

Métodos Geofísicos

Métodos eletromagnéticos



Princípios básicos

Em um levantamento EM



Determinar o que está embaixo da superfície



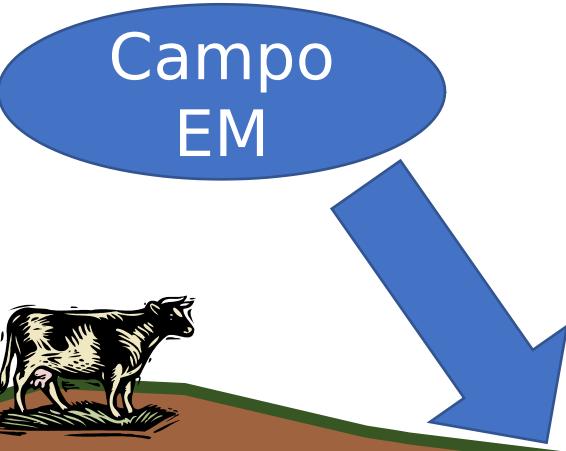
?

Determinar o que está embaixo da superfície

Campo
EM

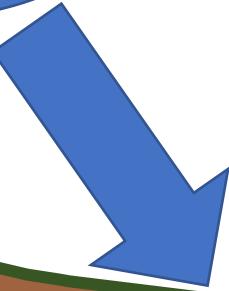


Determinar o que está embaixo da superfície



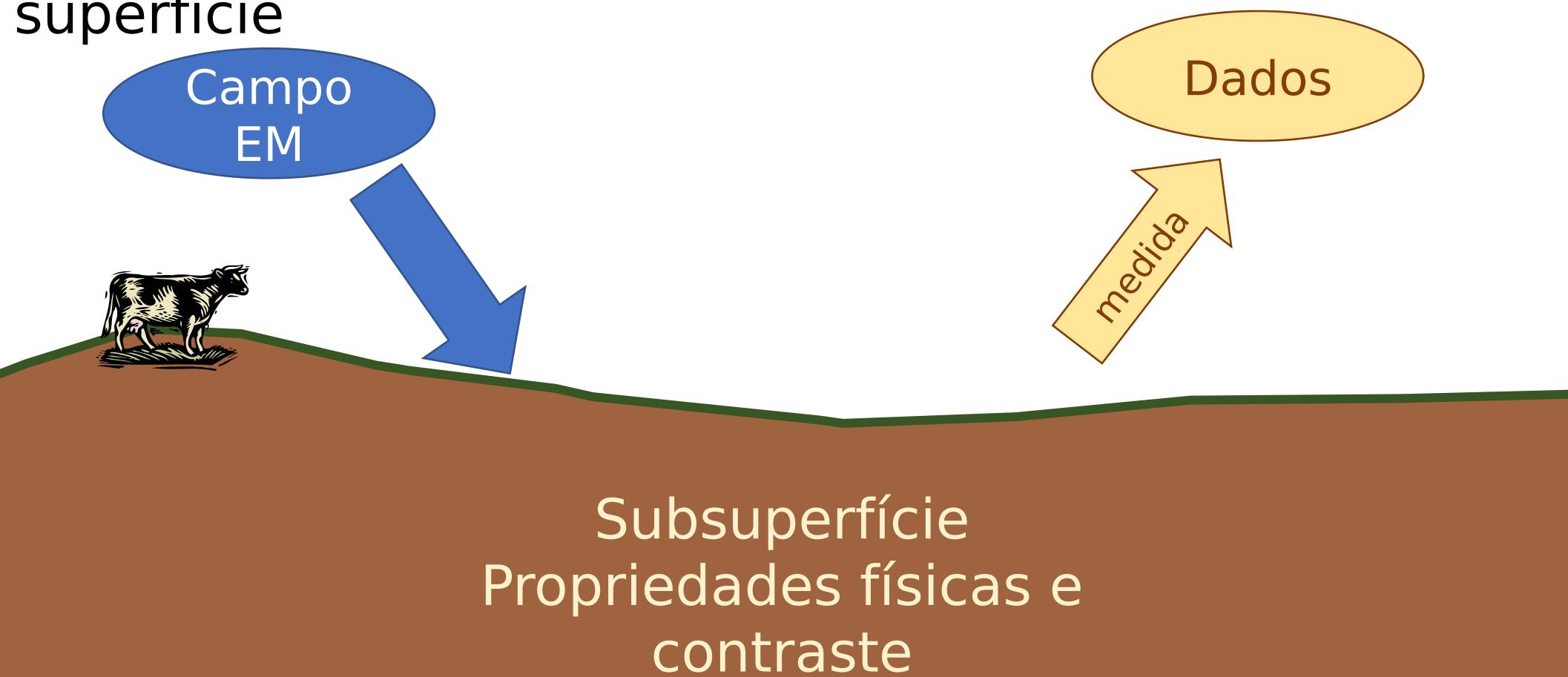
Determinar o que está embaixo da superfície

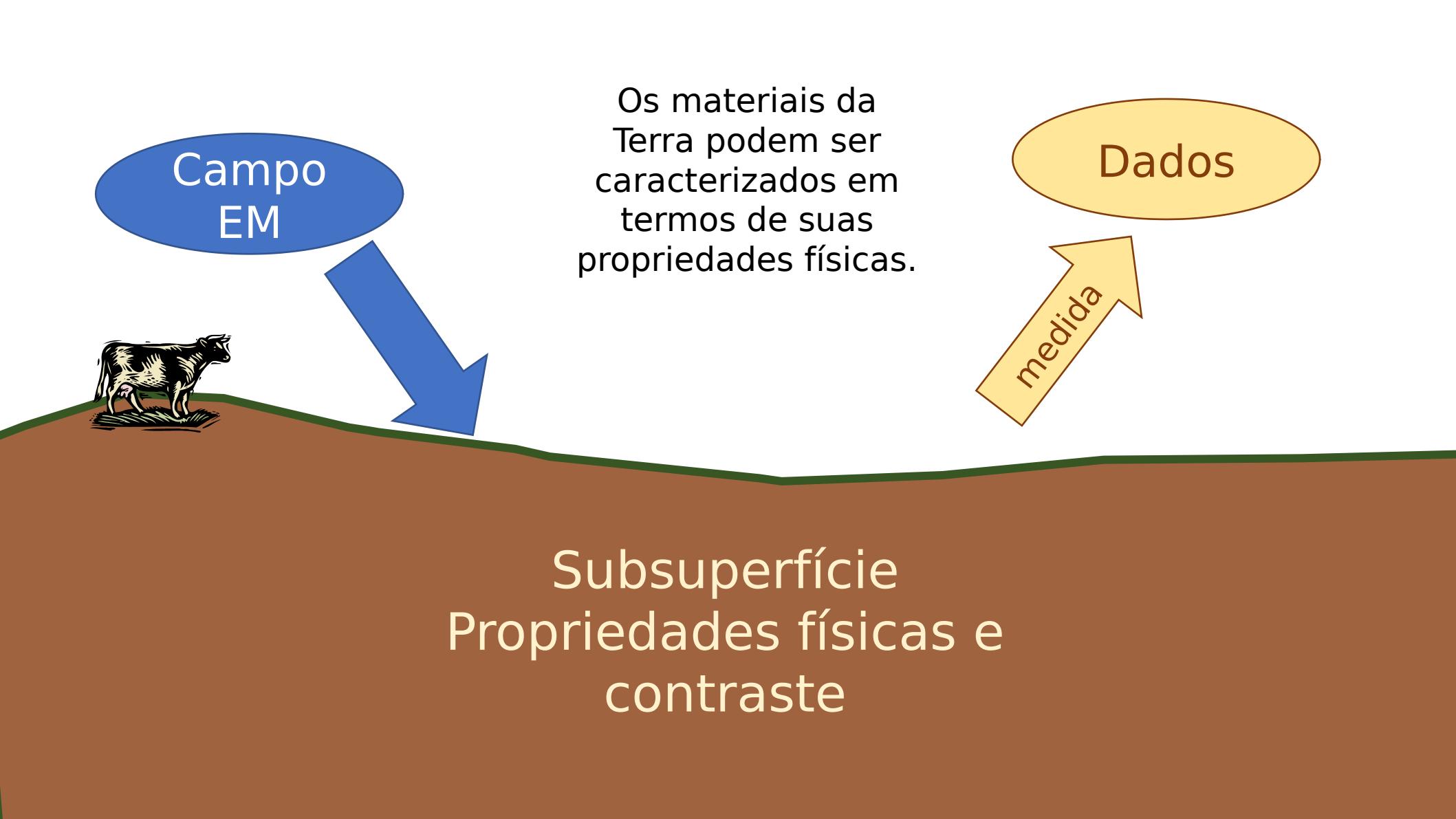
Campo
EM



Subsuperfície
Propriedades físicas e
contraste

Determinar o que está embaixo da superfície





Campo
EM

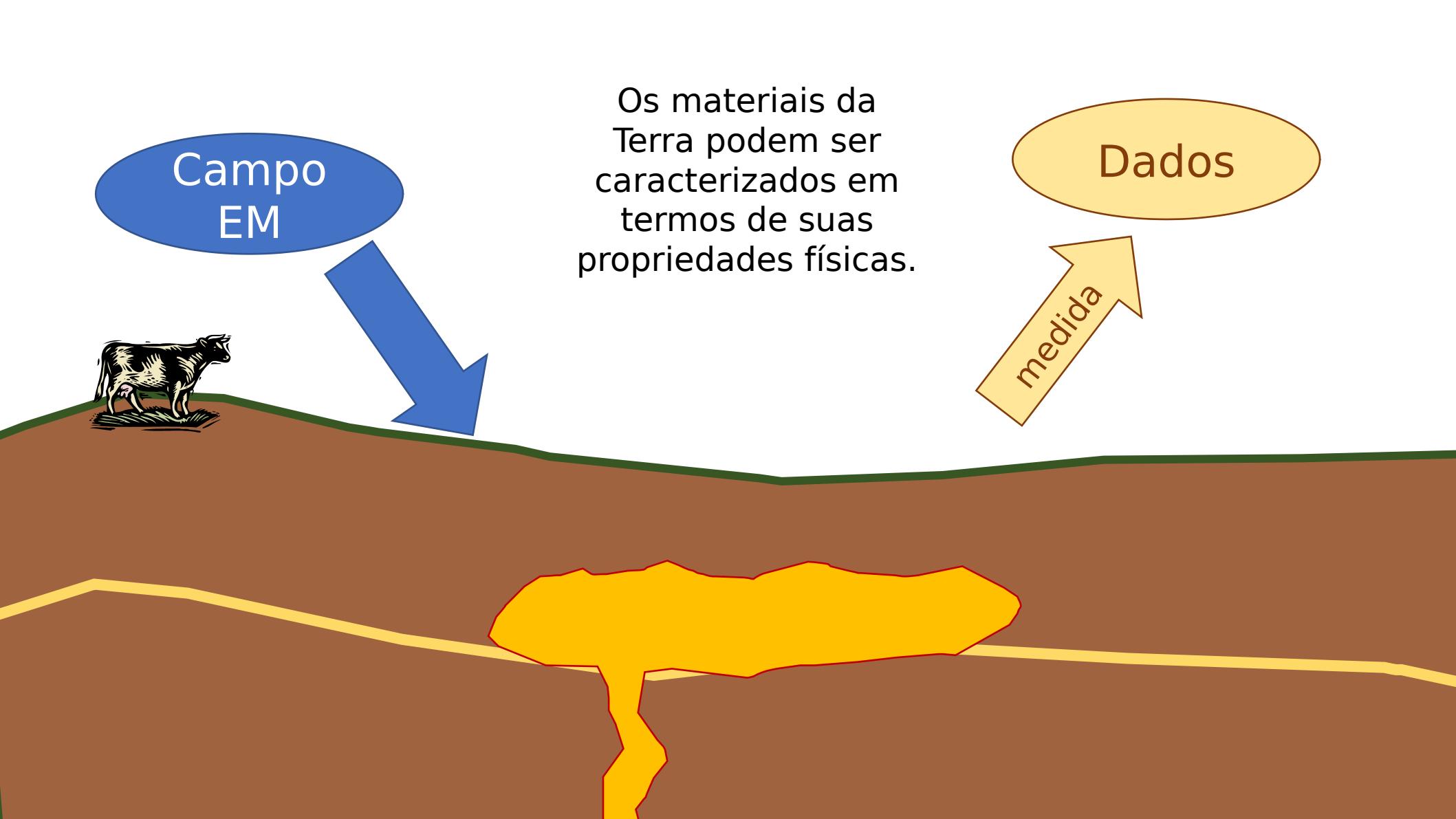
Os materiais da Terra podem ser caracterizados em termos de suas propriedades físicas.



