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GROUND PENETRATING RADAR APPLIED TO THE STUDY OF PEAT BOGS AND MOORS[1]

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(9 figures)

ABSTRACT.- Ground Penetrating Radar (GPR) is a shallow geophysical exploration technique based on the reflection of electromagnetic impulses. It gives a continuous image of the subsurface, like reflection seismics. The strong attenuation of radar waves in most soils is a major limitation. Peat however has very favourable electrical characteristics resulting in low attenuation and excellent results are obtained from GPR surveys. Several examples are discussed showing the wide range of possible applications.

RESUME.- Le radar de subsurface est une technique de prospection géophysique peu profonde basée sur la réflexion d'une impulsion électromagnétique. Le radar fournit un profil continu de la subsurface semblable à ceux obtenus en sismique réflexion. La forte atténuation des ondes radar dans la plupart des sols constitue une limitation majeure de la méthode. La tourbe présente cependant des caractéristiques électriques favorables entraînant une atténuation faible et on obtient ainsi d'excellents résultats. Plusieurs exemples sont discutés, montrant la vaste gamme des applications possibles.

1.- INTRODUCTION

Ground Penetrating Radar (GPR) is one of the most recent techniques in shallow geophysical exploration. It is based upon the reflection of an electromagnetic (EM) wave on the interfaces between layers.

Provided the electrical characteristics (resistivity and permittivity) are favourable, the method has been very successful in a wide range of applications like geological and environmental investigations, pipeline and rebar detection, ice thickness determination,.... The main advantage of GPR compared to other methods is to give a continuous image of the subsurface.

This paper will focus on the investigation of peat deposits, one of the most typical geological applications of GPR.

2.- THE RADAR METHOD

The GPR method is described in Ulriksen (1982) or Davis (1989).

The principle may be summarized as follows (fig.1).

A high frequency broadband EM impulse is radiated into the ground by a dipole antenna (transmitter). The central frequency depends upon the antenna: usually 80, 120 or 250 MHz for geological applications. The impulse propagates and part of its energy is reflected by interfaces like the peat-clay or peat-boulder contacts (fig.1a). These echoes are detected by the receiver antenna. The resulting signal or trace is shown on figure 1b: the initial impulse is immediately followed by a strong reflection on the ground surface. Deeper interfaces are shown by later reflections.

A main advantage of GPR is the high repetition rate of the system. Currently available instruments allow a scan rate of up to 50 traces per second. If the antenna is towed continuously along the profile, and the successive traces juxtaposed on the record, a continuous profile of the subsurface

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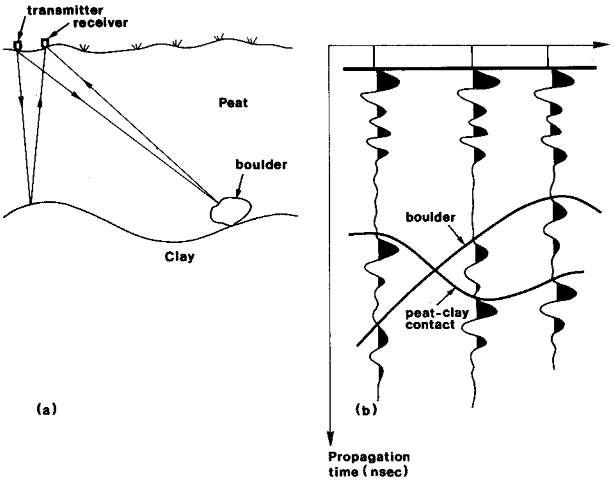

Fig.1.- (a) field layout
(b) record

will result. This procedure is similar to single trace marine seismics. On the record, plane reflectors (e.g. the peat-clay contact) will appear with their true shape while point reflectors (e.g. a boulder) will show the well known hyperbolic reflection (fig.1b).

Radar profiles may be displayed using the same techniques than for seismics: wiggle trace, variable area, variable density (grey scale) or colour scale.

Two important parameters must be considered:

- the **attenuation** of the wave because it determines the penetration of GPR;
- the **velocity** of the wave because it is needed to transform the time section (fig.1b) into a depth section, as in reflection seismics.

The propagation of the radar wave in a homogeneous ground is derived from Maxwell's equations. The resulting wave equation is:

$$\nabla^2 \underline{E} + k^2 \underline{E} = 0 \qquad [1]$$

with $\underline{E}$ electrical field (v/m)

$$k^2 = \omega^2 \mu \varepsilon + j\omega \mu \sigma \qquad [2]$$

ω	angular frequency	(rad/sec)
μ	magnetic permeability	(H/m)
ε	permittivity	(F/m)
σ	conductivity	$(\Omega^{-1}\ m^{-1})$.

In most cases, the wave propagates along the Z axis (vertical) and is horizontally polarized. A solution of the wave equation under these assumptions is:

$$\underline{E}\ (z,t) = \underline{E}_{(0)}\ e^{j(kz - \omega t)} \qquad [3]$$

A similar equation may be written for the magnetic field H.

