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Contribution of Geophysical Prospecting (1D) to Characterize a Precambrian Basement Aquifers Agadez Region (North, Niger)

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Abstract

In the Aïr massif, and more particularly in the Iférouane area, the basement is flush. Thus, the essential of water resources is contained in the discontinuous aquifers of basement. Indeed, the weathered and cracked basement is an excellent reservoir of groundwater. The objective of this study is to determine the areas favorable to establishment of productive drilling in the village of Ebourkoum. A methodological approach based on the combination of remote sensing and geophysics methods was implemented. The fracturing map developed highlighted three main accidents of directions N0˚ - N10˚, N30˚ - N50˚ and N130˚ - N140˚ in the said locality. The geophysical investigation mainly electrical prospecting has allowed to locate structures with high hydraulic potential below alluvium and alterites. Subsequently, drilling will be carried out in the areas retained.

Keywords

Fractured Aquifers, Electrical Prospecting, Basement, Remote Sensing, Aïr Massif, Niger

1. Introduction

Geophysical provides additional information in a study of fracturing from remote sensing techniques (satellite and aerial imagery) in the exploration of aquifers in a basement. It also accurately gives the position of fractures and better, it indicates the opening and depth of these latter.

Geophysical methods are many and varied, we have: electrical, gravimetric, seismic, magnetic and electromagnetic methods. Nowadays, apart from these so-called "classical" methods, there is PMR (Proton Magnetic Resonance) which measures the signal emitted by atomic nuclei of water molecule.

In West Africa, the most widely used geophysical methods in groundwater research are electrical methods and electromagnetism [1] [2] [3] have significantly reduced the failure rate of drilling [4] [5] [6]. In Ivory Coast [3] [7] [8] [9] and Burkina Faso [4] [10] [11], the combination of appropriate prospecting techniques (geophysical, structural) made it possible to detect fractures under the alteration layers, thus improving the success rate of drilling. The combined use of these techniques in large-scale in water research is not very developed in Niger [12].

In Niger, the use of geophysics dates back to the work of [13] [14] [15] which highlighted the thickness of alterites but also the structure of aquifers in sedimentary zones.

In Aïr massif, from 1962-1963, ORSTOM carried out gravimetric surveys and recently (2003-2004) two airborne geophysical campaigns on spectrometric, magnetometric and electromagnetic measures for mining research were carried out. In the same area, electrical geophysical measurements were conducted in 2012 as part of drilling deep basement fractures in some localities of the Aïr massif.

In this study, the electrical resistivity methods were preferred because they allow a good characterization of billing-alteration torque [16] [17] [18].

Concretely, it will be used: 1) electric trails to confirm and specify the position of the structures located on the satellite imagery and 2) electrical soundings to provide additional information in depth and to estimate the thickness of weathered above the basement. The information has been gathered and exploited in order to have a reference document that will allow to update the knowledge relating to potentialities of Aïr massif. The aims of this study are to identify a favorable area for drilling a borehole in Ebourkoum zone for water supply.

2. Presentation of Study Area

2.1. Geographic Location

The study area is located in Aïr massif in a rural municipality of Iferouane northeast of Agadez city (**Figure 1**).

Agadez region is hyper arid in its northern part and arid in its southern part [19]. The annual cycle highlights two main seasons: a very long dry season and a short rainy season [19]. This arid climate is characterized by low rainfall and high evaporation and the annual evapotranspiration is 2500 to 2600 mm/year [20]. The winds are strong and frequent in all seasons. 70% of the winds have a speed between 6 and 11 m/s while 20% have a speed greater than 11 m/s. The Saharan continental trade winds after having crossed the central ergs is enriched around Aïr massif sprinkling all the southern regions with fine dust [20]. For wet sequences the annual average rainfall varies between 135.9 and 147 mm while for dry sequences it is only 79 to 95.4 mm [21].

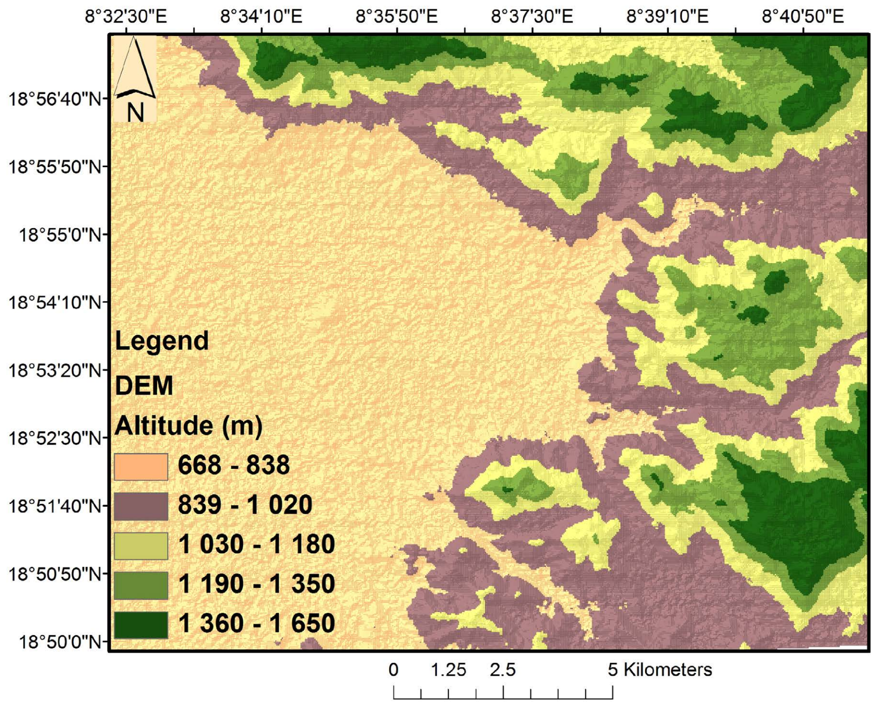

Figure 1. Location of study area.

2.2. Geological Context

The study area is in Aïr massif, where the geological setting is mainly represented by cristallophyllian formations (**Figure 2**) arranged along meridian axes that form the basement formed by leptynite (Tafourfouzel), gneiss (Serchouf) to the west and north-west, micaschists (Edoukel), gneiss (Azanguerene) in the center, chloroschists (Aouzegueur) and finally molasses in the east [22] [23] [24] [25]. They support various facies of granites among which two syn-tectonic groups are the most widespread, the Renatt type [26]. The late and post-tectonic, more diversified groups are in small scattered intrusions. Many veins of quartz, micro grained rocks or porphyry fill the fractures. Tectonics is manifested by the presence of characteristic structural directions of general orientation: N0˚, N70˚ and N160˚ [27] [28] [29].