Dados

medida

Subsuperfície
Propriedades físicas e
contraste



Campo
EM

Os materiais da Terra podem ser caracterizados em termos de suas propriedades físicas.

Dados



medida

Campo
EM

A diagram showing a cross-section of the ground. A blue arrow points from a blue oval labeled "Campo EM" (EM field) towards the ground. On the surface, there is a small illustration of a cow. Below the surface, there is a yellow irregular shape representing a geological feature. Three text boxes are placed around the diagram: one on the left describing conductivity, one in the center describing magnetic permeability, and one on the right describing dielectric permittivity.

Os materiais da Terra podem ser caracterizados em termos de suas propriedades físicas.

As propriedades de relevância para os métodos EM

Dados

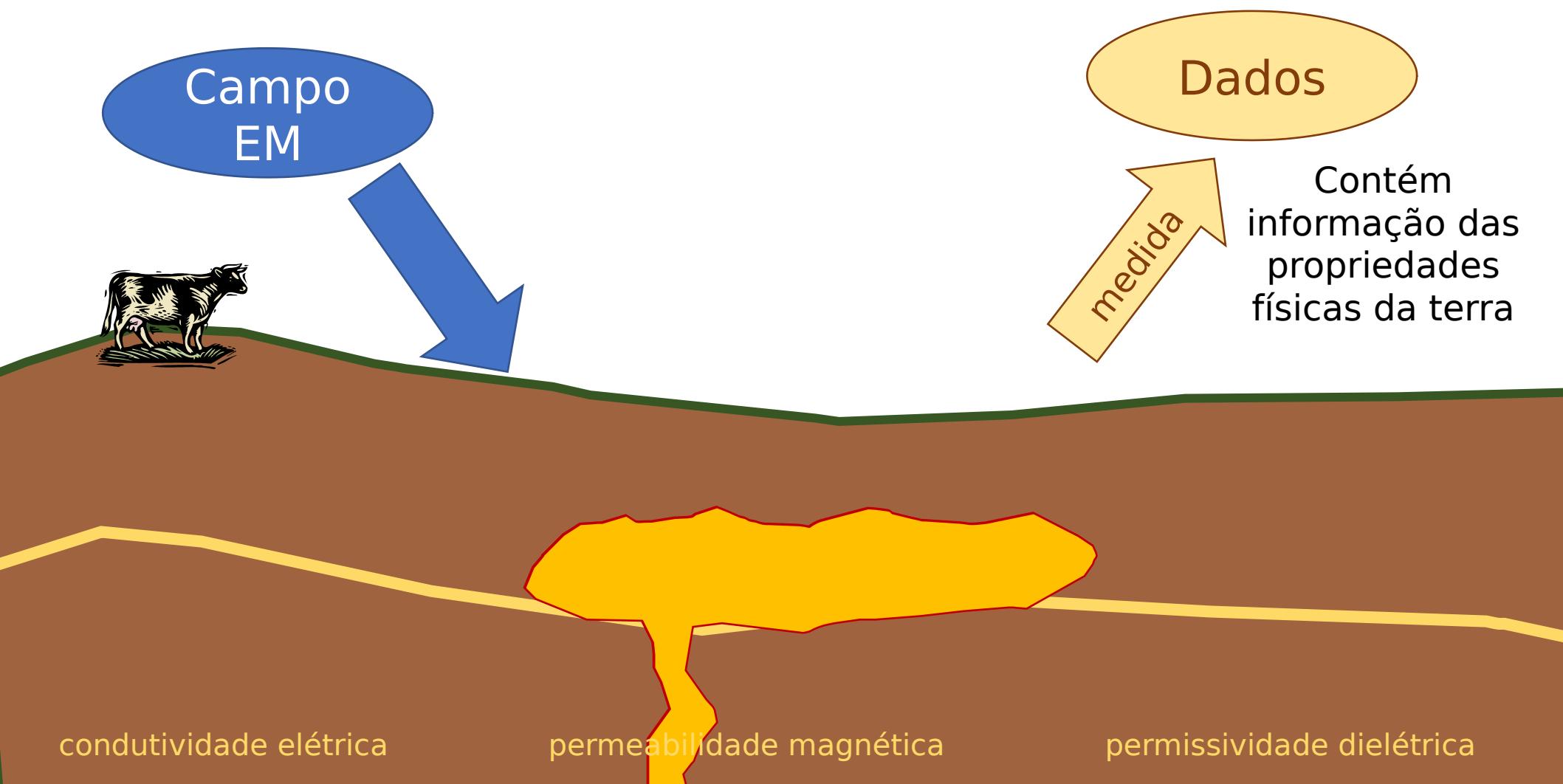
A diagram showing a cross-section of the ground. A blue arrow points from a blue oval labeled "Campo EM" (EM field) towards the ground. On the surface, there is a small illustration of a cow. Below the surface, there is a yellow irregular shape representing a geological feature. Three text boxes are placed around the diagram: one on the left describing conductivity, one in the center describing magnetic permeability, and one on the right describing dielectric permittivity.