For wave propagation to be significant against diffusion processes $\omega.\varepsilon$ must be much larger than σ (low loss condition). In other words the ground must be rather resistive. With this condition, and assuming the relative permeability equal to 1 which is true for most geological conditions, simple expressions for velocity (V) and attenuation (α) are derived from [3]:

$$V = \frac{c}{\sqrt{\varepsilon_r}} \qquad [4]$$

with c velocity of light in vacuum (0.3 m/nsec; 1 nsec = 10^{-9} sec)

ε_r relative permittivity

$$\alpha = 1620 \cdot \frac{1}{\rho\sqrt{\varepsilon_r}} \text{ in db/m} \qquad [5]$$

with ρ resistivity (Ωm).

It must be stressed that although the frequency is not explicit in [4] and [5] attenuation and, to a lesser extend, velocity are frequency dependant because resistivity and permittivity are frequency dependant.

From a practical point of view, the resistivity decreases when frequency increases resulting in stronger attenuation (less penetration) at higher frequencies.

Equation [5] shows that penetration, at frequencies around 100 MHz, ranges from several hundred meters in dry rock salt (very high resistivity) to less than a meter in clay (very low resistivity). The usually low resistivity of topsoil in a country like Belgium is the major obstacle to a widespread use of GPR.

Equation [4] shows the importance of permittivity for determining velocity; ε_r ranges from 1 (air) to 81 (water). For most shallow investigations, ε_r is mainly influenced by the water content. Together with frequency, velocity determines the wavelength ($\lambda = 2\pi.V/\omega$) and thus the vertical resolution.

To carry out a GPR survey, the choice of the right antenna is important. It must take into account the kind of target, the subsurface conditions and the expected resolution.

3.- RADAR CHARACTERISTICS OF PEAT

Peat is characterized by a high water content usually with very low mineralization. This results in electrical properties very well suited for GPR (Bjelm, 1980; Ulriksen, 1982):

- high resistivity resulting in low attenuation;
- high permittivity resulting in low velocity and good resolution.

For typical values like $\rho = 1000\ \Omega m$ and $\varepsilon_r = 68$ (water content 85%) equation [4] shows that the velocity is 0.04 m/nsec; with an 80 MHz antenna the wavelength is 0.5 m. Without signal shaping deconvolution the resolution should reach $\lambda/2$ or 0.25 m.

Equation [5] shows that the attenuation is only 0.2 db/m resulting in good penetration (10 m or more).

Peat usually overlies layers with much lower resistivity and water content like clay, silt or weathered bed rock. Due to the strong resistivity and permittivity contrast the reflection coefficient is high resulting in a distinct reflection at the base of the peat. Penetration below the peat will usually be negligible.

Reflections may also occur inside the peat due to variations in resistivity or permittivity related to various development stages, layers with higher mineral content, springs,....

4.- EXAMPLES

4.1.- Introduction

Several sites in southern Belgium (fig.2) have been surveyed to test the efficiency of the method. It must be stressed that the aim of these surveys was to show the range of possible applications rather than to study specific problems. Accordingly, all geological interpretations are indicative, further investigations and correlation with existing data being needed for final conclusions.

The equipment used for these surveys is a GSSI SIR 8 radar with an 80 MHz antenna. The system is connected to an EPC graphic printer for direct printout of the data in the variable density mode (grey scale).

