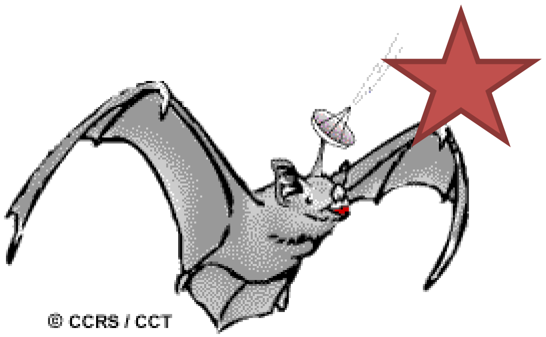


Rock Physics

From mm. to Km. scale

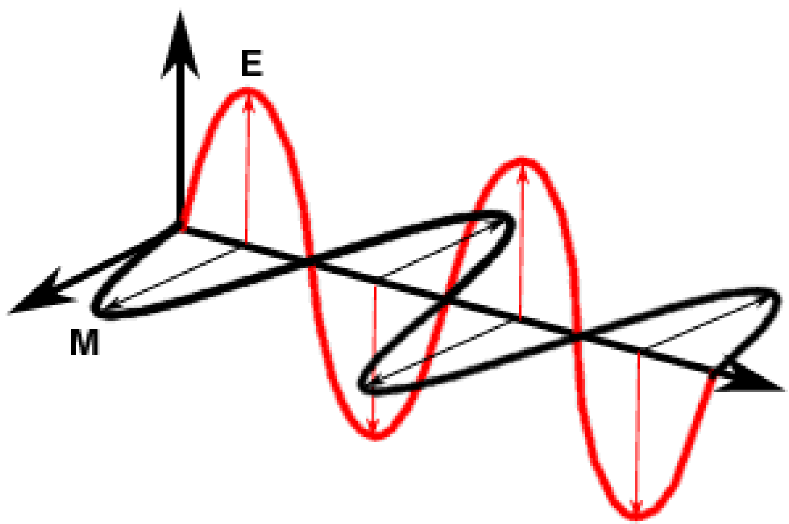
prof. M. Violay
marie.violay@epfl.ch

10. Ground-Penetrating Radar

➢ **<u>Georadar- or Ground probing radar</u>**

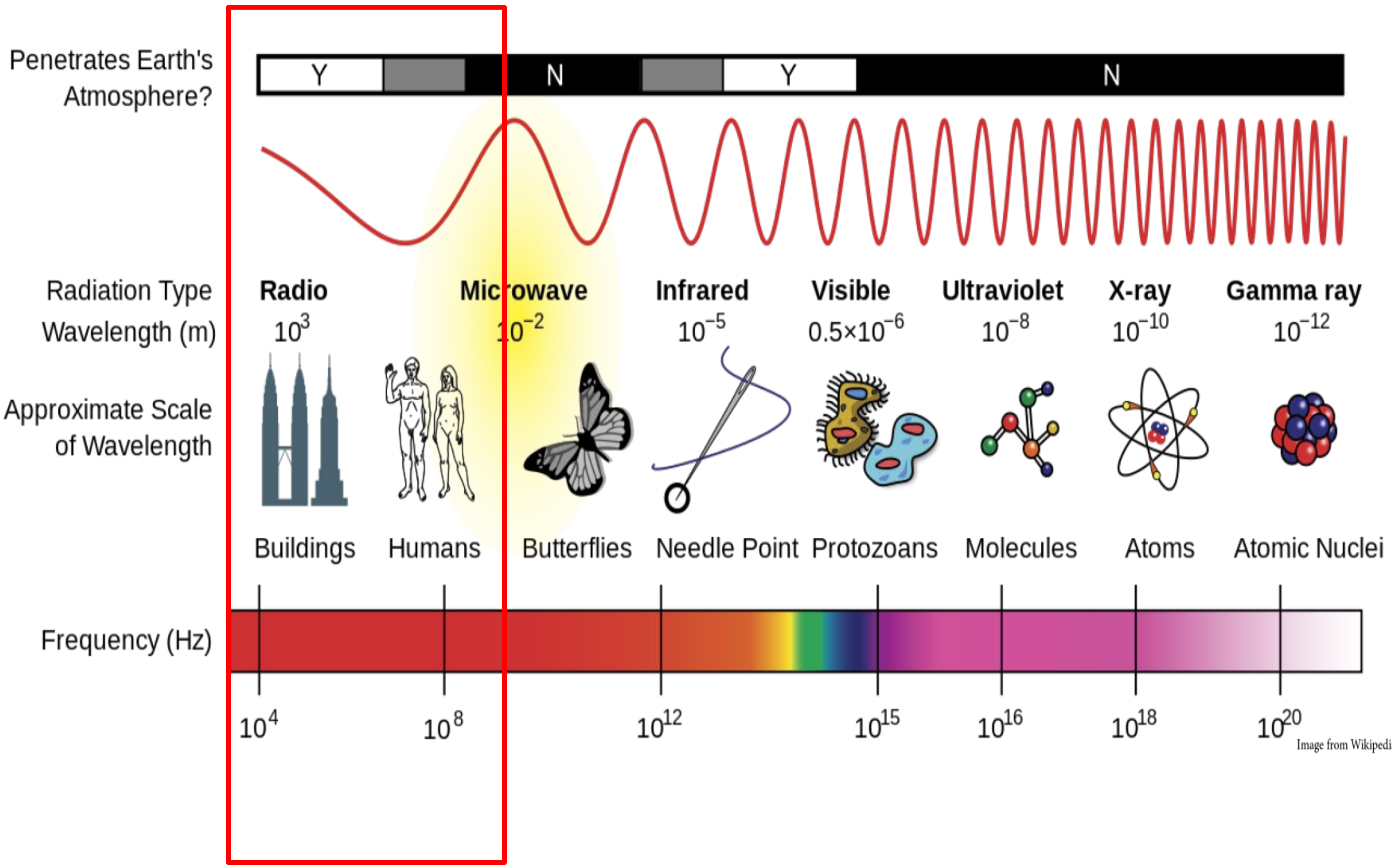
- Uses 10- 2000 MHz electromagnetic waves emitted in short "chirps" for probing.

➔ Electromagnetic waves : synchronized oscillations of electric and magnetic fields that propagate at the speed of light through a vacuum.



➢ Radar waves

MHz au GHz -10 m au 10 cm



➢ Principle

The propagation of electromagnetic energy at radar frequencies **is controlled by dielectric properties** in geologic materials, the method is sensitive to changes in dielectric permittivity of the bulk material.

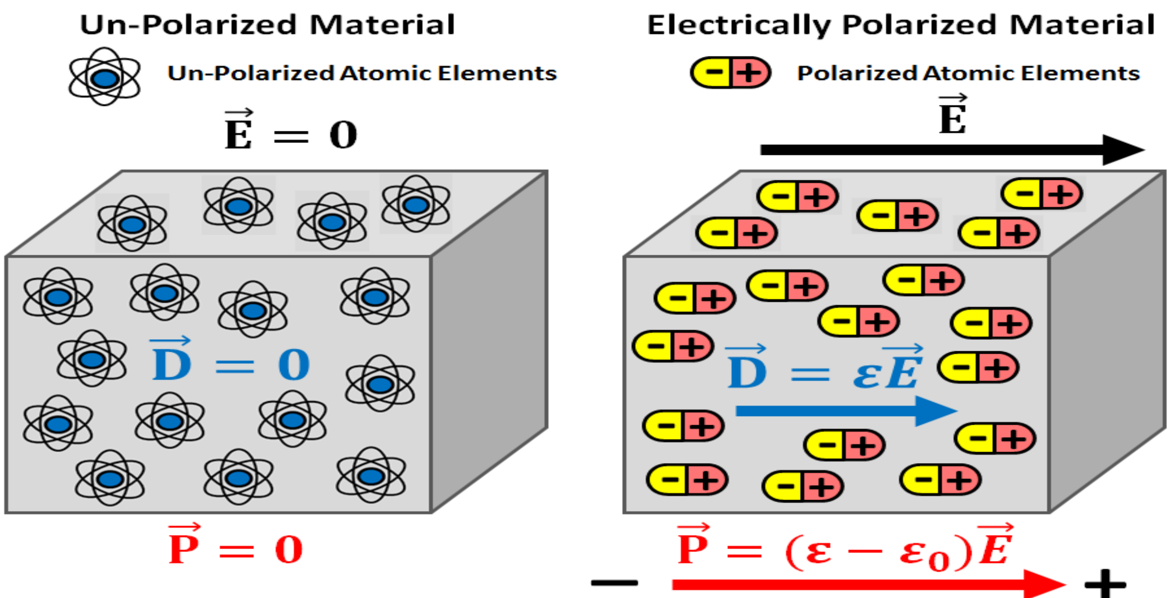
The dielectric permittivity of a material is **strongly related to its resistivity/conductivity**. **The higher the resistivity, the lower the dielectric permittivity, and the farther an electro-magnetic wave will propagate through that material without absorption.**

Permittivity

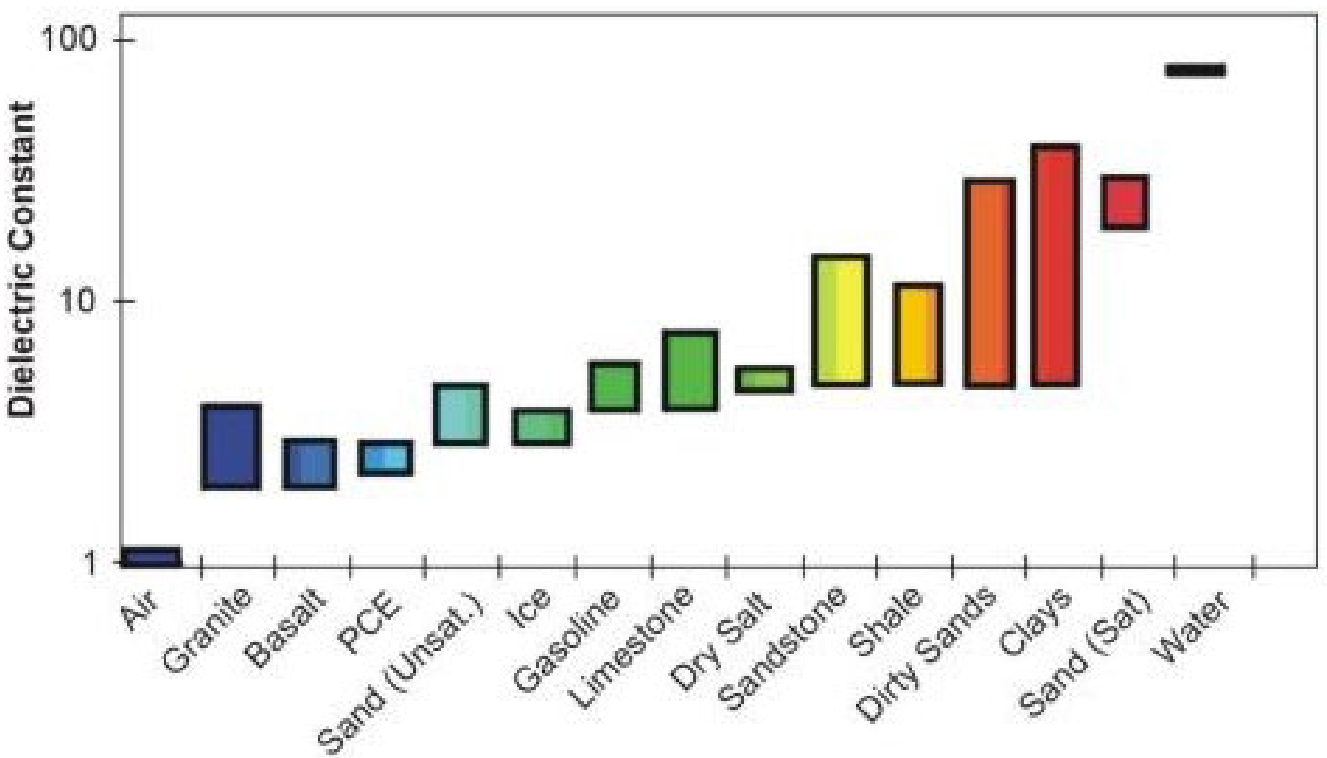
In electromagnetism, the electric displacement (induction) field D represents how an electric field E influences the organization of electric charges in a given medium, including charge migration and electric dipole reorientation. Its relation to permittivity in the very simple case of linear, homogeneous, isotropic materials with "instantaneous" response to changes in electric field is :

$$\boxed{D = \varepsilon E}$$

where the permittivity ε is a scalar. If the medium is anisotropic, the permittivity is a second rank tensor.



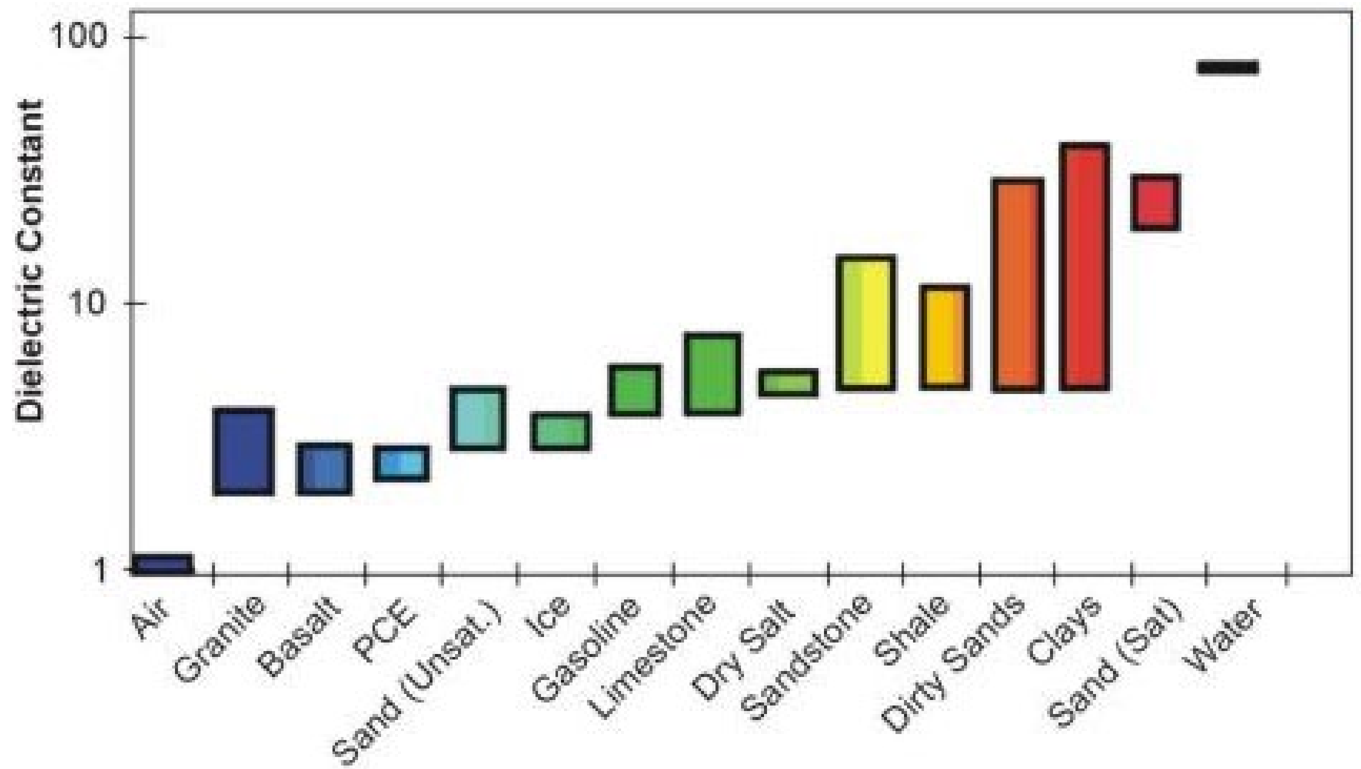
➢ Principle



Air permittivity : $\boldsymbol{\varepsilon_0 = \frac{1}{36\pi \cdot 10^9} = 8.85 \left[\frac{pF}{m}\right]}$

Material permittivity: $\varepsilon = \varepsilon_0 \cdot \varepsilon_r$

➢ Principle



Higher is the permittivity, stronger is the signal attenuation.