medida

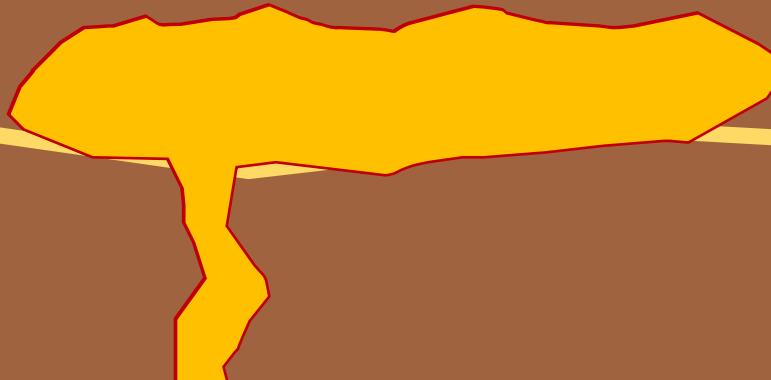
condutividade elétrica

permeabilidade magnética

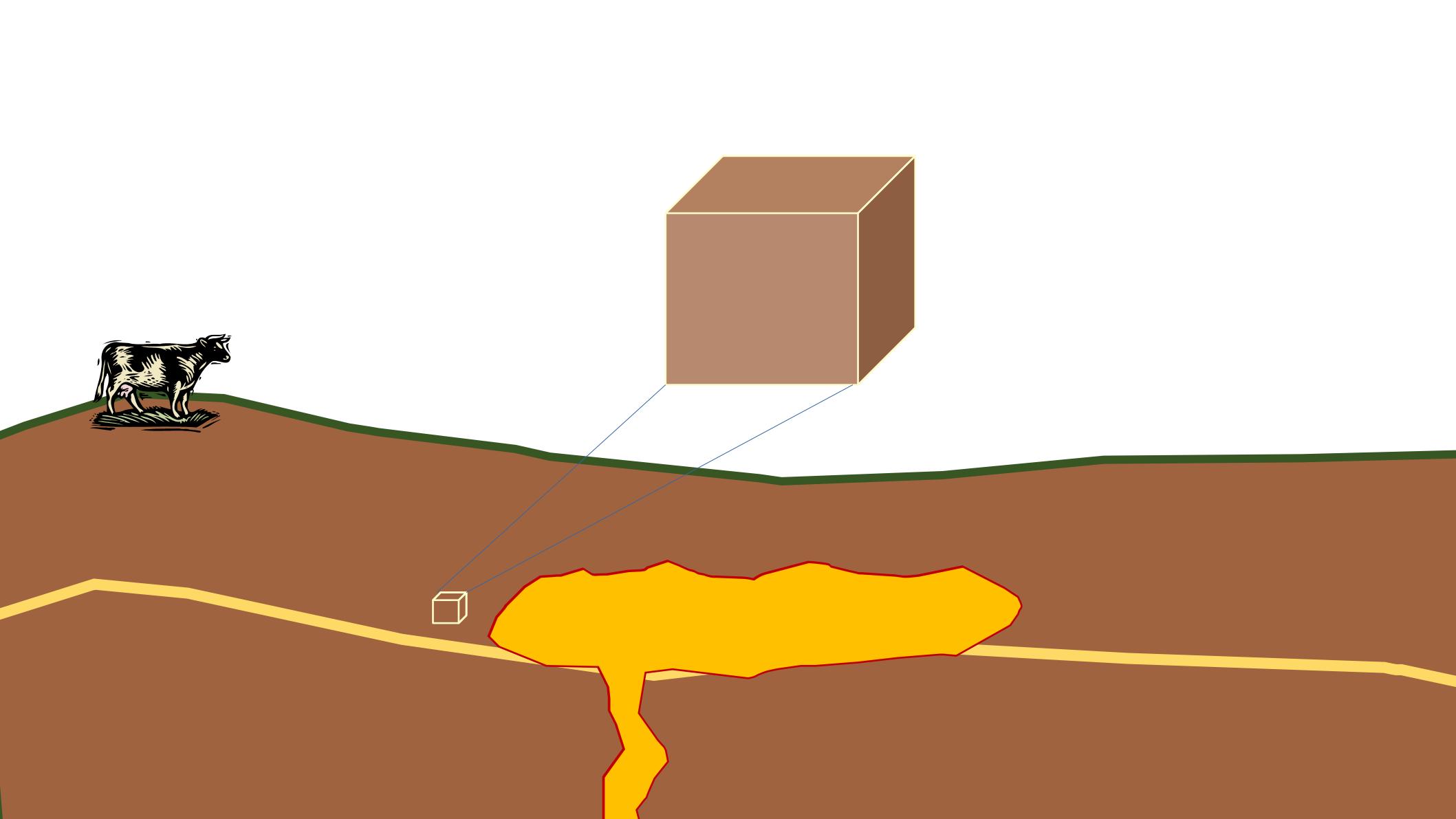
permisividade dielétrica

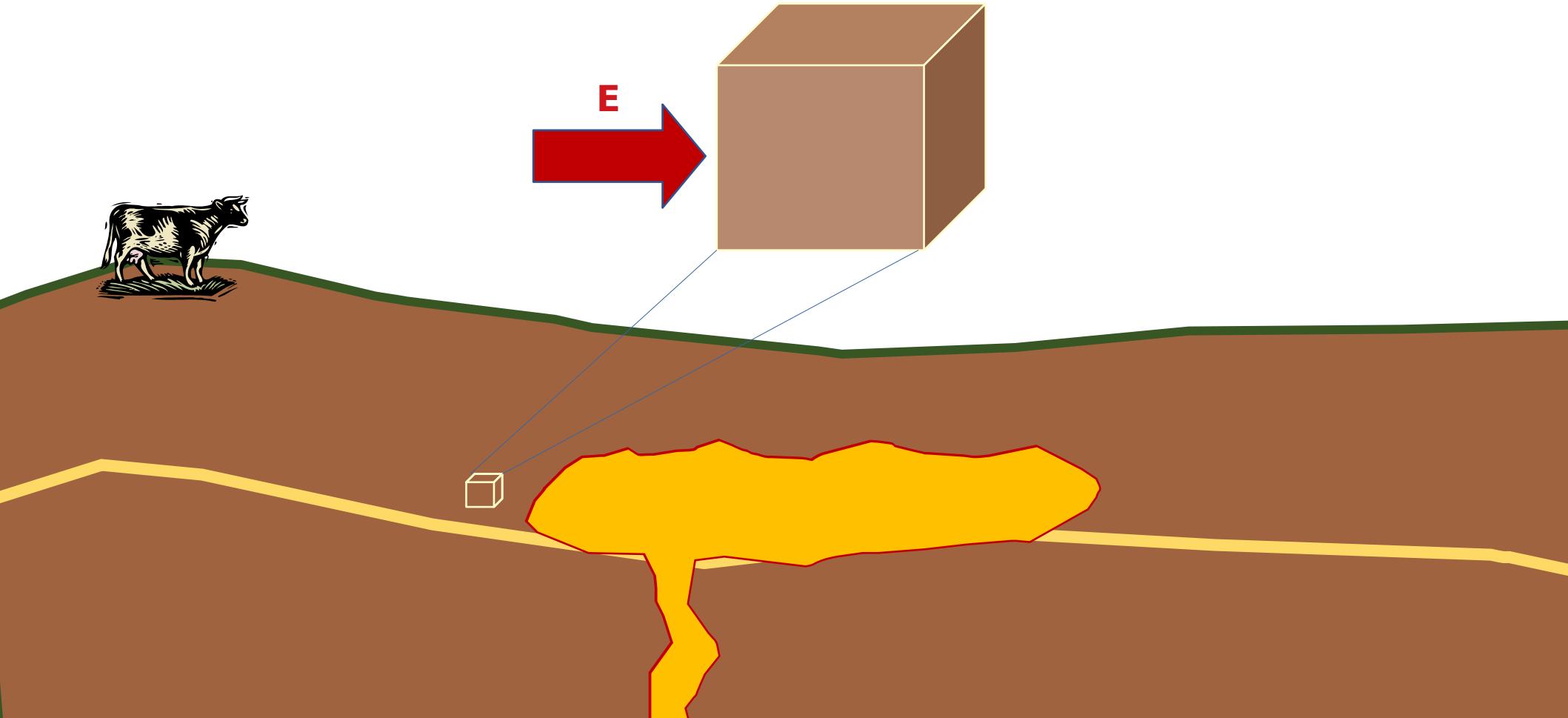


Como os campos EM interagem com a subsuperfície?