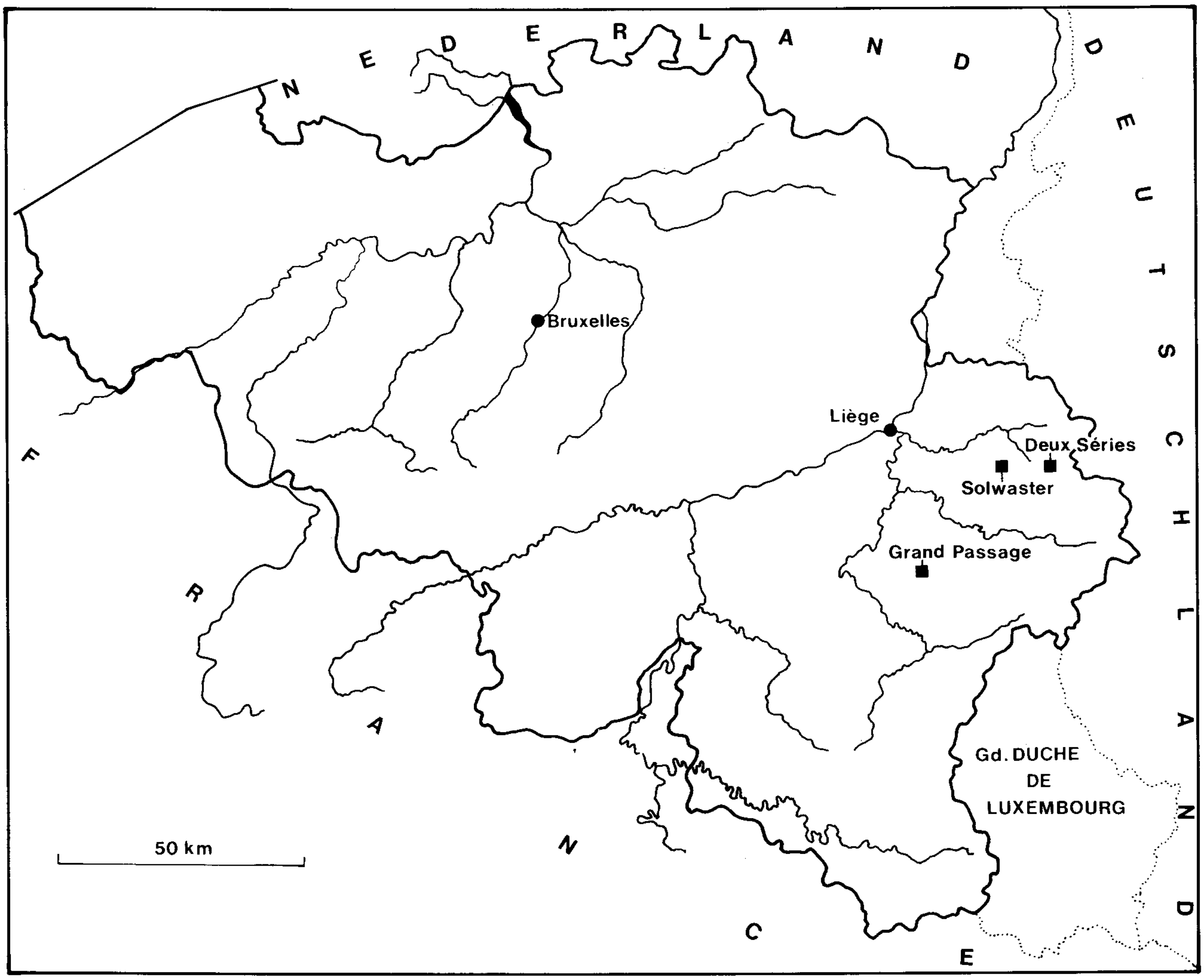

Fig.2.- Location of the test sites

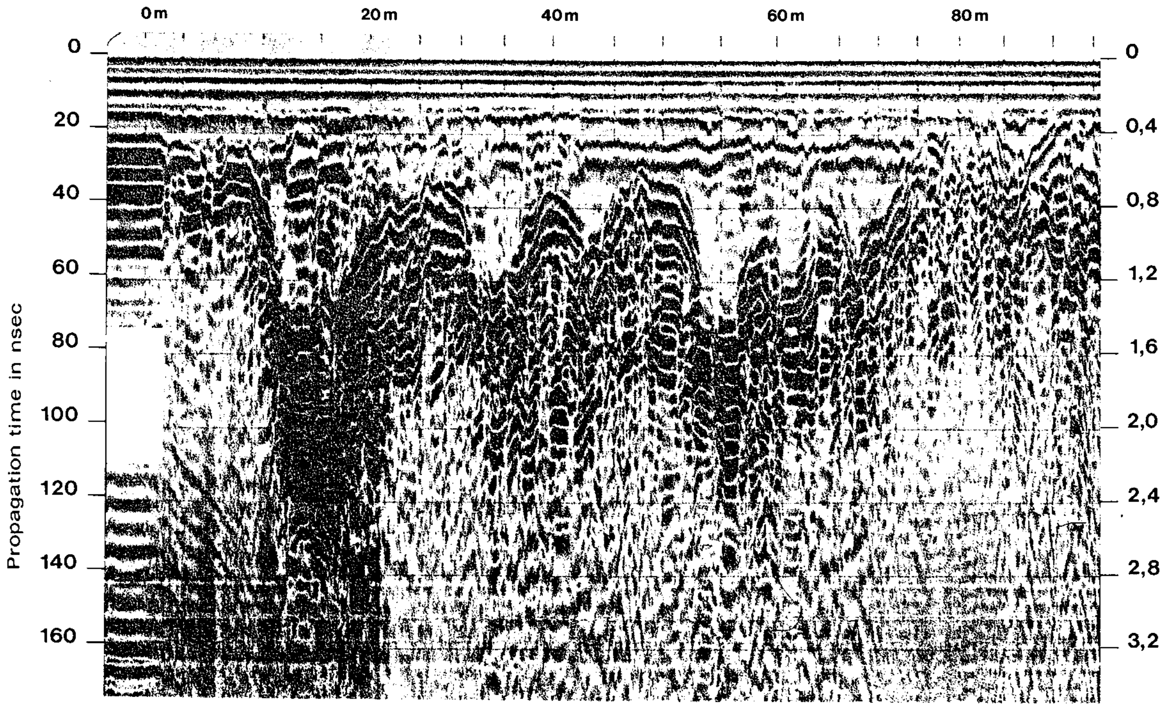

Fig.3.- Solwaster; profile PL2

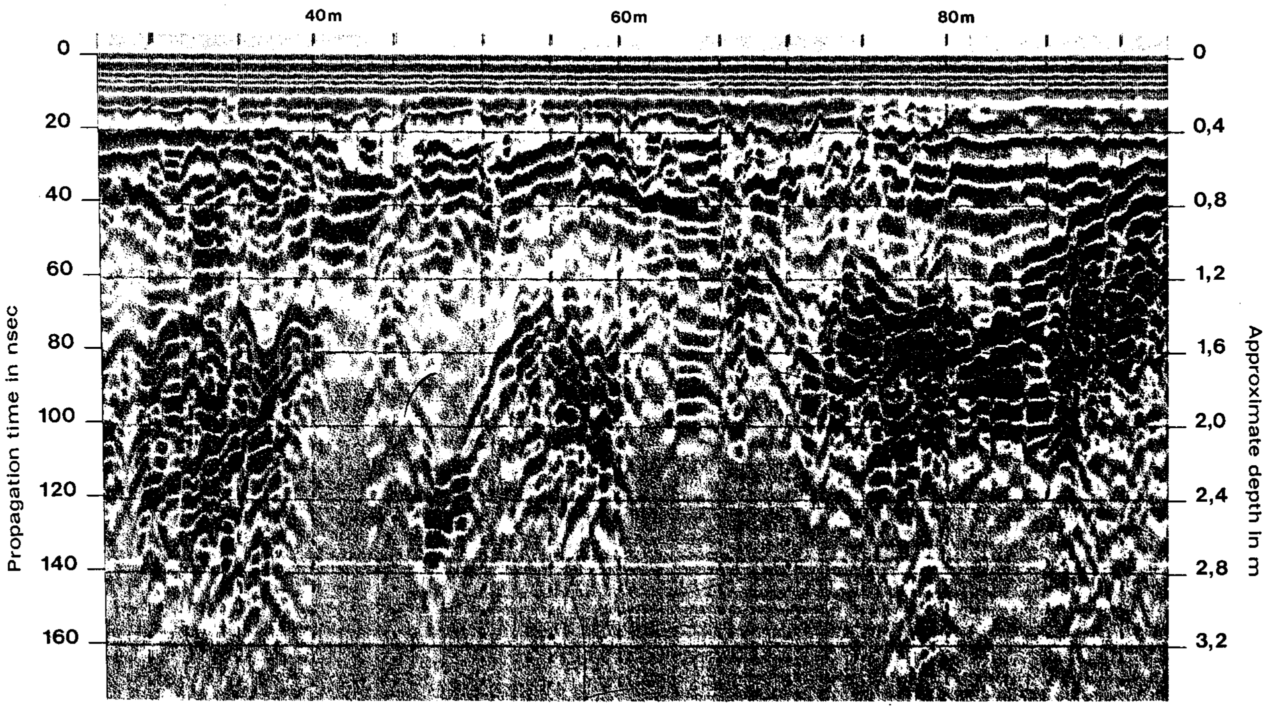

Fig.4.- Solwaster; profile PL1 (partim)

4.2.- Solwaster

The peat bog is located in the Hoegne valley. Excavations have shown that the peat thickness does not exceed 2 meters.

Lateral thickness variations are ubiquitous.

Profile PL2 is typical and shown on figure 3. The horizontal axis represents the distance in meters along the profile while the vertical axis represents propagation time (20 nsec/division in this case). For a velocity of 0.04 m/nsec, the corresponding depth scale is 0.40 m/division. Calibration based on comparison with boreholes is of course needed to obtain an exact depth scale.

The parallel bands from 0 to 10 nsec are the direct impulse transmitted by the antenna. From 10 to 30 nsec, strong reflections on the ground surface are seen. The very strong reflection seen later (30-70 nsec) is the peat-clay interface. Variation of peat thickness (0.5 to 1.3 m) on very short distances is obvious. In this case, the interpretation is straightforward because the reflection on the underlying clay is easy to identify.

However peat bogs in valleys often contain small amounts of clay either scattered in the peat or occuring as small layers or lenses. The resistivity thus decreases resulting in stronger attenuation and less distinct reflection on the top of the underlying clay as shown on part of profile PL1 (fig.4): from 40 to 75 m the strong reflection at 20-30 nsec is probably due to a higher clay content in the upper peat layer. This results in a faint and uneven reflection on the clay below the peat.

From 75 to 90 meters, the base of the peat is much more distinct (40-60 nsec).

4.3.- Grand Passage

The «Grand Passage» moor is located close to Baraque Fraiture at an elevation of about 600 m. The peat covers a large area on the Plateau. The site is described in Cosan (1970).

