Optimizing the Interpretation of Sub-surface Resistivity in Relation with Borehole Productivity in Basement Area Applied to Seno Province (Burkina Faso)

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Abstract: This study aims at identifying possible correlations between shapes, types of geophysical anomalies and borehole productivity according to geological and hydrogeological contexts. The methodology adopted was a two-pronged one—the first step sought to: (i) interpret the electrical resistivity values from horizontal profiling and vertical electrical sounding implemented in Seno province that preceded the drilling of 513 boreholes; (ii) interpret data from pumping tests carried out on boreholes having a discharge superior to 1 m³/h (“positive borehole”) by using Cooper-Jacob’s method. In the second step, according to geology, authors tried to identify possible correlations between each of the qualitative geophysical parameters: «shape of anomaly», «type of anomaly» and «type curve» on the one hand, and hydrogeological parameters such as discharge, alteration thickness, transmissivity and saturated level on the other. The results of this study have shown that the chances of having a positive borehole in Seno province are higher when the type of anomaly is TCC (80%), shape of anomaly is “W” and when type curve is “H” (80%) for all geological formations. Granitic formations are those that record higher discharges while schists record high transmissivity values.

Key words: Basement rocks, sub-surface resistivity, borehole, anomaly, productivity, Seno province, Burkina.

1. Introduction

Groundwater in basement area is a major resource for a large population of people in sub-Saharan Africa. Due to the ephemeral nature of surface water and its susceptibility to pollution, groundwater is the only realistic and affordable source of water to supply most of Africa’s needs. However, groundwater availability and mobilization are strongly influenced by the large variability in geology, geomorphology/weathering and rainfall (both current and historic) [1]. One of its most important advantages is its much slower response to climate variations [2].

In Burkina Faso, thousands of boreholes have been drilled as part of a rural water supply project, 28% of

boreholes have zero discharge and 83% of discharge are less than or equal to 3.6 m³/h [3]. The technique of implementation of the boreholes was partly based on photo-interpretation. Even if these techniques are presented as a panacea for groundwater exploration, they show mitigated results [4, 5]. Today, the electrical resistivity method has been applied most widely for groundwater investigations. The electrical resistivity method can estimate the thickness of overburden and also the thickness of weathered/fractured zones considered as hydrogeological target. But in Burkina Faso, despite the use of the resistivity method for groundwater investigation, the success rate of borehole barely reaches 50 percent [3, 6-8]. A typical example is the national program for clean water supply and sanitation (PN-AEPA) initiated recently by the authorities of Burkina Faso and supported by the BAD

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(African Development Bank). This program aims at drilling 1,100 “positive boreholes” (discharge higher than 0.7 m³/h, which is equivalent to hand pump rate) in different provinces of the Northern region. In the province of Seno, with a total of 513 boreholes drilled, 213 are dry (“negative”), which represents 42 percent of failure rate. The large number of dry boreholes is very costly for drilling program and considerably reduces the budget allocated for “positive borehole” realization.

In order to increase the success rate of boreholes in basement geological context under semi-arid climate condition, this study proposes to perform a qualitative interpretation of the sub-surface resistivity according to borehole efficiency. To do this, the Seno province is taken as a case study by reason of available data and the geological context which is representative of basement rock type encountered in Burkina Faso.

2. Study Site

Seno province (about 7,000 km²) is located in the extreme north of Burkina Faso in West Africa (Fig. 1). It belongs to the Sahel region covering almost 14% of the area of Burkina Faso. The climate is sahelian characterized by an annual rainfall oscillating between 400 mm and 600 mm. This varies very significantly from one year to another. Overall, there are two types of seasons: a rainy season from June to September and a dry season from October to May. The climatic conditions of Sahel are marked by high rainfall variability both spatially and temporally. By contrast, evapotranspiration is relatively constant from year to year. This large spatio-temporal variation of precipitation, coupled with the shortage of the rainy season, makes rainfall one of the most limiting ecological factors for crop production. The vegetation of Seno province gradually spreads

Fig. 1 Geological map of Seno province and location of boreholes.