GPR➔ sensible to water and clays

➢ **<u>Propagation and reflection of radio waves</u>**

- A la différence des méthodes EM inductives, les signaux EM utilisés en géoradar sont si hautes fréquences que l'induction est négligeable
- Les courants de *déplacement* dominent largement sur les courants de conduction
- Il es résulte que les ondes géoradar se *propagent* dans le sous-sol, comme les ondes sismiques

➢ Propagation and reflection of radio waves

- Velocity: $$\boxed{V = \frac{1}{\sqrt{\varepsilon\mu}}}$$
- Penetration depth: $$\boxed{\delta = \sqrt{\frac{2}{\omega\mu\sigma}} \approx 503\sqrt{\frac{\rho}{f}}}$$
- Spatial resolution: $$\boxed{r = \frac{\lambda}{4} = \frac{V}{4f} = \frac{1}{4f\sqrt{\varepsilon\mu}}}$$
- Impedance: $$\boxed{Z = \sqrt{\frac{\mu}{\epsilon}}}$$
- Reflection coefficient: $$\boxed{R = \frac{Z_2 - Z_1}{Z_2 + Z_1}}$$

- ε dialetric Permittivity ($F.m^{-1}$)
- σ Electrical conductivity ($Sm.m^{-1}$)
- μ Magnetic Permeability ($H.m^{-1}$)

Example

- Antenna at 100 MHZ + underground
  - $\varepsilon = 4\ \varepsilon_0 = 4*8.85x10^{-12}$
  - $\mu = \mu_0 = 4\pi x10^{-7}$
  - $\rho=100\ \Omega.m$

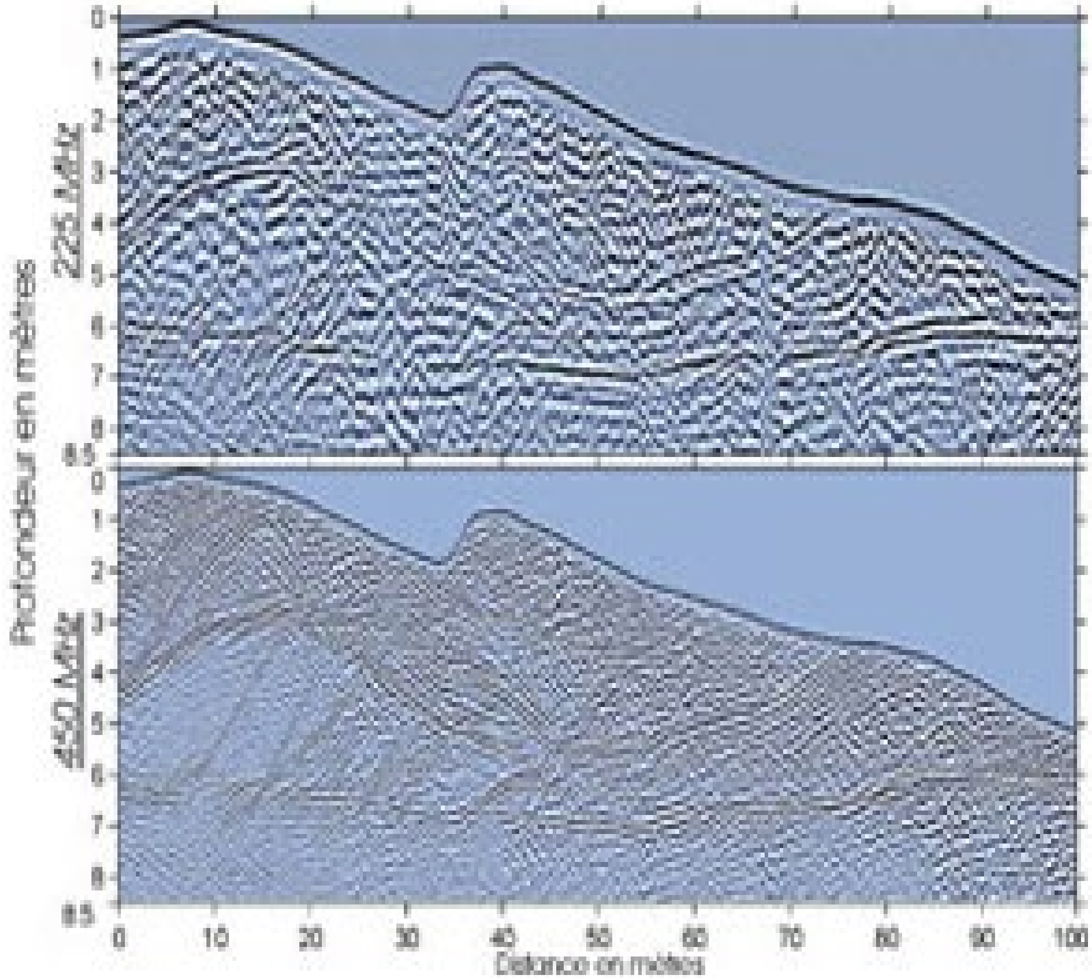
$$\boxed{V = \frac{1}{\sqrt{\varepsilon\mu}} = \frac{1}{\sqrt{4 * 8.85x10^{-12} * 4\pi x10^{-7}}} = 1.5x10^{8}\,m/s}$$

$$\boxed{\delta \approx 503\sqrt{\frac{\rho}{f}} = 503\sqrt{\frac{100}{100x10^{6}}} = 50.3\,cm}$$

$$\boxed{r = \frac{V}{4f} = \frac{1.5x10^{8}}{4 * 100x10^{6}} = 37.5\ cm}$$

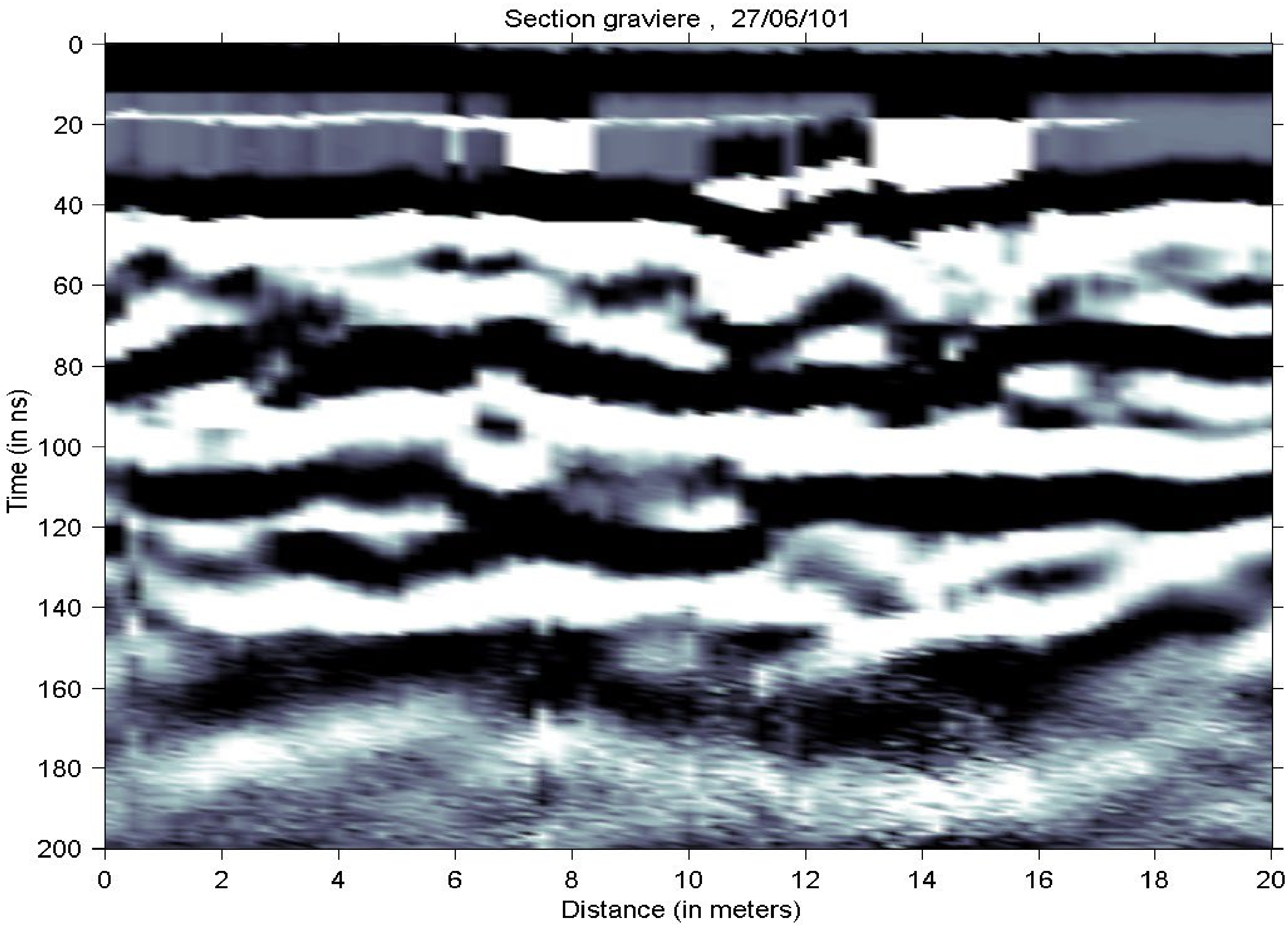
➢ **Frequency**

- Depth of investigation depends on the frequency
- Influence the resolution
- GPR has the highest resolution in subsurface imaging of any geophysical method, approaching centimeters under the right conditions.



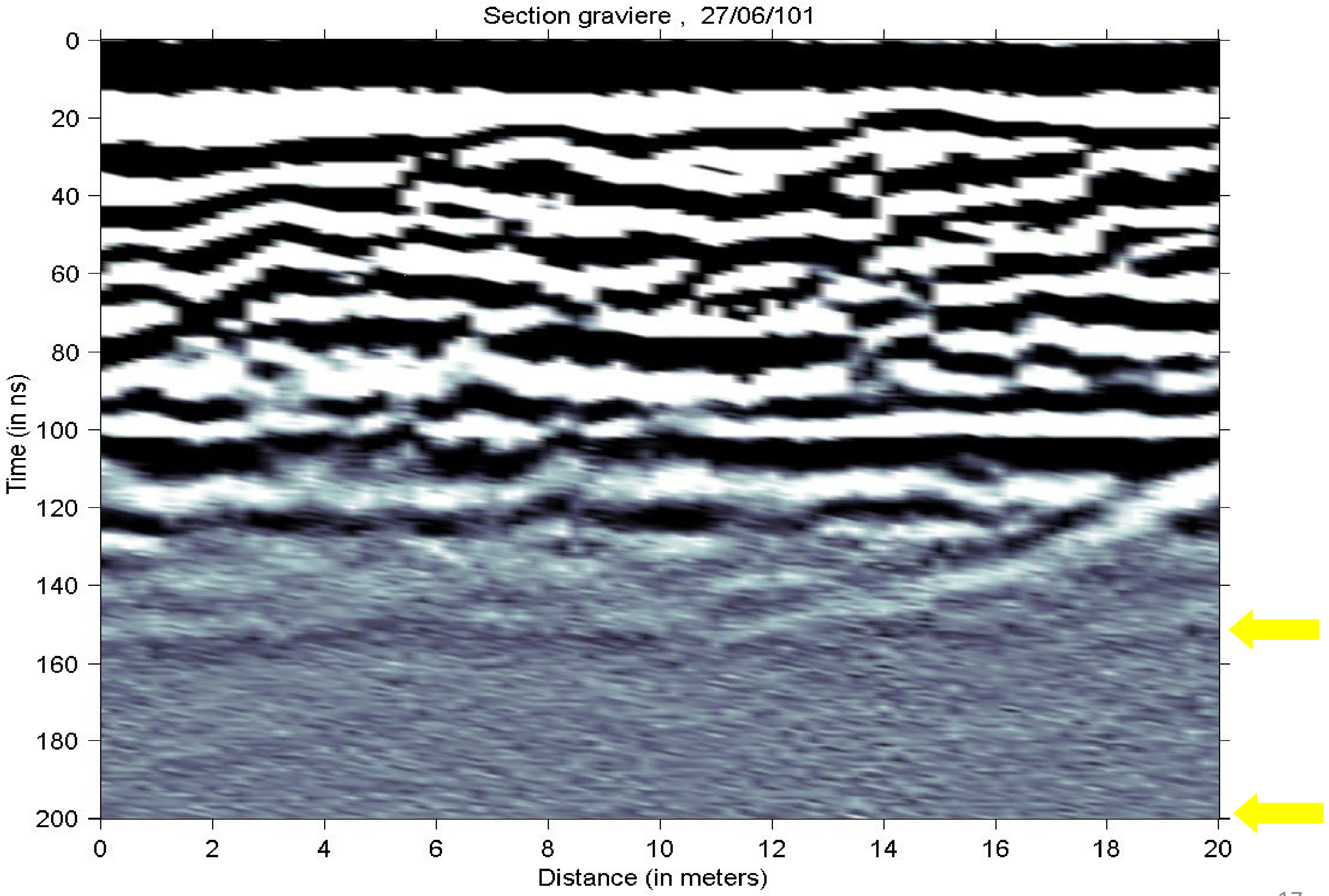
➢ **Frequency**

50 MHz



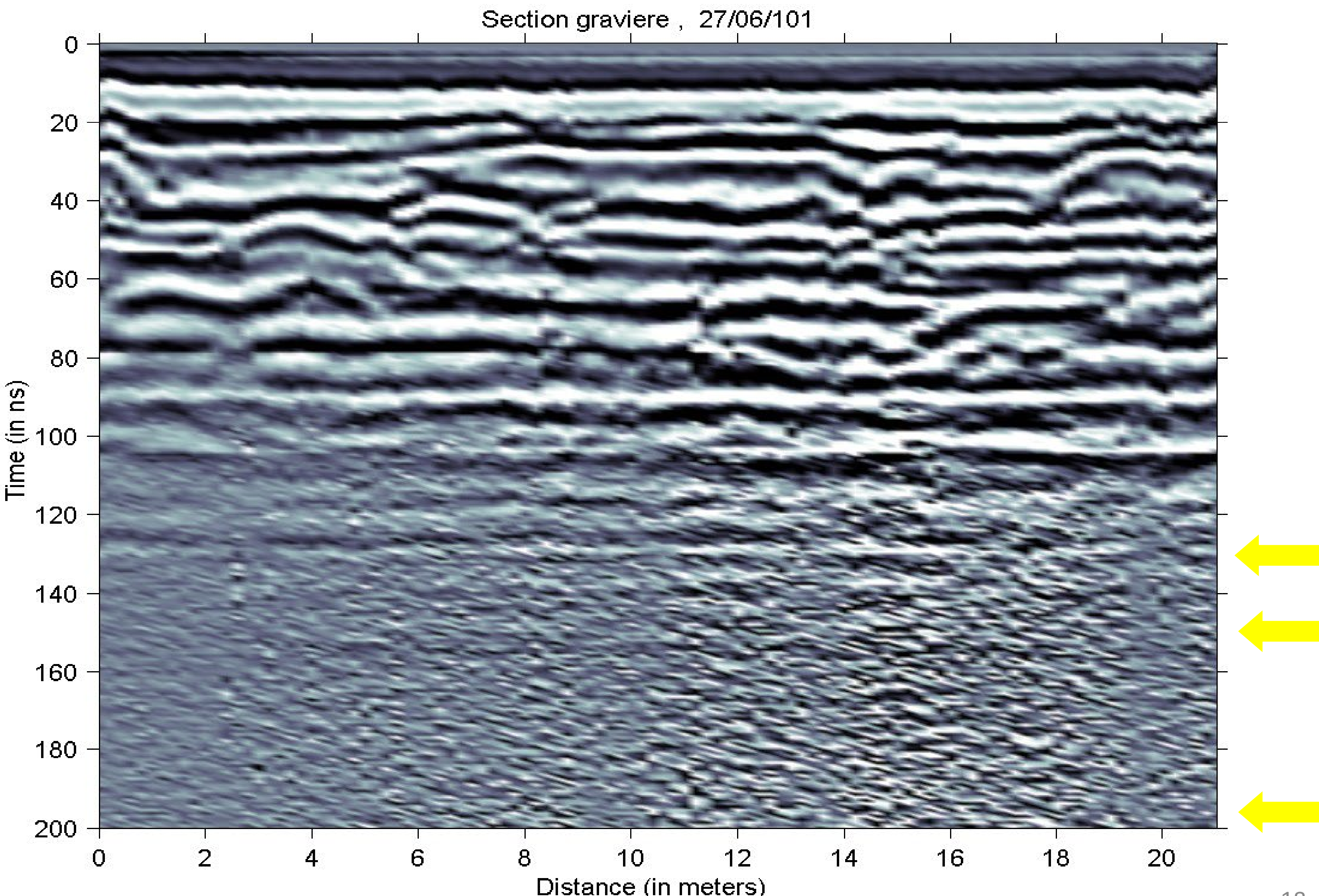
➢ **Frequency**

100 MHz



Frequency

200 MHz



2.5. *RÉFLEXION ET TRANSMISSION DES ONDES ÉLECTROMAGNÉTIQUES.* 28

Matériau	Constante di-électrique	Conductivité électrique (mS/m)	Vitesse (m/ns)	Atténuation (dB/m)
Air	1	0	0.3	0
Eau distillée	80	0.01	0.033	0.003
Eau fraiche	80	0.5	0.033	0.1
Eau salée	80	3000	0.01	1000
Sable sec	3-5	0.01	0.15	0.01
Sable saturée	20-30	0.1-1	0.06	0.03-0.3
Calcaires	4-8	0.5-1	0.12	0.4-1
Argiles	5-40	2-1000	0.06	1-300
Granite	4-6	0.01-1	0.13	0.01-1
Sel sec	5-6	0.01-1	0.13	0.01-1
Glace	3-4	0.01	0.16	0.01

TAB. 2.1 – *Ordre de grandeur de différents paramètres physiques (constante diélectrique, conductivité électrique, vitesse et atténuation) à une fréquence de 100 MHz pour divers matériaux.*

When Dielectric constant increases ; attenuation increases; no wave propagation

Tableau 1 : *Constante diélectrique et Vitesse des ondes EM de certains matériaux géologiques*

Matériaux	*Constante diélectrique relative (κ)*	*Vitesse des ondes EM (m/ns)*
air ou vide	1	0.3
eau douce	81	0.033
eau de mer	81	0.033
glace	3-4	0.15-0.17
Sables (secs)	3-6	0.12-0.17
Sables (humides)	25-30	0.05-0.06
Grès (humide)	6	0.12
Calcaire (sec)	4	0.15
Calcaire (humide)	8	0.11
Granite (sec)	5	0.13
Granite (humide)	7	0.11
Basalte (humide)	8	0.11
Argile (saturé)	8-25	0.06-0.11
Sel (sec)	5-6	0.12-0.13