Figure 5 shows part of profile L1 realized along the highmoor summit. The time scale is 40 nsec/division corresponding to an approximate depth scale of 0.8 m/division.

The direct pulse and surface reflection are visible during the first 40 nsec. The peat-clay contact is clearly indicated by a strong reflector at 290 nsec corresponding to a depth of 5.6 meters. Available boreholes confirm this depth. The base of the peat is very even.

It is interesting to observe several reflectors inside the peat. They are due to small changes in water content or resistivity themselves due to variations in composition of the peat or presence of layers with higher mineral content.

A systematic comparison with borehole or trench data is required to understand the meaning of these reflectors and to elaborate a «radar stratigraphy».

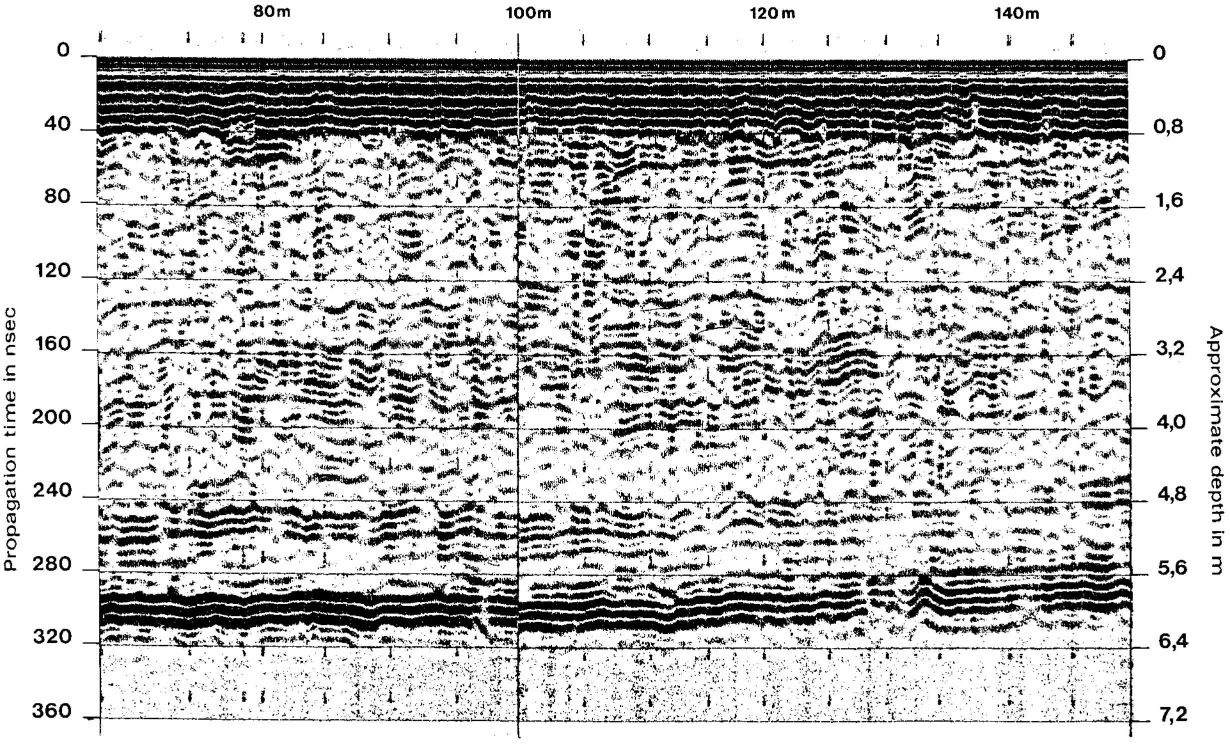

Fig.5.- Grand Passage moor; profile L1 (partim)