Fig. 2 Idealized single-phase weathering paleo profile in a hard-rock aquifer, crosscut by the current topography [12].

from thorn-bush steppe to phytogeographic domain of sahelian north [9]. On hydrographical terms, Seno province consists of many natural ponds, shallows and intermittent rivers. The main rivers are the Gourol, the Yali, the Faga and the Sirba. Most of these rivers take their source from the right side of the Niger River Faso. Nevertheless, we may note the presence of some small dams. Most surface reserves (ponds and small dams) dry up some time after the rainy season. The relief is characterized by the presence of dune cords, mounds and hills, valleys and hollows, red brown soils, brown soils, hydromorphous soils, glacis and skeletal soils.

Like the geological formations of Burkina, the geological history of Seno province is inscribed in one of West Africa's craton. The main geological formations are:

(1) Granites and gneisses which are a large part of the country set up before the "Birimian" tectono-volcanic phase (2,000 to 1,880 mya).

(2) The Birimian formations comprising metamorphosed sedimentary or volcanic rocks and syntectonic granites.

(3) Post-tectonic granitic intrusions embedded in previous geological formations.

The terrain is characterized by the presence of dune

ridges, mounds and hills, valleys and depressions, red brown soils, brown soils, waterlogged areas, glacis, as well as skeletal soils [10].

Geological formations described above are the main aquifers of the study site. According to Refs [3, 11-14], these aquifers are characterized from top to bottom by Fig. 2:

- *Laterite*: An iron or bauxitic crust, which can be absent due to erosion or to rehydration of hematite in a latosol (for iron crusts) or to resiliification of gibbsite/boehmite into kaolinite (for bauxitic crusts).
- *Saprolite*: A clay-rich material, a few tens of meters thick (where it has not been eroded), is derived from being prolonged in situ decomposition of bedrock. Because of its clayey-sandy composition, the saprolite can attain quite a high porosity, depending on the lithology of the parent rock—its effective porosity is mainly between 3% and 10% [12, 13, 15]. It also generally displays quite a low hydraulic conductivity [12]. As a result, where saturated, the saprolite layer mainly contributes to storage in the overall composite aquifer.
- *Fissured layer*: This is generally characterized by a dense horizontal fissuring in the first few meters and a downward decreasing density of subhorizontal and

subvertical fissures [12-14, 16-18]. The fissured layer designated by hydrogeologist as hydrogeological target during drilling phase is characterized by a denser horizontal fissuring and mainly ensures the transmissive function of the overall composite aquifer.

- *Fresh basement*: This is permeable only locally, where deeper discontinuities are present. Even though these discontinuities can be as permeable as the fissures induced by weathering processes, in most geological contexts their density at depth is much lower than that within the fissured layer. At catchment scale, and for water resource applications, fresh basement can be considered.

3. Data Set

This section may be divided by subheadings. Two main sets of data have been used for optimizing the interpretation of sub-surface resistivity in relation to borehole productivity in Seno province. These data concern 191 measurement points where complete data (geophysical and hydrogeological) are available:

- Geophysical data: these are the apparent electrical resistivity values recorded from horizontal profiling and vertical electrical sounding investigations implemented in several villages where boreholes were drilled later;
- Hydrogeological data obtained during and after drilling. These are air-lift discharge, thickness of saprolite, thickness of saturated zone, and drawdown values versus time recorded during well test. These latter are the data obtained from short duration pumping test (two hours at a discharge similar to that of the hand pump: 0.7 m³/h to 1 m³/h).

4. Data Processing

Two main steps are adopted for data processing. The first one consists of interpreting separately geophysical data and hydrogeological data collected during drilling and well test. The second one consists of identifying statistical laws between geophysical and hydrogeological parameters for each geological

formation of the study site.

