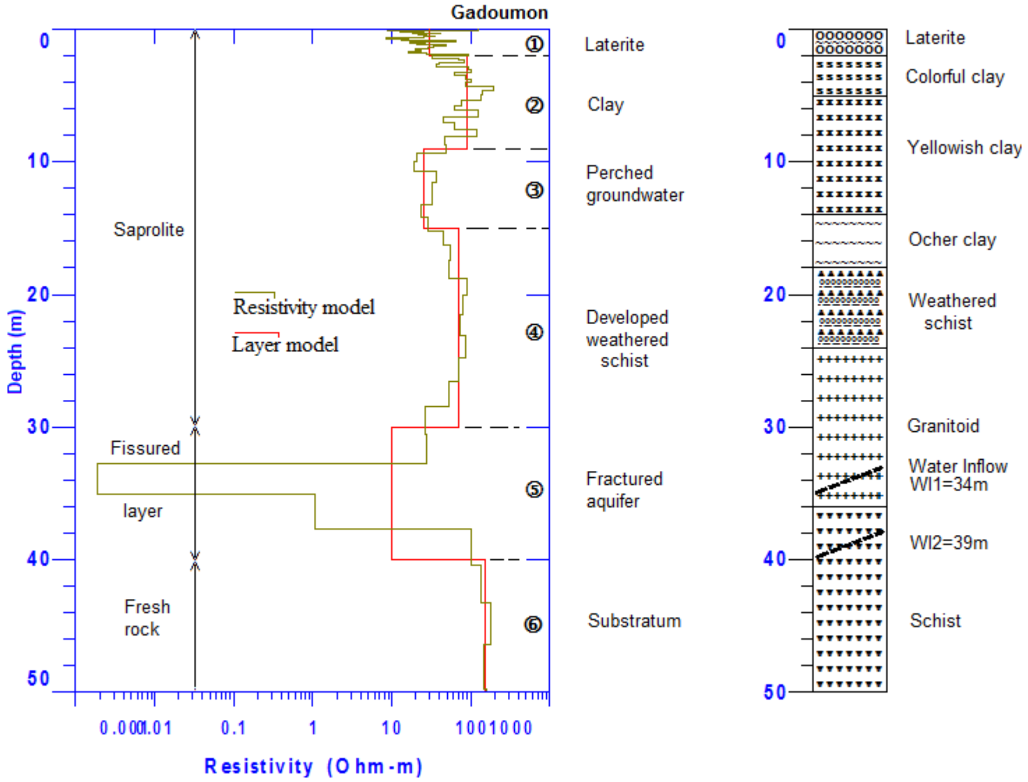

Figure 5 - 1D six-layer inversion model (resistivity/depth) from Gadoumon site, with well log
This model worked well for Kolokpo and Dalevogo sites EM soundings, Figure 1).

IV. 2 2D resistivity section of the investigation area

Geophysical EM soundings surveys allowed us not only to map the major structures more precisely, but also to add subsurface information, such as the thickness of weathered rocks. The aim was to build a local-scale geometrical model of the geological structure of the investigated area.
The EM images, lithologs, resistivity logs and hydraulic parameters are found consistent between each other. The distribution of electrical resistivity of the geological discontinuity is useful providing indices for groundwater detection and aquifer location. Finally, we set an arbitrary boundaries between the fissured zone and the unweathered rock, and between fissured zone and the saprolite. The section (Fig. 6) presents the major fractures and three distinct weathering profile layers (fresh rock, fissured zone and weathered rocks).
Along the profile, armor appears on the surface, confirmed by several outcrops and the shoulder of the topography. Armored areas sometimes thick, are cut by erosion. The underlying alterite seems to be of variable nature (sand, clays depending on the location) and probably fully saturated.