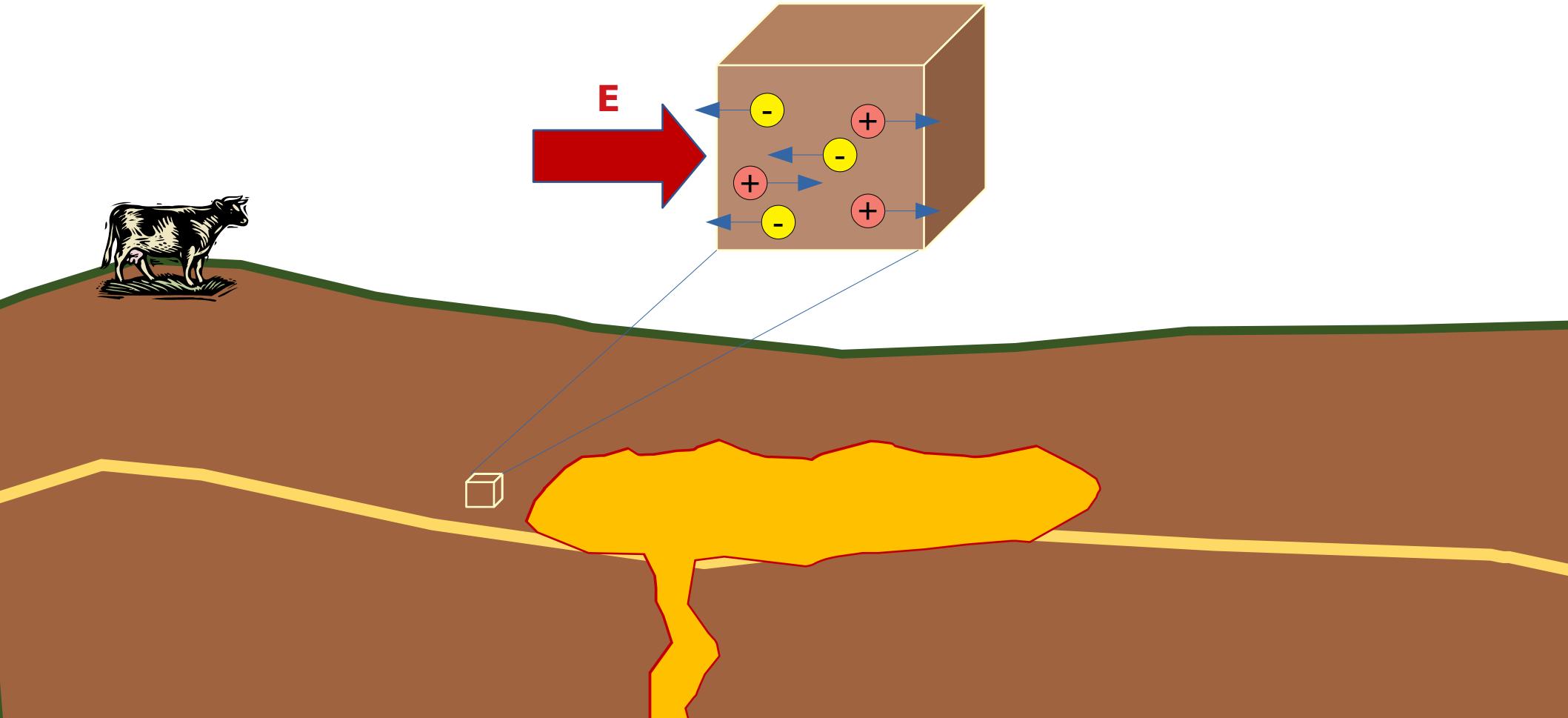


Propriedades físicas das rochas

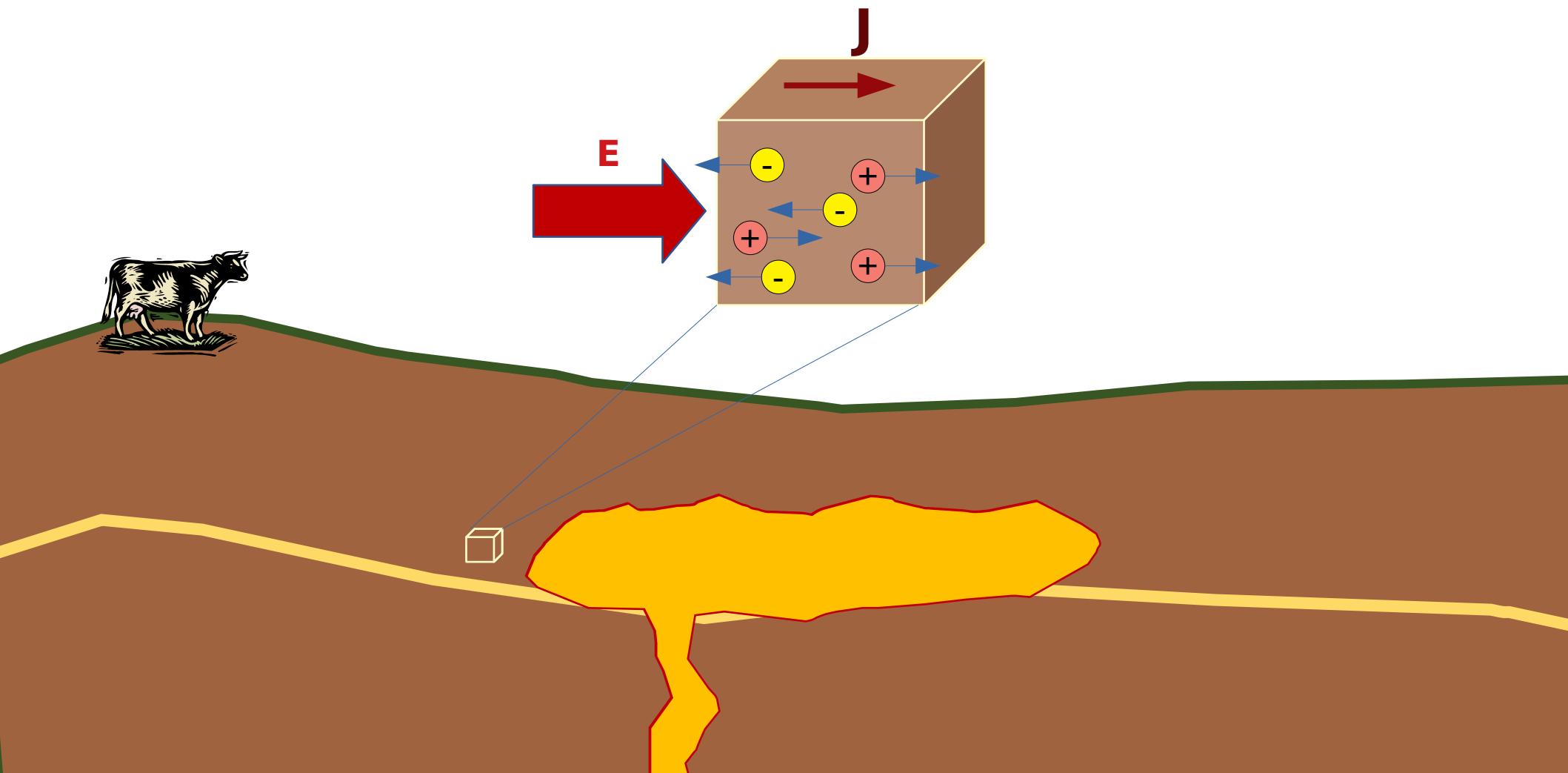




Cargas livres movem-se através do material
ao longo da direção do campo aplicado



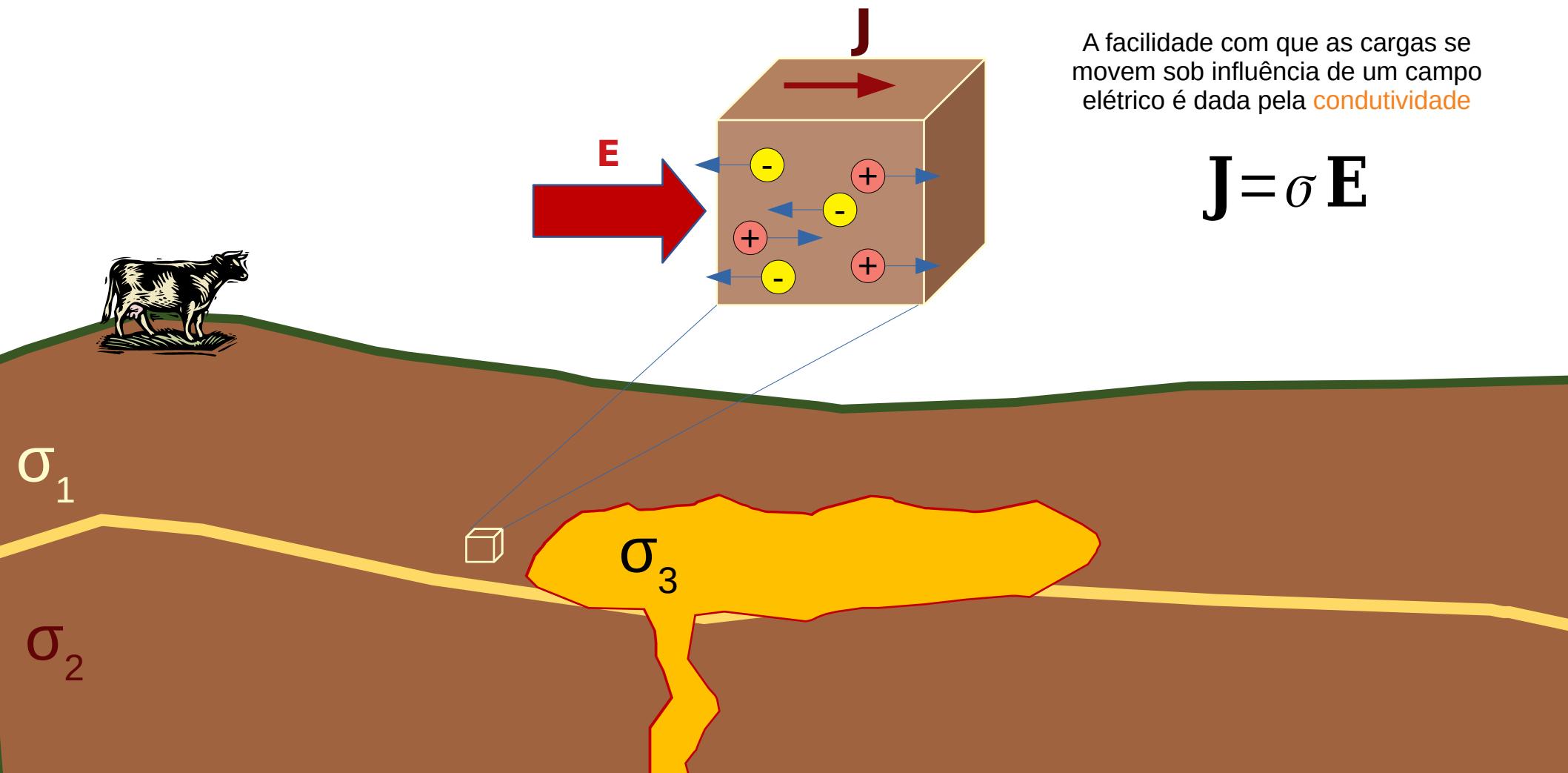
Cargas livres movem-se através do material
ao longo da direção do campo aplicado



Cargas livres movem-se através do material ao longo da direção do campo aplicado

A facilidade com que as cargas se movem sob influência de um campo elétrico é dada pela **condutividade**

$$\mathbf{J} = \sigma \mathbf{E}$$

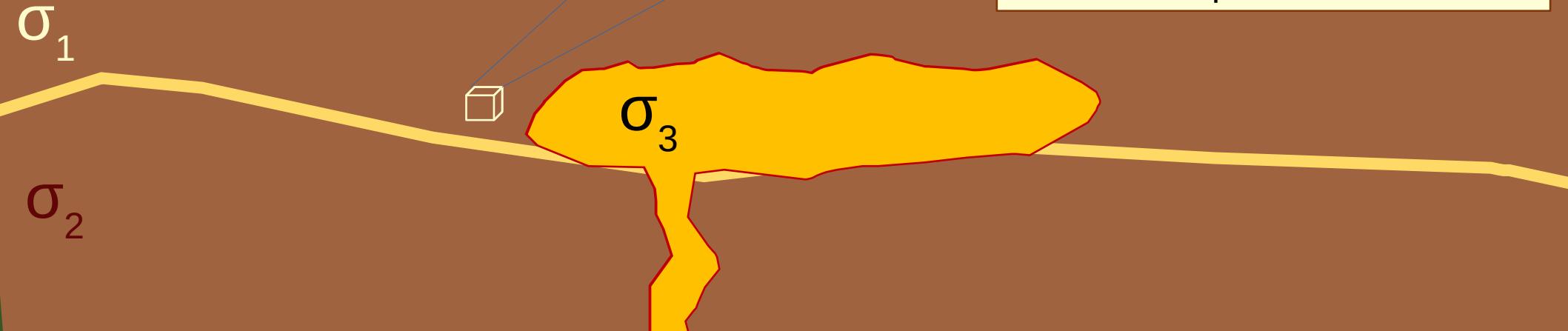
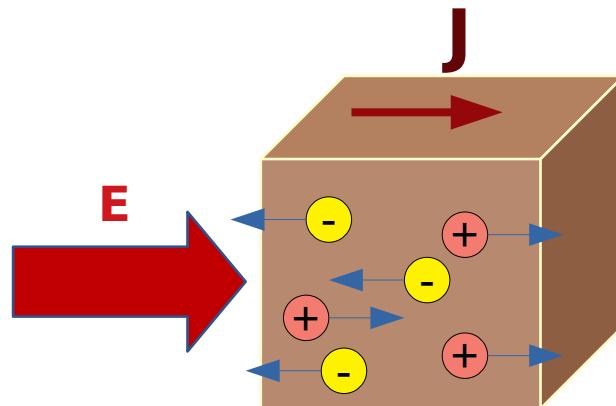


Cargas livres movem-se através do material ao longo da direção do campo aplicado

A facilidade com que as cargas se movem sob influência de um campo elétrico é dada pela **condutividade**

$$\mathbf{J} = \sigma \mathbf{E}$$

é a constante de proporcionalidade entre o fluxo de corrente elétrica e o campo elétrico



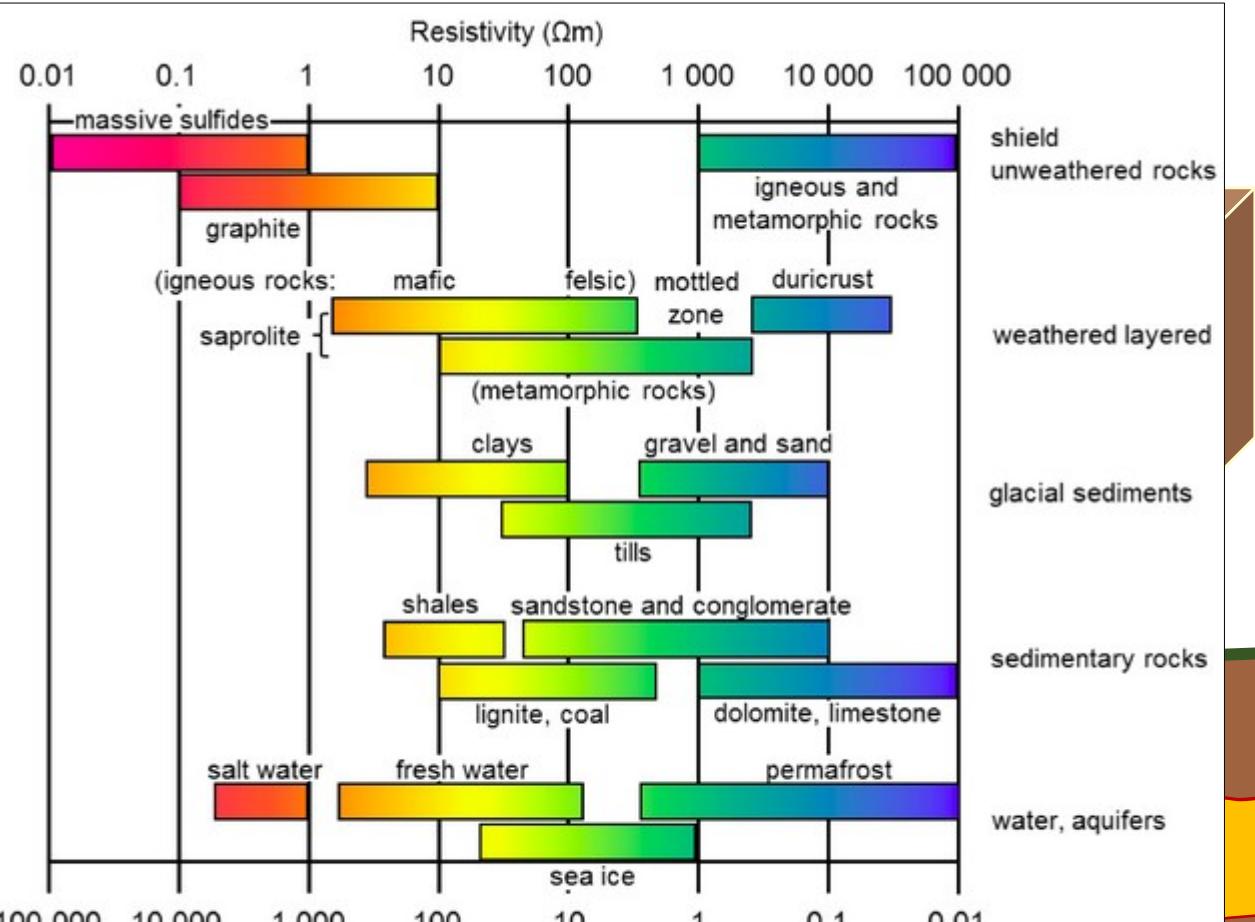


Fig. 14 Electrical conductivity and resistivity of common rocks.

Cargas livres movem-se através do material ao longo da direção do campo aplicado

A facilidade com que as cargas se movem sob influência de um campo elétrico é dada pela **condutividade**

$$\mathbf{J} = \sigma \mathbf{E}$$

é a constante de proporcionalidade entre o fluxo de corrente elétrica e o campo elétrico

Importância na geofísica

A maioria dos levantamentos EM explora contrastes na condutividade elétrica para imagear a subsuperfície.