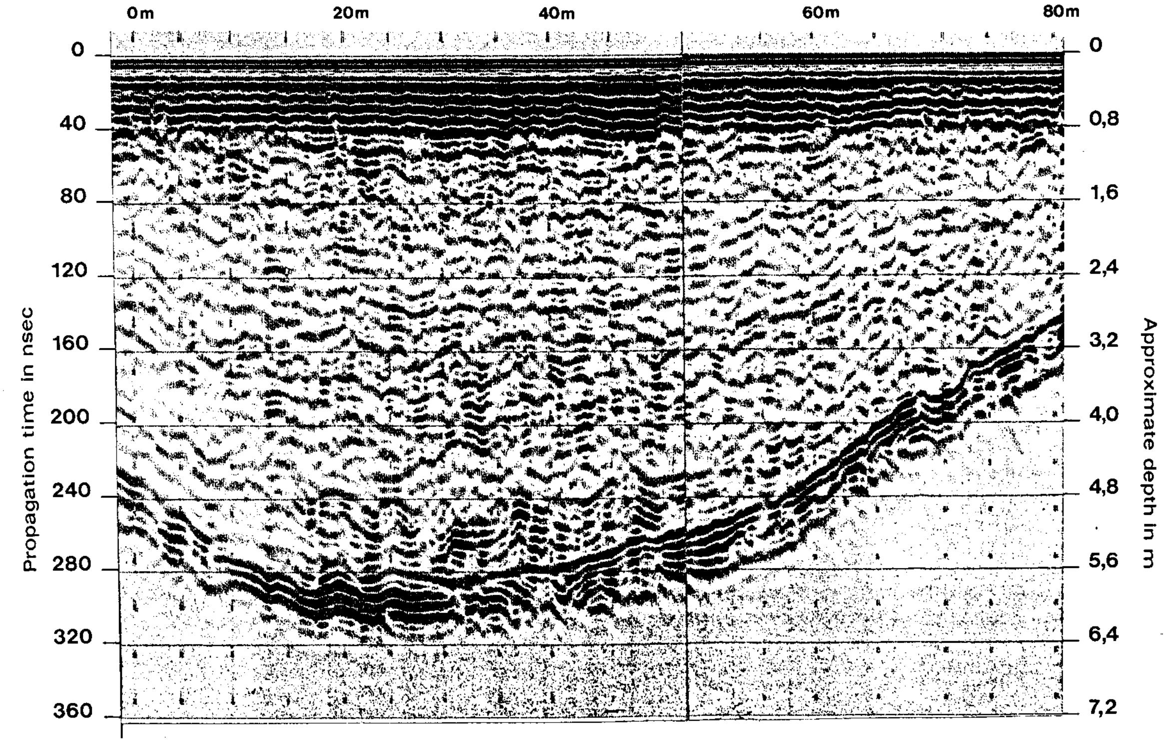

Fig.6.- Grand Passage moor; profile T1

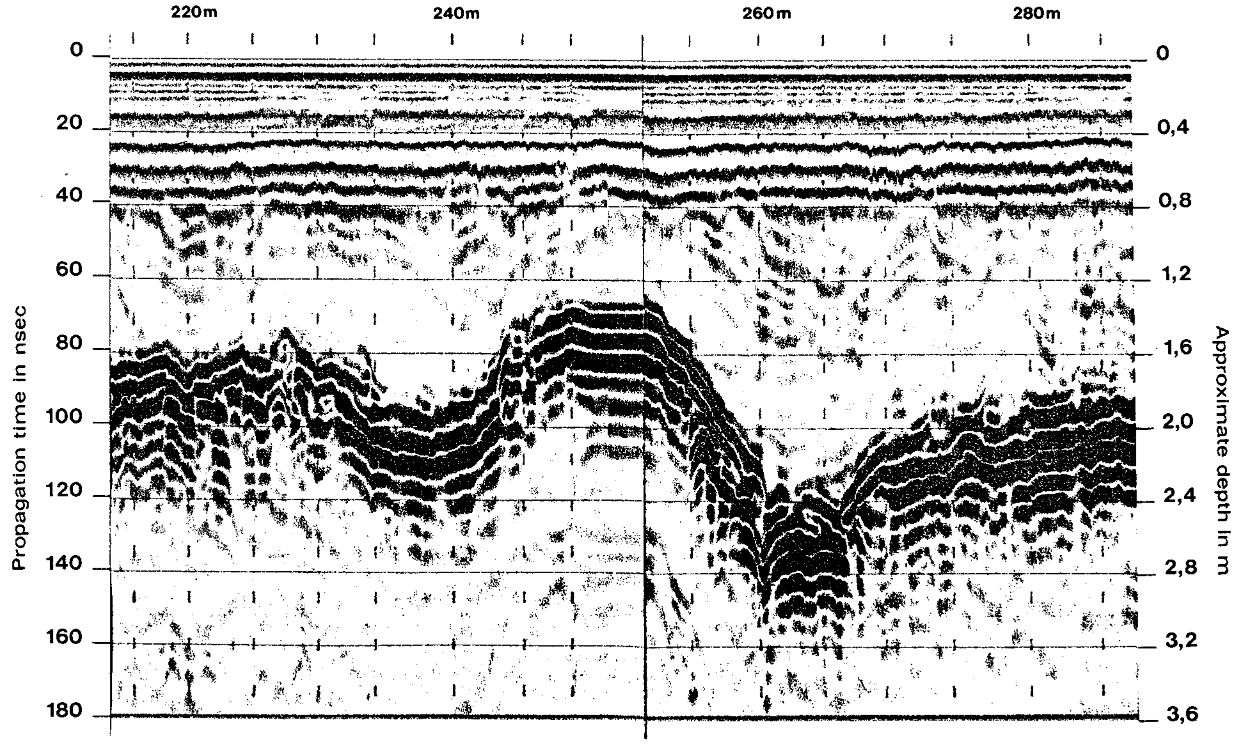

Fig.7.- Deux Séries moor; profile L1 (partim)

Figure 6 shows profile T1 crossing the highmoor.