4.1 Interpreting Geophysical and Hydrogeological Data

For each locality (or village) where a drilling was conducted, electrical profile and sounding curves were obtained by Schlumberger array (Fig. 3). The resistivity measurement technique on the field requires that a small station interval (in this case 10 m) be used in order to map the anomaly. Four electrodes were placed along a straight line on the ground surface with the order AMNB, but with $AB \geq MN$. For any linear, symmetric array AMNB of electrodes, the resistivity ρ is given by Eq. (1): [19].

$$\bar{\rho} = \pi \left[\frac{\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2}{MN} \right] \frac{\Delta V}{I} \quad (1)$$

Where ρ = apparent resistivity, AB = distance between the current electrodes (metres), MN = distance between the potential electrodes (meters), ΔV = potential difference measured between the potential electrodes (volts), and I = applied current strength (milliampere, MA).

A profile configuration of 10/70 (i.e. 10 m for 1/2 MN and 70 m for 1/2 AB) was initially used ($AB = 140$ m, $MN = 20$ m). An increase in the success rate of the boreholes was achieved by using simple geophysical investigations to target the thickest zones of weathering. The VES (Vertical Electrical Soundings) were based on the modeling of the resistivity properties of horizontally layered ground by measuring the apparent resistivities at the surface.

The principle is that current was introduced into the ground by means of two current electrodes and the potential drop between a second pair of electrodes (potential electrodes) placed in line in between the pair was measured. A proportion of the current penetrated deeply into the ground and the depth of penetration increased with increasing electrode spacing.

The electrical profile (resistivity value versus displacement) and VES (resistivity values versus

Fig. 3 The Schlumberger configuration.

depth) are plotted in order to identify the “type of anomaly”, “the shape of anomaly” for electrical profiles and the “type curve” for VES. This is done without taking into account the status “dry” or “productive” (discharge higher than 0.7 m³/h (rate of hand pump)) boreholes. Here, the term “anomaly” designates a resistivity contrast highlighting structures differing from the surrounding environment by their physical characteristics.

Drawdown data versus time obtained during short duration pumping tests (2 hours) carried out on boreholes having a pumping rate greater than 0.7 m³/h are interpreted in order to estimate the instantaneous productivity of each borehole. To do so, Jacob’s method was used (Eq. (2)) to determine the transmissivity. Strictly, the duration of the pumping does not allow determining a transmissivity in the literal sense. Transmissivities calculated here, however, are good indicators which allow comparison between boreholes. The graphical representation of drawdowns (s) versus the logarithm of the time is a line whose slope allows the determination of the transmissivity (T).

$$s(t) = \frac{Q}{4\pi T} \ln t + \frac{Q}{4\pi T} \ln \left(\frac{4\pi T}{r^2 S} \right) \quad (2)$$

where s [m] represents the drawdown, t [s] the time since the pumping started, Q [m³/h] the pumping rate, T [m²/s] the transmissivity, r [m] the distance between the pumping well and the observation well, and S [-] the storativity. Note that ln represents the natural logarithm.

4.2 Statistical Analysis

Statistical analysis aims at identifying according to geology eventual correlations between each of the qualitative parameters “shape of anomaly”, “type of anomaly” and “type curve” on the one hand and hydrogeological parameters such as discharge, alteration thickness, transmissivity and saturated level on the other hand. This statistical analysis is based on crosstabs or contingency tables. To do so, nine variables were selected: “status” (negative or positive of the borehole), “type of anomaly”, “shape of anomaly”, “lithology”, “type curve”, “saturated level”, “transmissivity”, “discharge” and “alteration thickness”.

The total number of observations is 191. It will be, firstly, depending on geology, to determine the “success” and “failure” rates of boreholes realized in the province according to “types of anomaly”, “shapes of anomaly” and “type curve”. Secondly, for each type of geological formation, the class frequencies of “alteration thickness”, “saturated level”, “discharge” and “transmissivity” are assessed according to the same geophysical parameters.

5. Results and Discussion

5.1 Descriptive Statistics of the Different Variables

Descriptive statistics of geophysical and hydrogeological parameters reveal each of them the following information:

- Lithology

The analysis of 191 lithologs from boreholes shows 3 types of bedrocks: granite, schists and green rocks. These various formations occupy 77.5%, 15.2% and 7.3% respectively. Green rocks are metavolcanites. The term greenstone is used because of the combination of the colour of amphibols, chlorites, sericites and epidotes involved in their composition [20]. Schists, meanwhile, are metasediments exhibiting a sandstone structure.