2.3. Hydrogeological Context

From hydrogeological, the aquifer system in such a geological context is of a discontinuous type and generally constituted by a surface reservoir with a mainly capacitive role consisting of basement alterites, valley alluvium and a lower reservoir of more or less deep fractures [18] [27] [30]. This last reservoir has a mainly conductive role and drains the upper aquifer of the alterites. The area of Iférouane is located in a center of Aïr, the basement (**Figure 2**) is almost flush in this part the infiltration and storage of water could be done only in a fractured or altered areas. Under these conditions only fractures in relation to the areas of concentration of runoff (spreading areas, talwegs) will be fed. Moreover, the low rate of water renewal in this area, resulting in high residence times, locally induces strong mineralization of groundwater. The hydraulic supply (traditional wells and modern wells) in the study area reach the altered basement and their depths vary from 15 to 25 m with a thin wave of water.

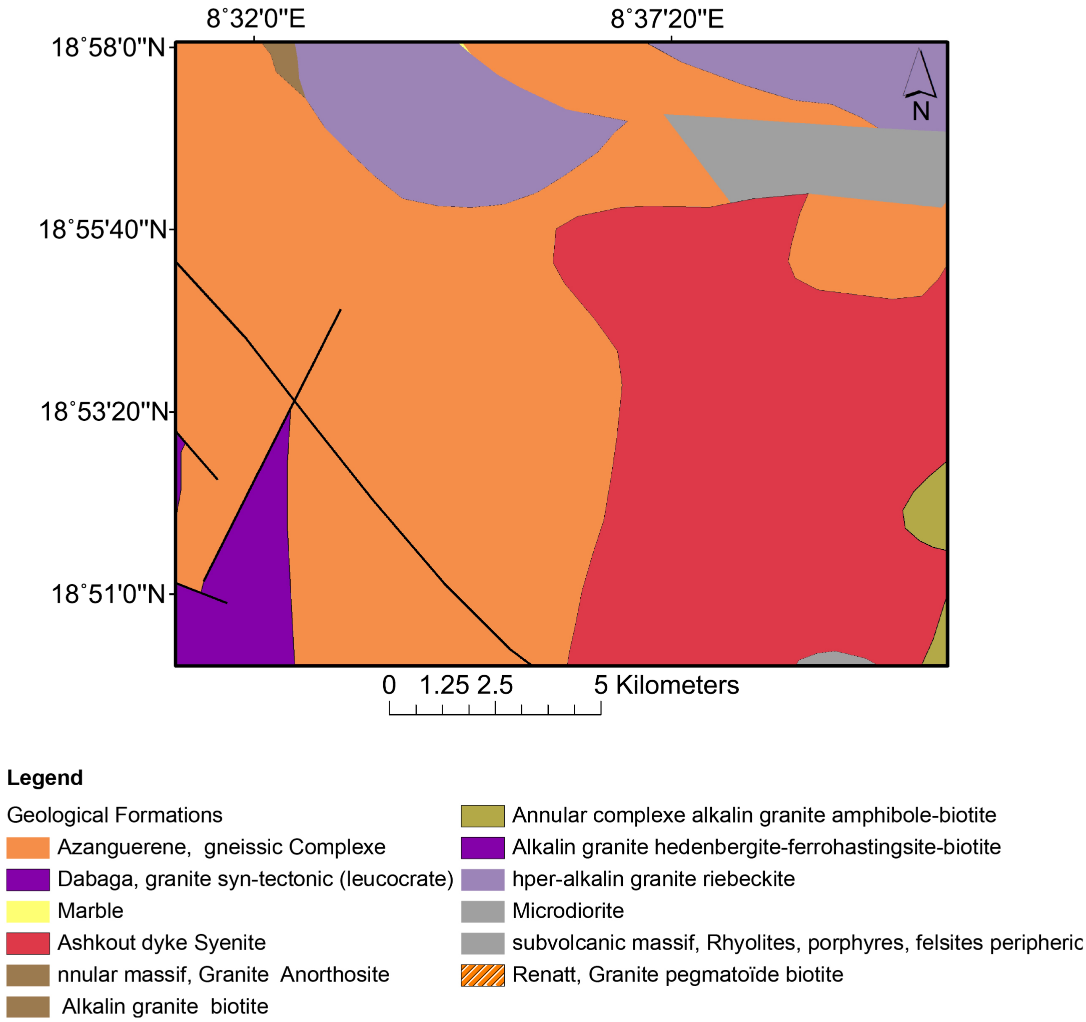

Figure 2. Geological map of study area.

3. Material and Methods

3.1. Material and Data

In this study, a Digital Elevation Model (DEM, 30 m of resolution, scenes: 17-008 and 17-009, SRTM 30 M, NASA, USGS/2011), a topographic map of the Timia sector (Timia sheet NE-32-XV) at 1/200,000^e, and a geological map of Aïr [31] at 1/500,000^e.

The equipment used to acquire geophysical data is constituted by "Syscal junior plus" resistivimeter and its accessories as well as a GPS. The data treatment was processed using ArcGIS 10.3 software for processing map data and IX1D Interpex (MEBA) for processing geophysical data.

3.2. Methodology

In a basement area, hydrogeological prospecting is essential for the establishment of boreholes. Thus structural maps play an important role and these discontinuities are characterized by their direction, their opening and their geological origin [32].

3.2.1. Structures Cartography

Several hydrogeological studies [1] [13] [21] [33] have shown the importance of Digital Elevation Model (DEM and satellites images) in the mapping of fractures related to tectonics fracturing and alteration in a location of aquifers in basement area. The DEM stumpage technique has proven its worth in mapping discontinuity of tectonic origins [27]. This approach allowed to improve the visibility of lines and these are reported by manual methods (digitalization).

The lineaments thus reveal are subsequently validated by comparing them with field data and structures from the geological and topographical map. This allowed to distinguish structures of tectonic origin and those of anthropogenic origin (roads, electrical lines, etc.). Thus, the lineaments obtained after the validation are tectonic origin and have a fracturing value.