When Dielectric constant increases V decreases

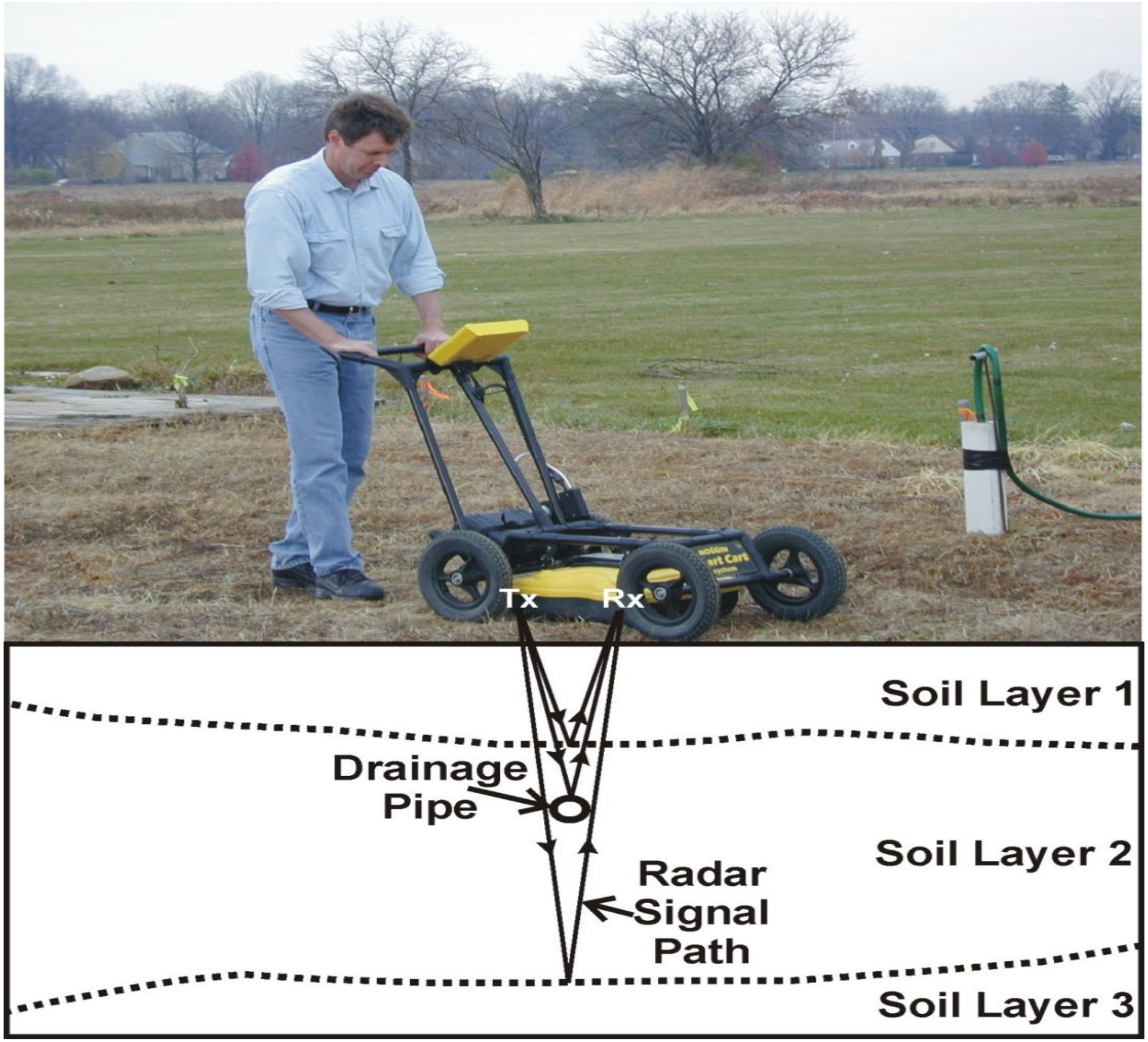
➢ Methods

- A **transducer** generates a broadband (10-1000 MHZ) electromagnetic wave (impulse). A specially directed antenna emits the pulse into the ground. As the wave travels through the ground, it is reflected, deflected and absorbed by varying degrees of the material (soil, water) through which it travels.

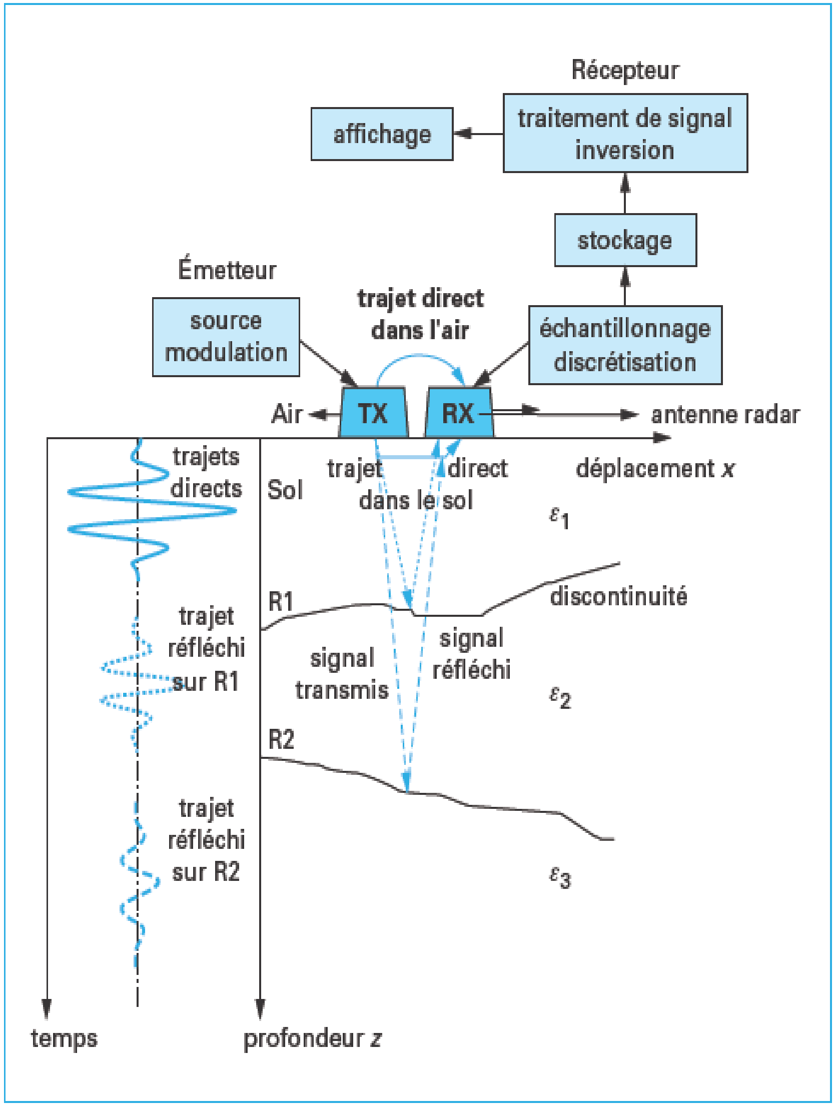
As the radar reflects off of materials it ‘echo locates' materials, or objects, of different electromagnetic conductivity within a matrix, for instance, a pipeline, storage tank, contaminant or re-bar in a matrix of soil or concrete.

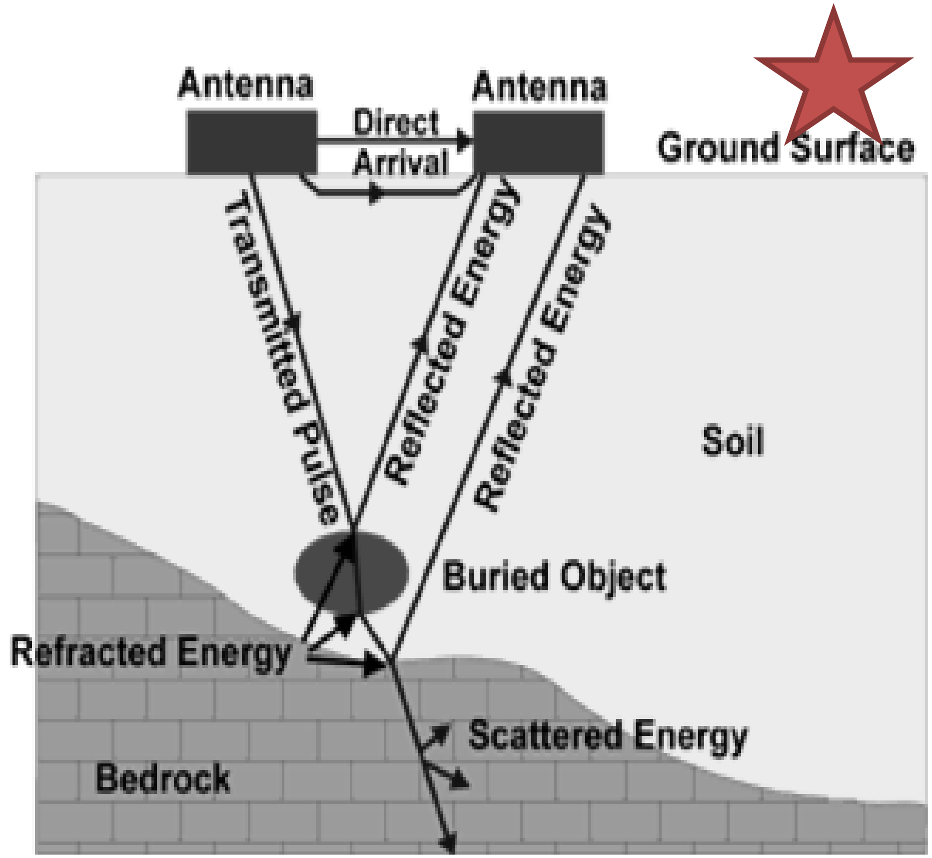
- The **receiver** in the antenna will pick up the return signal to be processed by the radar unit. The radar unit will then plot a mark on a vertical scale based on the time it took for each signal to return. The radar unit will also analyze the characteristic properties of the waves, mainly the amplitude.

The severity of change in amplitude of the transmitted signal is based on the conductivity and dielectric properties of the reflective target.


Tx
Rx
Soil Layer 1
Drainage Pipe
Soil Layer 2
Radar Signal Path
Soil Layer 3

➢ Methods





Direct wave
Reflected wave
Diffracted waves

Relation to seismic reflection

Similarities:

- Processing procedures (filtering, stacking, migration);
- Appearance of the zero-offset section;
- Resolution-frequency relationships;
- Interpretation techniques.

Differences:

- Nanoseconds (*ns*) instead of milliseconds (*ms*);
- Sub-meter vertical resolution and ~10-100 m penetration.
- Electrical properties instead of acoustic impedance;
- Very sensitive to buried metallic objects.
- Velocities decrease with depth
  - ➢ Rays bend *toward* the vertical;
  - ➢ Free-air arrival is the *fastest;*
  - ➢ Faster attenuation;
  - ➢ Large velocity contrasts.
- Sub-meter resolution.

Thus, GPR is a valuable complementary technique to shallow seismics.

➢ **Methods**

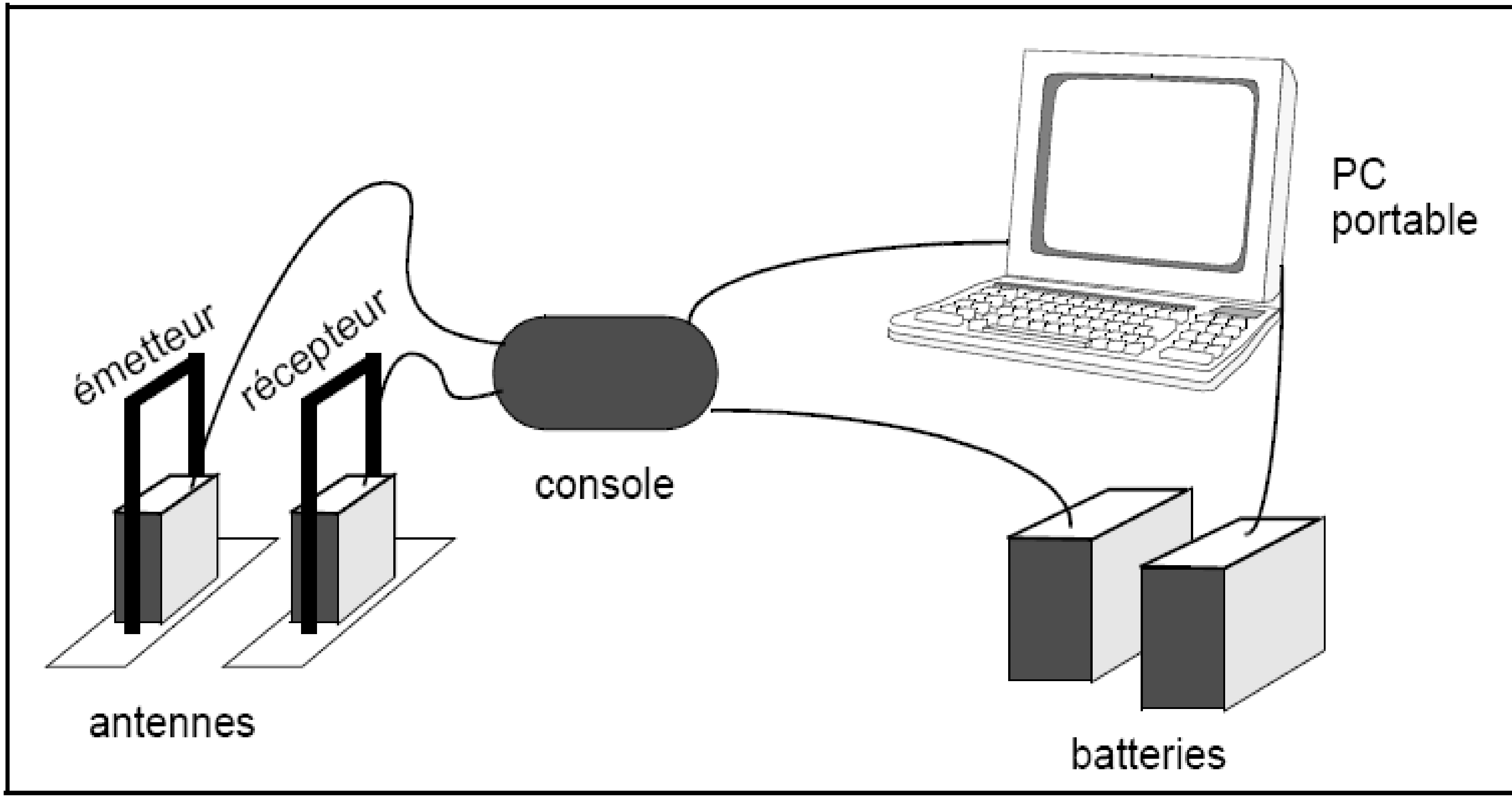
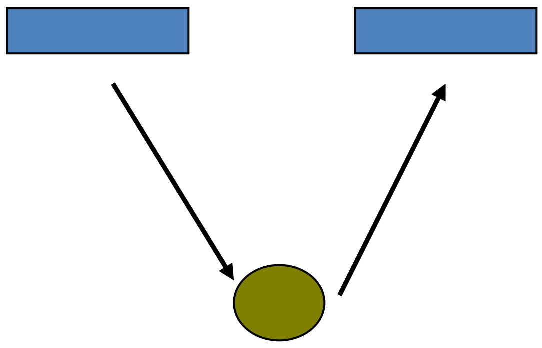


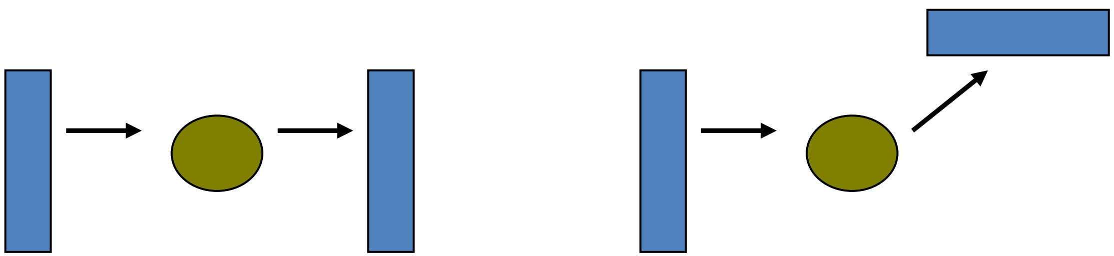
figure 21: Présentation schématique d'un système géoradar.