- Boreholes status

The status “negative” or “positive” is defined on the basis of the discharge of success close to that of hand pump (0.7 m³/h). Then, strictly, a borehole whose air lift discharge is above this discharge is called “positive”; otherwise it is called “negative”. However, in the case of this study, it has sometimes happened that some boreholes are equipped with a discharge of 0.4 m³/h due to the hydrogeological complexity of the locality and the difficult access of the population to water. For this reason, the authors will then retain 0.4

m³/h as success discharge. The analysis of 191 boreholes, for which all necessary data for this study are available, reveals 145 positive boreholes and 46 negative boreholes.

- Shape of anomalies of resistivity profiling

The analysis of 191 profiles of electrical resistivity reveals a predominance of shapes «U» (34 %) and «W» (33%) followed by shapes «V» (28.8%), and «M» (3.1%) and «K» (1%) (Table 1). Shapes “C” and «H» have not been identified.

- Type of anomaly of resistivity profilings

The type of anomaly WCC (“Wide Conductor Compartment”) represents 53.40% of anomalies, followed by the type of anomaly TCC (“Tight Conductor Compartment”) at a rate of 41.4% and by the type of anomaly LC (“Conductor Level”) with 5.2% (Table 2). The low representation of this later is due to the fact that geophysicists generally have a high preference for anomalies of types TCC and WCC, coupled with the fact that they avoid as far as possible siting boreholes on anomalies of type LC.

Table 1 Frequency of shape of anomaly.

Shape of anomaly	Illustration (resistivity versus distance)	Frequency (%)
«U» curved anomaly		34
«W» large anomaly whose conductive part is disturbed by one or more resistant		33
«V» sharp anomaly		28.8
«M» anomaly shaped V or U between other conductive anomalies		3.1
«K» geological contact anomaly showing one or more conductors in contact		1

Table 2 Frequency of type of anomaly.

Type of anomaly	Illustration (resistivity versus distance)	Frequency (%)
«WCC», width of conductive zone ranging between 30 and 80 m		53.4
«TCC», width of conductive zone ranging between 10 and 30 m		41.4
«LC», anomaly as level of low resistivity		5.2

- Type curve

The most recurrent type curve is «H» shape or «boat bottom» shape with 69.6% of effectives. Shape «A» represents 28.8%. Shape «KH» is the least represented with only 1.6% (Table 3).

- Transmissivity

The values of transmissivity vary from $10^{-6} \text{ m}^2 \cdot \text{s}^{-1}$ to $10^{-2} \text{ m}^2 \cdot \text{s}^{-1}$. Transmissivity values have been grouped into three (3) arbitrary classes of intervals: $(0-10^{-6})$; $(10^{-6}-10^{-4})$; $(10^{-4}-10^{-2})$. These classes represent 23.6%, 20.4%, 56% of the effectivity of boreholes respectively.

- Discharge

It's about air lift discharges measured at the end of drilling. For this study, the authors considered four (4) arbitrary classes $(0; 6)$, $(6; 12)$, $(12; 18)$ and higher than $18 \text{ m}^3/\text{h}$. Authors noted that 91.6% of boreholes had a discharge between $0 \text{ m}^3/\text{h}$ and $6 \text{ m}^3/\text{h}$. The classes of discharge $(6 \text{ to } 12)$, $(12 \text{ to } 18)$, and greater than $18 \text{ m}^3/\text{h}$ represent 5.2%, 2.6% and 0.5% of positive boreholes respectively.

- Alteration thickness

The alteration thickness retained is the one provided

by lithologs no matter the “positive” or “negative status” of the borehole. The classes of alteration thickness arbitrary considered are: $(0; 5)$, $(5; 10)$, $(10; 15)$, $(15; 20)$, $(20; 25)$, $(25; 30)$ and $\geq 30 \text{ m}$. These classes represent 15.2%, 22.5%, 29.8%, 17.3%, 7.3%, 5.8% and 2.1% of boreholes respectively.