The combined application of remote sensing and geophysical (electrical methods) allow to provide valuable information in a location of altered and fractured areas that are favorable for accumulation of groundwater in basement areas. This approach has two stages. The first involves a geomorphological aspect leading to the implementation of electrical methods (trails and electric soundings) and the second leads to the choice of a location of water supplies.

3.2.2. Geophysical Approach

Geophysical methods measure the physical parameters of the subsoil from surface. That of electrical resistivity consists in injecting a direct current in the ground with the electrodes A and B to measure the difference of potential between two other electrodes M and N between A and B. The electric lifts allow a lateral investigation in order to determine the discontinuities in the basement, while electric soundings provide a better understanding the succession of lithology [33].

In the framework of this study, the electric trails were made according to the rectangle gradient device with the following geometric characteristics: AB = 300 m and 200 m, MN = 10 m and sometimes the Schlumberger device (AB = 200, MN = 20). The measuring step is 10 m. The electrical soundings were carried out according to the Schlumberger device, in line with the apparent resistivity anomalies determined by electric trails (**Figure 3**). The data acquired with these two techniques to build resistivity profiles and electrical soundings (ES).

The geophysical data acquisition equipment used consists of a Syscal resistivimeter and its accessories and a GPS. The aquis data were processed from IX1D software for geophysical data processing.

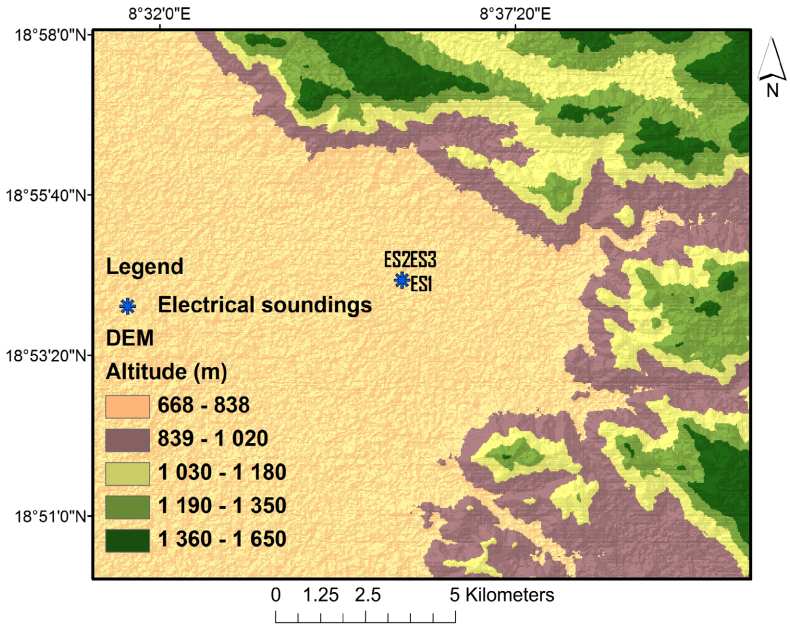

Figure 3. Location of electrical surveys.

4. Results

4.1. Lineaments Analysis

The stumpage of a Digital Elevation Model (DEM) is allowed to mapping the major lineaments of Ebourkoum area (Table 1). Analysis of this map shows that the main directions in number of lineaments are N0˚ - N10˚, N160˚ - N170˚, N140˚ - N170˚ and N120˚ - N130˚. The secondary directions are N130˚ - N140˚, N50˚ - N60˚, and N170˚ - N180˚ (Table 1). For lineaments length network, the major lineaments indicate the directions: N40˚ - N50˚, N30˚ - N40˚, N130˚ - N140˚ and N160˚ - N170˚. Secondary directions are N140˚ - N150˚, N60˚ - N70˚, and N50˚ - N80˚ (Table 1).

Table 1. Percentage of fractures in number and cumulative lengths from DEM (N = 237).

Materials	Directions	% Number of fractures	Directions	% cumulated in length of fractures
DEM (HillShad)	N0˚ - N10˚	19%	N40˚ - N50˚	20%
	N140˚ - N170˚	8%	N30˚ - N40˚	14%
	N120˚ - N130˚	8%	N130˚ - N140˚	9%
	N130˚ - N140˚	6%	N160˚ - N170˚	9%
	N30˚ - N50˚	6%	N140˚ - N150˚	8%
	N50˚ - N60˚	5%	N60˚ - N70˚	6%
	N170˚ - N180˚	5%	N150˚ - N160˚	6%
	Others	<5%	N70˚ - N80˚	5%
			N50˚ - N60˚	5%
			Others	<5%

The lineaments map obtained by remote sensing (**Table 1**) show that the directions in number of lineaments are N0˚ - N10˚ (19%), N140˚ - N170˚ (8%), N120˚ - N130˚ (8%), N130˚ - N140˚ (6%) and N170˚ - N180˚ (5%). Thus, fracturing is heterogeneous because only the direction family N0˚ - N10˚ exceeds 10%. For major lineaments, the direction families N40˚ - N50˚ (20%), N30˚ - N40˚ (14%), N130˚ - N140˚ (9%), N160˚ - N170˚ (8%) and N150˚ - N160˚ (6%) are the most important and represent the mega shears zones (**Table 1**).

4.1.1. Comparative Analysis of Lineaments and Structural Map

The superposition between the network of lineaments from Digital Elevation Model (DEM) of remote sensing and that of geological map shows a certain concordance of the mapped lineaments. In addition, lineaments from satellite imagery are generally superimposed on fractures identified in the field (**Figure 4**). However, on the geological map the density of fractures is low because of the scale of the latter. Thus, the validation of the map realized lineaments was done on the basis of field data.

The fractures identified on DEM are most often superimposed on those resulting from field measurements. Nevertheless, on geological map the density of faults is very low and this could be explained by a difference in scale between the two supports. Indeed, the satellite images (25 * 25 m) have a resolution much higher than geological map (1/200,000).

