THE PROTON MAGNETIC RESONANCE METHOD FOR GROUNDWATER INVESTIGATIONS

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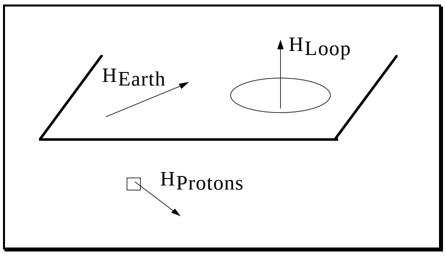
PRINCIPLE OF THE PROTON MAGNETIC RESONANCE METHOD

The PROTON MAGNETIC RESONANCE (PMR), also known as the Nuclear Magnetic Resonance (NMR), is a property of hydrogen protons which produce a magnetic field when they are excited by an alternative field in the presence of a static magnetic field. Most hydrogen atoms located in the ground are coming from water molecules. The direct detection of water can thus be envisioned with such a method, while conventional geophysical methods only provide structural information.



In the PMR method, three magnetic fields have to be considered:

1. the Earth's field, the amplitude of which determines the precession frequency of the protons.
2. The excitation field, produced by a current into a loop laid on the surface of the ground, at a frequency equal to the precession frequency (called the Larmor frequency).
3. The relaxation field produced by the protons excited by the previous field. The amplitude of the relaxation field measured at the surface, after the excitation current is turned off, is directly linked to the number of protons which have been excited and thus to the water content.

Source of the field	Nature of the field	The field .....
Earth	Static	... determines the precession frequency (0.5G => 2kHz)
Loop	Alternative	... excites the protons and causes their precession
Protons	Alternative	... is proportional to the water content

PMR AND PROTON MAGNETOMETRY

The PMR property is already commonly used by geophysicists in proton magnetometers, for measuring the amplitude of the Earth's magnetic field: in that case, the protons excited are those located in the sensor unit, the measured quantity is the resonance frequency of the protons and the physical quantity determined is the amplitude of the Earth's magnetic field, the variations of which are related to the magnetic underground structures. In the application of PMR to groundwater detection , the protons excited are those located in the ground, the measured quantity is the amplitude of the proton relaxation field and the physical parameter determined is the water content of the underground versus depth.

	Proton magnetometry	PMR for groundwater
Excited protons	Sensor protons	Underground protons
Measured quantity	Signal frequency	Signal amplitude
Physical parameter	The amplitude of the Earth's field	The water content of layers

PMR BASIC EQUATIONS

The precession frequency f_0 of the protons subjected to the Earth's magnetic field H_0 is determined by the relation:

$$f_0 = H_0 \ \gamma / 2\pi$$

where γ the gyromagnetic ratio of the protons [$\gamma = 0.268$ Hz/nT]

The decay of the relaxation field produced by the protons after the excitation current has been turned off is given by the relation:

$$E = E_0 \exp(-t / T_2^*) \sin(2\pi f_0 t + \varphi_0)$$

where T_2^* is the time constant of the decay and φ_0 is the phase shift between the excitation current and the relaxation voltage measured in the loop.

T_2^* is of the order of a few tens milliseconds for clay bound water and of the order of a few hundreds milliseconds in pore free water.

The expression of the relaxation voltage measured at the surface just after the excitation current has been turned off is:

$$E_0 = \int_v 2\pi f_0 H_\perp(r) M_0 f(r) \sin\left(\frac{\gamma}{2} H_\perp(r) q\right) dv$$

where:

M_0	is the magnetic moment of the water molecules
f(r)	is the water content
q	is the pulse moment (intensity x duration)
$H_\perp(r)$	is the component of the excitation field perpendicular to the Earth's field for a unitary current (I = 1A)

In the latter equation, it can be seen that the excitation field appears not only as a multiplicative term in the integrand which is usual in Physics, by also as an argument in a sine function, which is less usual and corresponds in fact to the proper response of the protons to the excitation.