Métodos EM (FDEM) de domínio de frequência, EM de domínio de tempo (TDEM), EM de fonte controlada marinha (CSEM) e fontes naturais (MT).

Durante estas pesquisas, um transmissor envia sinais EM variáveis no tempo para o solo, os quais subsequentemente induzem correntes elétricas. A intensidade das correntes induzidas e os campos secundários que elas produzem dependem da distribuição das condutividades em subsuperfície.

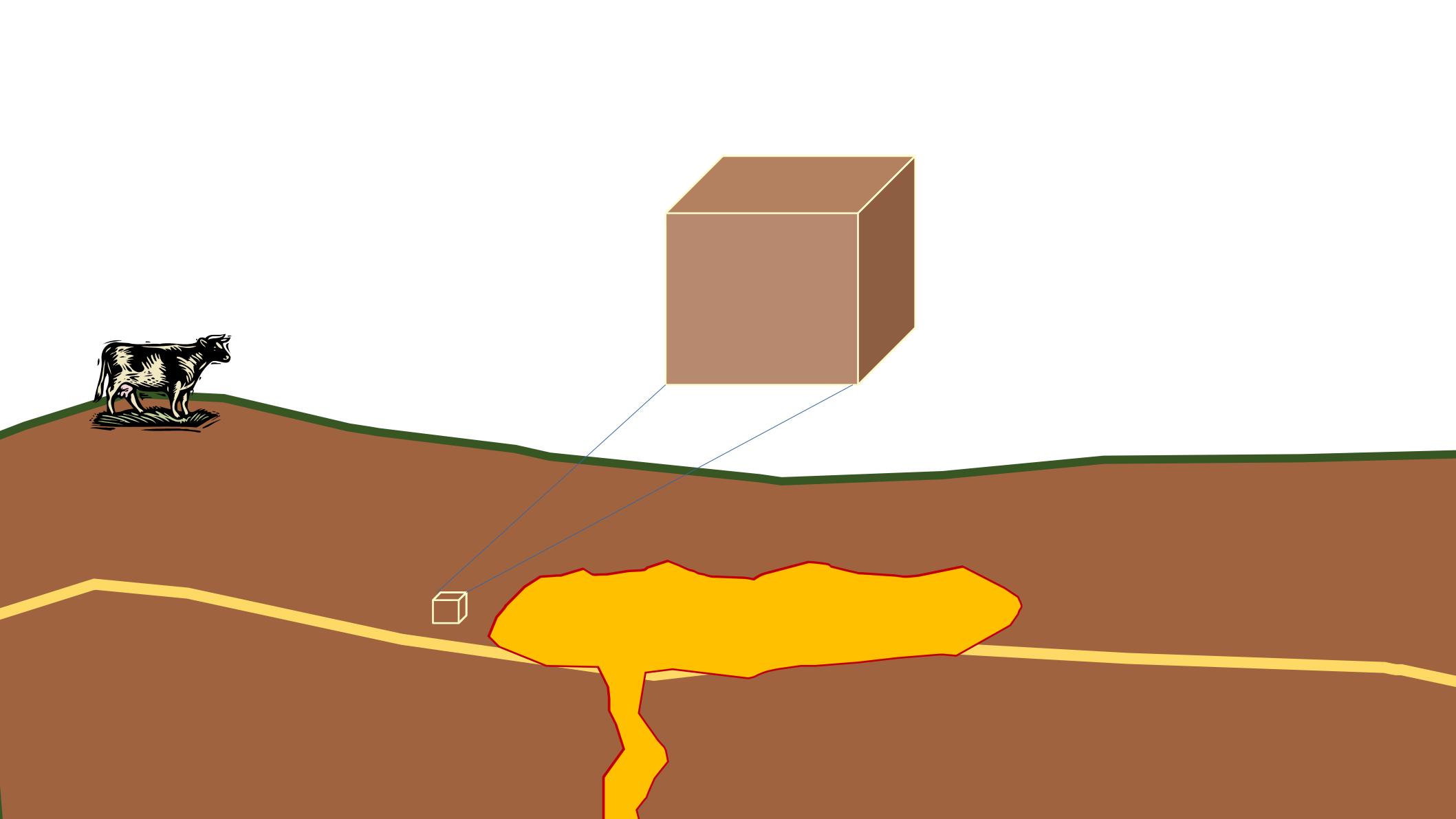
Cargas livres movem-se através do material ao longo da direção do campo aplicado

A facilidade com que as cargas se movem sob influência de um campo elétrico é dada pela **condutividade**

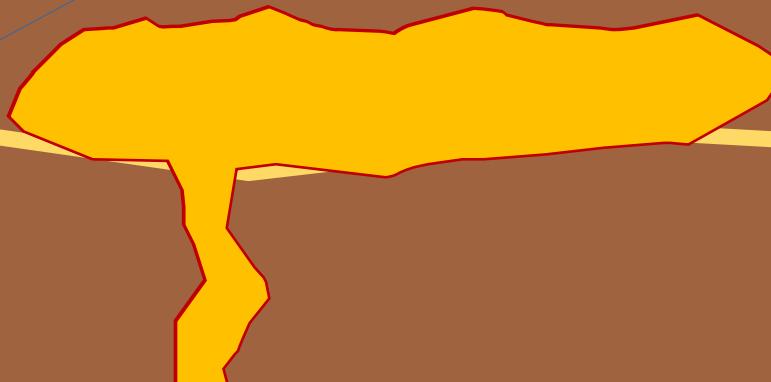
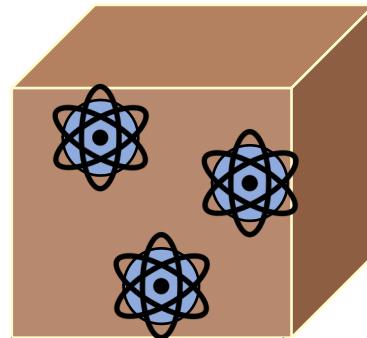
$$\mathbf{J} = \sigma \mathbf{E}$$

é a constante de proporcionalidade entre o fluxo de corrente elétrica é o campo elétrico