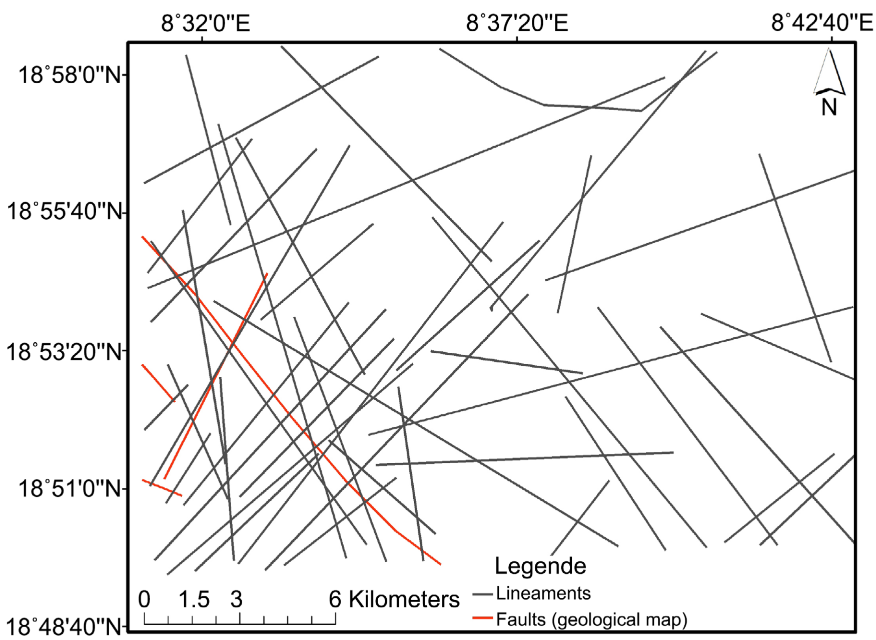

Figure 4. Overlay map of lineaments and structural data.

4.1.2. Structural Synthesis

The synthesis of structural studies and fracturing mapping work resulting from the [27] studies in Aïr area show that the main directions of fracturing affecting Aïr massif over long distances are N-S (N0˚ - N10˚), NE-SW (N30˚ - N50˚) and

N130˚ - N140˚. These orientations affect the land over several kilometers and these lineaments are organized according to N-S orientations in accordance with the shear of Raghane [1]. The directions NW-SE and NE-SW are fewer (Figure 5). These directions are according with regional accidents.

In addition, the fractures network (N0˚ - N10˚) representing the Raghane shear zone is represented in the granites of Ebourkoum zone.

Despite the limitations of remote sensing method that do not allow to identify lineaments below the alterites, these methods are essential in hydrogeological prospecting and gives interesting results in a basement area. Hence the interest of combining these two methods (remote sensing and geophysics).

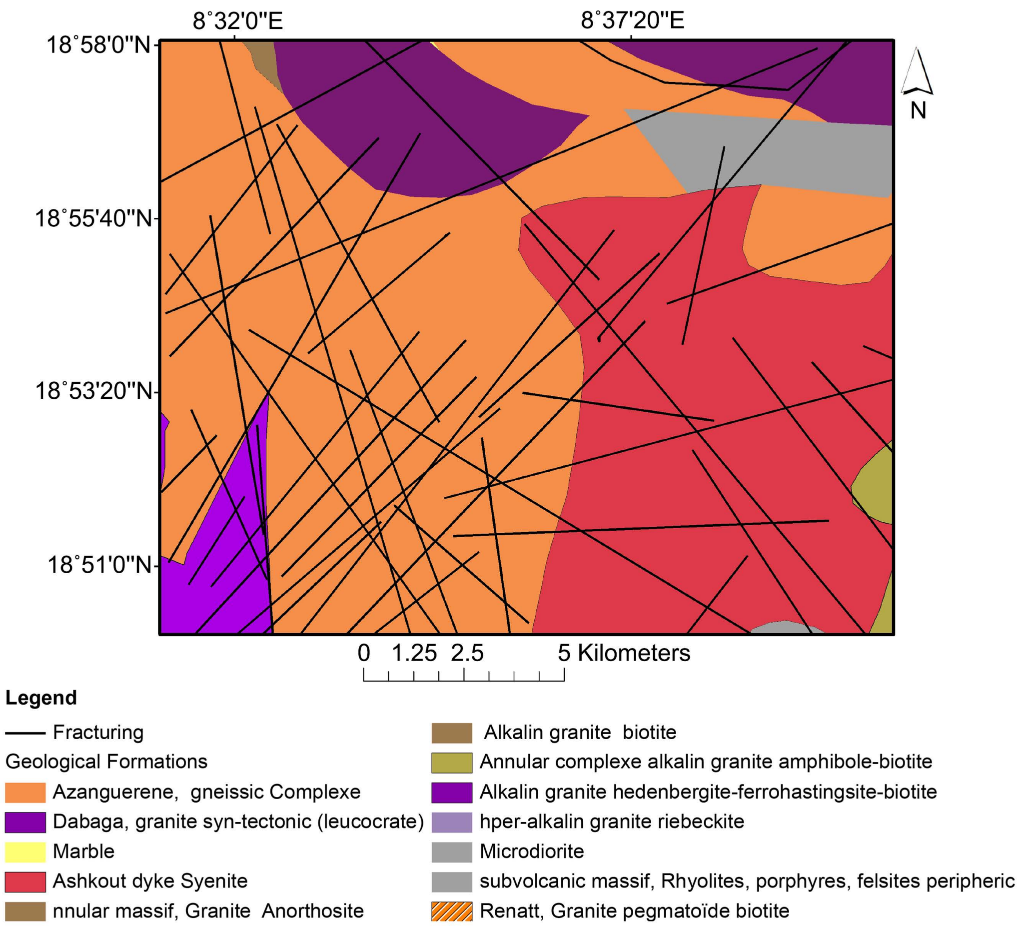

Figure 5. Fracturation map of study area.

4.2. Electrical Trails

Electric drag and electric sounding were carried out in Ebourkoum (Azimut: 140˚, AB = 300/200m, MN = 10 m). The profile (Figure 6) allows the investigation of depth to 40 and 60 m. It shows a first zone of 0 to 50 m characterized by an anomaly of 300 Ω·m. Between the abscissas 60 and 80 m, the second zone probably represents a fractured basement. It is characterized by resistivity varying of 180 to 200 Ω·m.

The profiles TE1 and TE2 (**Figure 6**) realized following the direction E-W are implanted in Ebourkoum valley near Tamgak mount in order to highlight the fractures which often coincide with valleys in basement areas. These two resistivity profiles highlight three (3) conductive anomalies ($\rho 1$ = 300, $\rho 2$ = 180, and $\rho 3$ = 400 Ω·m) respectively at the 50 m, 70 m and 80 m of the profile. The pace of the curves is generally decreasing. However, these decrease regularly in the first zone (from 0 to 50 m) followed by a second zone of collapse (50 m to 100 m) characterized by an alternation of low and high values of apparent resistivity. This succession of anomalies of "W" type is characteristic of fault zones [1].

