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# Geophysical survey methods adapted to substratum

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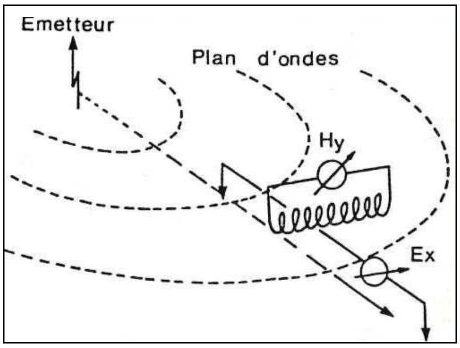
For many years (from the 80s), especially in the West of France, the most common geophysical survey has been the VLF method to search groundwater in the substratum. This method stemming from the mining exploration in Canada was implemented for the first time in Vendée by the DDAF to look for groundwater resource. This technique was used by the COGEMA to locate the tectonic contacts between the granite of Mortagne-sur-Sèvre and the surrounding formation, places of uranium mineralizations. Mr. Bresson, at that time departmental hydrogeologist, knew how to develop this method in search of faulted structures, the most convenient to groundwater flow.

## I. ELECTROMAGNETIC METHOD VLF

### I. 1 Principle

Electromagnetic prospecting method is based on the measurement of the electromagnetic wave disturbance in the ground. The electromagnetic method VLF (Very Low Frequency) use radio waves of very low-frequency (15 to 25 kHz) emitted by distant and powerful broadcasting stations, used for military purpose.




An electromagnetic wave is constituted of two fields, magnetic and electric, which are perpendicular between them and to the direction of the wave propagation. The magnetic field (Hy) is tangential; the electric field (Ex) is radial to the wave plane (Geonics Limited, on 1979).

By means of a crossed antenna, VLF instruments measure the horizontal and verticals components of the magnetic field. The electric component is measured by difference of potential between two classic or capacitives electrodes spaced out by 5 or 10 meters. Devices also measure the phase shift between the magnetic and electric components of the field.

The apparent resistivity of the ground is a function of the value of the electric and magnetic fields, it is directly given by the device.

Investigation depth varies according to the wave frequency but also according to the ground resistivity. This depth is as high as the frequency is low and the resistivity is strong. The investigation depth admitted for this equipment is $\mathbf{P = 3.6} \sqrt{\rho_a}$. It can vary from ten to hundred meters according to the ground resistivity.

### I. 2 Apparent resistivity measurement - Directional effect

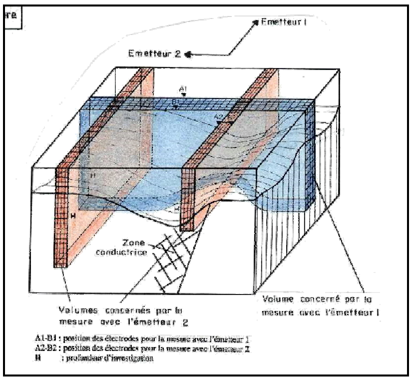
Basic maps are the apparent resistivity maps, because the values are directly given by the device. These maps highlight the resistivities distribution on all the prospected area in a more or less wide stitch. Conductive axes, which can represent fractured zones, and resistance axes (veins) are revealed.

Besides the visualization of these axes, this method has the advantage to highlight the anisotropie of the prospected field. Indeed, this technique is directional, measures are made in the emitter axis.

Every resistivity measure concerns a vertical rectangular parallelepiped which width is the distance between both electrodes and length is infinite, its orientation is perpendicular to the emitter direction.

The highlighted structures are then perpendicular to the transmitter.

It is common use to work with two perpendicular emitters to minimize the effects of anisotropy and to reveal all the existing anomalies in the ground.