The results are similar to those described on L1. Thickness of the peat ranges from 4 m on the edges to 5.6 m in the middle of the profile. The base of the peat is actually horizontal, the thickness variations being due to the topography. A static correction should be applied to the data in order to represent the true geometry.

4.4.- Deux Séries moor

The site is located on the Hautes Fagnes plateau about 3 km NE of Baraque Michel.

Part of a 500 m long profile (L1) is shown on figure 7. Time scale is 20 nsec/division or an approximate depth scale of 0.4 m/division. As for the previous example the base of the peat is clearly indicated by a strong reflection on the underlying clay (70 to 120 nsec or a depth ranging from 1.4 to 2.4 m). Some inner structures are also visible. A transverse profile (T2) centered on L1 at 250 m is shown on figure 8.

Although the strong vertical scale distorsion should be kept in mind, the geomorphological features shown on both profiles are very interesting. They are probably related to periglacial events (palsa).

More profiles would be needed for a complete analysis of the area and correct interpretation of these facts.

Amongst other features, it seems noteworthy to mention the presence at 260 m on profile L1 and 40 m on profile T2 of a 20 nsec (0.4 m) high «scarp». It might be due to recent movements along a fault, the scarp being preserved from erosion by the peat. It should also be noted that on profile T2 a fairly strong reflection occurs from 20 to 40 meters at 60-80 nsec (1.2 to 1.6 m depth). Such a reflection might be due to a change in water content or conductivity itself due to a small mineral spring emerging from the above mentionned scarp. Such mineral springs occurring along faults are well known in the area.

Of course additional informations are needed to confirm such interpretations but it is obvious that GPR on moors is an ideal tool to detect such features because it gives a continuous image of the subsurface and because it is so sensitive to changes in resisitivity and permittivity.

Figure 9 shows another part of profile L1. Thickness of the peat increases up to nearly 4 m. Distinct point reflectors (boulders) are detected at 361 m and 405 m just above the peat-clay contact.

5.- FURTHER DEVELOPMENTS

Although the available results are already very interesting further improvements would still increase efficiency and quality of results.

The system as it was used is heavy and needs a 220 V power supply. Replacing the graphic printer by a small digital acquisition unit would reduce the weight and allow a 12 V DC power supply.

Improving the dynamics of the system is also important. In this case, the radar had an 8 bit A/D converter and the graphic printer a 4 bit A/D converter. The resulting low dynamics requires tedious non linear gain adjustments to get good printouts. The amplitude information is partly lost. The new generation of radars use 16 bit A/D converters which is much better. Of course the printer must be adapted accordingly and colour displays or variable area displays should be preferred.

Data processing could increase the accuracy of the interpretation. Emphasis should be put on static corrections to take into account the topography, wave shaping deconvolution to increase vertical resolution and migration to get a true geometrical description of the base of the peat.

The geological interpretation of the data remains of course the main point. The elaboration of a «radar stratigraphy» based on systematic correlation of radar results with all other available information is required.

6.- CONCLUSION

Ground Penetrating Radar is the only geophysical method enabling continuous profiling of peat deposits.

Test measurements on several sites in Belgium gave excellent results showing that the method would be very useful for a wide range of applications on moors like:

- mapping accurately peat thickness;
- study of geomorphological features related to the periglacial period;
- description of the inner structure of the moors for paleoecological or paleoclimatological studies;
- detection of recent tectonic activity;
- mapping of layers with high mineral content like tephra falls;
- detection of mineral springs;
- detection of archaeological features.