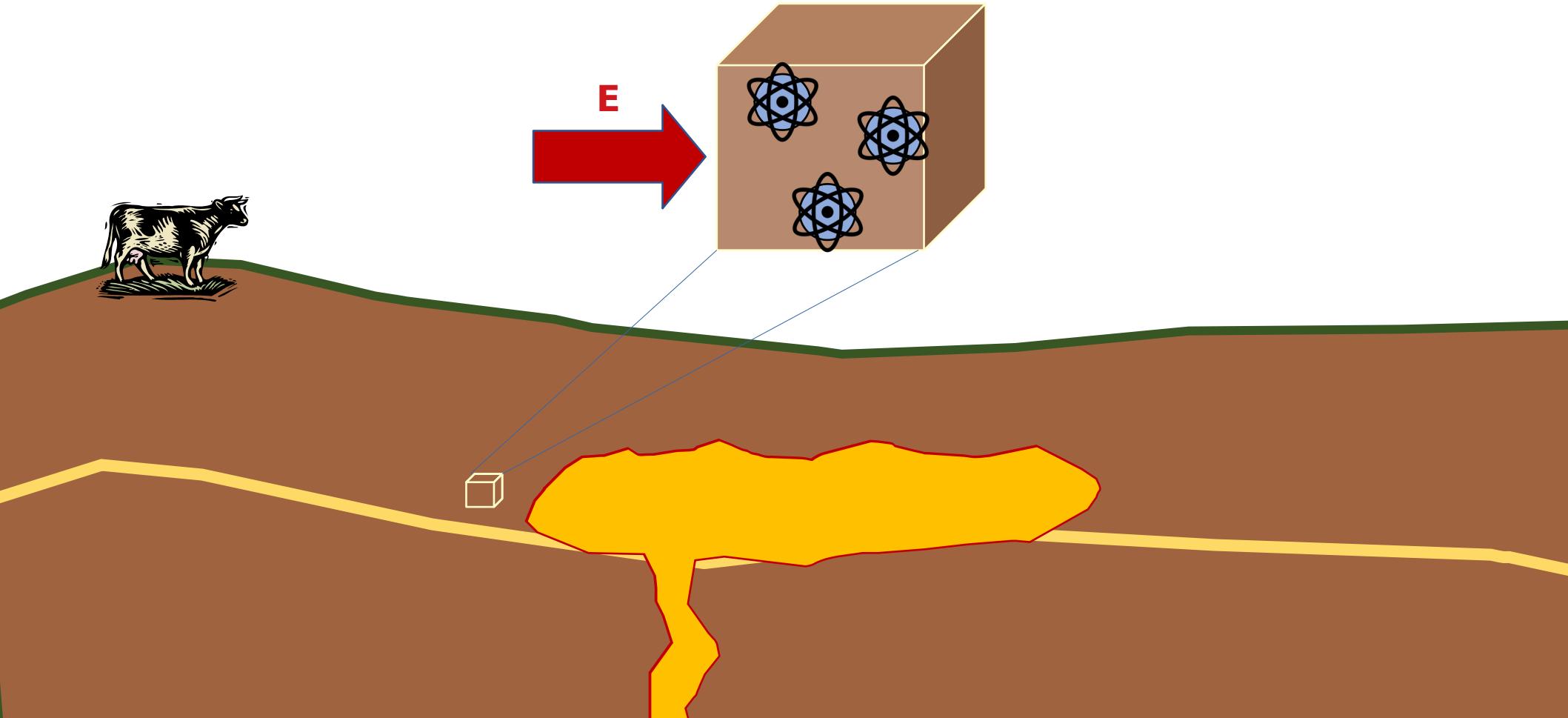




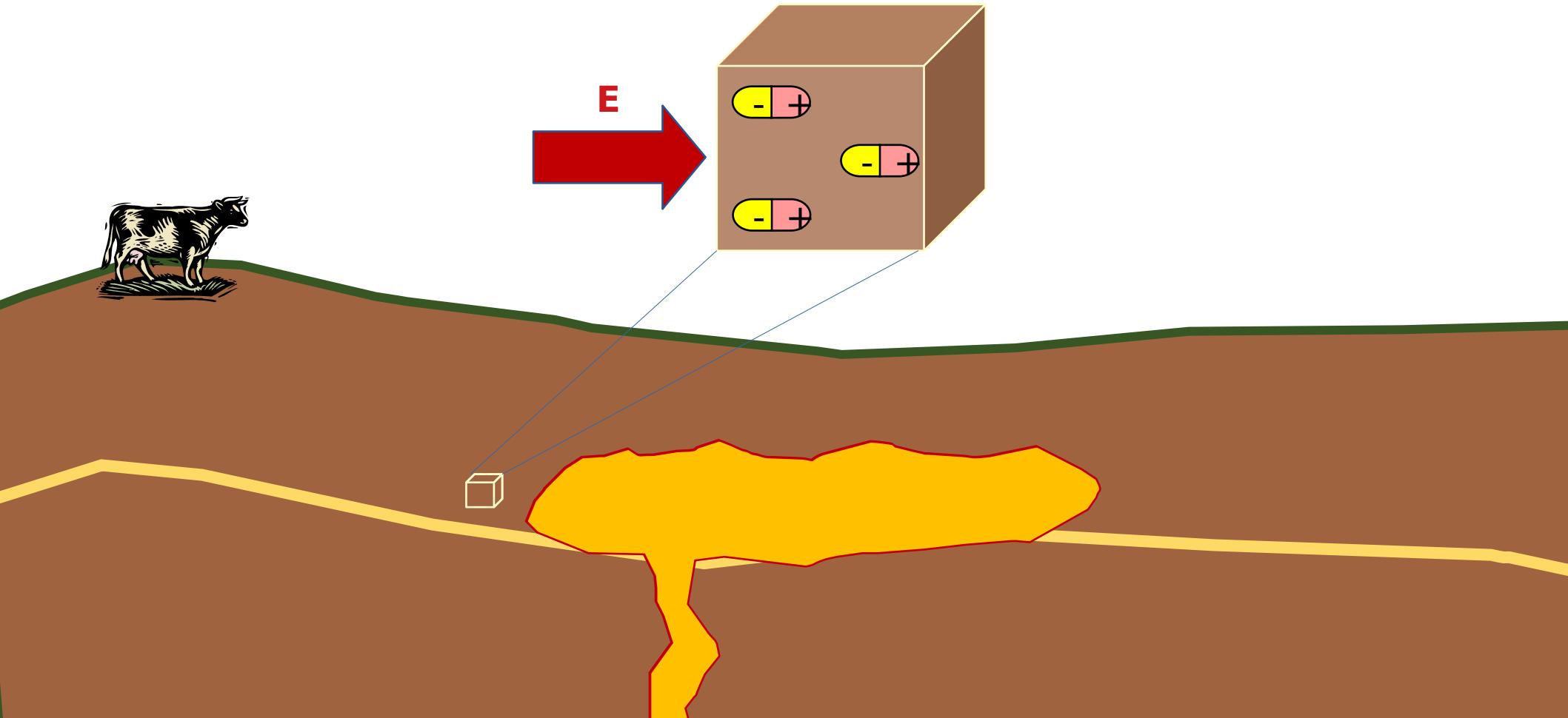
Cargas não polarizadas



Cargas não polarizadas

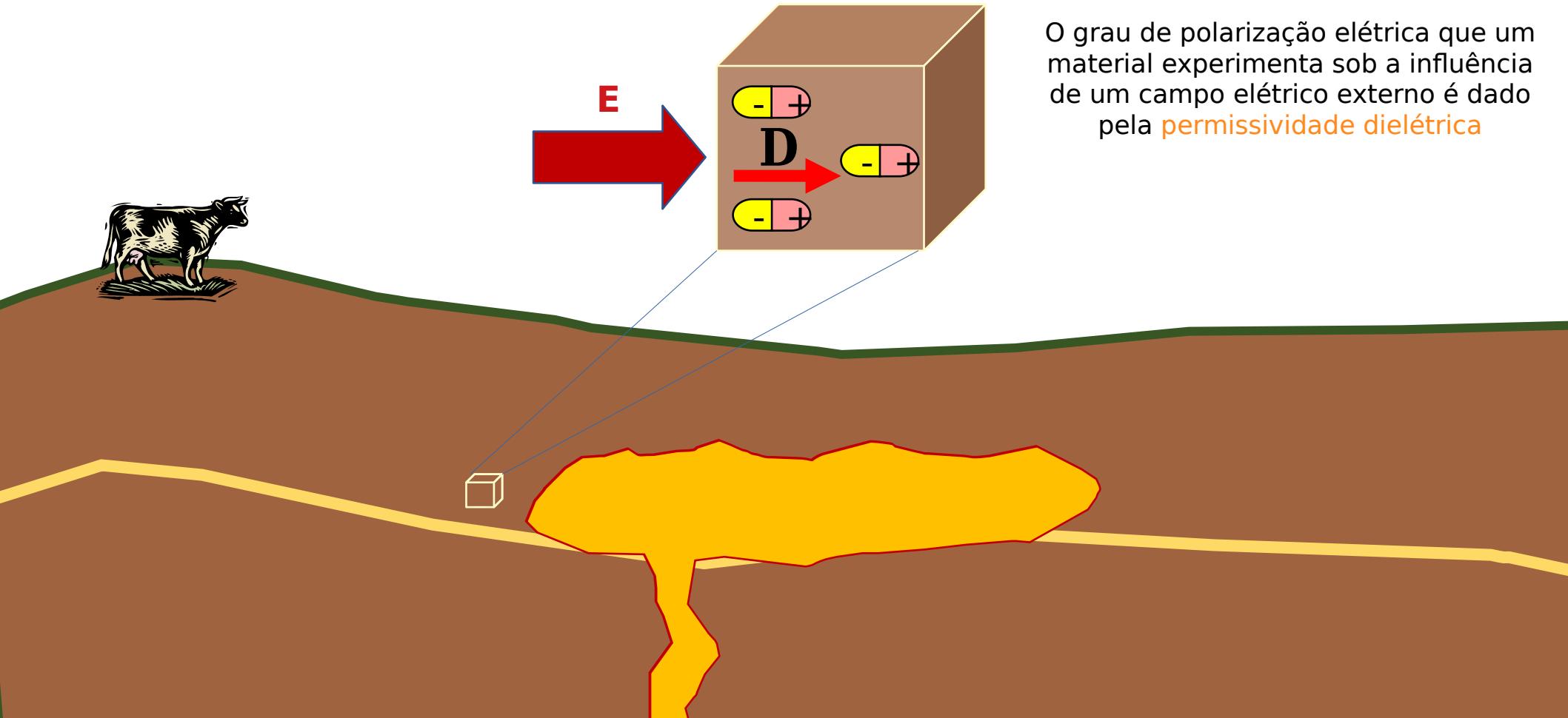


Cargas eletricamente polarizadas



Cargas eletricamente polarizadas

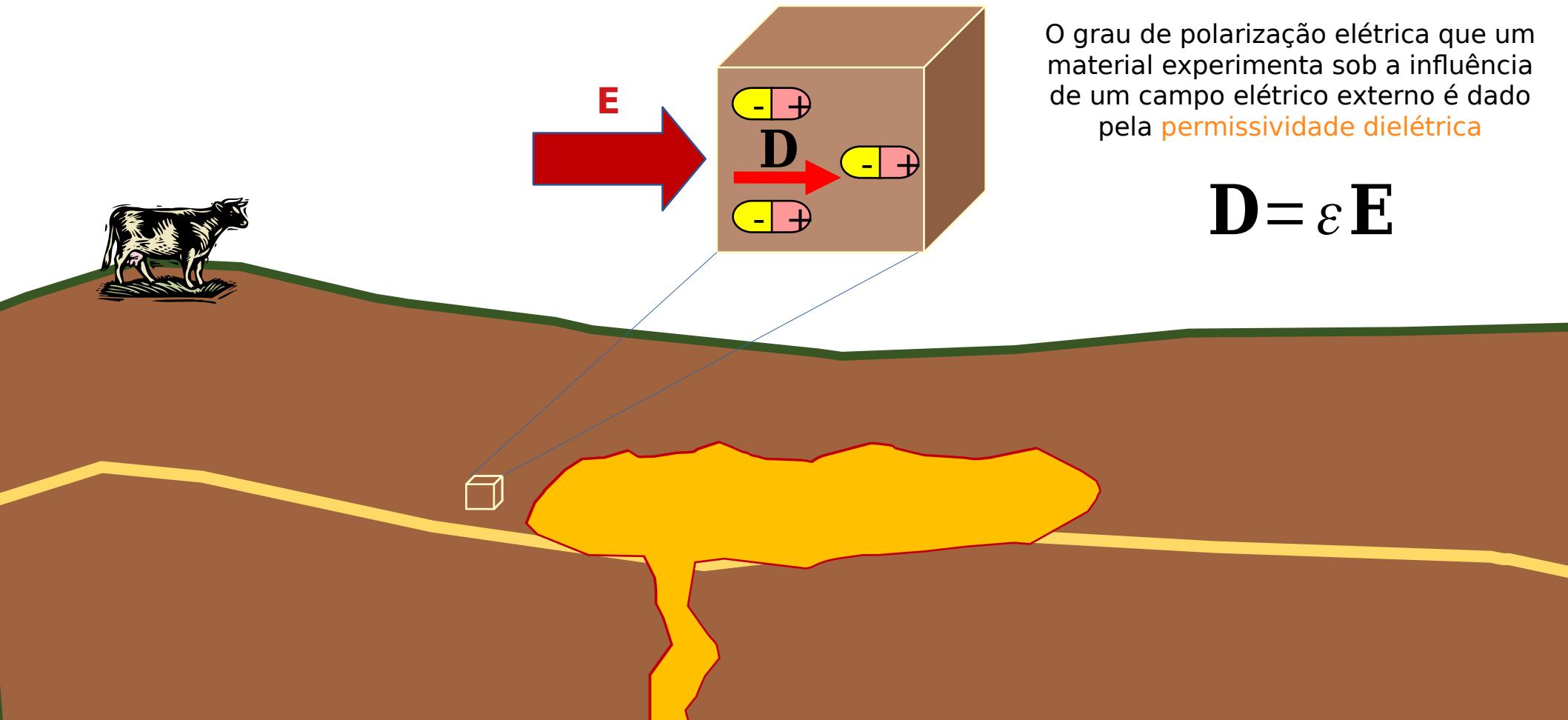
O grau de polarização elétrica que um material experimenta sob a influência de um campo elétrico externo é dado pela **permissividade dielétrica**



Cargas eletricamente polarizadas

O grau de polarização elétrica que um material experimenta sob a influência de um campo elétrico externo é dado pela **permissividade dielétrica**