➢ <u>Acquisition</u>

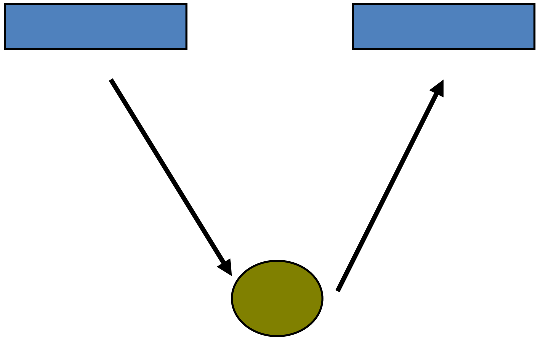
reflexion → easy method :

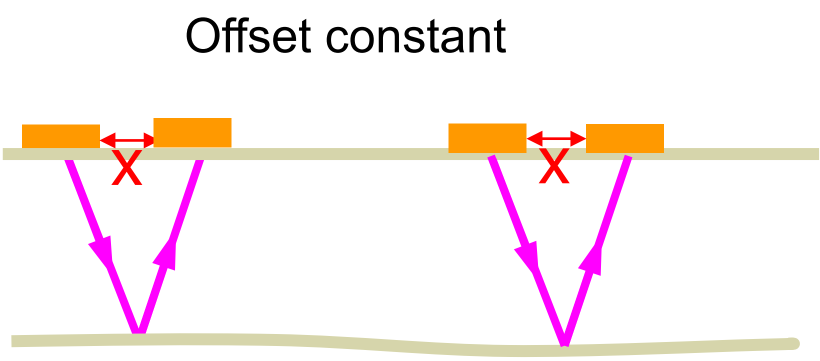


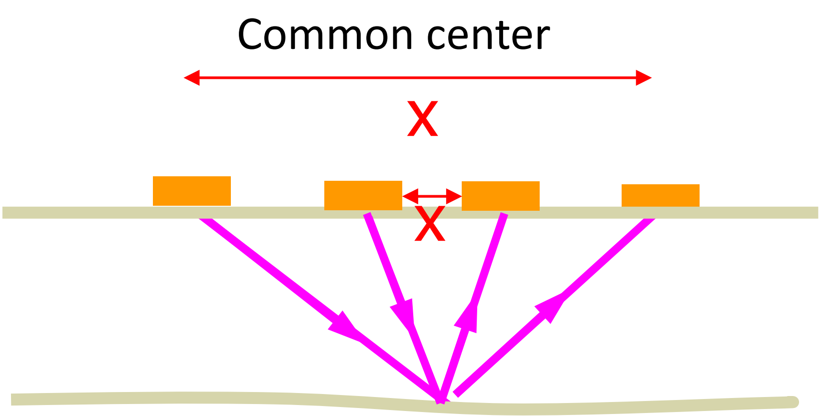
transmission (Borehole) :



Acquisition







Acquisition

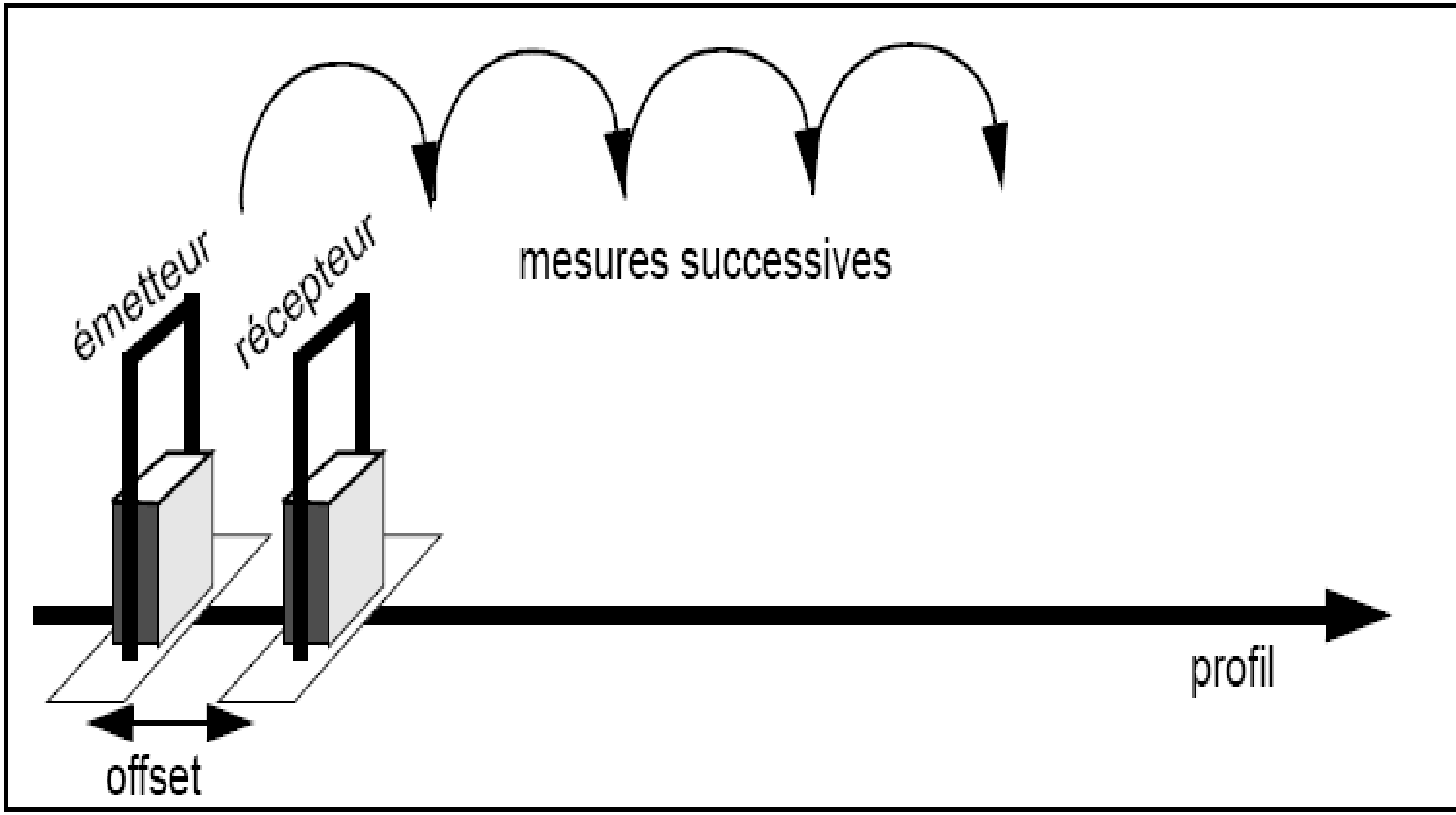
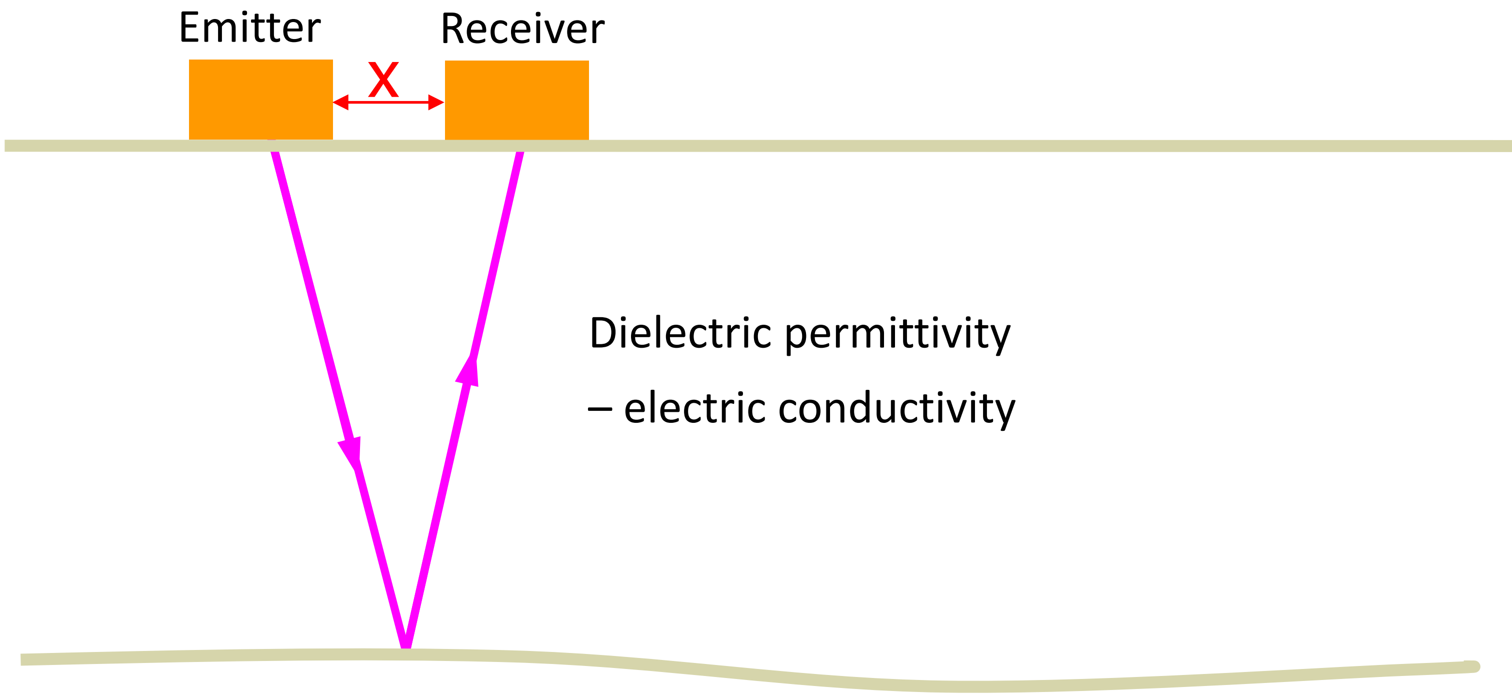
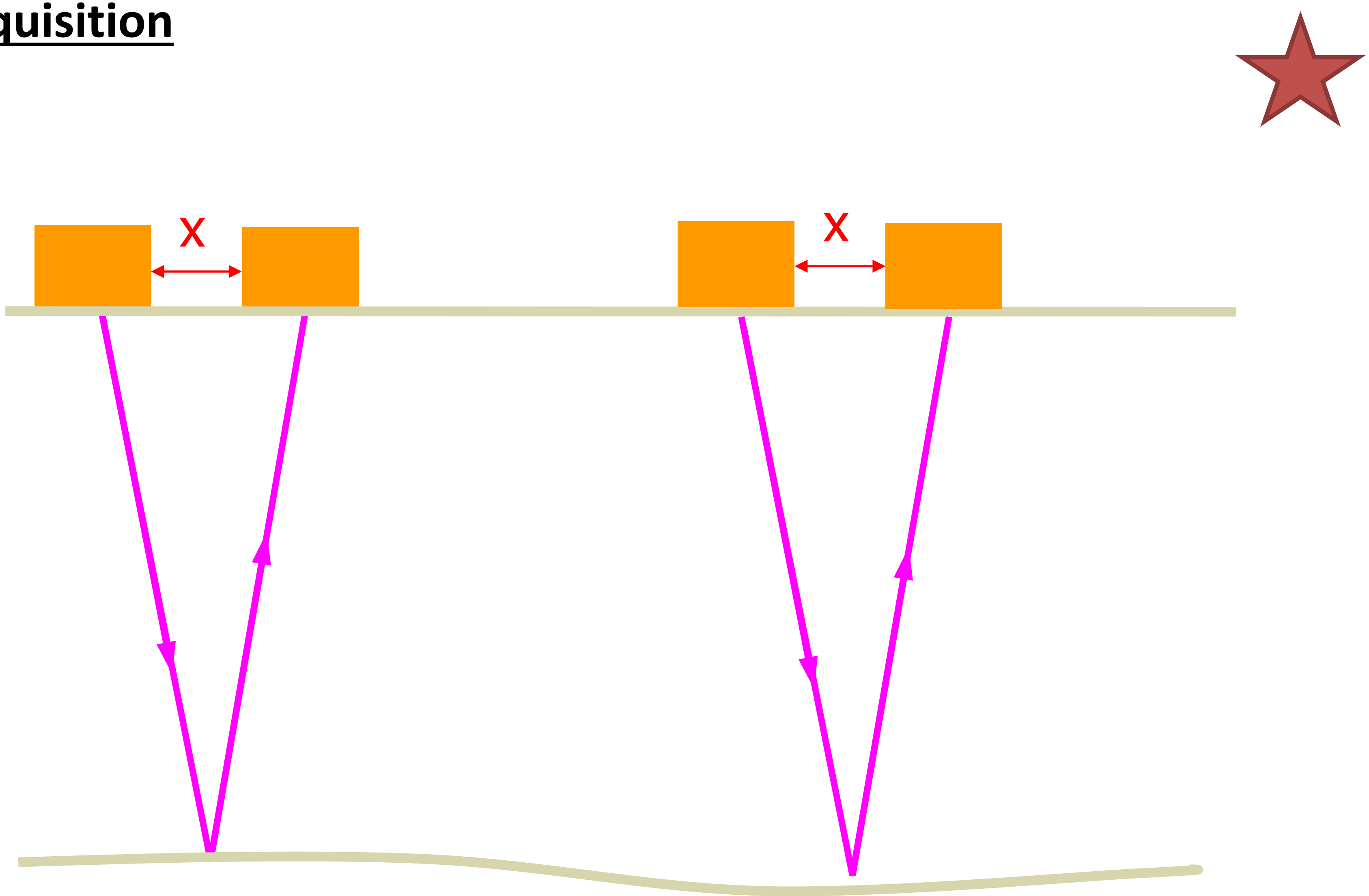


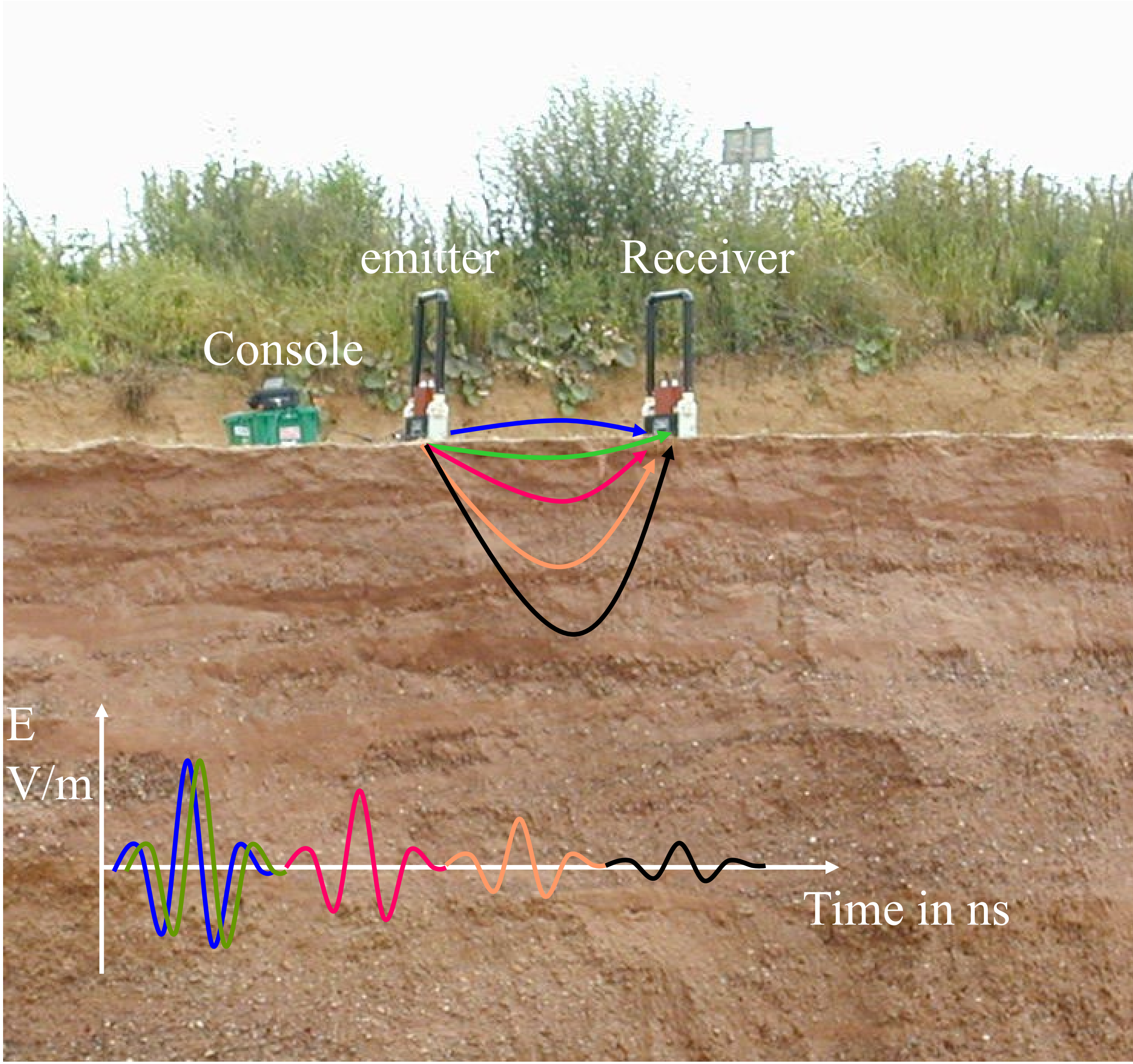
figure 22: Schéma de l'acquisition à offset constant. Chaque mesure successive donne lieu à une trace.