The wavelength of this sine function depends, on the one hand, on the excitation field which is depth dependant, and on the other hand, on the pulse moment: it is therefore understandable **that the depth of investigation of the system** is closely related to the pulse moment. In practice, for a given value of the pulse moment, the main part of the signal comes from the deepest arch of the Sine function, whose position in depth is proportional to the pulse moment: lower moments thus lead to shallow investigations, while higher moments lead to deeper investigations.

The amplitude of the Earth's magnetic field has to be measured at the location of the measurements for determining the precession frequency of the protons which is proportional to this amplitude. Besides, the magnetic moment of water molecules is also proportional to this amplitude, and the relaxation voltage is thus proportional to the square of the Earth's magnetic field amplitude. **The dip of the Earth's field** in the area of the survey has to be estimated from regional magnetic maps for an adequate quantitative modelization, as in the previous equation the component of the excitation field which has to be taken into account $H_\perp(r)$ is that perpendicular to the Earth's field.

When the ground is infinitely resistive, the excitation field H(r) is the primary field of the loop in free space. **When the ground is conductive**, the excitation field is the total field (primary and secondary). A conductive ground will lead to a lower excitation field than a highly resistive one, and the depth of investigation will decrease when conductivity increases, for a given value of the pulse moment. The phase shift between the PMR signal and the excitation current in the loops permits to determine the ground conductivity and to improve the quantitative interpretation of PMR soundings.

INVESTIGATION DEPTH OF PMR

In surface PMR measurements, the depth of investigation depends on two main factors:

- **The surface of antenna** which determines the maximum volume investigated: roughly speaking, this volume is limited by the cylinder passing through the antenna and limited to a depth equal to the diameter of the antenna.

- **The moment of the excitation pulse** (product of the intensity of current by the duration of the pulse) which permits to investigate the various layers located between the surface and the maximum depth determined by the surface of the antenna.

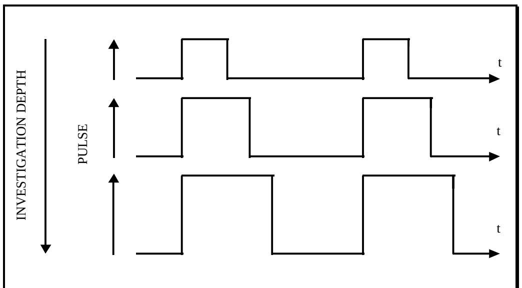
Two other factors which depend on the local field conditions also influence the depth of investigation :

- **The rock resistivity**: a conductive ground leads to a lower depth than a resistive one, for a given antenna surface and pulse moment

- **The Earth's magnetic field**: the larger the Earth's field amplitude, the higher the signal amplitude, and the easier the detection of deep aquifers; besides, the dip of the Earth's field also influences the depth of investigation which is slightly greater for a vertical field (pole condition) than for a horizontal field (equator position).

PMR AND ELECTRICAL SOUNDING

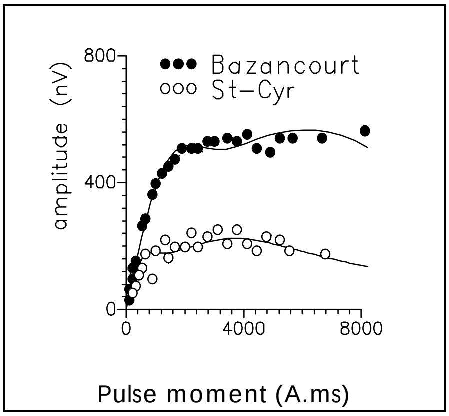
As shown in the previous section, it is possible from surface measurements to determine the water content at various depths of investigation, that is to say to carry out an "PMR sounding" somewhat similar to a "Vertical electrical sounding" (VES) well known from geophysicists and hydrogeologists: in an electrical sounding, the parameter which sounds the ground is AB/2 (half length of the transmitting line), the measured quantity is the electric field and the physical parameter which aims at being determined is the true resistivity of the various layers at depth; in a PMR sounding, the parameter which sounds the ground, beside the loop size, is the moment of the excitation pulse (product of the intensity of current at the resonance frequency by the duration of the pulse), the measured quantity is the magnetic field produced by the excited protons and the physical parameter which aims at being determined in the water content of the various layers at depth.