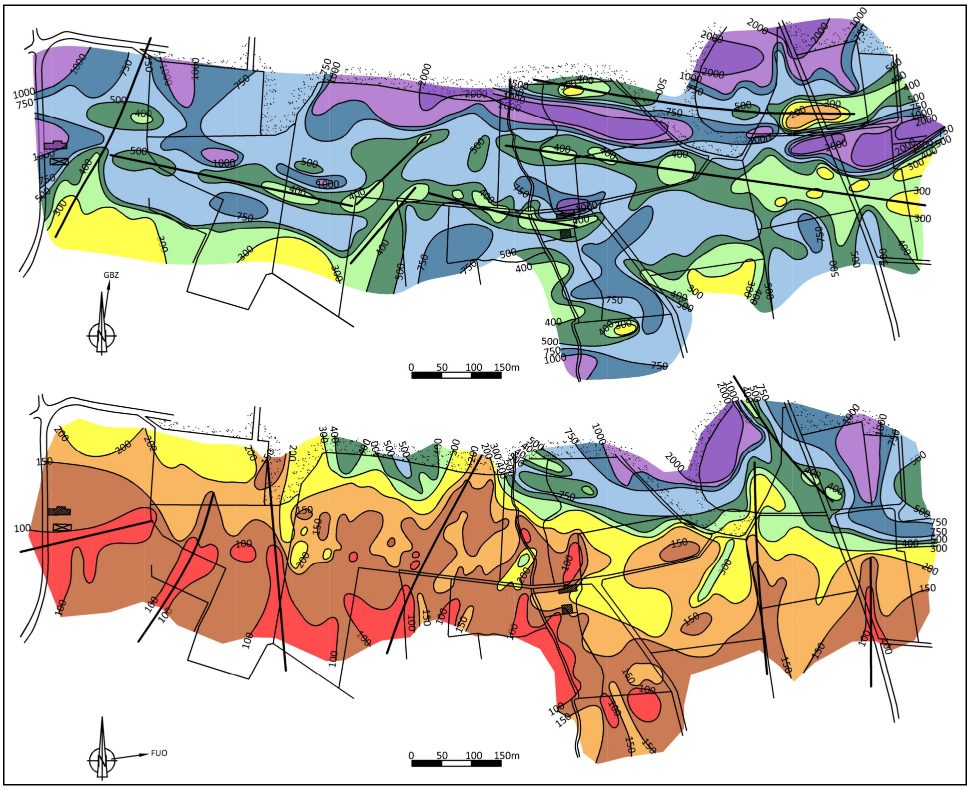




*Figure 1 - Grand-Champ (Morbihan, France) - Highlighting the ground anisotropy - At the top, emitter perpendicular to the schistosity – At the bottom, emitter subparallel - In the Northeast quarter are the Lanvaux Orthogneiss, at the South, the Paragneiss and Mica-schists of Bains-sur-Oust*

The knowledge of the bedrock nature and structure allows to improve a borehole positioning. Indeed, the productive drillings are often located at the contact between granitic intrusions and schists.

## I. 3 Resistivty measurement - Bilayer model interpretation

Given that the apparent resistivity maps do not allow a precise borehole positioning, we tried to make interpretations from the other recorded data. Besides the apparent resistivity value, the device gives the measure of the phase angle between the magnetic and electric components of the field.

This value, called phase shift, allows to know the distribution of the in depth ground according to a bilayer model :

- phase shift  equal to 45°, all the ground included by the measure is homogeneous ;
- phase shift lower than 45°, the top layer is more conductive than the bed rock ;
- phase shift up to 45°, the model is upside down, the first horizon is more resistant.

HP. Grissemann and G. Reitmayr (1978) proposed a calculation method to estimate the thickness and resistivity of the bedrock from the apparent resistivity and the phase shift, assuming a resist value for the top layer resistivity.

This interpretation method allows to have a good picture of the bedrock structure and to make a better borehole positioning. If we apply this model to the previous measurements, we can have a good view of the in depth ground organization.