Acquisition



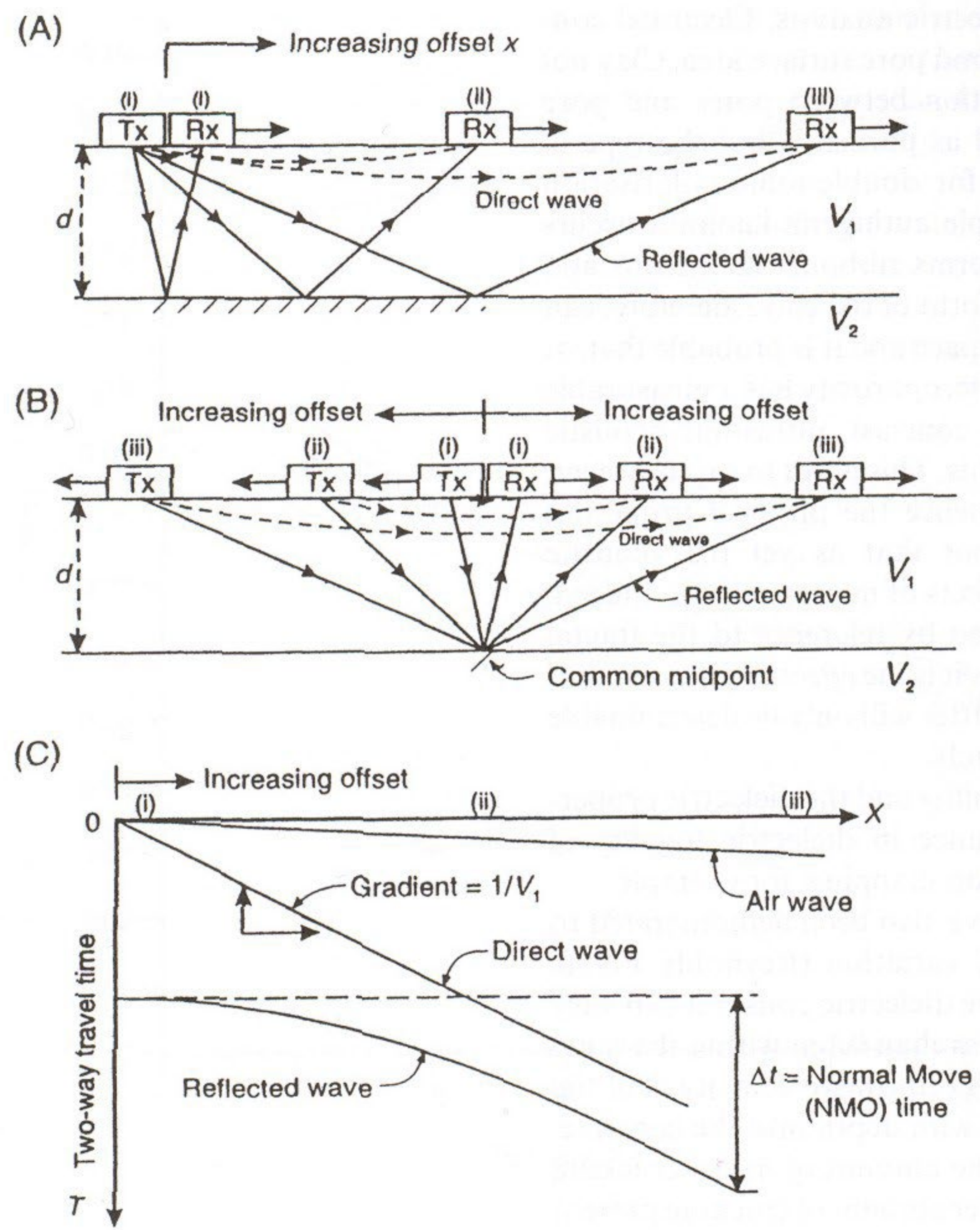
➢ Acquisition

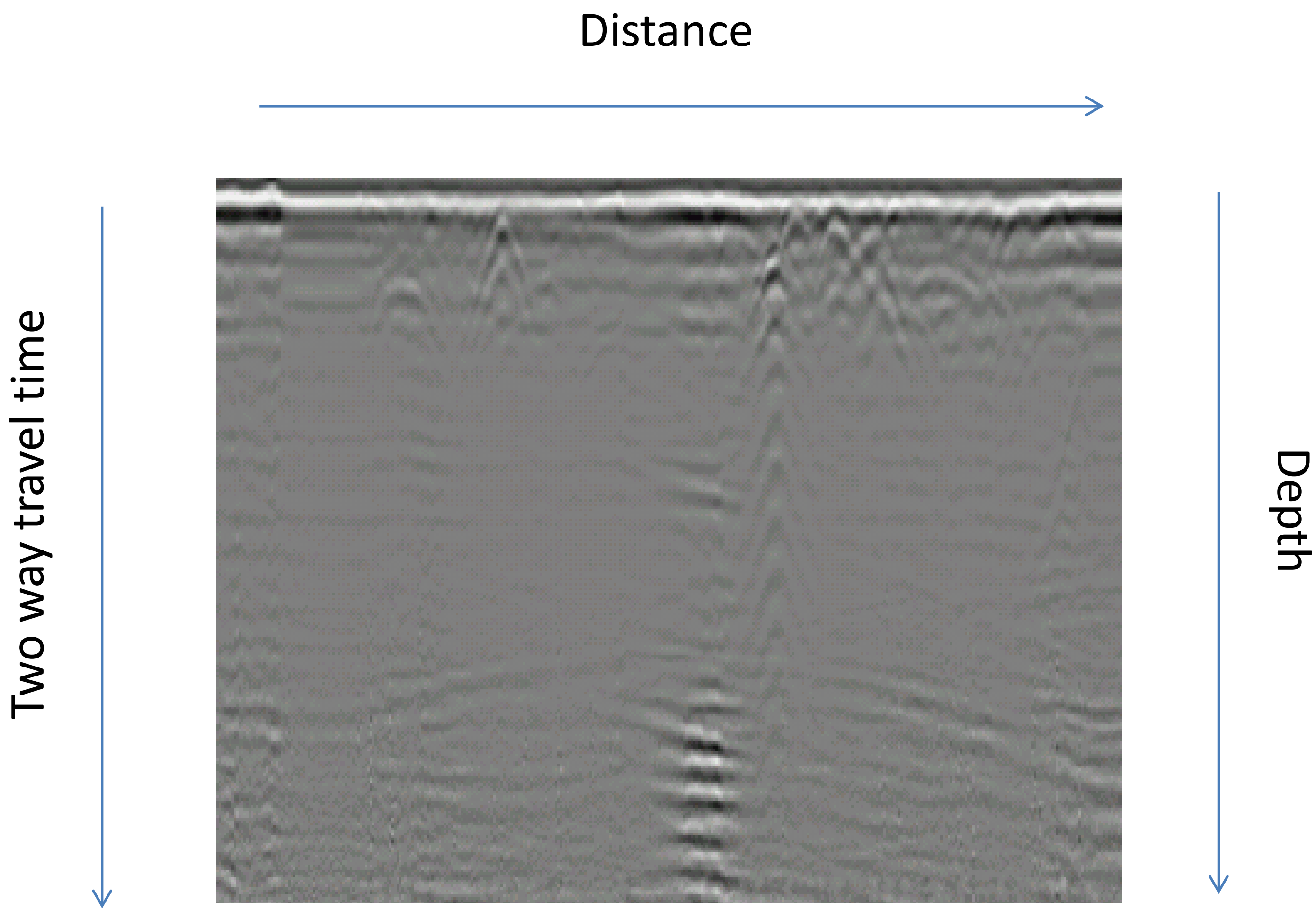




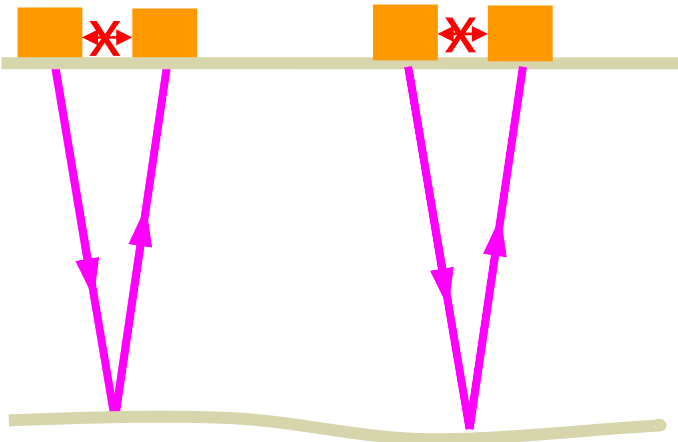
Direct wave in air
Direct wave in soil
1st Reflected
2nd Reflected
3rd Reflected
...

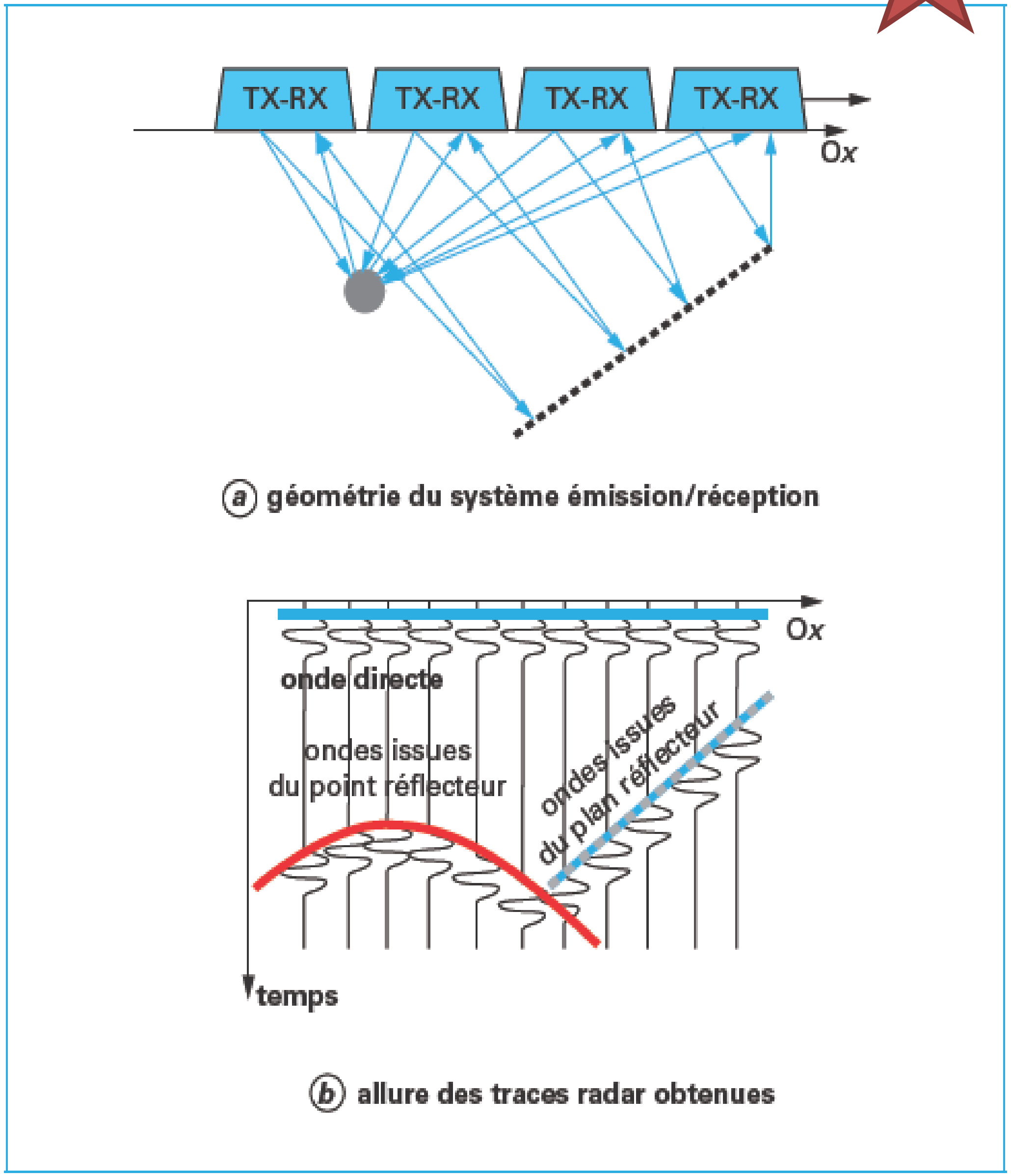
31


(A)
Increasing offset x
(i)
(i)
(ii)
(iii)
Tx
Rx
Rx
Rx
Direct wave
d
V_1
Reflected wave
V_2
(B)
Increasing offset
Increasing offset
(iii)
(ii)
(i)
(i)
(ii)
(iii)
Tx
Tx
Tx
Rx
Rx
Rx
Direct wave
d
V_1
Reflected wave
Common midpoint
V_2
(C)
Increasing offset
(i)
(ii)
(iii)
0
X
Gradient = $1/V_1$
Air wave
Direct wave
Two-way travel time
Reflected wave
Δt = Normal Move
(NMO) time
T