PULSE AND DEPTH INVESTIGATION

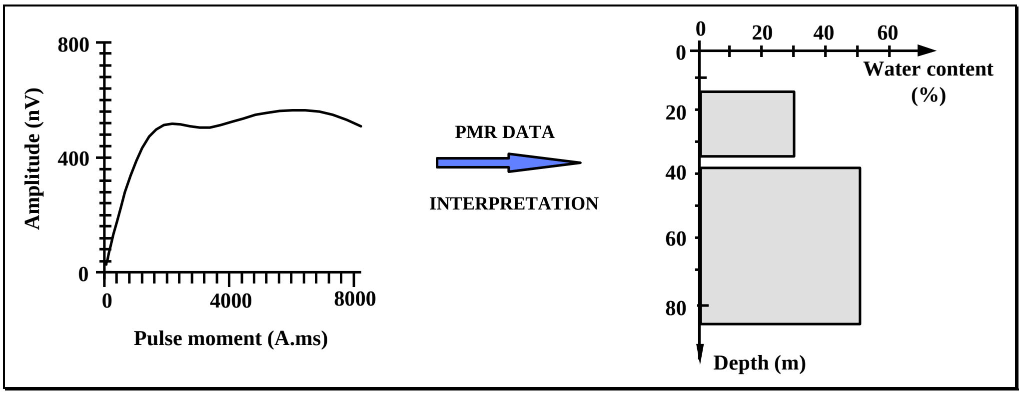
	VES SOUNDING	PMR SOUNDING
Parameter which sounds the ground	Length of Tx line AB/2	Pulse moment q = It
Measured quantity	Electric field	Proton magnetic field
Physical parameter estimated	True resistivity of each layer	Water content of each layer

INTERPRETATION OF PMR DATA



Interpreting PMR data consists in determining the water content of each layer, in the hypothesis where the underground is stratified at the scale of the loop dimensions. The inversion consists in processing the raw data for the whole set of pulse moments corresponding to the various depths of investigation. As for electrical sounding interpretation, indetermination and equivalence properties exist in PMR in the theoretical solutions given by inversion algorithms. However, some parameters are well defined such as the product of the thickness of a thin layer by its water content. Once again, a major advantage of the PMR method compared to more traditional methods is that PMR involves a parameter directly linked to the presence of water.

The interpretation also permits to determine the decay time constant of each layer by inverting the decay time constant of the measured signals for the whole set of pulse moments: thus, each aquifer layer can be characterized by the mean size of its pores, which is a good indicator of its permeability.



SYNTHETIC PMR SOUNDING

To have a clear understanding of the sounding capability of the PMR method, it is useful to compute the PMR response of theoretical 1D models.

Influence of the water level (fig. 1)

A two layer model has been used with 0% water for the upper one and 20% water for the lower one. The depth of the water level (top of the lower layer) has been set up at 10, 20 40 and 80 m respectively. The amplitudes of the received voltage versus the pulse moment clearly point out the influence of the pulse moment on the depth of investigation.

Effect of a water layer of finite thickness (fig. 2)

A three layer model has been used to represent an aquifer (20% water) included between two dry layers (0% water). The thickness of the water bearing layer has been fixed to 10 m in all cases ; its depth increases from 10 to 30, 50 and 70 m. The position of the maximum of the response is indeed shifted to the right side (high values of pulse moment) when the depth of the water layer increases.