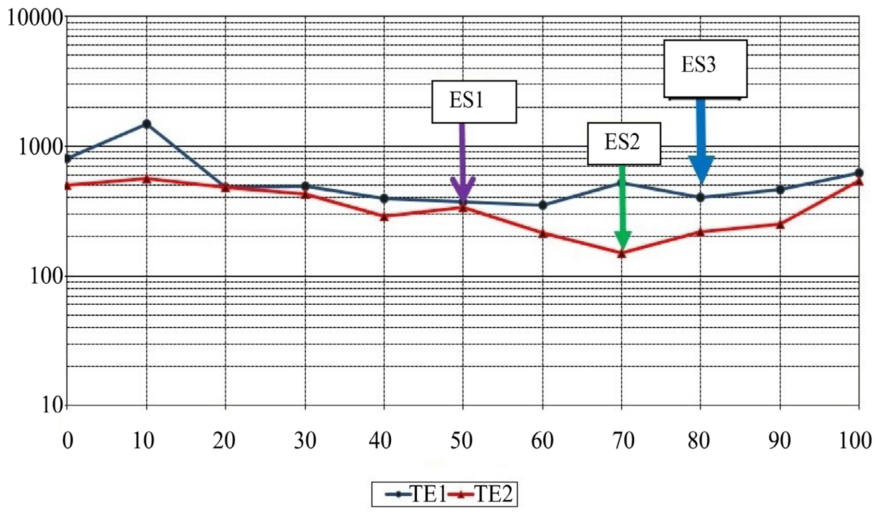

Figure 6. Trails curves.

4.2.1. Superposition of Electrical Soundings (ES)

The overlay curves of electrical soundings (**Figure 7**) are 60 m for ES1 and 40 m for ES2. The curves show a positive separation, the resistivity in ES2 lower than those in ES1) between AB/2 = 10 m and AB/2 = 100 m. It means that a better saturation in water at 40 m than at lower depth. On the other hand, there is a trend inversion beyond AB/2 = 100 m.

4.2.2. Electrical Soundings

In order to characterize the vertical succession of lithology and the hydrogeological interest of these anomalies, the electric sounding ES1 (**Figure 8(a)** and **Figure 8(b)**) was carried out in the right of the latter at point 50 m of the profile (ρa = 300 Ω·m). This first indicates a presence of three layers with a very resistant spring corresponding to the sandy clay covering of about 2 m thick and a resistivity between 1288.7 and 122.57 Ω·m. Moreover this layer show a high value of conductivity and would be formed of alluvium probably saturated in water or saturated alterites. This conductive part at a thickness of about 32 m and a resistivity is varying from 48.40 to 233.35 Ω·m. This conductive medium seems to represent the succession of a different horizon which are among others the alluvium, alterites, and cracked areas above the basement.

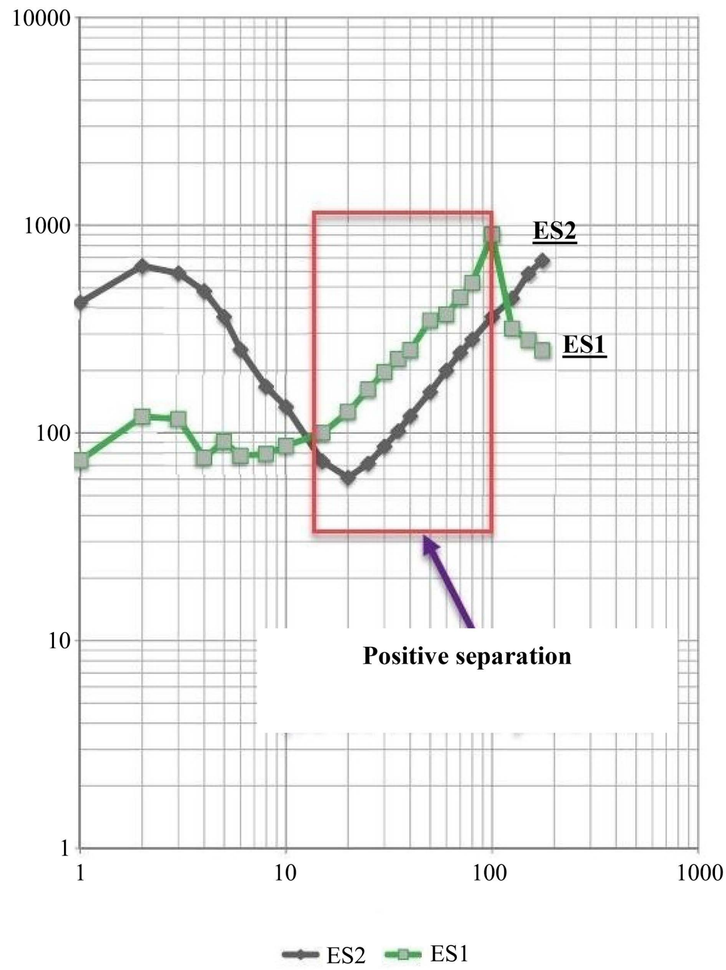

Figure 7. Separtion curves of ES1 and ES2.