$$\mathbf{D} = \epsilon \mathbf{E}$$

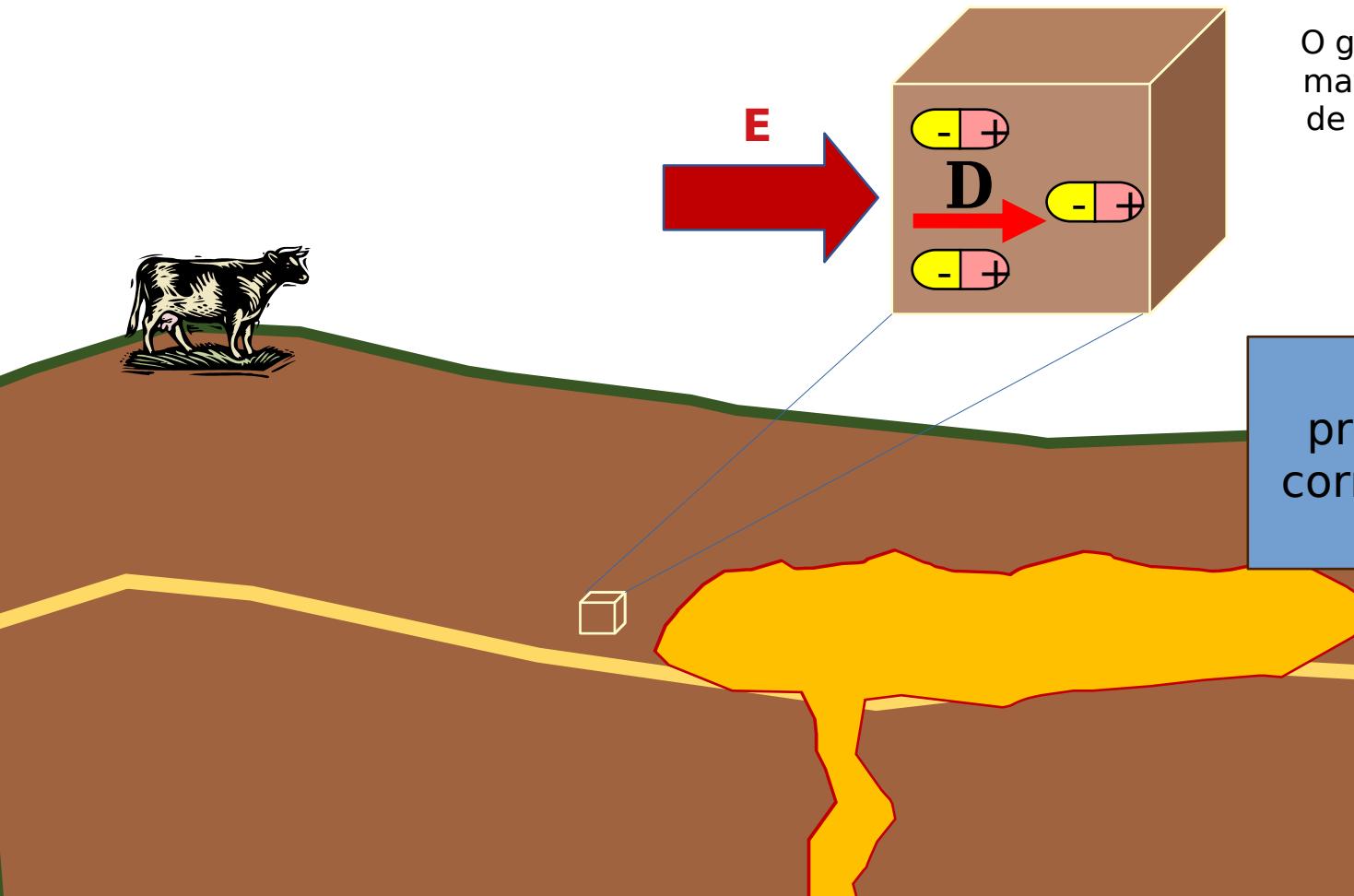


Cargas eletricamente polarizadas

O grau de polarização elétrica que um material experimenta sob a influência de um campo elétrico externo é dado pela **permissividade dielétrica**

$$\mathbf{D} = \epsilon \mathbf{E}$$

é a constante de proporcionalidade entre a corrente de deslocamento e o campo elétrico



Importância na geofísica

A permissividade dielétrica é a propriedade física mais importante no GPR.

Afeta a atenuação, o comprimento de onda e a velocidade dos sinais de ondas de rádio à medida que se propagam através da Terra. Determina a reflexão e a refração dos sinais de ondas de rádio como interfaces

Só é significativa para freqüências suficientemente altas e é geralmente negligenciada quando se usa a maioria dos sistemas EM.

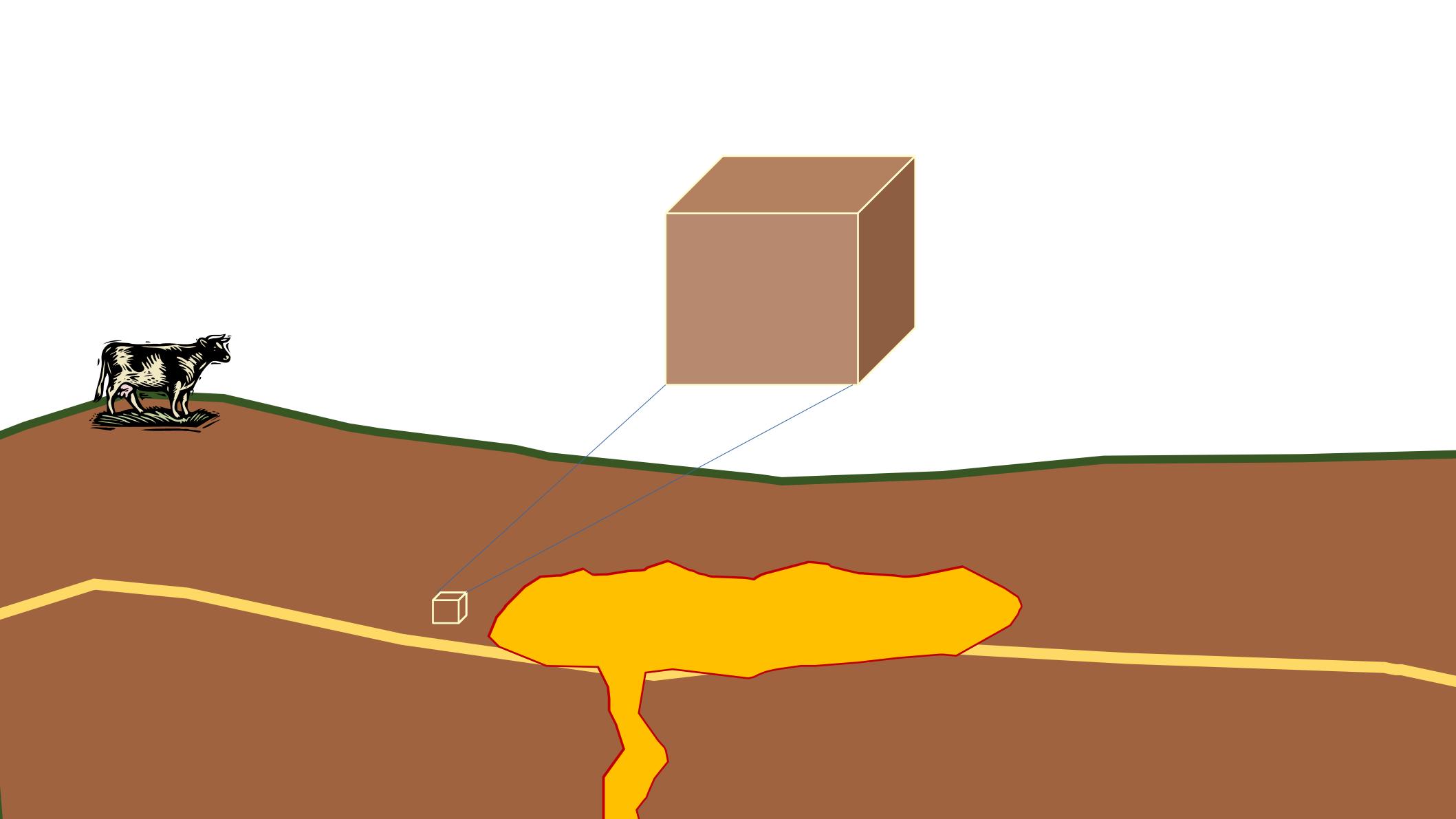
Cargas eletricamente polarizadas

O grau de polarização elétrica que um material experimenta sob a influência de um campo elétrico externo é dado pela **permissividade dielétrica**

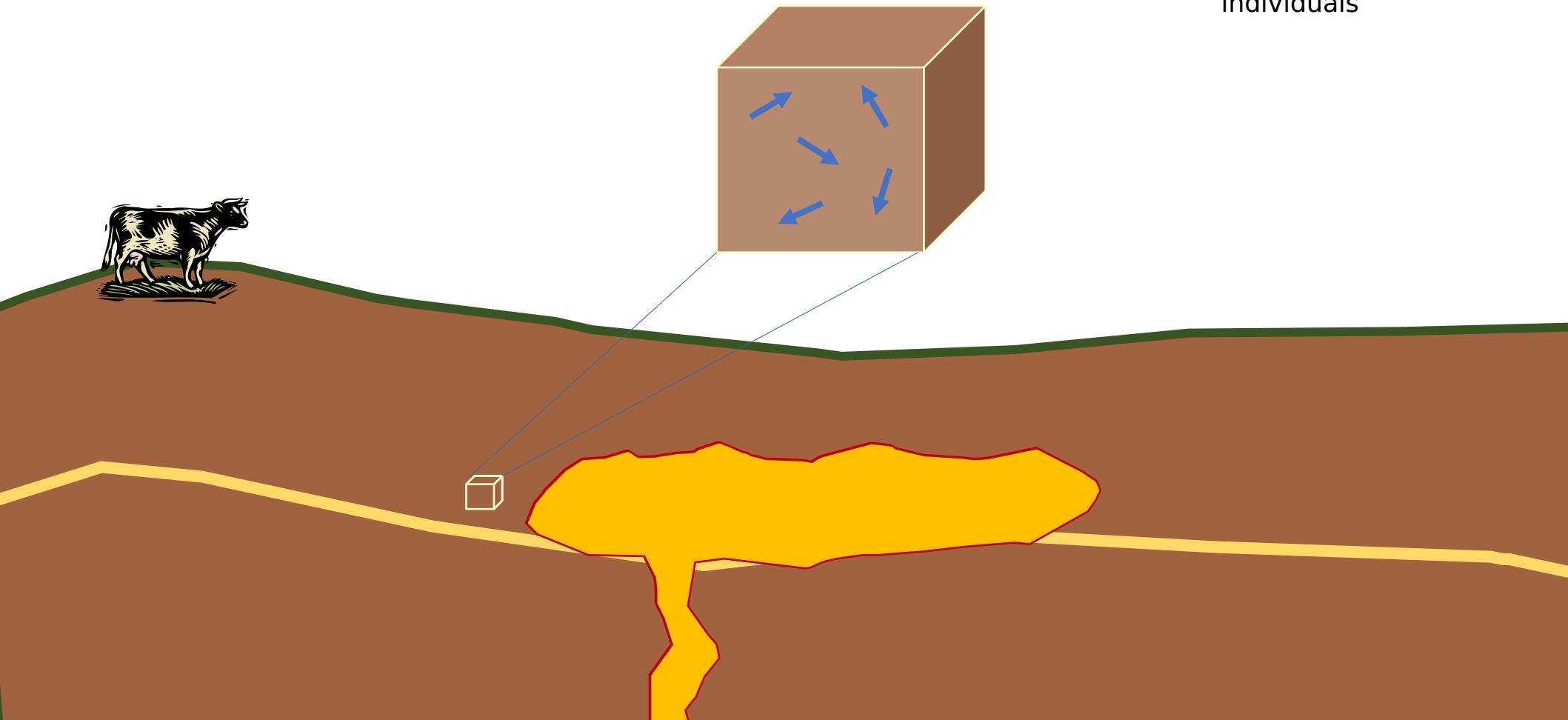
$$\mathbf{D} = \epsilon \mathbf{E}$$

é a constante de proporcionalidade entre a corrente de deslocamento e o campo elétrico