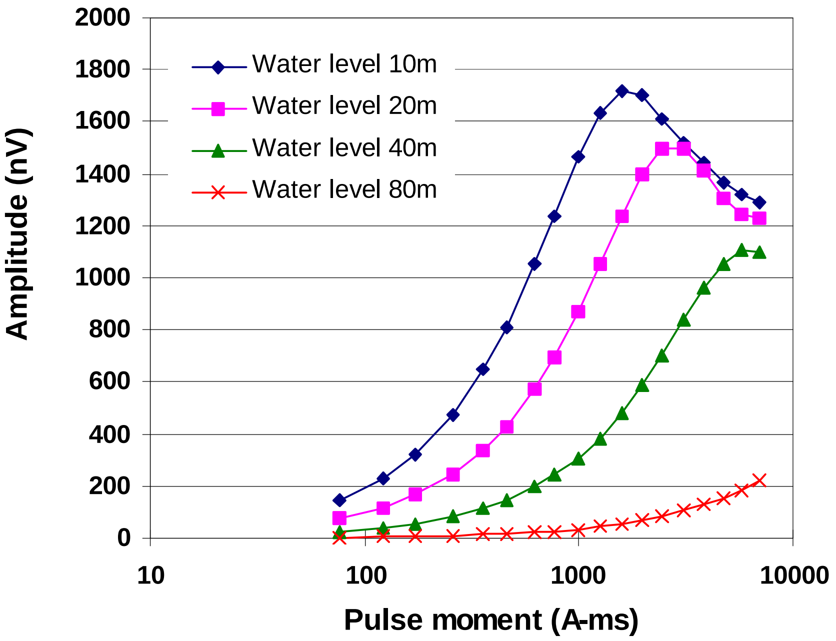


Fig 1: PMR response of a very thick layer with 20% water content, as a function of pulse moment, for various layer depths (water level). Loop diameter is 100m

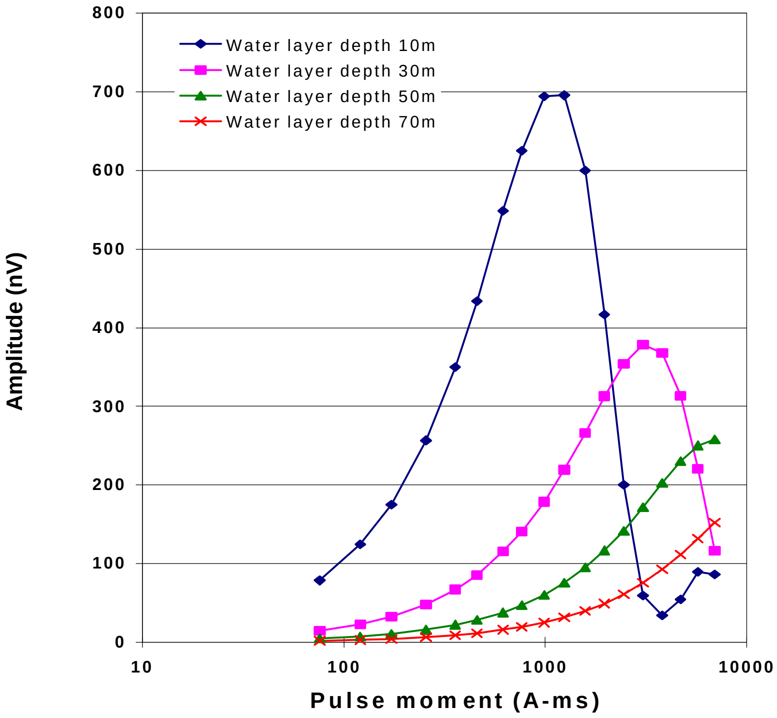


Fig 2: PMR response of a 10m thick layer with 20% water content, as a function of pulse moment, for various layer depths. Loop diameter is 100m.

Contribution of each depth in an homogeneous ground (fig. 3)

An homogeneous ground has been sliced in many layers each one having the same water content (20%) and the same thickness (1m). The response of each layer has been plotted versus depth for given values of the pulse moment: approximately 0.1, 0.5, 2 and 8 A.ms. Once again, the sounding capability of the pulse moment can be checked, the response of lower moments mostly coming from shallow layers while that of higher moments mostly coming from deeper layers.