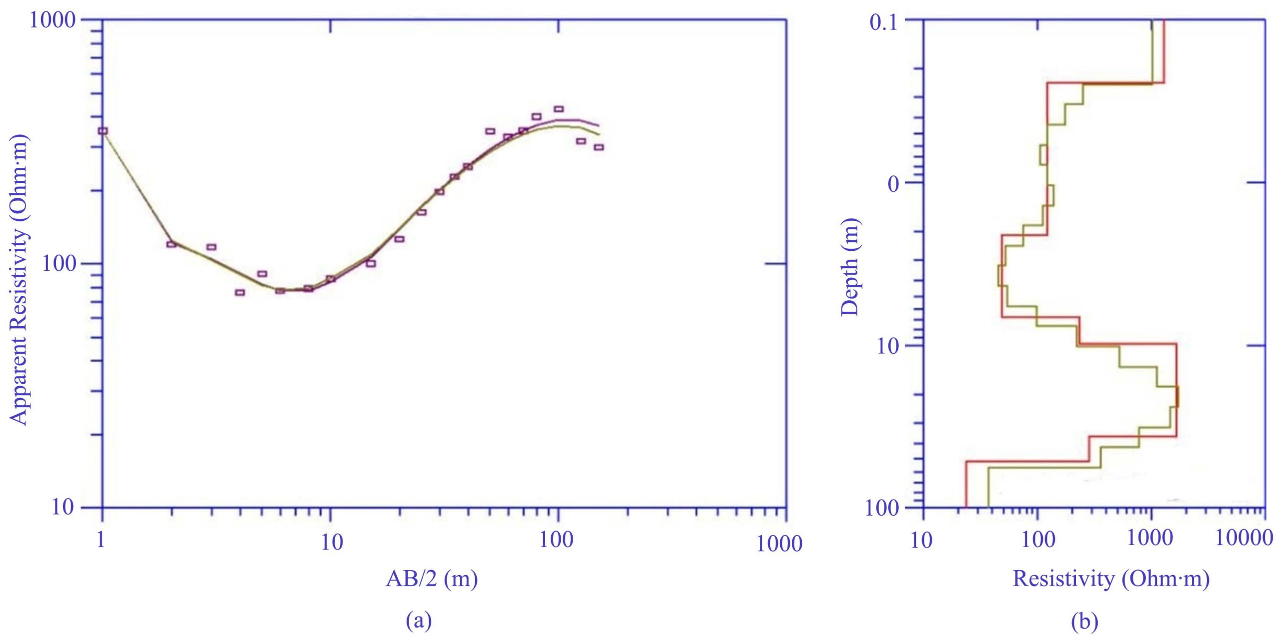

Figure 8. (a) Electrical sounding (ES1) and (b) Inversion and model of Electrical sounding (ES1).

Finally, the third horizon defined by the rising part characterizes the basement whose resistivity tends towards the infinite. The geophysical model indicates that the basement is reached at a depth of 104.6 m. However, resistivity measurements have not made it possible to distinguish each type of aquifer with resistivity of its own. This would probably be due to a small thickness of this latter. This was observed by [12] in a different crystalline context.

The electrical survey SE2 (**Figure 9(a)** and **Figure 9(b)**) carried out above the conductive anomaly of the profile P2 (ρa = 180 Ω·m) gave a curve of "boat bottom" type corresponding to the succession of three layers [1] [6]. The first and the second layer represent the dry sand and shallow clay deposits of resistivity between 1259.1 and 702.04 Ω·m and a thickness around 2 m. The conductive complex has 32 m thickness. The conductive complex show 32 m of thickness and a resistivity between 19.947 and 229.21 Ω·m, refers to the second level formed of saturated alluvium, saturated alterites and cracked horizon above a basement. In addition, the transition between alluvium-alterites-fissured basement is observed around 104 m depth at the ES2 soundings. This is not similar with the interpretations of ES1 sounding. The third field of infinite resistivity (36,550 Ω·m) reflects the basement which is reached at a depth of 104 m. The modelling and reversals of soundings data (**Table 2**) gives an overview of the different lithology interpreted from the electric soundings and are in accord with them.

Table 2. Modelling and reversals of eclectric soundings data.

Resistivity (Ω·m)	ES1_MODEL		SMR (%)	Lithology
	thickness (m)	Depth (m)		
1288.7	0.24316	0.24316		
122.57	1.869	2.1121		sand, alluviums
48.404	28.6452	30.7573		
233.35	32.0043	62.7616	9.45	
1645.9	26.463	89.224		altered/fractured basement
282.36	15.417	104.642		
23.512				
Resistivity (Ω·m)	**ES2_MODEL**		**SMR (%)**	**Lithology**
	thickness (m)	Depth (m)		
1259.1	0.2264	0.2264		
702.04	1.8793	2.1057		sand, alluviums
229.21	30.5586	32.6643		
19.947	31.5557	64.22	9.17	
511.76	23.9519	88.172		altered/fractured basement
4613.2	13.992	102.164		
36,550				basement

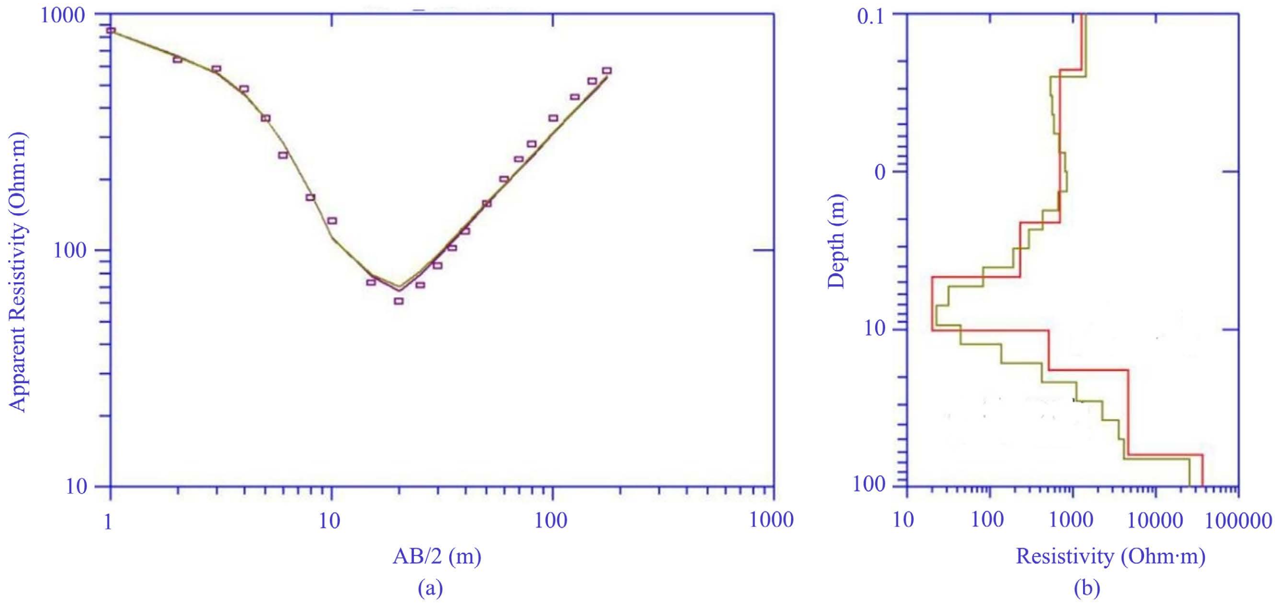

Figure 9. (a) Electrical survey (ES2) and (b) Inversion and model of Electrical sounding (ES2).