- Saturated level

The saturated level has been obtained after the subtraction of the static level from the total drilled depth. These values are indicative of the heights of water column in the boreholes. In the case of this study, the classes of the saturated level considered are: $(0; 12)$, $(12; 24)$, $(24; 36)$, $(36; 48)$, $(48; 60)$ and $\geq 60 \text{ m}$. These classes represent 24.1%, 5.8%, 30.4%, 27.2%, 9.9% and 2.6% respectively.

5.2 Relationships between Success Rate and Geophysical Parameters

5.2.1 Success Rate and Type of Anomaly

The analysis of the success rate according to the type of anomaly (TCC, WCC and LC) reveals that this one varies according to the type of geological substratum in the following way (Fig. 4): the type of anomaly best

Table 3 Frequency of type curve.

Type curve	Illustration (resistivity versus pseudodepth)	Frequency (%)
«H», curve as «bottom boat»		69.6
«A», curve as rising branch		28.8
«KH», curve starting by a bell curve and finishing by a shape of boat bottom		1.6

represented on the three geological formations is TCC with a rate of 80%. Type LC slightly represented (5% of anomaly) is only (found) on granite and gives a success rate nearly 90%. This rate is greater than all success rates on granite, no matter the type of anomaly. The success rate of type LC would probably be due to

the fact that it indicates zones of extended fractures contrary to the two other types (TCC and WCC). On the other hand, types TCC and WCC have almost the same chances of success for granite and for green rock while for schist, type TCC shows a success rate definitely higher than WCC.

Fig. 4 Evolution of success rate according to the type of anomaly and geology.

Fig. 5 Evolution of the success rate according to the shape of anomaly and geology.

5.2.2 Success Rate and Shape of Anomaly

Considering all three geological formations, anomalies of shape “W” have the highest success rate with 84%, and then come anomalies of shapes “V” and “U” with 76% and 71% respectively (Fig. 5). Shapes of “K” and “M”, representing only 1% and 3.1% of the shapes of anomalies, have not been taken into account in this analysis because of their unrepresentativeness. An analysis by geological formation shows that on granites, shapes of anomaly «W» and «V» present the highest success rates with values nearly identical

around 80%. On schists, shapes of anomaly “W” and “V” show high success rates of 100% and 91%, respectively. The same observation is made on green rocks where the same shapes «W» and «U» predominate with 80% and 75%, respectively. An analysis by shape of anomaly considering the three principal geological formations reveals that for shape «W» schists show the highest success rate (100%), then come green rocks and granites with nearly identical rates (80%). The authors make the same report for the shape of anomaly «U», except that at this level green

Fig. 6 Evolution of the success rate according to the types curves and geology.

rocks show a high success rate compared to granites. Concerning the shape of anomaly “V”, granites present the highest success rate (80%), then come schists (67%) and green rocks (50%).

5.2.3 Success Rate and Type Curve

The analysis of the success rate according to type curve (Fig. 6) concerns the types of the most recurrent soundings on the site; namely, type curve «H» (69% of effectives) and type curve A (29%). On all three geological formations, type curve “H” shows the highest success rate (82%). In a detailed way, the success rates for these type curves for granites, schists and green rocks are 80%, 91% and 82% respectively. Concerning type curve A, granites show nearly identical values (near 60%). Green rocks show the lowest rates of success.

5.3 Correlation between Hydrogeological and Geophysical Parameters

The statistical analysis based on contingency tables between hydrogeological parameters (discharge, transmissivity, saturated level and alteration thickness) considered as parameters of boreholes productivity and geophysical parameters (type of anomaly, shape of anomaly and curve type) allowed the identification of correlations which may exist between them according to the nature of bedrock.