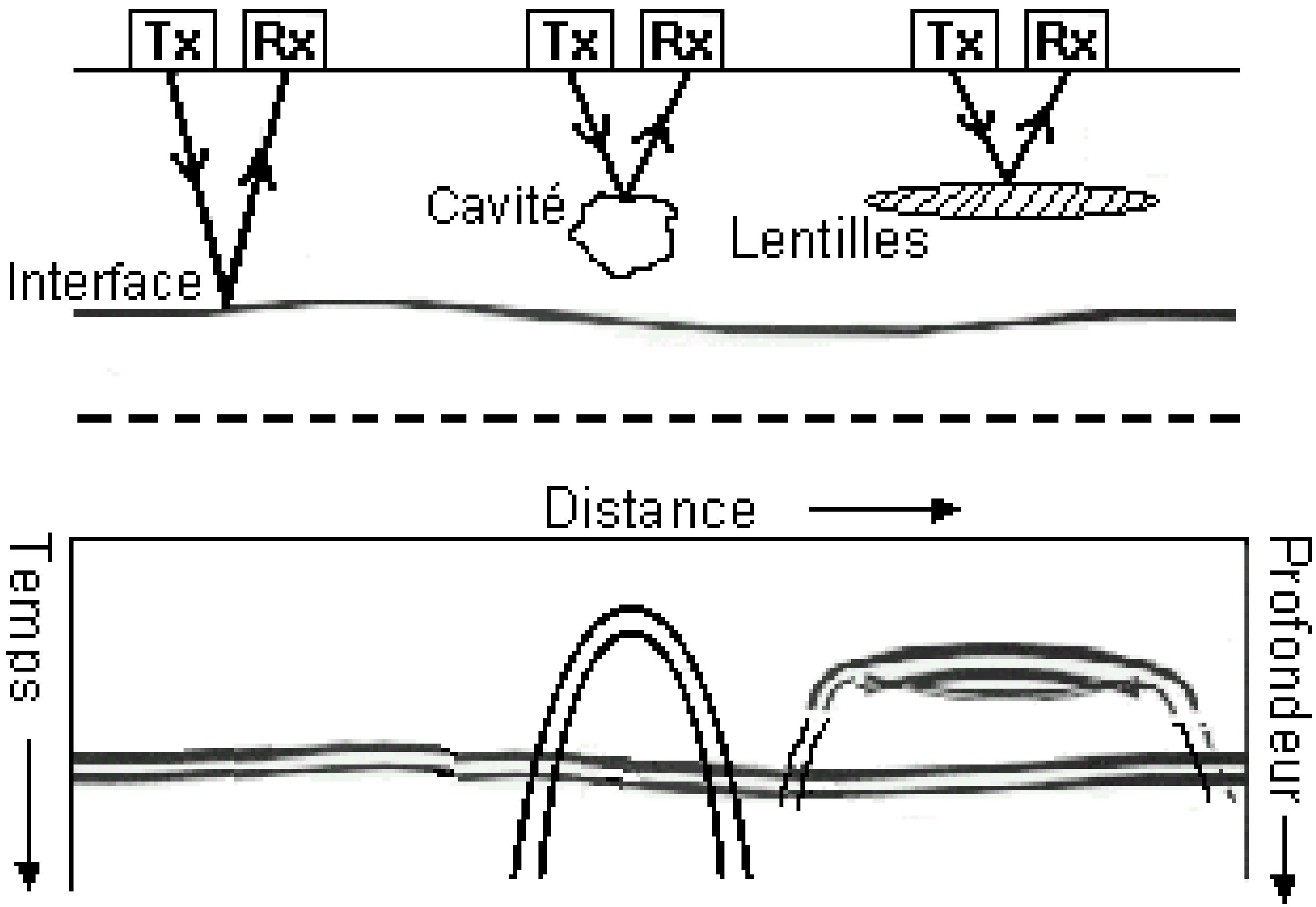

Distance
Two way travel time
Depth

➢ Interpretations

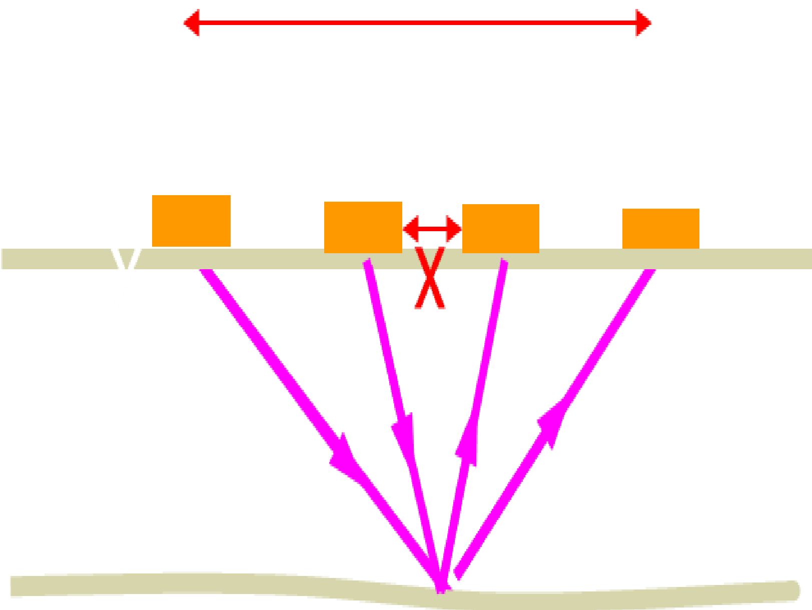


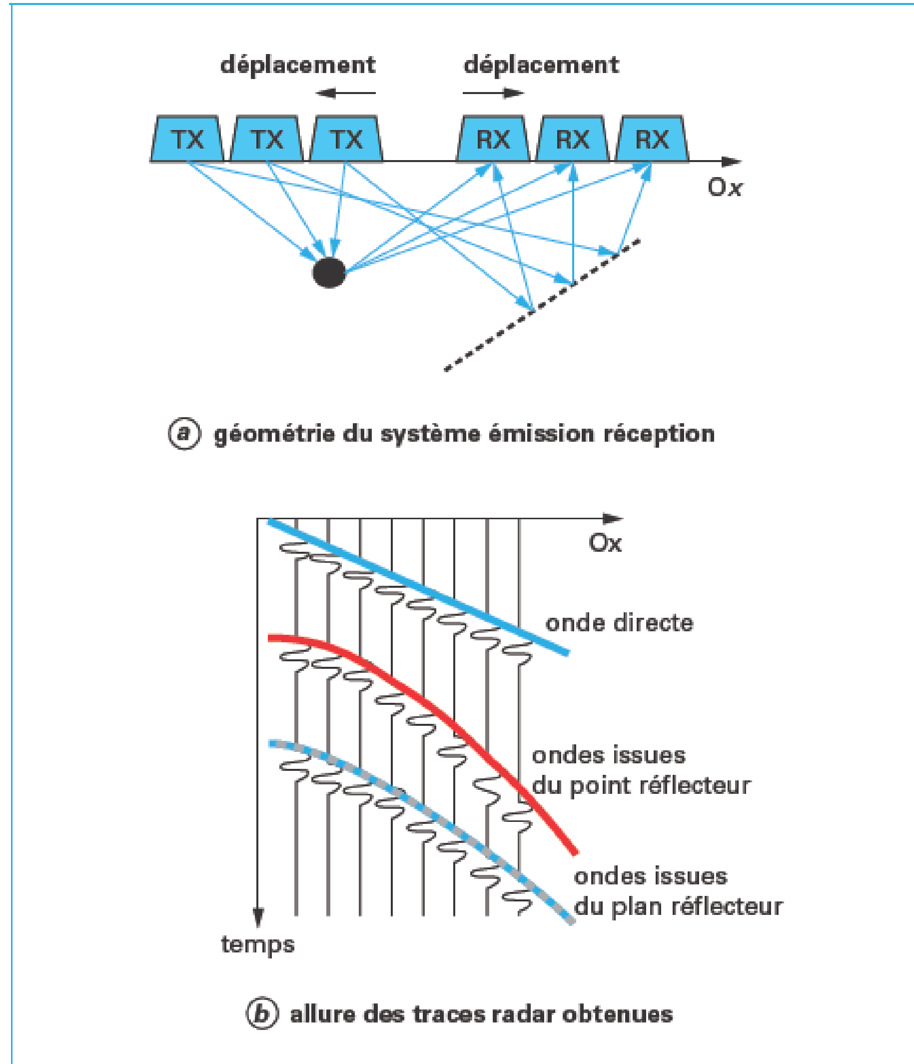


Interpretations

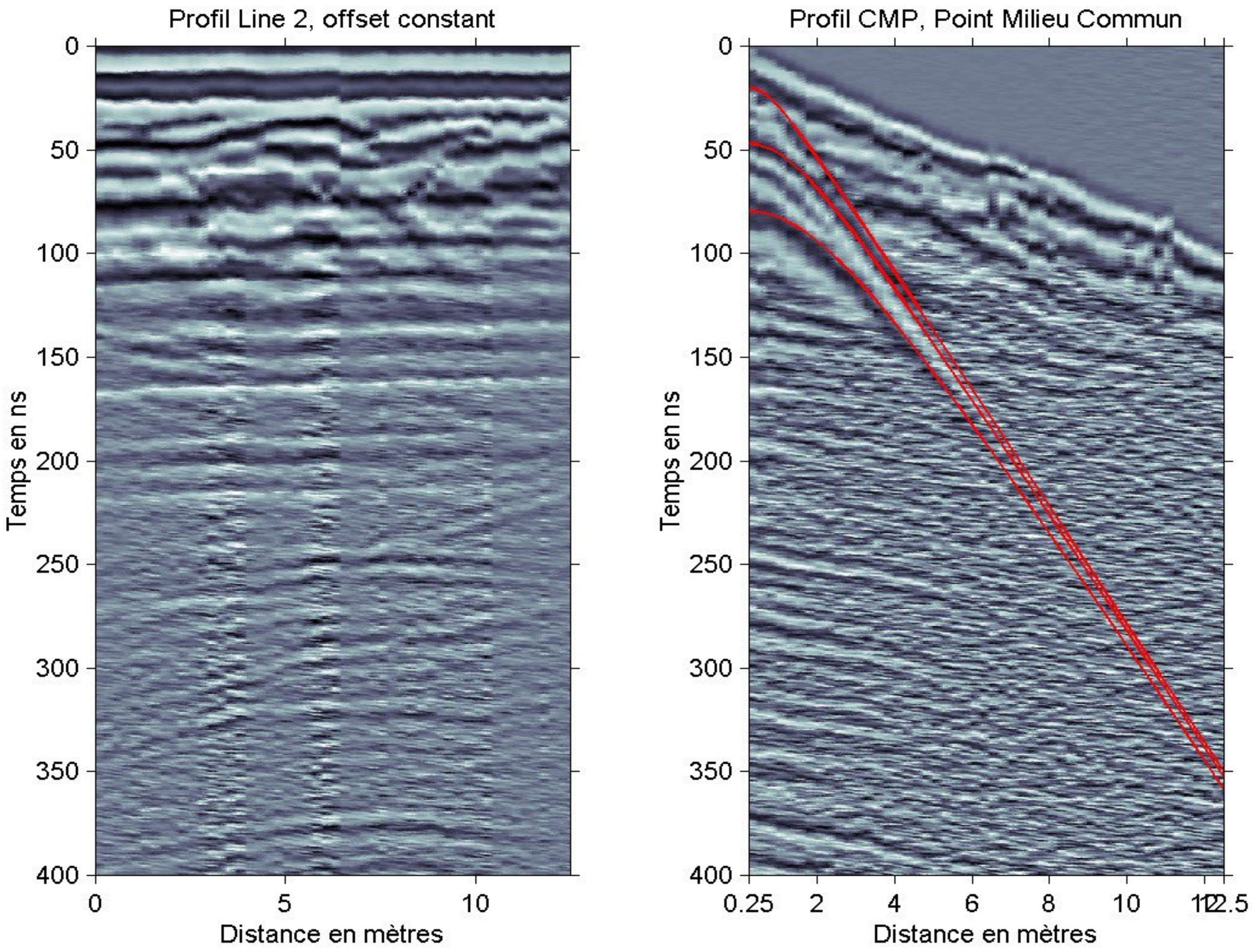


➢ Interpretations



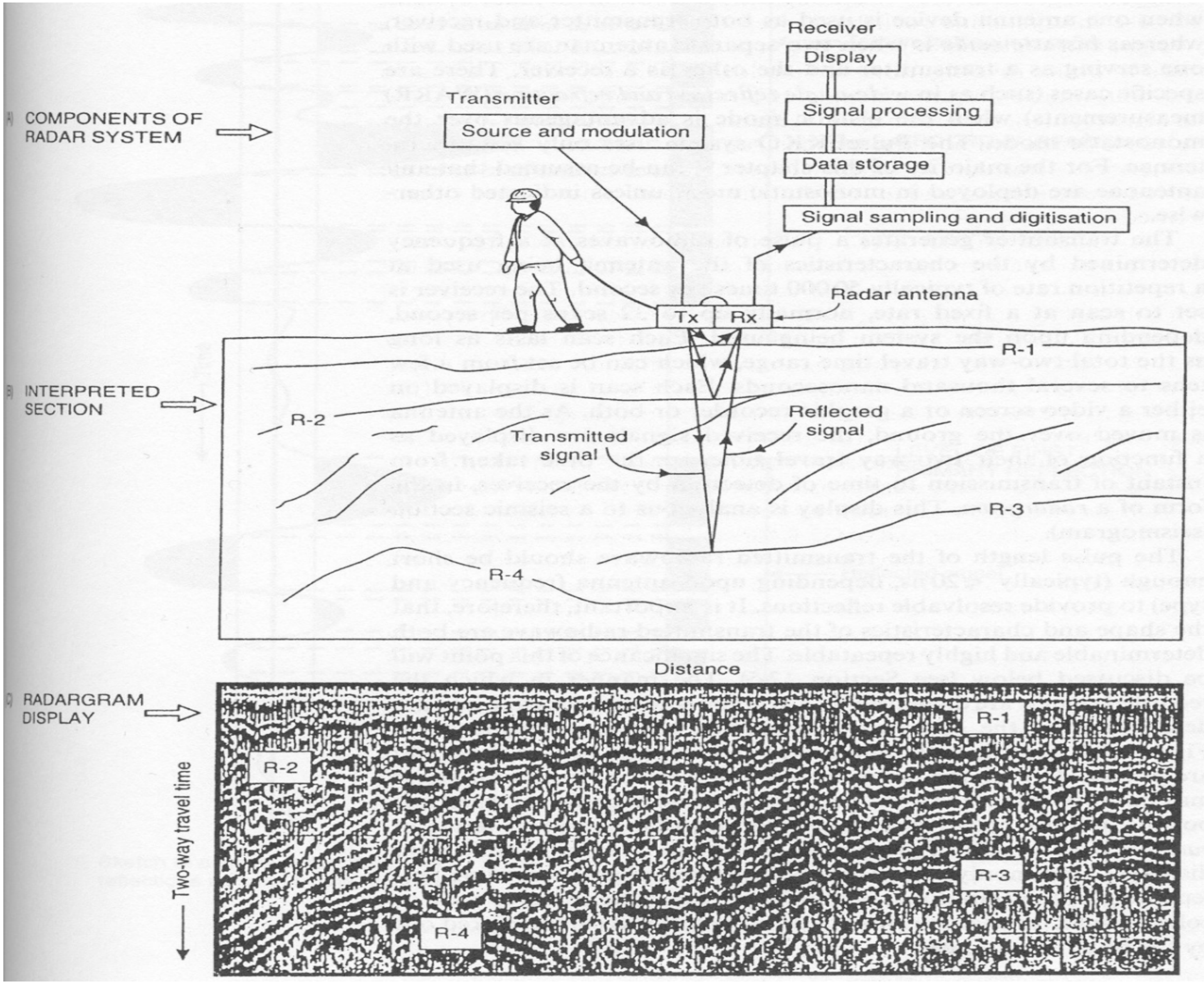


➢ Interpretations



<u>Réflexion</u>
Offset
constant

Data processing



➢ **GPR applications**

Geological:

- Detection of natural cavities and fissures
- Subsidence mapping
- Mapping sand body geometry
- Mapping of superficial deposits
- Soil stratigraphy mapping
- Glacial geological investigations
- Mineral exploration and resource evaluation
- Peat thickness mapping and resource evaluation Permafrost
- investigations
- Location of ice wedges
- Fracture mapping in rock salt
- Location of faults, dykes, coal seams, etc.
- Geological structure mapping
- Lake and riverbed sediment mapping

GPR applications

Environmental:

- Contaminant plume mapping
- Mapping and monitoring pollutants within groundwater
- Landfill investigations
- Location of buried fuel tanks and oil drums
- Location of gas leaks
- Groundwater investigations

Glaciological:

- Ice thickness mapping
- Determination of internal glacier structures
- Ice movement studies
- Detection of concealed surface and basal glacier crevasses
- Mapping water conduits within glaciers
- Determination of thickness and type of sea and lake ice Subglacial
- mass balance determination
- Snow stratigraphy

➢ **GPR applications**

Engineering and construction:

- Road pavement analysis
- Void detection
- Location of reinforcement (rebars) in concrete
- Location of public utilities (pipes, cables, etc.)
- Testing integrity of building materials
- Concrete testing

Archaeology:

- Location of buried structures
- Detection and mapping of Roman Roads, etc. Location of
- post-holes, etc.
- Pre-excavation mapping
- Detection of voids (crypts, etc.)
- Location of graves
- Forensic science:
- Location of buried targets (*e.g*. bodies and bullion)

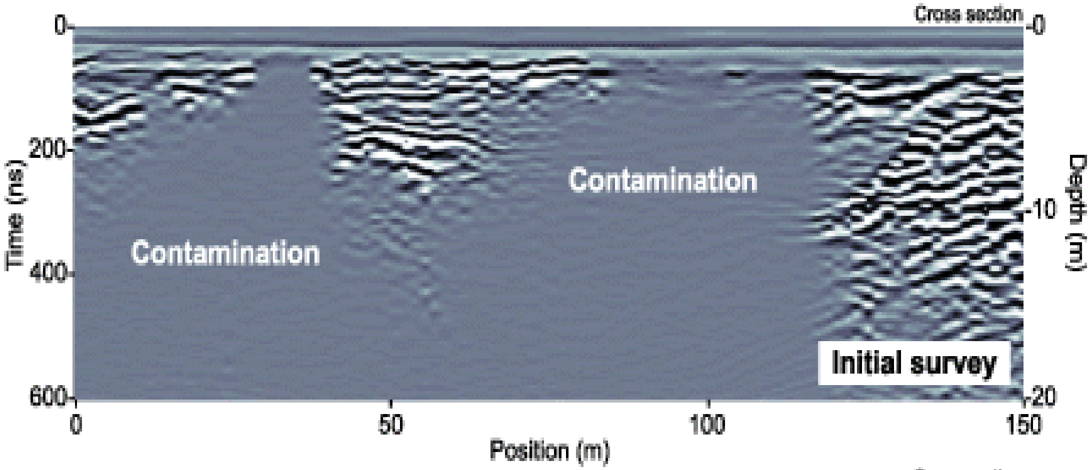
➢ GPR equipment

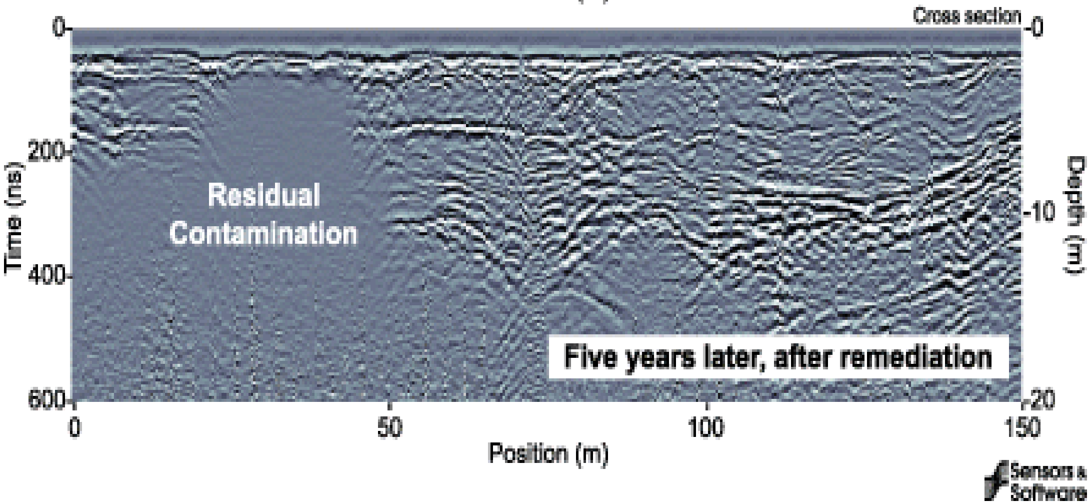
Applications

Applications

➢ Environmental applications

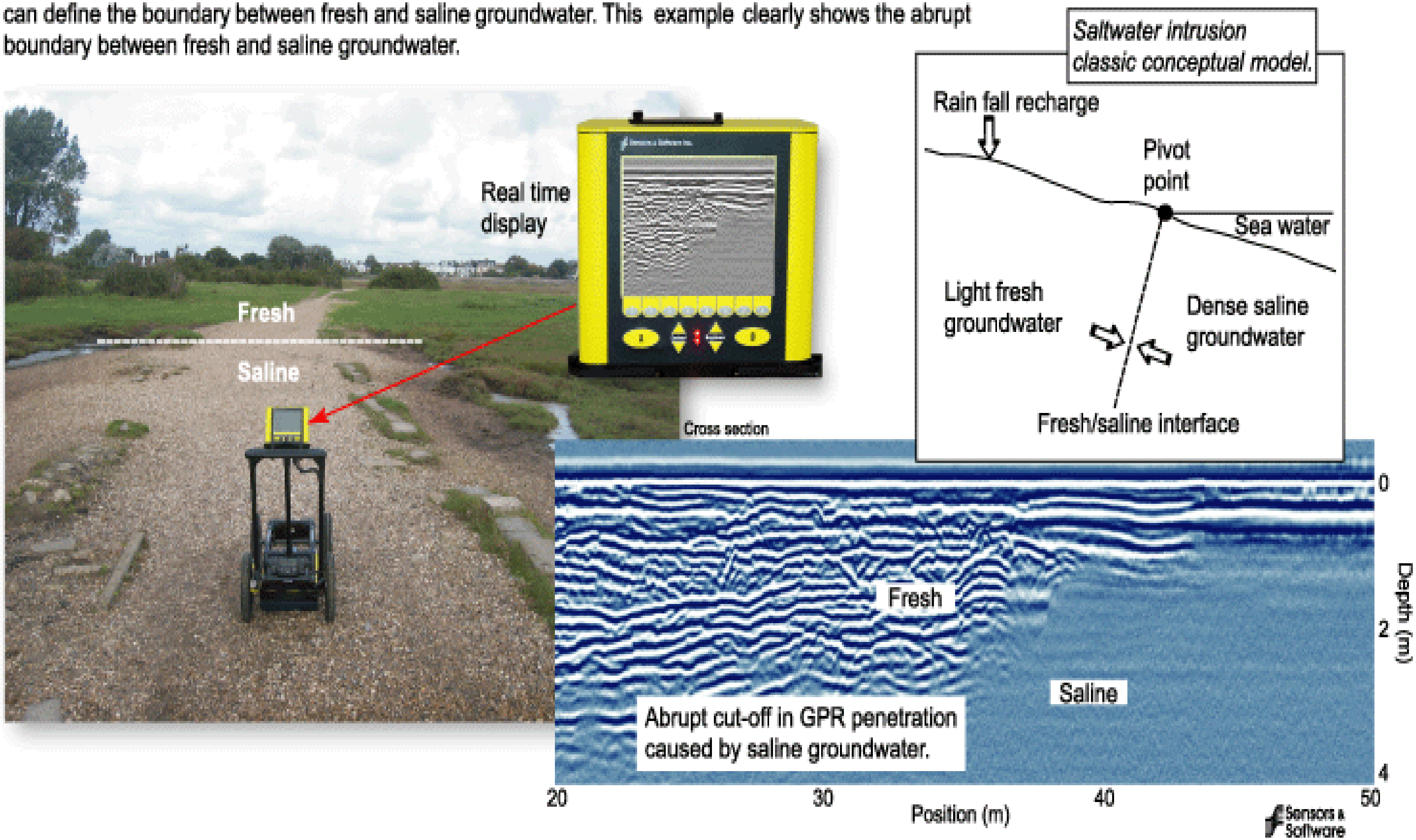
Electrically conductive groundwater contamination preferentially absorbs GPR signals so GPR is an effective tool in mapping the extent of the contamination. This example shows reflection mode surveys in an area of chloride-contaminated groundwater near a landfill site before and after remediation. Five years after remediation began, GPR signal penetration had increased significantly, indicating that the remediation effort was successful.