5. Discussion

The structures identified in Iférouane department and particularly in Ebourkoum village, are a results of DEM interpretation. These structures show an overview of the fracturing of underground mouse.

Studies on fracturing from digital medium mainly satellite images and the Digital Elevation Model (DEM) have highly contributed to the identification of these structures which can be confirmed by geophysical investigation [1] [6] [13] [21]. These geological structures have a great importance in hydrogeological prospecting. However it must be confirmed by geophysical prospecting [12].

Geophysical data (trails and electric sounding) improved the success rate of drilling. However, they are sometimes accompanied by failure because the distribution of water resources is random in areas of complex geology such as the basement area [1]. In addition, the constraint of installing boreholes in areas often near villages, instead of areas favorable to groundwater existence, induces strong incertitude of aquifers presence [1]. This gives geophysics its importance in the basement area [1]. The success rate does not allow to highlight some local differences due to certain parameters such as lithology and fracturing.

Prospecting by trails and electric soundings shows that underground is affected by structures similar to fracturing. However, electric soundings do not allow to determine exactly some structures and therefore, the proposed interpretations must be considered with reserve and also as hypotheses [1] [21].

The electric trails profile can be realized in a reduced way in order to identify with specific structures but also too little penetrating to characterize them [6]. In addition, in complex geological contexts such as that of Air (flush basement), low electrical resistivity values do not indicate precisely the existence of the groundwater. Their variation can be considered as water saturated environments or interpreted as the presence of clay horizons in underground [1] [12] [13].

6. Conclusions

The main major structures identified and the lineaments highlighted on DEM correspond to geological accidents that affected the Pan-African basement of Aïr massif. This method based on remote sensing approach and validated by structural measurements in the field and geological data, shows the suitability and validity of this method. The identified linear structures are potential areas for groundwater accumulation. Thus, they constitute an important tool which helped for aquifer zones identification. However, this approach based on DEM use must be accompanied by geophysical studies to detect structures covered by weathered rocks.

The fracturing map highlighted many accidents of directions N0˚ - N10˚, N30˚ - N50˚ and N130˚ - N140˚ which are the major orientations and can reach several kilometers. The direction N0˚ - N10˚ is that of raghane shear zone that crosses the Aïr massif following the direction N-S which are deep fracutres. Geophysical prospecting allowed to precisely locate the structures mapped in depth and to determine their characteristics and aquifers existence. However, despite the geophysical investigation, this area of Aïr massif records some failures in the realization of drilling. Thus, geophysical studies must be carried out in depth throughout Iferouane department in order to reduce the failure rate.

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Conflicts of Interest

The all authors declare no conflict of interest in this publication.

References

[1] Kouakou, K.E.G., Lasm, T., Sombo, B.C., Ta, M.Y., Baka, D. and Kouadio, K.E. (2014) Contribution of Geophysics in Structural Study and in Identification of Fissured Aquifers in the Department of Dabakala (North Central of Côte d'Ivoire). *International Journal of Innovation and Applied Studies*, **8**, 1752-1769.

[2] Koussoube, Y. (2010) Hydrogeology of the Sedimentary Series of the Piezometric Depression of Gondo (Sourou Basin): Burkina Faso/Mali. University Pierre and Marie Curie-Paris VI.

[3] Kouassi, A.M., Ahoussi, K.E., Yao, K.A., Ourega, W., Yao, K.S.B. and Biemi, J. (2012) Analysis of the Productivity of Cracked Aquifers in the N'zi-Comoé Region (Central East of Ivory Cost). *LARHYSS Journal*, No. 10, 15. http://www.larhyss.net/ojs/index.php/larhyss/article/view/129

[4] Savadogo, N. (1984) Geology and Hydrogeology of the Crystalline Basement of

Haute-Volta: Regional Study of the Sissili Watershed. Scientific and Medical University of Grenoble, Grenoble.

[5] Maxime, G.F., Solange, O.Y.M., Théophile, G., Théolphile, L., Jean, B. and Nestor, K.Y.K. (2014) Analysis of the Productivity of the Fissure Aquifers of the Paleoproterozoic Basement of the Katiola Region (North-Central of Ivory Coast). *European Scientific Journal*, **10**, 5 p. https://core.ac.uk/download/pdf/236416273.pdf

[6] Koudou, A., Adiaffi, B., Assoma, T.V., Sombo, A.P., Amani, E.M.E. and Biemi, J. (2013) Design of a Decision Support Tool for Groundwater Prospecting in the Basement Area of South-Eastern of Ivory Coast. *Geo-Eco-Trop*, **37**, 211-226.

[7] Kouadio, E.K., Nagnin, S. and Savane, I. (2010) Drilling Depth Optimization Strategy in Basement Context: Application to the Denguele Region, North-West of Ivory Coast. *Revue des sciences de l'Eau*, **23**, 1-15. https://doi.org/10.7202/038921ar

[8] Koffi, Y.B., Ahoussi, K.E., Ake, G.E., Kouassi, A.M. and Biemi, J. (2013) Study of the Geologic, Hydrogeological and Geophysical Environment of a Site for the Establishment of a Technical Landfill Centre in Attiekoi in the District of Abidjan (South of Ivory Coast). *Journal of Asian Scientific Research*, **3**, 762.

[9] Assemian, E.A. (2014) Study of the Productivity of a Basal Aquifer and Statistical Approach for the Determination of Potentially Productive Depths: Case of the Bongouanou Region, Eastern of Ivory Coast. *Revue des sciences de l'eau*, **27**, 81-97. https://doi.org/10.7202/1021984ar

[10] Nakolendousse, S. (1991) Methodology for Assessing the Productivity of Aquifer Sites in Burkina Faso: Geology, Geophysics, Remote Sensing. Grenoble 1.

[11] B. FASO (2003) The Different Signatures of Crystalline Basement Fractures in the Sahelo-Sudanian Zone of Burkina Faso (Bidi Watershed, Yatenga Province). *Télédétection*, **3**, 419-427.