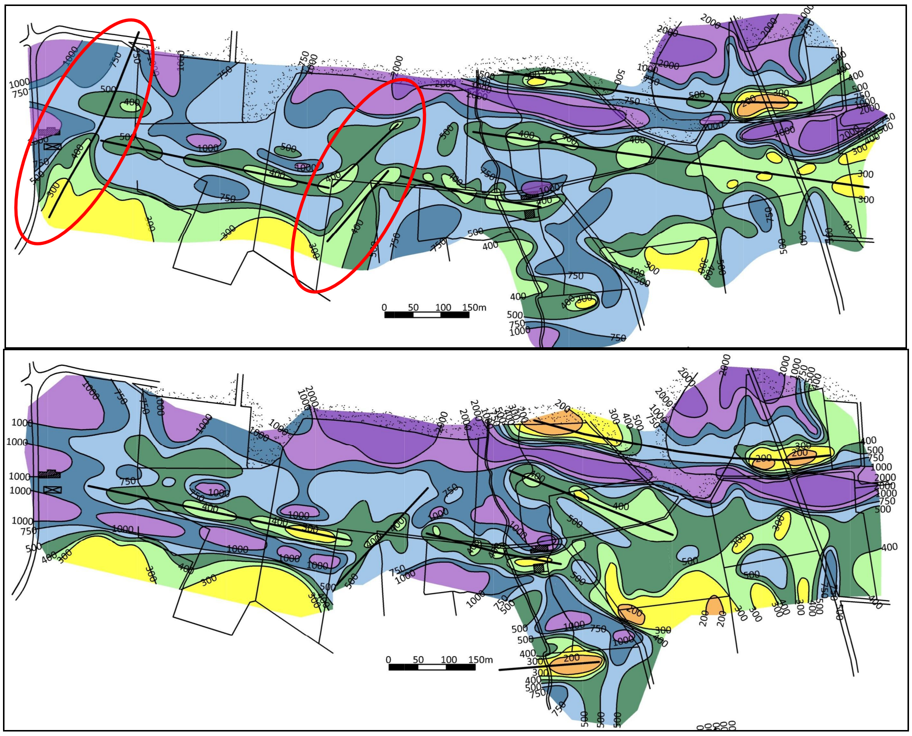
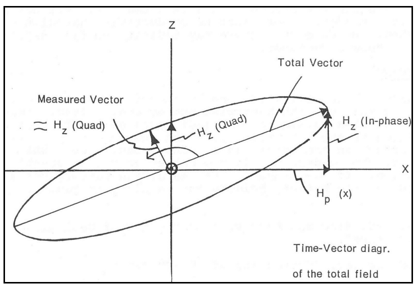


*Figure 2 - For a single emitter - At the top : apparent resistivity - At the bottom : image of the bedrock under the weathered formation. The structures get organized differently.*

## I. 4 Magnetic measurements

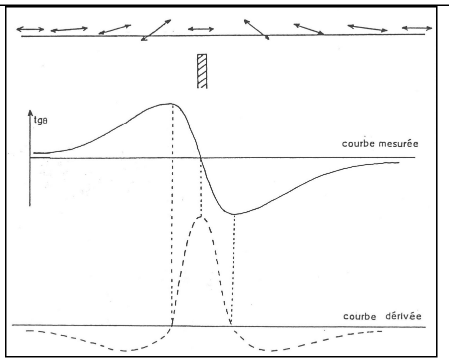
Always in the interest of taking advantage of all the acquired measures, interpretation methods were developed from the magnetic data.

Close to a conductive body, electromagnetic waves are distorted; these distortions are measured on the ground surface.
In a homogeneous substratum, the magnetic field has only a horizontal component, while close to a conductive vein, appear two vertical components, one in phase, the other one in quadrature (Geonics Limited, on 1983).




The device gives the horizontal component and the vertical components, phase and quadrature, of the magnetic field.

From these date variations, it is possible to locate the conductive zones in the unweathered bedrock. The plotting of these values on graphs allows to locate the conductive zone on the inflexion point of the curve.
Magnetic data processing is made by derivation and smoothing. This treatment aims at erasing high frequencies anomalies and at making more readable profiles or maps, by transformation of inflexion points in maxima (Geonics Limited, on 1983)




O Martiré (1991) developed a method to calculate the distribution of the angle of phase in depth, from the works of Fraser (1969) and Karous-Hjelt (1983). The results are reported either on maps, or on vertical profiles of the ground. The latter, called pseudosections, indicate the dip of conductive bodies.