5.3.1 Discharge and Geophysical Parameters

• Discharge and shape of anomaly

The distribution of frequency classes according to the shape of anomaly and geology (Fig. 7) reveals that the classes of discharges higher than 18 m³/h are met only on granites. Classes of discharges (6; 12), (12; 18) show a higher frequency on granites and schists than on green rocks. Frequencies of these classes of discharges are recorded on shapes of anomaly «U» and «V». In contrast, shape “W” presenting the highest success rate does not show high frequencies of high discharge. For the same shape of anomaly, green rocks present highest frequencies of classes of discharge whereas on schists, it (shape «W») records discharges only between 0.4 and 6 m³/h.

• Discharge and type curve

The distribution of classes of discharges according to the type curve (Fig. 8) shows that whatever the nature of the bedrock and the considered class of discharge, type curve «H» presents highest frequencies of classes of high discharge. Boreholes with a discharge more than 18 m³/h are only met on granites. Concerning the type curve «A», it only records discharges between 0.4 and 6 m³/h on green rocks while on granites and schists, discharges higher than 6 m³/h are recorded. In terms of productivity based on air lift discharge, granitic formations are the most productive followed by schists.

Fig. 7 Evolution of frequencies of classes of discharges according to the shape of anomaly and geology.

Fig. 8 Evolution of frequencies of classes of discharge according to the types curves and geology.

5.3.2 Transmissivity and Geophysical Parameters

The previous analysis based on the evolution of classes of discharge (air lift) does not indicate the sustainability of this one. Thus, an analysis based on the transmissivity which is a measure of the amount of water that can be transmitted horizontally through a unit with the full saturated thickness of the aquifer under a hydraulic gradient of 1 according to geophysical parameters is done.

• Transmissivity and type of anomaly

According to the type of anomaly and lithology (granites, schists and green rocks), the distribution of frequencies of transmissivity classes (Fig. 9) reveals that on schists, type of anomaly WCC shows at the

same time the highest frequencies of low ($0; 10^{-6}$) and high ($10^{-4}; 10^{-2}$) values of transmissivity. Still considering schists, the type of anomaly TCC is the one which does not record the low class of transmissivity values (lower than 10^{-6} m²/s); except this type of anomaly on schists, all other types of anomalies, regardless of the nature of the bedrock, show nearly identical frequencies of the three transmissivity classes. Furthermore, types WCC and TCC on each granite and green rock formation show frequencies nearly identical for the three transmissivity classes.

• Transmissivity and shape of anomaly

The analysis of transmissivity according to the shape of anomaly (Fig. 10) shows that no matter the nature of

Fig. 9 Evolution of frequencies of transmissivity according to the type of anomaly and geology.

Fig. 10 Evolution of frequencies of classes of transmissivity according to shapes of anomaly and geology.

the bedrock, every shape of anomaly records the three classes of transmissivity, except shape «W» on schists which only records the two superior classes of transmissivity. However, the latter has not shown high frequencies of high discharge classes during the analysis of the evolution of discharges according to the shape of anomaly. On each schists and green rocks formation, the shape of anomaly «V» which recorded high frequencies of high discharge classes shows highest frequencies of low values of transmissivity. Considering all the shapes of anomalies on each of the geological formations, shape «W» would probably be the one which records high values of transmissivity.

- Transmissivity and type curve

Granites, schists and green rocks record the three

transmissivity classes (Fig. 11). The class $(0; 10^{-6})$, which constitutes low values of transmissivity, has the same frequency irrespective of the type curve on each geological formation. On each formation, the type curve «H» records the highest frequency of high values of transmissivity on schist; that is in agreement with the evolution of frequencies of discharges according to the type curve (cf. IV 2.2).

5.3.3 Alteration Thickness and Geophysical Parameters

- Alteration thickness and type of anomaly

The analysis of frequencies of thicknesses classes of alteration according to the type of anomaly (Fig. 12) shows that on schists and green rocks, the type of anomaly WCC records the highest frequencies of

Fig. 11 Evolution of frequencies of classes of transmissivity according to the types curves and geology.