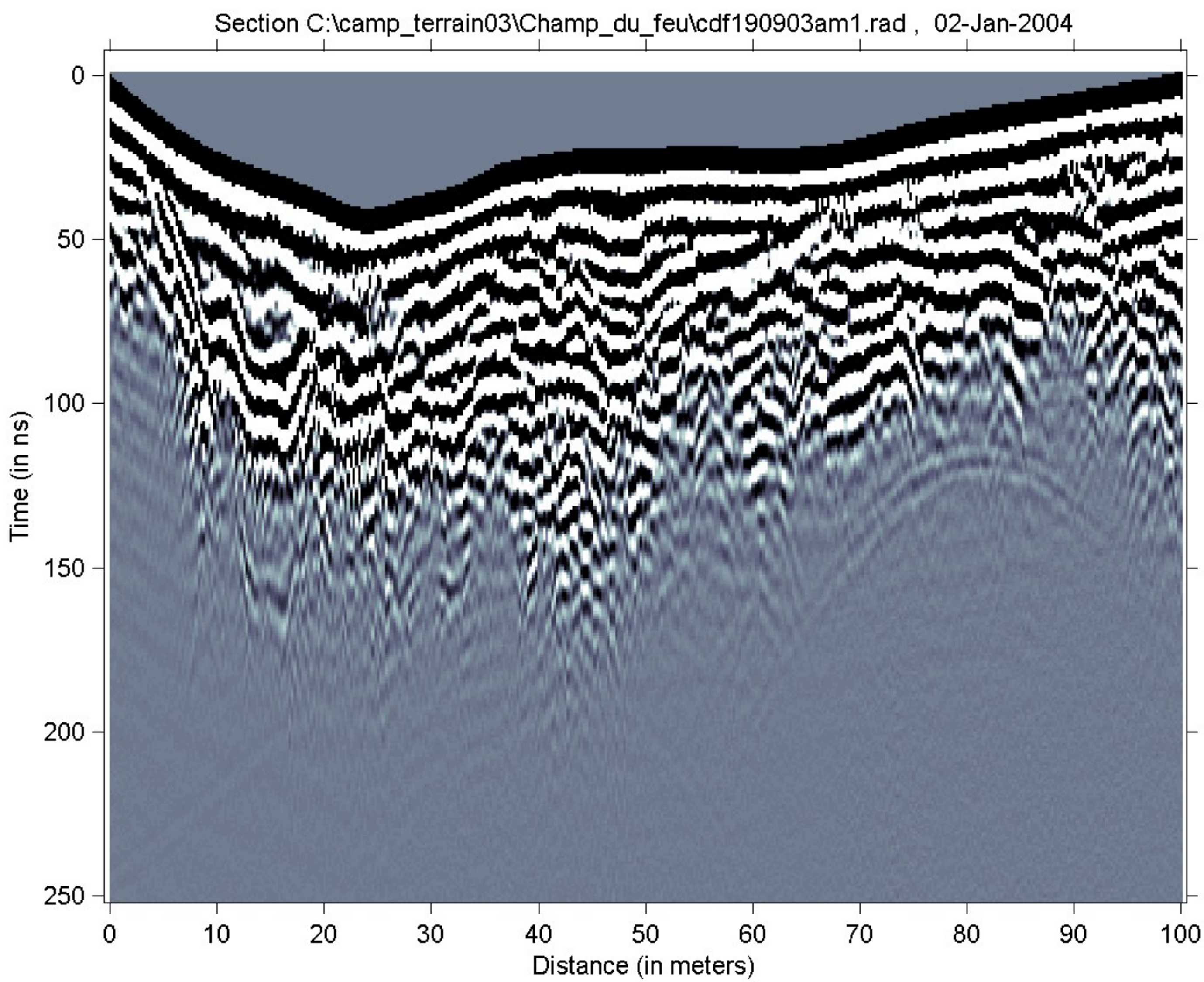


➢ Salt infiltration

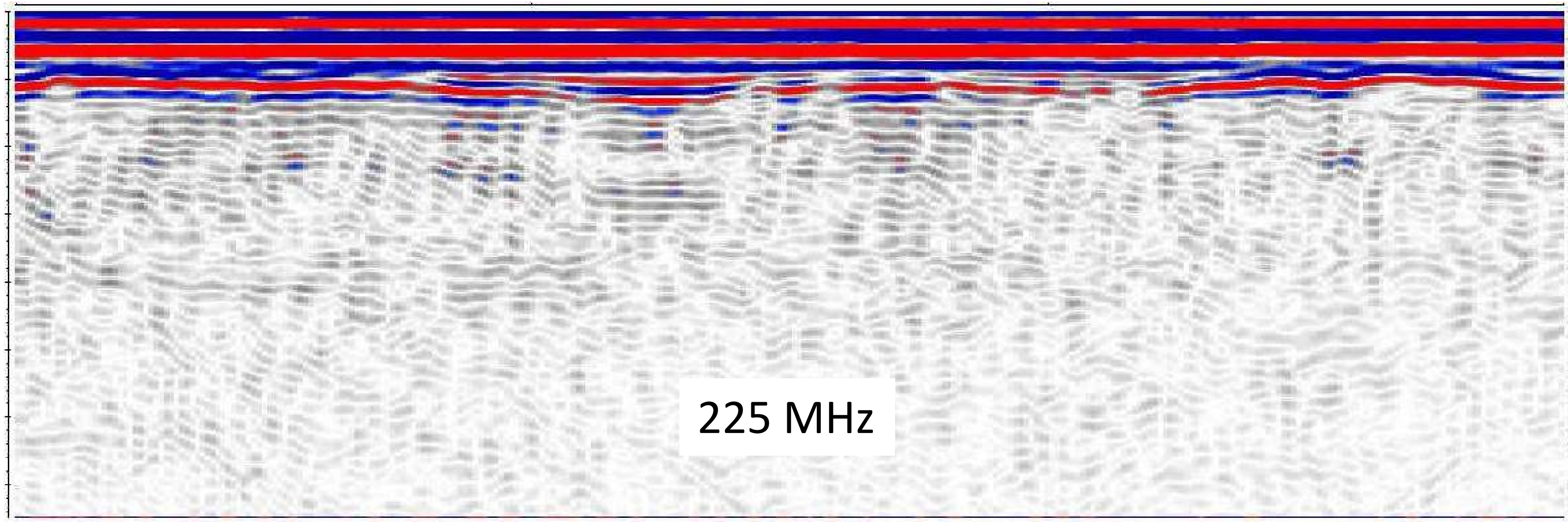
In coastal areas, the supply of fresh groundwater can be disrupted by the influx of saltwater into shallow aquifers. GPR is highly sensitive to the presence of saline water. Reflection GPR in coastal areas often can define the boundary between fresh and saline groundwater. This example clearly shows the abrupt boundary between fresh and saline groundwater.