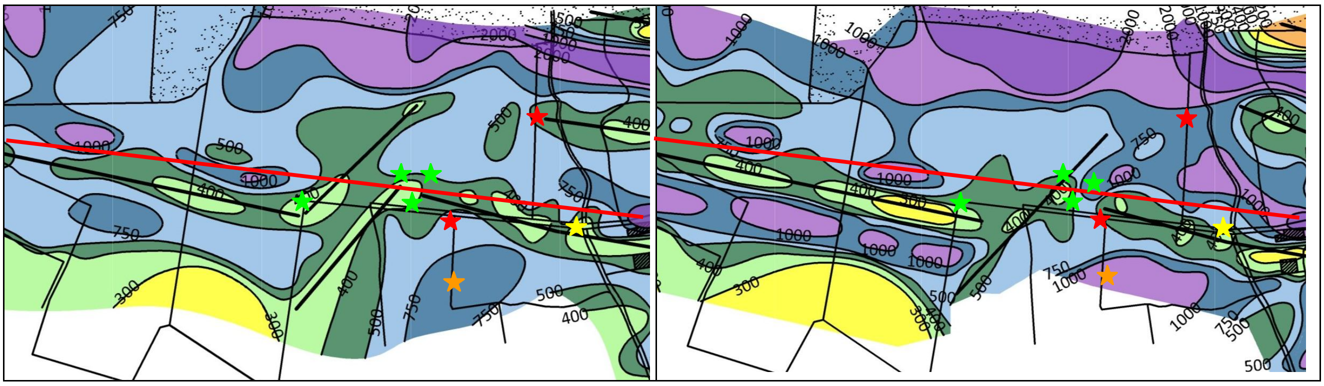


*Figure 3 - Location of the magnetic profile across the conductive axes, on the left side, apparent resistivity map, on the right side, bedrock resistivity map.*

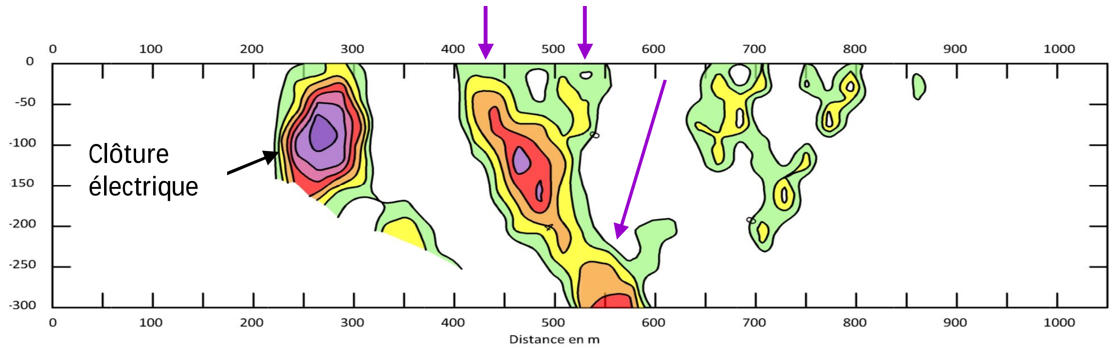



*Figure 4 - Representation of the resultant pseudosection showing two shallow conductive axes on the top and just a deep one.*

Even with theoretical depths, this type of representation allows a better borehole positioning close the interesting structures.
The results of this survey gave good flow rates (more than 50 $m^3$/h) for the exploration drilling represented by the green stars (fig. 3).

The VLF method, in despite of the limited investigation depths, always gives satisfaction for groundwater research, because it is a fast and easy technique to implement.

However, the emitter sources are not mastered, emitters are not still active or directed in a satisfactory way. Geonics markets a specific emitter; but it is a 1 km loop to be settled far enough from the prospected area to respect the flatness of the wave.

## II. ELECTRICAL TOMOGRAPHY

As the VLF method are not always carried out and/or to confirm the existence of deep fractures, it is more and more often asked to implement electric tomography. Generally, the protocol of data acquisition is the protocol Schlumberger, which highlights the vertical structures, the spacing between electrodes are 5 m, and a 315 m deployed length. Investigation depths are also limited to about fifty meters.

The results are not always easy to understand, because of the important integration of the ground, the fracture location is not precise.