Fig. 12 Evolution of classes of frequencies of alteration thickness according to the type of anomaly and geology.

large alteration thicknesses (20; 25, 25; 30). On granites, this is rather the type of anomaly TCC which records the highest frequencies of classes of large alteration thickness at the expense of class WCC. Green rocks record low frequencies of classes of low alteration thickness (0; 5, 5; 10) whereas on granites and schists, frequencies of classes of low alteration thickness are high with values nearly identical (70% and 75%).

- Alteration thickness and shape of anomaly

Green rocks have alteration thickness larger than schists and granites (Fig. 13). Considering all shapes of anomaly on each of the three principal geological formations of the study site, the shape of anomaly “W” on green rocks records the highest frequencies of classes of large alteration thickness (20; 25, 25; 30). On

granites and green rocks, the shape of anomaly “U” records the high frequencies of classes of low alteration thickness while on schists it is rather the shape of anomaly “V” which records high frequencies of classes of low alteration thickness.

- Alteration thickness and type curve

The analysis of frequencies of classes of alteration thickness according to the type curve (Fig. 14) shows that on each of the geological formations, the type curve “H” records the highest frequency of classes of large alteration thickness. Comparing the values of frequencies of this type curve on the three geological formations, the key point is that green rocks present thicknesses of alteration more frequent than on schists and on granites. Granites are the only formations that record for each curve type the lowest class of alteration

Fig. 13 Evolution of frequencies of classes of alteration thickness according to the shape of anomaly and geology.

Fig. 14 Evolution of frequencies of classes of alteration thickness according to the type curves and geology.

thickness. Concerning class “A”, schists show relatively higher frequencies of classes of large alteration thickness than green rocks and granites.

5.3.4 Saturated Level and Geophysical Parameters

• Saturated level and type of anomaly

The analysis of saturated level according to the type of anomaly (Fig. 15) shows that on the whole three geological formations, both classes of low and high saturated levels are at the same time recorded on all the types of anomalies except type TCC on schists. Type of anomaly TCC on green rocks presents highest frequencies of classes of high saturated level. However, this same type of anomaly records on schists the highest frequencies of classes of low saturated level. On granites, types of anomaly TCC and

WCC record practically the same frequencies of classes of saturated level except for class (48; 60) whose frequency is higher than that of type of anomaly TCC.

• Saturated level and shape of anomaly

On the three types of geological formations, all the types of anomaly record frequencies of all classes except for shape “W” on green rocks which records only levels higher than 24 m (Fig. 16). Shape of anomaly “W” on green rocks records the highest frequency of saturated level. Shape of anomaly “V” on schists has the highest frequency of class of lowest saturated level. On granitic formations, shapes “U”, “V” and “W” record nearly identical frequencies of the different classes.

Fig. 15 Evolution of frequencies of classes of saturated level according to the type of anomaly and geology.

Fig. 16 Evolution of frequencies of classes of saturated level according to the shape of anomaly and geology.

- Saturated level and type curve

The evolution of frequency of classes of saturated level according to the type curve and geology (Fig. 17) reveals that both classes of low and high values of saturated level are recorded for each type curve. Whatever the type of geological formation, type curve “H” records the highest frequencies of classes of high values of saturated level. For each type curve, frequencies of the lowest class of saturated level are nearly identical no matter the geological formation.

5.4 Discussion

The types of anomaly, the shapes of anomaly recorded in Seno province are in agreement with those recorded in basement rocks and are representative of discontinuous mediums. The types curves (“H” and “A”) recorded are also in agreement with the

conceptual model of basement rocks proposed by Toe, G. [12]. Indeed, from top to bottom, two schemes of layers succession are as follows: (i) presence of three layers whose first is altered with an argileous tendency of low resistivity ($80 \Omega \cdot m$ to $120 \Omega \cdot m$), the second which corresponds to the fissured layer slightly altered with values of intermediate resistivity ($200 \Omega \cdot m$ to $700 \Omega \cdot m$) and the third which is the fresh basement with high values of resistivity (higher than $800 \Omega \cdot m$). This model matches with type “A” (resistivity which increases by level); (ii) presence of three terrains whose first is altered, almost dewatered, and covered by hardened iron crust of high resistivity values ($400 \Omega \cdot m$ to $800 \Omega \cdot m$), followed by the fissured layer slightly altered with values of resistivity exceeding $800 \Omega \cdot m$. This model matches with type “H” (one conductor layer between two resistant layers).