[12] Boukari Ousmane, I. and Konaté, M. (year) Synergistic Approach between Spatial Technique and Field Data for the Identification of Fissured Basement Aquifers in Semi-Arid Environment (Liptako, South-West Niger).

[13] Abdou Babaye, M.S. (2012) Assessment of Groundwater Resources in the Dargol Basin (Lip-tako-Niger).

[14] Boucher, M. (2009) Contribution des études géophysiques à la modélisation des eaux souterraines d'un aquifère poreux au Niger semi-aride: An overview. *Comptes Rendus Geoscience*, **341**, 800-809. https://doi.org/10.1016/j.crte.2009.07.008

[15] Boucher, M., Favreau, G., Massuel, S. and Vouillamoz, J.-M. (2006) Hydrogeological Characterization of the Free Aquifer of Continental Terminal 3 (CT3) in Niger by the Proton Magnetic Resonance (RMP) Method. Rapport Final BRGM/RP-54746-FR & Rapport IRD, 106 p.

[16] Pierre, D.S., Yacouba, O., Dimitri, S.D., Serge, K.K., Dégine, G.S.P. and Nicolas, K.L. (2023) Identification of Fracture Aquifers in Cryallophyllian Medium: Contribution of the Electrical Resistivity Method (Bouna, North-East of Ivory Coast). *International Journal of Innovation and Applied Studies*, **38**, 637-648.

[17] Nicaise, Y., Bertrand, A.H., Marc, Y.T. and George, A. (2019) Contribution of Remote Sensing and Geophysics to the Mapping of Hydraulically Active Fractures in the Central-Western Region of Benin.

[18] Joseph, A. and Frangi, J.P. (1989) Modelling of an Effective Groundwater Recharge in Sub-Desert Region: Case of the Téloua Oasis, Niger. *Journal of African Earth Sciences* (*and the Middle East*), **9**, 317-326. https://doi.org/10.1016/0899-5362(89)90074-2

[19] Morel, A. (1973) Villages and Oases of the Monts Bagzans (Aïr-Niger Massif). *Re-*

vue de Géographie Alpine, **61**, 247-266. https://doi.org/10.3406/rga.1973.1319

[20] Gallaire, R. (1995) Hydrology in Sub-Desert Environments: The Case of Aïr (Niger). Paris 11.

[21] Alhassane, I., Maman Sani, A.B., Issoufou, S., Bachir, S.M. and Boureima, O. (2018) Contribution of ETM+ Images and Digital Terrain Model (DTM) to Fracture Mapping in Mountainous Region: Timia Sector (Aïr Massif, North of Niger). *European Scientific Journal*, 14, 103 p. https://eujournal.org/index.php/esj/article/view/10648

[22] Black, R., Lameyre, J. and Bonin, B. (1985) The Structural Setting of Alkaline Complexes. *Journal of African Earth Sciences* (1983), **3**, 5-16. https://doi.org/10.1016/0899-5362(85)90019-3

[23] Pouclet, A., Ahmed, Y., Baubron, J.-C., Bellon, H. and Morel, A. (1994) Age and Establishment of Cenozoic Volcanism in the Graben of Téfidet (Rift System of Eastern Niger). *Comptes Rendus de l'Académie des Sciences* (*France*), *Série II*, **318**, 683-690.

[24] Pouclet, A., Lee, J.-S., Vidal, P., Cousens, B. and Bellon, H. (1994) Cretaceous to Cenozoic Volcanism in South Korea and in the Sea of Japan: Magmatic Constraints on the Opening of the Back-Arc Basin. *Geological Society*, *London*, *Special Publications*, **81**, 169-191. https://doi.org/10.1144/GSL.SP.1994.081.01.10

[25] Moreau, C., Rocci, G., Brown, W.L., Demaiffe, D. and Perez, J.-B. (1991) Palaeozoic Magmatism in the Aïr Massif, Niger. In: Kampunzu, A.B. and Lubala, R.T., Eds., *Magmatism in Extensional Structural Settings*: *The Phanerozoic African Plate*, Springer, Berlin, 328-352. https://doi.org/10.1007/978-3-642-73966-8_13

[26] Baka, D., *et al.* (2011) Characterization of Transmissivity in the Fractured Reservoirs in the Oumé Area (Centre of Cote d'Ivoire). *American Journal of Scientific and Industrial Research*, **2**, 310-322. https://doi.org/10.5251/ajsir.2011.2.2.310.322

[27] Ahmed, Y., Soumaila, A., Nouhou, H. and Harouna, M. (2017) Petrographic and Geochemical Characteristics of Cenozoic Volcanism of the Téfidet Ditch (Aïr, Eastern Niger). *Sciences de la vie*, *de la terre et agronomie*, **4**, 110 p.

[28] Liégeois, J.-P., Abdelsalam, M.G., Ennih, N. and Ouabadi, A. (2013) Metacraton: Nature, Genesis and Behavior. *Gondwana Research*, **23**, 220-237. https://doi.org/10.1016/j.gr.2012.02.016

[29] Joseph, A. (1991) The Aïr, Water Tower of the Desert Band of Ténérés (Niger). *Revue de Géographie Alpine*, **79**, 71-86. https://doi.org/10.3406/rga.1991.3587

[30] Raulais, M. (1959) Geological Sketch on the Crystalline Air Massif (Niger). *Bulletin de la Société Géologique de France*, **7**, 207-223. https://doi.org/10.2113/gssgfbull.S7-I.2.207

[31] Rey, F. (2007) Groundwater Resources in the Bearnais Ranges (Pyrénées-Atlantiques, France): Geometry and Hydrogeological Functioning of Four Carbon Aquifers. Bordeaux 1.

[32] Corgne, S., Magagi, R., Yergeau, M. and Sylla, D. (2010) An Integrated Approach to Hydro-Geological Lineament Mapping of a Semi-Arid Region of West Africa Using Radarsat-1 and GIS. *Remote Sensing of Environment*, **114**, 1863-1875. https://doi.org/10.1016/j.rse.2010.03.004

[33] Liégeois, J., Benhallou, A., Azzouni-Sekkal, A., Yahiaoui, R. and Bonin, B. (2005) The Hoggar Swell and Volcanism: Reactivation of the Precambrian Tuareg Shield during Alpine Convergence and West African Cenozoic Volcanism. *Special Papers-Geological Society of America*, **388**, 379. https://doi.org/10.1130/0-8137-2388-4.379