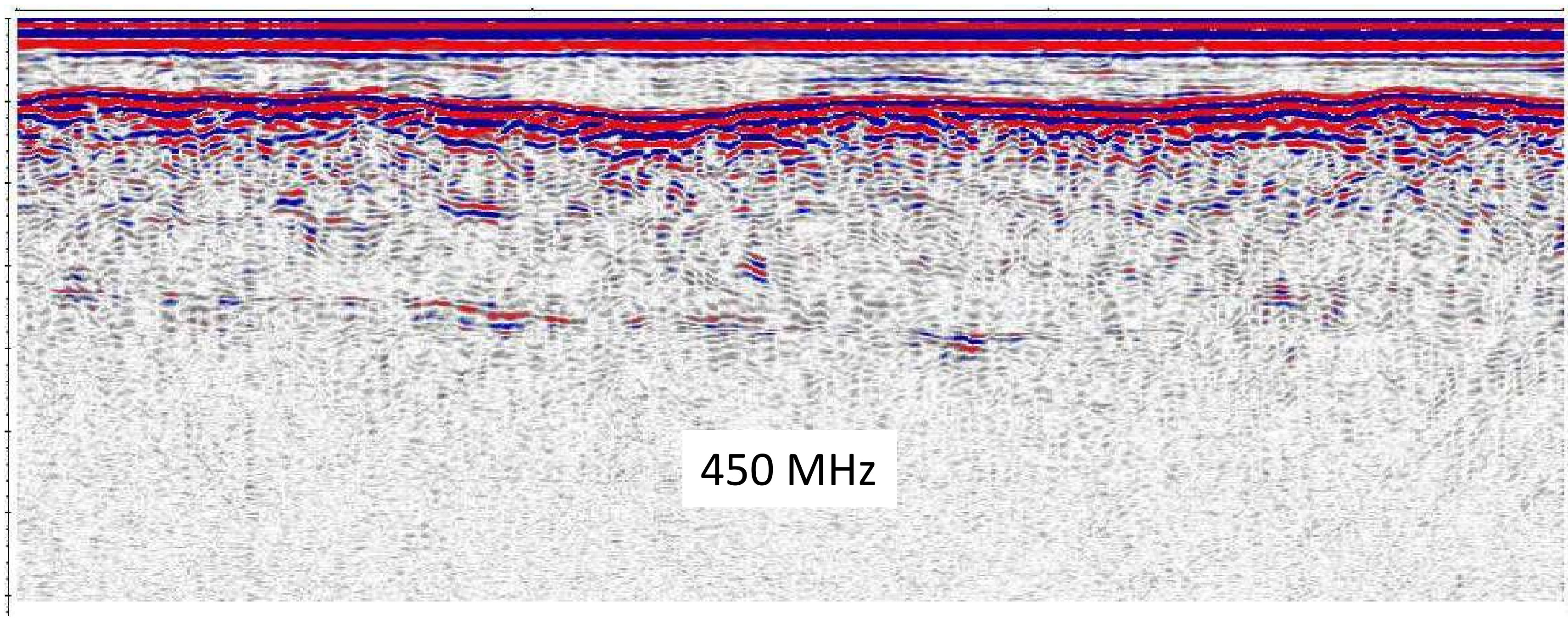


➢ Soil thickness

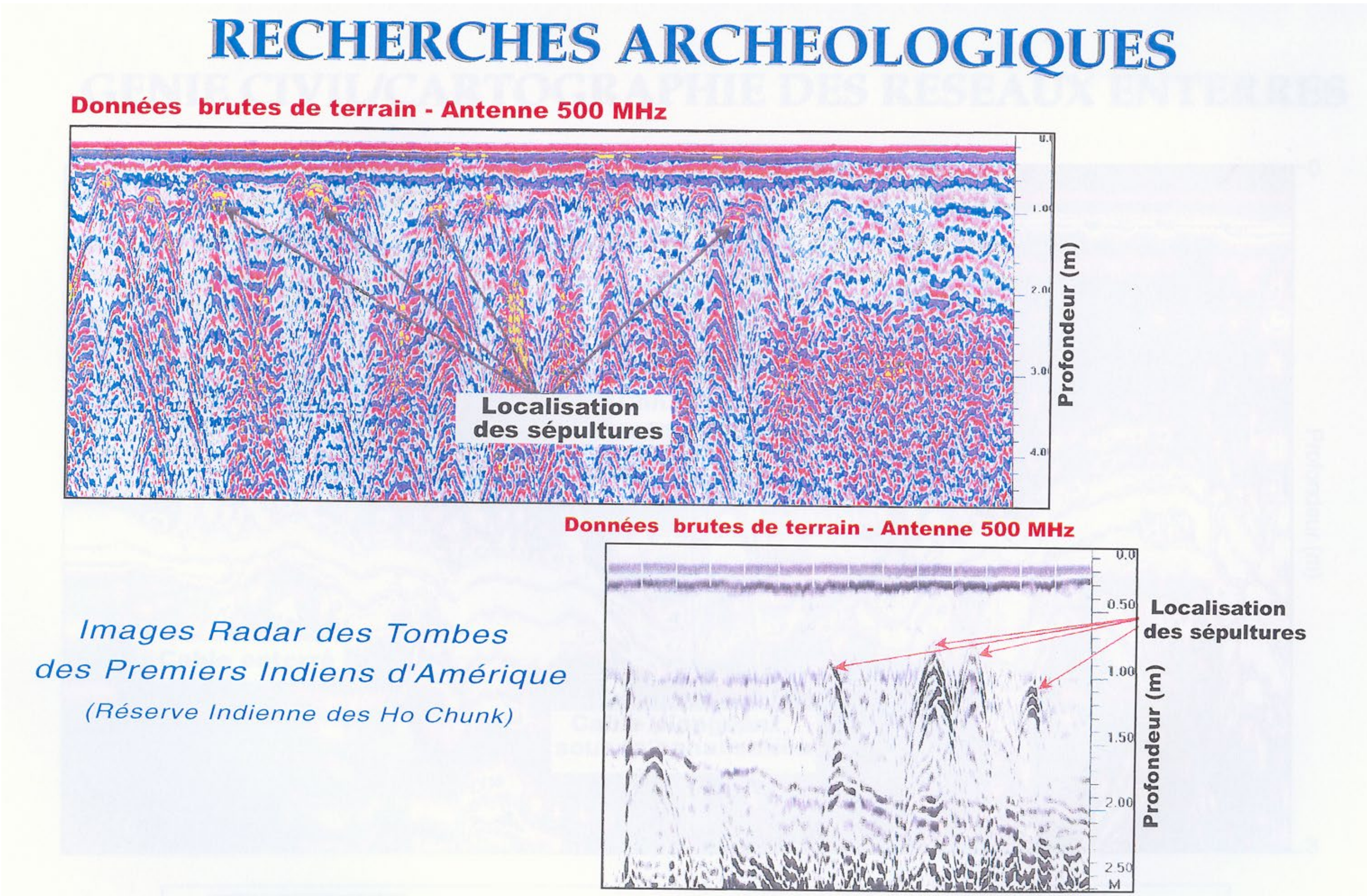


➢ **Snow thickness**

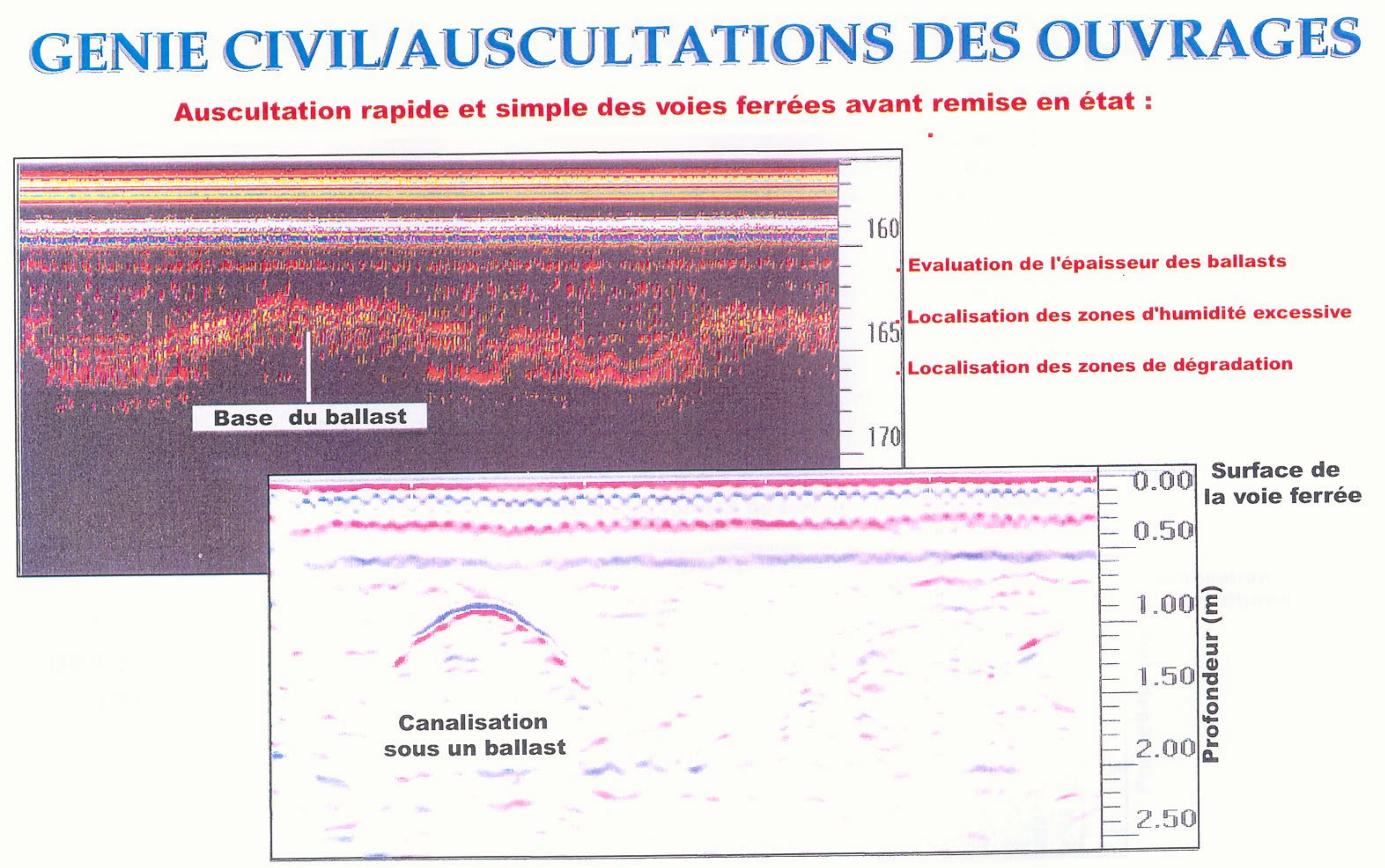




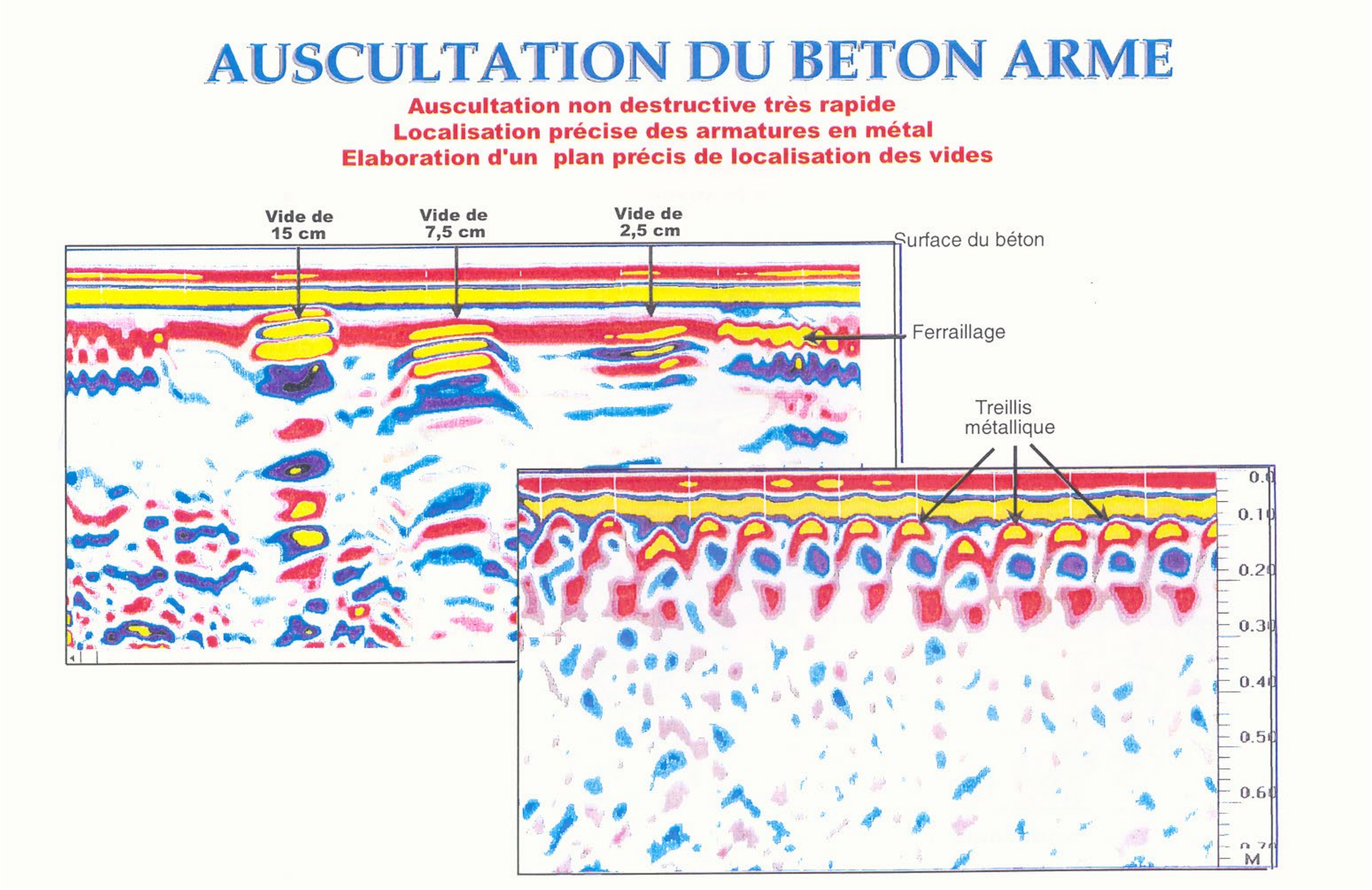
➢ Archeology


RECHERCHES ARCHEOLOGIQUES
Données brutes de terrain - Antenne 500 MHz
Localisation des sépultures
Profondeur (m)
Données brutes de terrain - Antenne 500 MHz
0.50
1.00
1.50
2.00
2.50
M
Localisation des sépultures
Profondeur (m)
Images Radar des Tombes des Premiers Indiens d'Amérique
(Réserve Indienne des Ho Chunk)

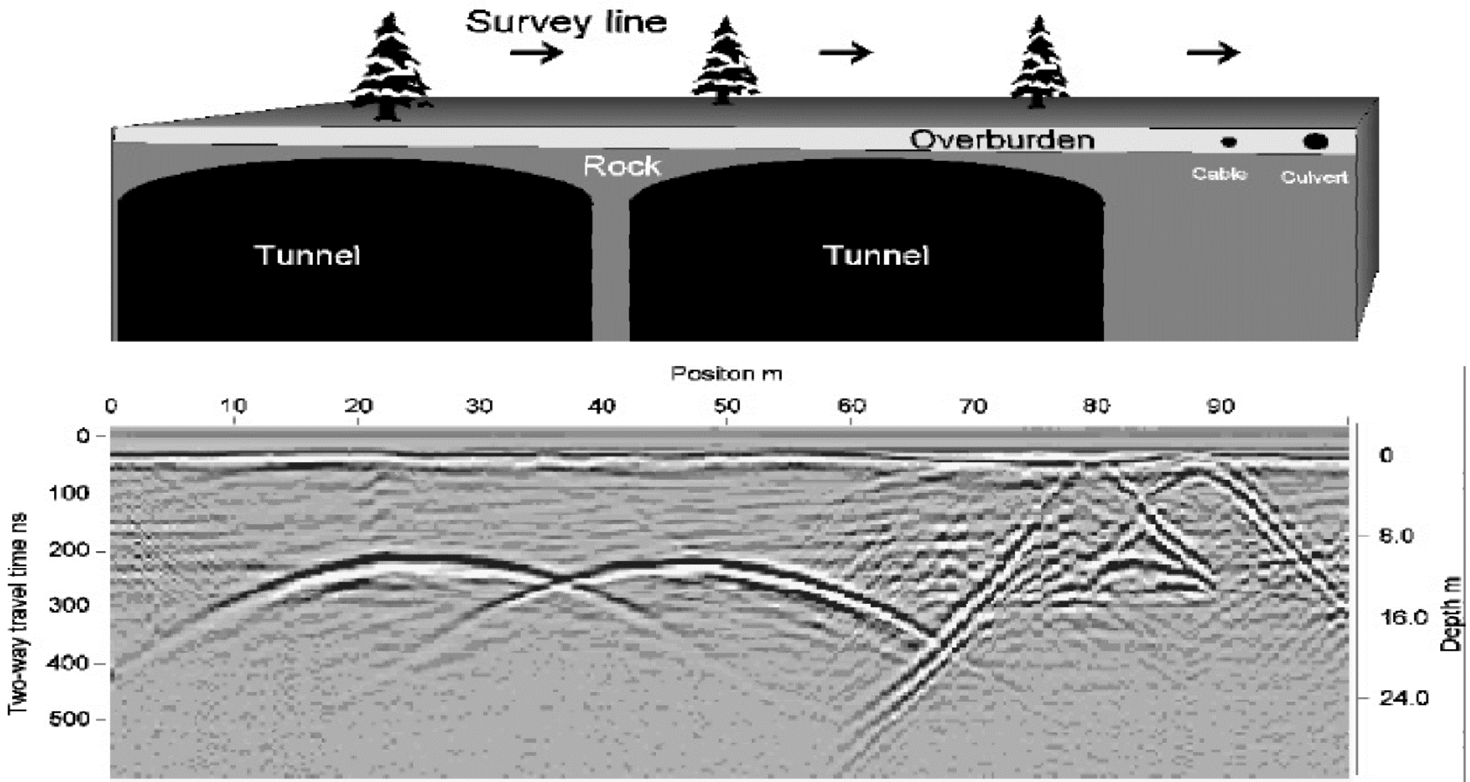
➢ Civil engineering



➢ Civil engineering



➢ **Detecting tunnels**



- **50-Mhz GPR locates two tunnels at 11 meters depth**
- **GPR locates a cable and culvert**
- **GPR defines overburden thickness**

figure 1: échafaudage transportable avec l'équipe de mesure (profil radial en jaune) et chariot de transport en rail

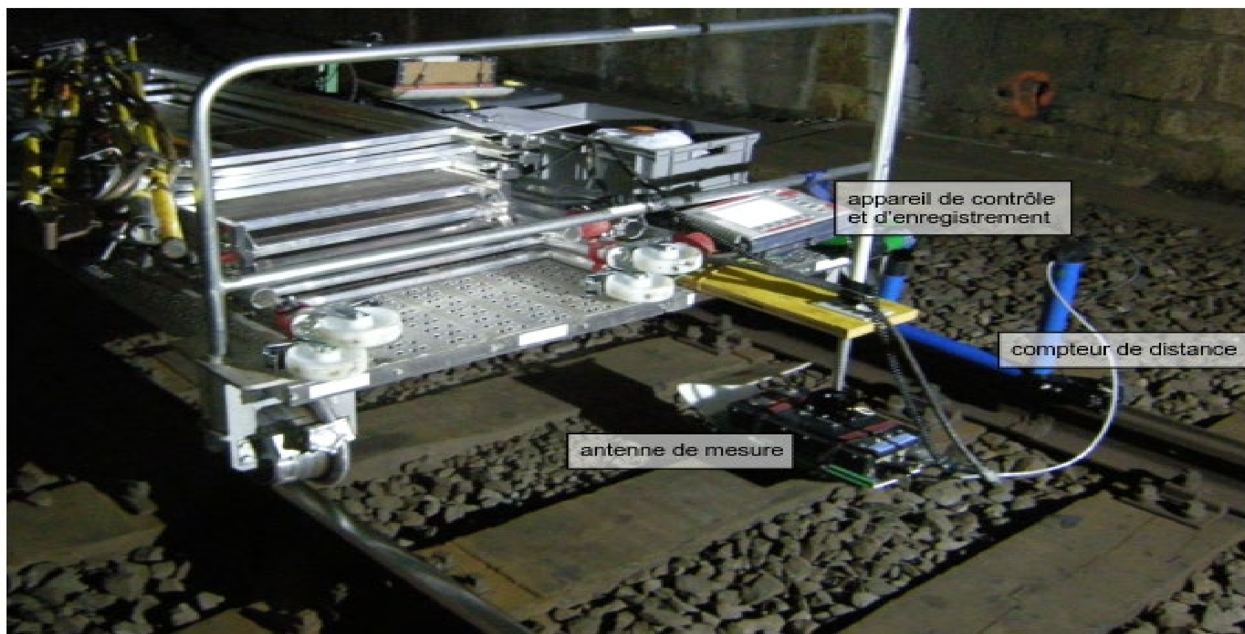
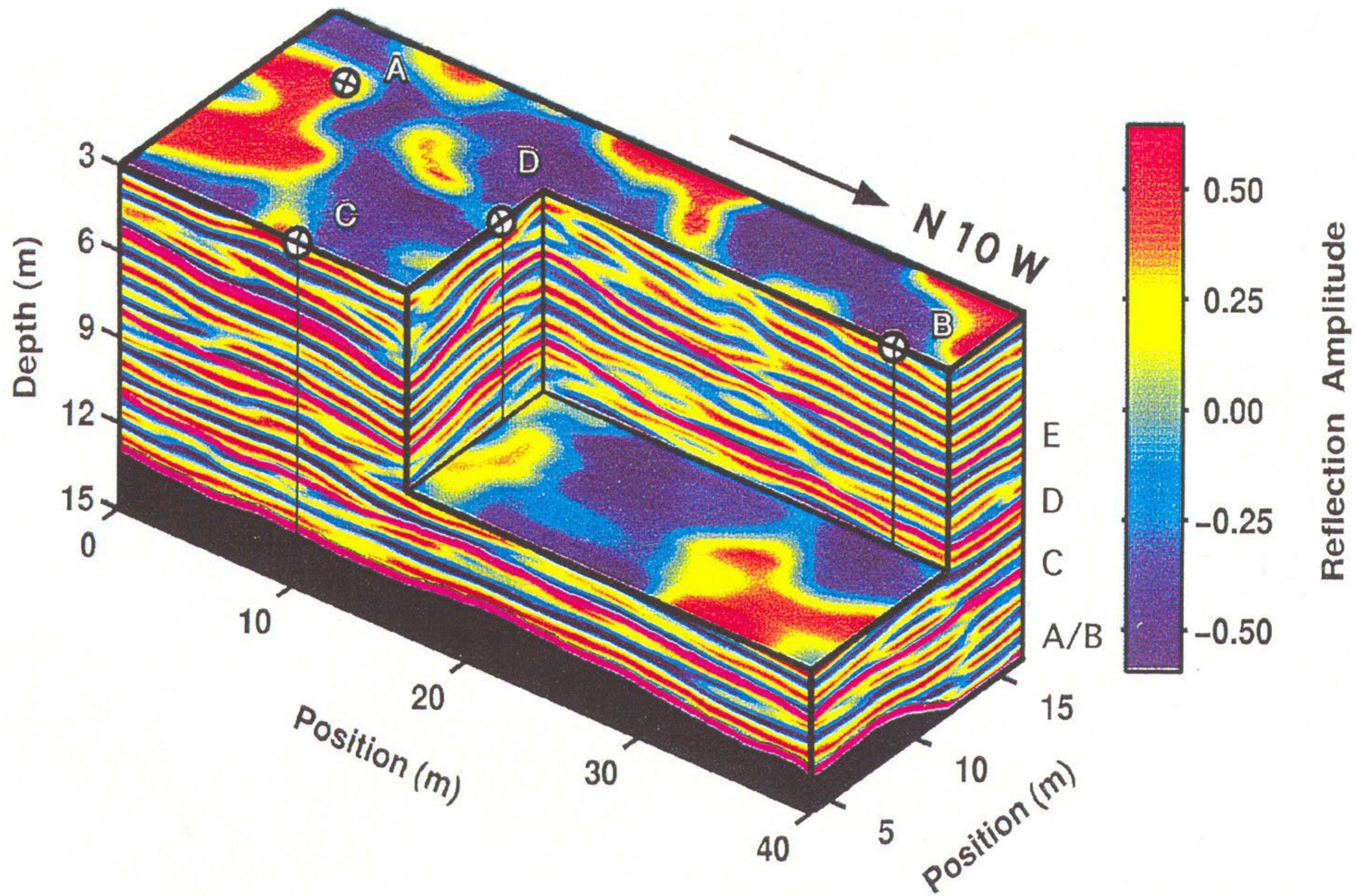


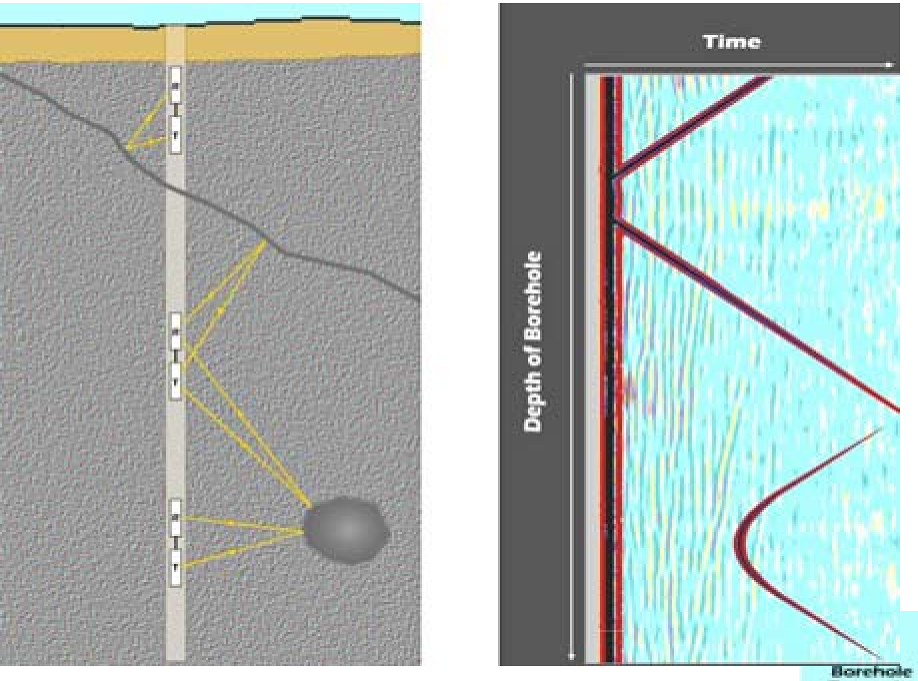
figure 5: installation du système de mesure sur le chariot en rail pour l'auscultation du ballast

➢ **3 D radiagram**

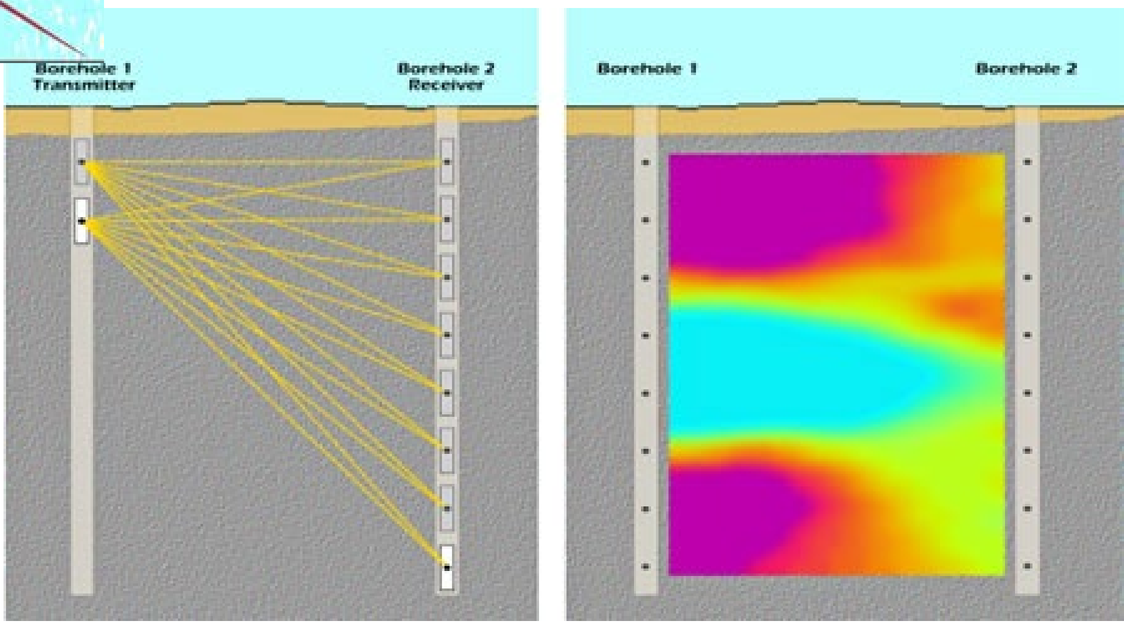


➢ Borehole measurements

Reflexion



Transmission



➢ Calibrating GPR with borehole measurements