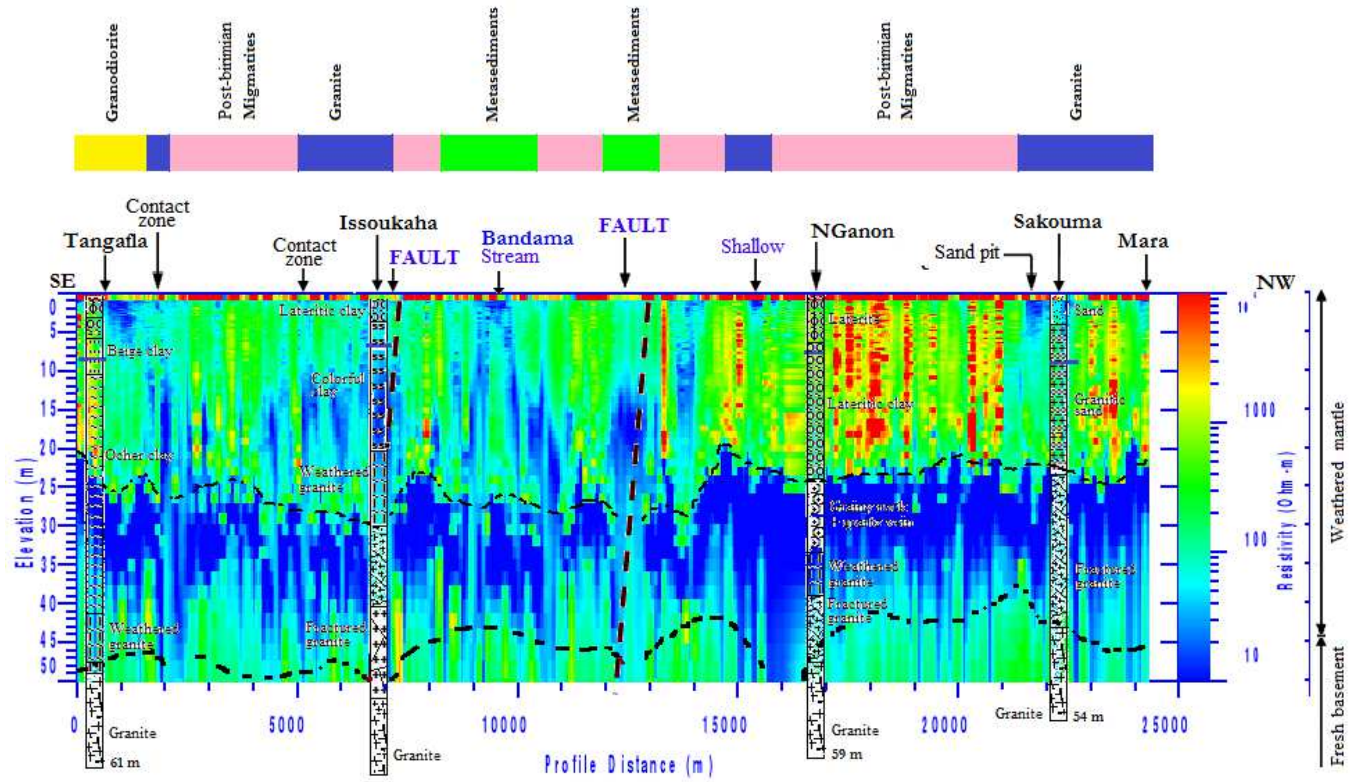

Figure 6 - 1D Resistivity section with geology settings, drilling logs, weathering profile, hydrogeology boundaries under large EM profile SE-NW on investigation area.

From the standpoint of the aquifer geometry, the obtained results give rise to a resistivity section which highlights resistivity contrasts related to geological contrasts one hand, and on the other hand a correlation between the drilling logs and resistivity section obtained (Figure 6).
Two boundaries are derived, a first interface (which is down) corresponding to the top of the basement, and a second interface (which is up) corresponding to the base of lateritic clay and arenas. The groundwater level is less than 10 meters from the ground. So we are in the presence of a water table, on charge under clays, having a variable thickness between 15 and 30 meters. From the geology perspective, there is a difference between the SE and NW that is not represented by the geological map. Resistivity section identifies areas of the geological contacts, major fractures that are recharging drains of the water table.