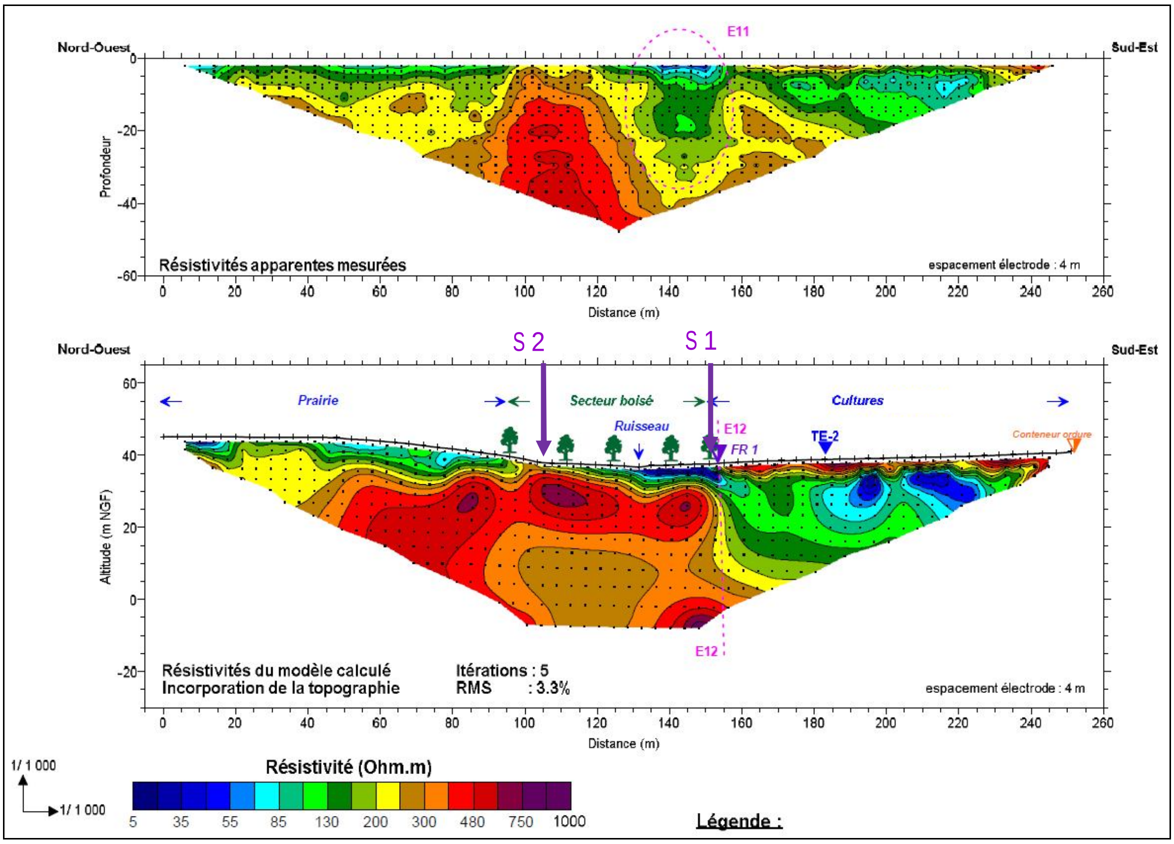



*Figure 5 - Plouénan (Finistère, France) – Implementation of an electrical tomography in the basement - At the top, raw data, at the bottom : inversion results*

On the tomography (fig. 5), the results seemed to show the existence of a clear contact between two resisting compartments at the Northeast, more conductive at the Southeast, a borehole was then positioned at this place.

Water inlets were found deeply (from 105 to 118 m) for cumulative flow rate of 11 $m^3/h$. The hydrogeologist who monitored the project positioned a new borehole on the other side of the wood land, water inlets were more displayed, between 55 and 85 m, and cumulative flow rate was 38 $m^3/h$. The tomography shows at that place high resistivities until 25 m (greater than 450 ohms.m), lower deeply (250 to 300 ohms.m), but beyond 45 m, the information is non-existent.

To reach more important depths, it is necessary to use bigger devices with more spaced out electrodes (and a more powerful system of injection), knowing that the precision will be lesser ; or use a pole-dipole protocol with an electrode at the infinity (at least 6 times the length of the deployed length device), which can raise problems for its deployment on the field.

## III. NEW METHODS TO IMPLEMENT

Given that groundwater researches are made more and more deeply : 150 - 200 m, the classical geophysical prospection surveys are not any more adapted. Other methods must be used to master the borehole positioning, none is ideal, they all have limitations.