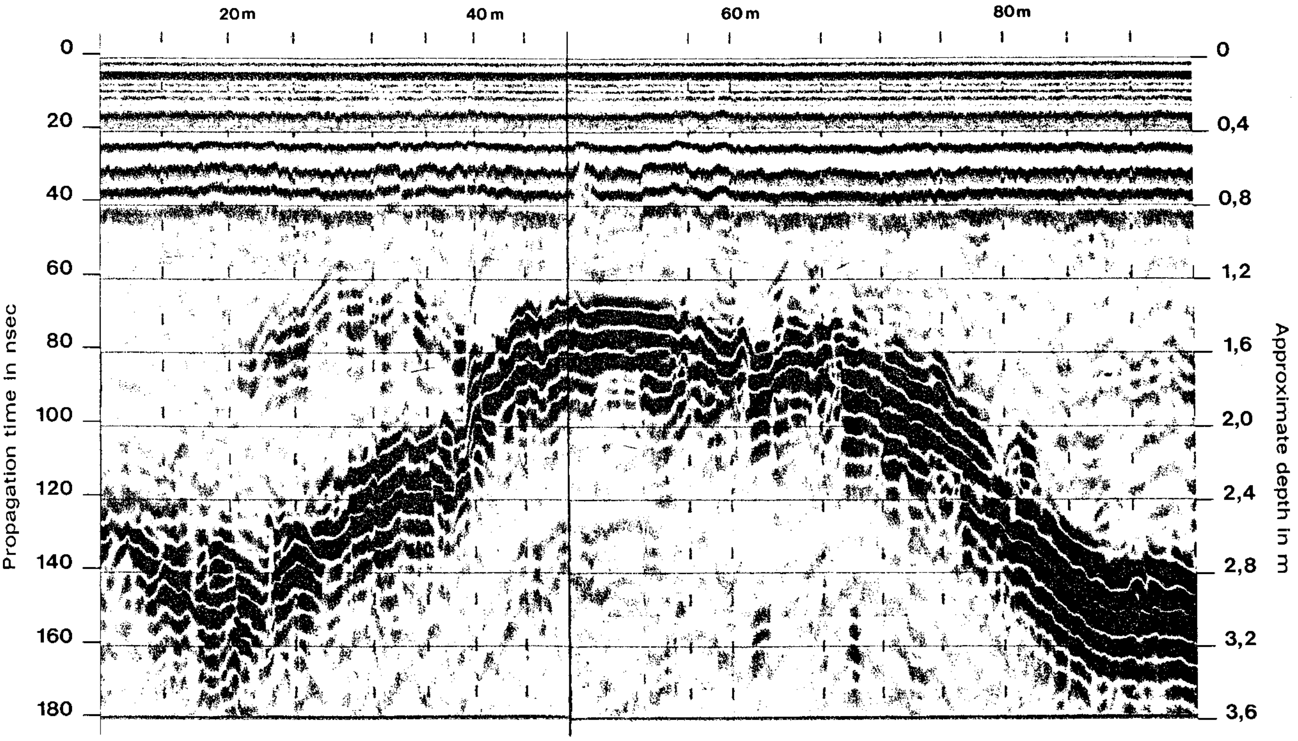

Fig.8.- Deux Séries moor; profile T2

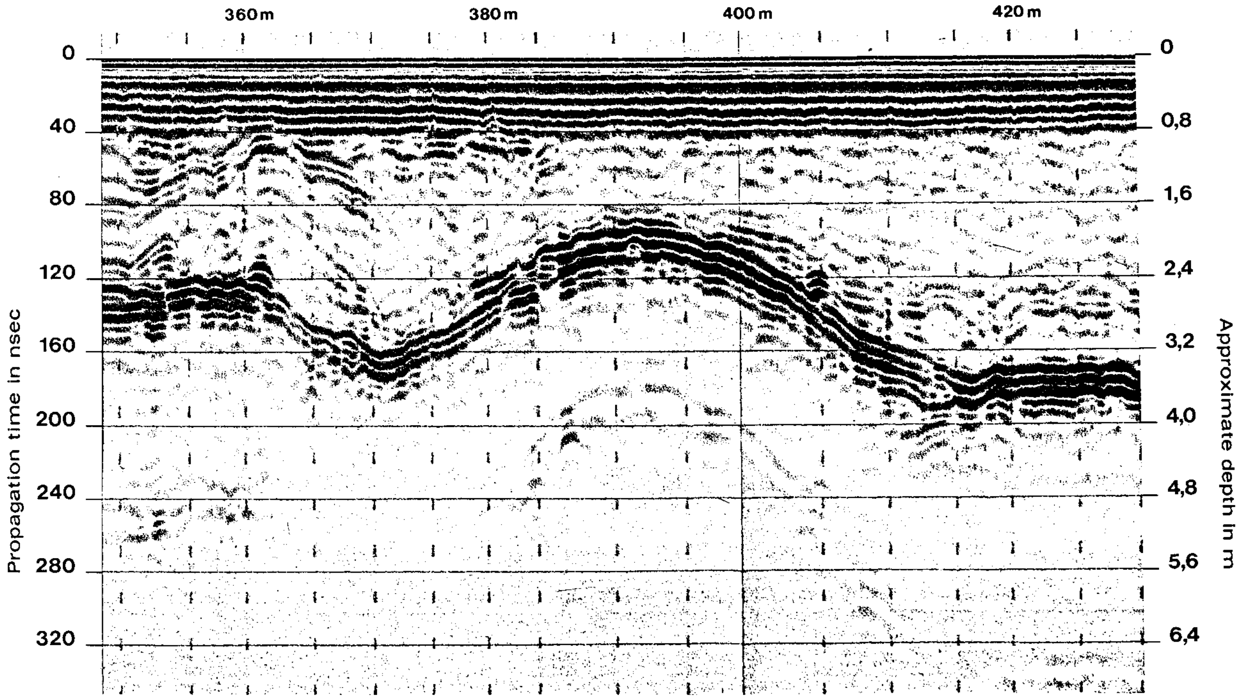

Fig.9.- Deux Séries moor; profile L1 (partim)

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