Fig. 17 Evolution of frequencies of classes of saturated level according to the shape of anomaly and geology.

Previous analysis and data collected from drilling showed that the chances of having a positive borehole in Seno province were higher when the type of anomaly was TCC (80 %), the shape of anomaly was “W” (84%) and the type curve was “H” (80%) for the whole geological formations. By contrast, type of anomaly LC only recorded on granites gives better chances of success. In terms of air lift discharge, the same geophysical parameters record the highest discharges. The highest discharges are recorded on granites for types of anomaly “V” and “W”. These anomalies would probably be linked to minor fractures setting up themselves from both sides of a major accident for shape “V” and to parallel fractures for shape “W”. The estimation of the productivity from the transmissivity reveals that these same geophysical parameters on schists record good values of transmissivity. So, granites which record the highest air-lift discharges are not the formations which record the highest values of transmissivity. This would probably be due to the fact that schists show saturated levels greater than those of granites. This explanation, only based on the importance of saturated level, could not support this observation because green rocks present higher thicknesses of alteration and higher levels than all the formations of the province, so long as

they are not more transmissive. Another explanation which could justify this observation would be the interaction between the altered layer and hydrogeological target which is fissured layer. Indeed, on schists, the flow transfer from the overlaying alteration (having a strong storage capacity) to the fissured layer can be facilitated by the conversation of schistosity which is subvertical [4].

The thicknesses of alteration measured during drilling show that high values are recorded for the same geophysical parameters. By contrast, the highest values of saturated thicknesses are recorded on green rocks. According to Wyna, R. et al. [14], who studied weathering profiles on the same type of geological formations having undergone the same geological set up, the difference in profile thickness of the three different rocks in Seno province is linked to (i) the susceptibility of the rock type (or associated weathering profile) to the iron crust process and (ii) the susceptibility of the iron crust to dismantling, which depends on the resistance of the alterite underlying the iron crust. The granite rock is less prone to the iron crust process than schist, which is itself less prone than the green rocks. The alterite from schist and green rocks is more resistant to dismantling than alterite from granites. These different considerations explain why

the thickness of the granite profile is smaller than that of volcano sedimentary rocks. The difference in thickness between schist and green rocks is linked to the fact that iron crust is better developed in green rocks than in schist. In the green rocks domain, the resistance of the profile to dismantling is illustrated by the presence of different types of iron crust levels, which are evidence of palaeo surfaces set-up from Mio-Pliocene to recent Quaternary. Finally, the mafic nature of the green rocks basement also plays a role in the iron crust process due to its abundance in ferromagnesian elements.

6. Conclusion

In Seno province, it is accepted that potential groundwater reserves exist in basement rocks. The occurrence of groundwater is highly localized. The analysis of 1D electrical resistivity method used to locate sustainable groundwater sources reveals that to implement “positive borehole”, anomalies of shape “W” and type curve “H” regardless of the nature of the substratum and the types of anomaly “Conductor Level” (LC) for granite, “Tight Conductor Compartment” (TCC) and “Wide Conductor Compartment” (WCC) for both schist and green rock are most favorable.

Boreholes having “high discharge” are associated with anomalies of shape “V” and “U” for granite, “V” for schist and “W” for green rock. Formations which record highest values of transmissivities are schists on shape of anomaly «W».

This study would deserve to be continued using 2D electrical methods in order to be free of problems of equivalence and suppression of layers which can occur while interpreting soundings of resistivity in 1D. Indeed, a similar experimental diagram can be interpreted by infinity of solutions and a large contrast in resistivity between bedrock and altered layer often masks the presence of suppressed layer of intermediate resistivity representing fissured bedrock that often contains significant quantities of water, encountered during drilling. In addition, the implementation of

MRS (Magnetic Resonance Sounding) sounding where the anomalies are located would lead to an appreciation of their (anomalies) water content and specific yield.

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