### III. 1 High resolution seismic reflection

Seismic reflection survey is based on the basement capacity to send back a "echo" every time the emitted waves meet a change of the crossed rocks properties. These reflectors are surfaces which bound the various layers of the basement, or fractures, or heterogeneous zones within the rock.

Contrary to other exploration geophysics methods, this technique allows a high resolution even at great depths. To be operational, it is necessary to have seismic reflectors, ie layers with contrasted speed and/or density. This method is particularly well adapted to define the underground geometry and to locate the sub-vertical faults with offset, the horizontal accidents, as well as the geological contacts which slope is lower than 45 °.

### III. 2 Proton magnetic resonance (PMR)

The main interest of this method is its faculty to recognize directly and only water molecules. The hydrogeological interpretation of the recorded signals completes the classical geophysics tools that measure not directly the groundwater, but the whole porous media.

The PMR principle is based on the resonance signal of the hydrogen nuclei (protons) contained in water molecules in response to an electromagnetic signal of given frequency.
The pulse signal is created by the flow, in a cable displayed on the ground, of a very powerful current generating a magnetic field which modifies the energy balance of the water molecule protons in the substratum. Cutting off the current at the end of brief time - several tens of milliseconds - cause a return to balance of these protons which send back a relaxation signal in the form of an electromagnetic field.

The investigated volume by a PMR sounding is defined as a vertical cylinder which diameter is approximately 1,5 times the loop diameter, centered on this one and of height equal to this diameter. The maximal investigation depth of the marketed device, without conductive grounds, is about 120 m.

The investigation depth decreases when the ground conductivity increases, and in the presence of surface water in the weathered horizon, there is a screening effect which decreases the PMR method capacity to study the deep part of the bedrock aquifers.

### III. 3 Time Domain ElectroMagnetic (TDEM)

The TDEM method is based on the measurement of the magnetic field temporal response. The principle consists in displaying on the ground a cable loop in which we create a static magnetic field by passing an electric current flow. Then, cutting the power as fast as possible: it creates a flow difference and an induction in the ground that creates a secondary field, which we measure for example in the center with a smaller cable reel.

The secondary field is decreasing with time. Greater the time is, deeper is the obtained information. The study of the decay shape is translated by a sounding curve connecting the apparent resistivity (y axis) to time (x axis) in a similar way to electric soundings. This curve is studied and inverted to reconstitute the resistivity variation as a function of depth.

The TDEM method is very sensitive to conductive grounds and to the position of their top, and determines them more precisely than electric soundings. However, the resistant grounds (greater than 500 ohms.m) are badly differentiated.

## III. 4 Multifrequency electromagnetic methods

Slingram's electromagnetic methods are based on the measurement of the electromagnetic waves disturbance in the ground. These methods work in the following way:

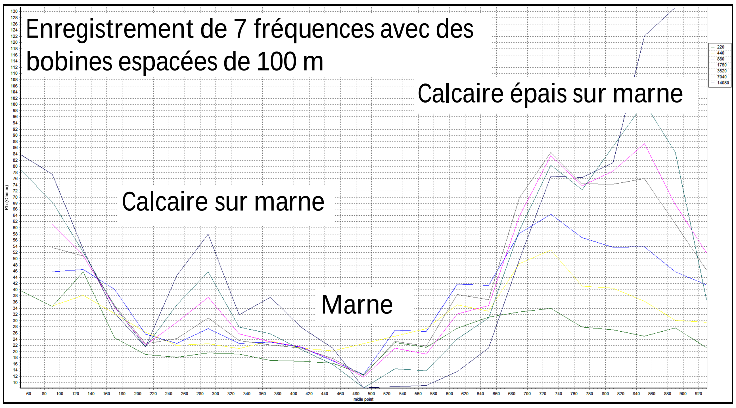
- a primary magnetic field is emitted by an emission loop by circulating an alternative electrical current ;
- from its emission, the primary field creates in the ground, by induction effect, electric currents which can be modified by the basement heterogeneity ;
- these induction currents create a "secondary" magnetic field, which frequency is identical to the primary field.

The sum of fields is then measured by the receiver coil. The primary field known, it is possible to deduct the apparent electric conductivity of the ground.