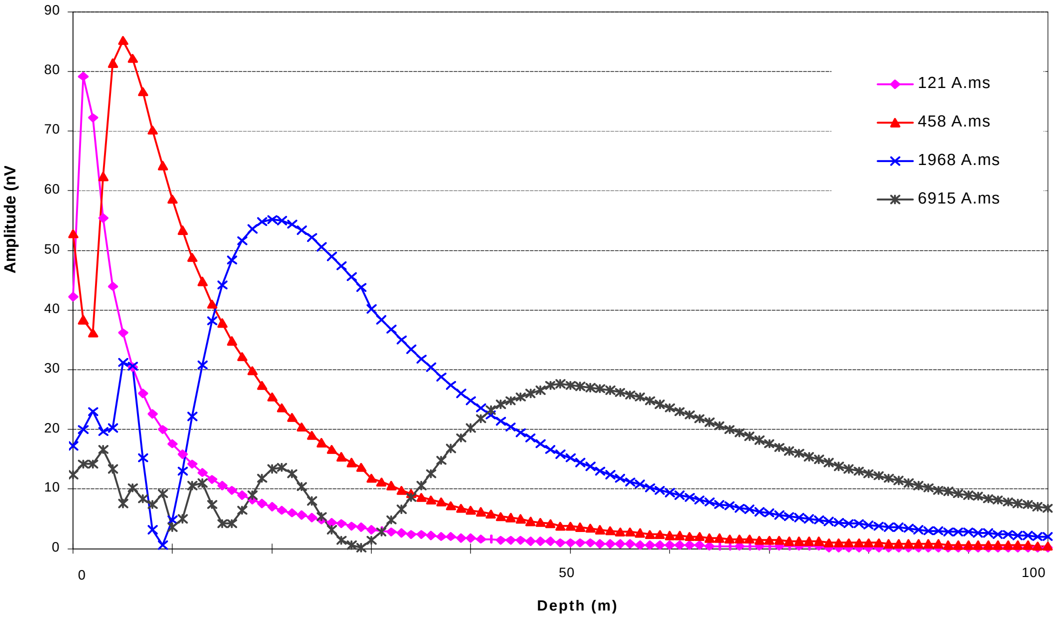
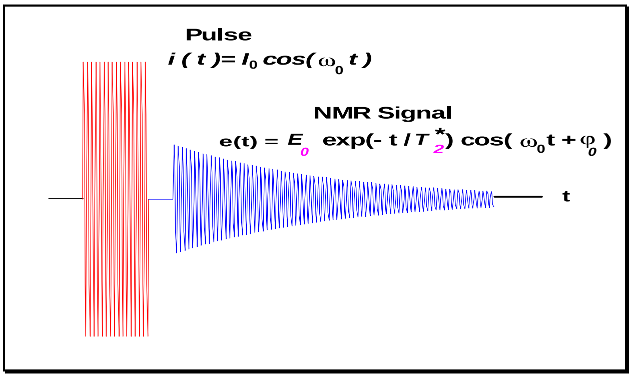


Fig 3 : Contribution, as a function of depth, of each elementary layer to the PMR response of an homogeneous ground with 20% water content, for various pulse moments. Loop diameter is 100 m.

PHYSICAL PARAMETERS DETERMINED WITH PMR

In a PMR survey, the various parameters which are measured once an excitation pulse has been transmitted into the loop are the following ones:

- The amplitude E_0 of the relaxation field produced by the protons, just after the excitation current has been turned off; E_0 is directly linked to the water content.
- The decay time constant T_2^* of the relaxation field which is related to the pore size, and which permits to distinguish between pore free water and clay bound water.
- The phase shift φ_0 of the relaxation field with respect to the excitation current in the loop, which is linked to the resistivity of the ground.



Measured quantity (versus pulse moment)	Physical parameter (versus depth)
Amplitude of the PMR signal	Water content
Decay time constant of the signal	Mean Pore size
Phase shift between signal and current	Rock layer resistivity

SOME REFERENCES TO KNOW MORE ABOUT PMR

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