V. CONCLUSION

The EM Promis method is efficient for geological investigations in hard rock area, especially on our study site, with very little electromagnetic noise. It is efficient to locate aquifers, but not the groundwater level (water table on charge). The method is effective for identifying infiltration and recharging poles such as the river and fault zones that can affect the whole armor and build drains recharge of the aquifer. The EM Promis method was successfully used to determine the aquifer geometry and to delimit the bedrock. The geoelectrical models derived from the EM soundings in the basin show the presence of fractured zones (water inflow) under the saprolite.

References

Chilton P.J., Foster S.S.D. (1995). Hydrogeological characterization and water-supply potential of basement aquifers in tropical Africa. *Hydrogeol. J. 3*, pp. 36–49.
Dewandel, B., Lachassagne, P., Wyns, R., Maréchal, J.C., Krishnamurthy, N.S., (2006). A generalized 3-D geological and hydrogeological conceptual model of granite aquifers controlled by single or multiphase weathering. *J. Hydrol. 330*, pp. 260–284.

Durand, V., Deffontaines B., Leonardi, V., Guerin, R., Wyns, R., De Marsily, G., and Bonjour, J-L., (2006). A multidisciplinary approach to determine the structural geometry of hard-rock aquifers. Application to the Plancoet migmatitic aquifer (NE Brittany, W France). *Bulletin de la société géologique de France, 177 (5)*, pp. 227-236

Dutta S., Krishnamurthy N.S., Arora T., Rao V.A., Ahmed S., Baltassat J.M. (2006). Localization of water bearing fractured zones in a hard rock area using integrated geophysical techniques in Andhra Pradesh, India. *Hydrogeol. J. 14*, pp. 760–766.

Géomines (1982). Inventaire hydrogéologique appliqué à l'hydraulique villageoise. Carte de Korhogo, cahier n°6, République de Côte d'Ivoire, ministère des Travaux publics et des Transports, Direction centrale de l'hydraulique, 44p.

Holland M. and Witthüser K.T. (2011). Evaluation of geologic and geomorphologic influences on borehole productivity in crystalline bedrock aquifers of Limpopo Province, South Africa. *Hydrogeol. J. 19*, pp. 1065-1083.

Lachassagne P., Wyns R., Bérard P., Bruel T., Chéry L., Coutand T., Desprats J.-F. & Le Strat P. (2001). Exploitation of high-yields in hard-rock aquifers: downscaling methodology combining GIS and multicriteria analysis to delineate field prospecting zones. *Ground Water, 39*, 4, pp. 568-581.

Lachassagne P.,Wyns R., Dewandel B. (2011). The fracture permeability of hard rock aquifers is due neither to tectonics, nor to unloading, but to weathering processes. *Terra Nova 23*, pp. 145–161.

McNeill J., (1990). Use of electromagnetic methods for groundwater studies. Geotechnical and Environmental Geophysics, vol. 1. SEG, Tulsa, Oklahoma, pp. 191–218.

Schamper C., Rejiba F., and Guérin R. (2012). 1D single-site and laterally constrained inversion of multifrequency and multicomponent ground-based electromagnetic induction data: Application to the investigation of a near-surface clayey overburden. *Geophysics, Vol. 77, No. 4*; pp. WB19–WB35.

Vouillamoz J.M., Lawson F.M.A., Yalob N., Descloitres M. (2014). The use of magnetic resonance sounding for quantifying specific yield and transmissivity in hard rock aquifers: The example of Benin. *Journal of Applied Geophysics 107*, pp. 16–24.

Wyns R., Baltassat J.-M., Lachassagne P., Legtchenko A., Vairon J. & Mathieu F. (2004). Application of Proton Magnetic Resonance Soundings to groundwater reserve mapping in weathered basement rocks (Brittany, France). *Bull. Soc. géol. Fr., 175, 1,* pp. 21-34.

Yadav G.S., S.K. Singh, (2007). Integrated resistivity surveys for delineation of fractures for ground water exploration in hard rock areas. *Journal of Applied Geophysics 62*, pp. 301–312.