The multifrequency electromagnetic method allows the emission of several primary fields of different frequencies. For a given device (space out, orientation), many frequencies are proposed, each frequency characterized by a penetration depth. It means that for a single device, there will be so many depths of investigation as selected frequencies. Several inter-electrode spaces are available between 20 and 400 m.

These devices are free of any contact with the ground and allow the implementation of profiles in a very fast way, about 2 minutes for 10 frequencies with the 200 m device. The equipment is however very cumbersome and heavy to operate. The biggest constraint is the transfer of all the device in context of bocage (hedges, fences, electric lines, etc.).

The results are presented in the form of conductivity or resistivity curves according to the various available frequencies. There is no specific software for data inversion, required to obtain of a terrain model. The inversion can be done by using the electric soundings interpretation softwares, but remains delicate to implement and is not satisfactory.




## III. 5 Audiofrequency magnetotelluric (AMT)

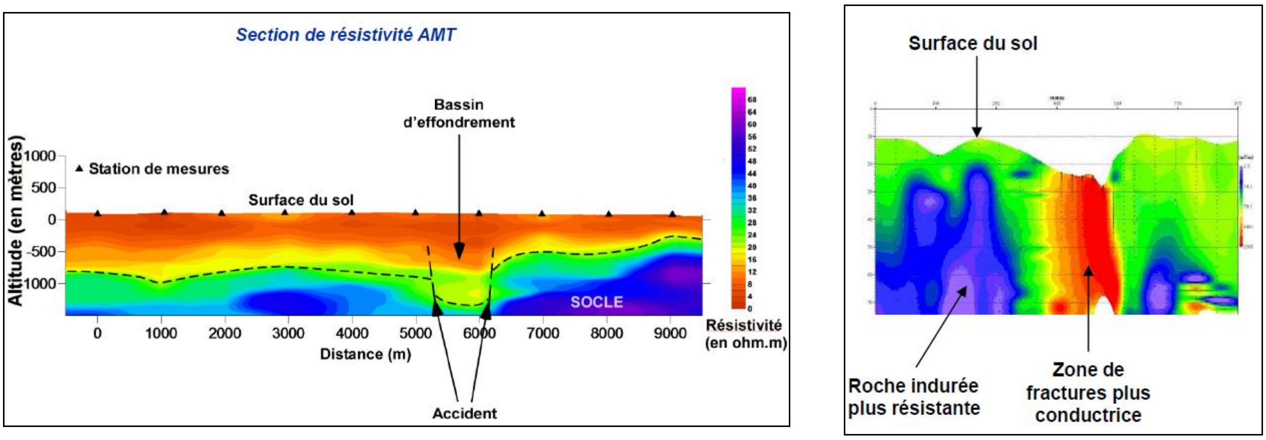
The AMT method is a passive method of electromagnetic sounding, it is based on the measurement of the electric and magnetic components of natural EM fields. The main magnetic sources are the natural fluctuations of the magnetic field in the ground, which is characterized by a wide frequency spectrum. The natural magnetic field penetrates into the ground and its temporal variation creates an electric current in the conductive rocks, called the telluric current. The latter induce another magnetic field, called "secondary magnetic field". It is about the same principle as for the superficial electromagnetic measures.

The geomagnetic field's variations used in the magneto telluric measurement are those which frequency stands between $10^{-4}$ and $10^{3}$ Hz. These variations are due to several different phenomena:

- frequencies greater than 1 Hz are mainly generated by the tropical thunderstorms. Their geographical distribution is such as at anytime of day there is probably a thunderstorm.
- for frequencies lower than 1 Hz, the natural fluctuations of the electromagnetic field are due to the complex interactions between the solar radiation and the earth's magnetic field.

By measuring simultaneously on the ground surface the electric field and the associated magnetic field, it is possible to infer a vertical cross section of the underground resistivity directly above the measuring station. The measurement device is characterized by four electrodes to measure electric fields Ex and Ey (dipoles length between 50 and 100 m) and of three magnetic coils to measure the components Hx-Hy-Hz of the magnetic field. The measures are made according to regularly spaced out stations. The acquisition can be rather long approximately 2 hours.

The results show that the method seems well adapted to highlight faulted structures in big depth. Furthermore, it integrates less ground than the previous methods.




*Profil 7 - Example of AMT restitution - CGG document*

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