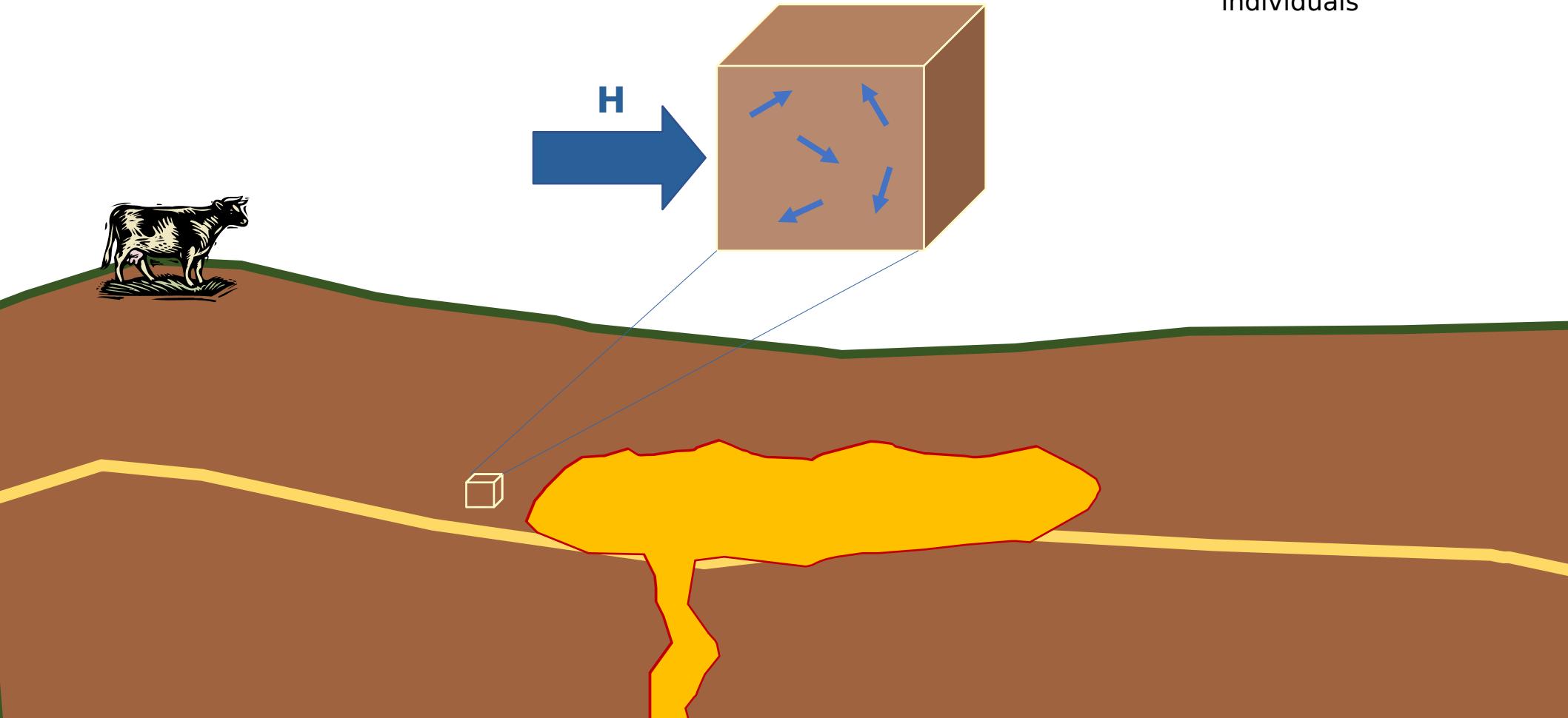




Momentos de dipolo magnéticos individuais

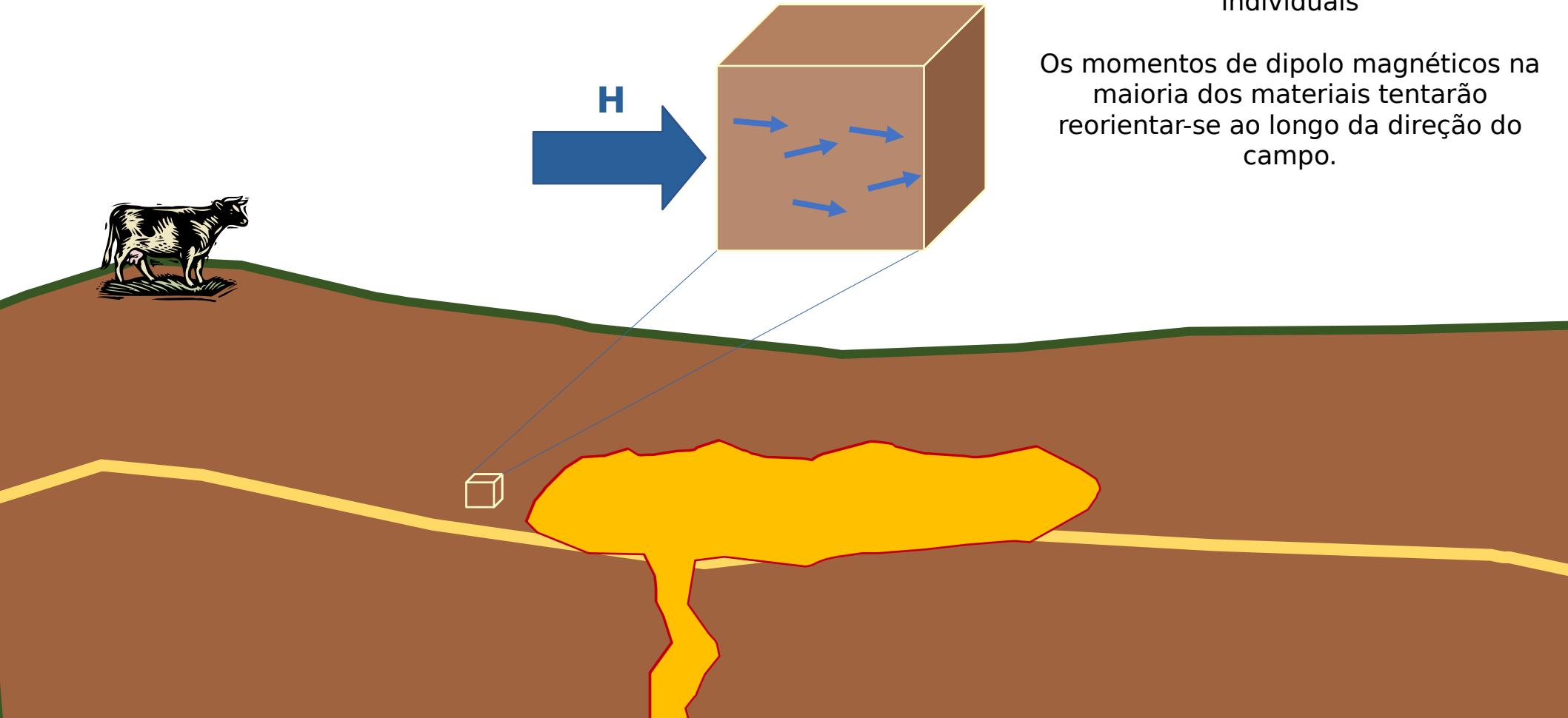


Momentos de dipolo magnéticos individuais



Momentos de dipolo magnéticos individuais

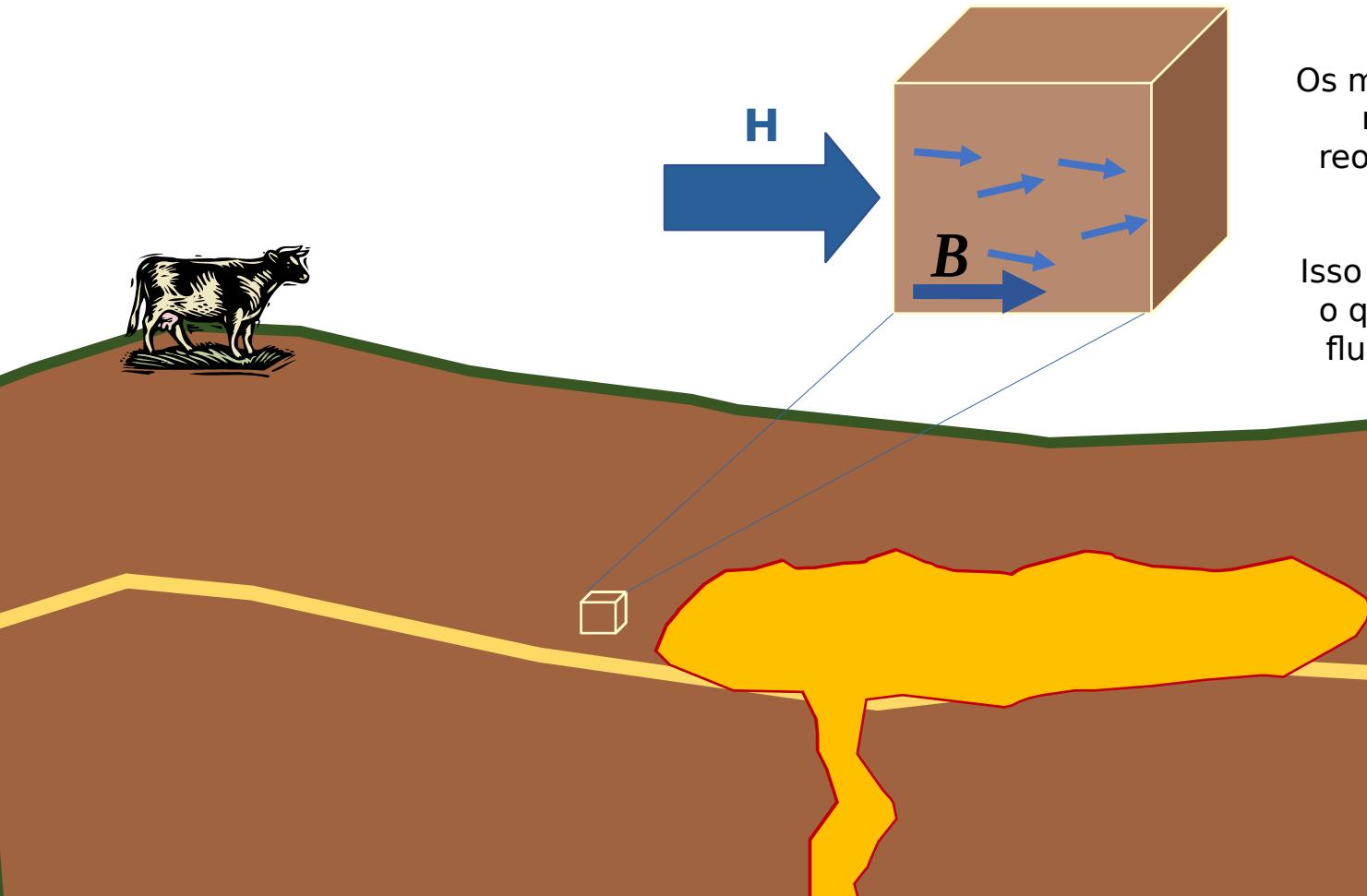
Os momentos de dipolo magnéticos na maioria dos materiais tentarão reorientar-se ao longo da direção do campo.



Momentos de dipolo magnéticos individuais

Os momentos de dipolo magnéticos na maioria dos materiais tentarão reorientar-se ao longo da direção do campo.

Isso gera uma magnetização induzida, o que contribui para a densidade de fluxo magnético dentro do material



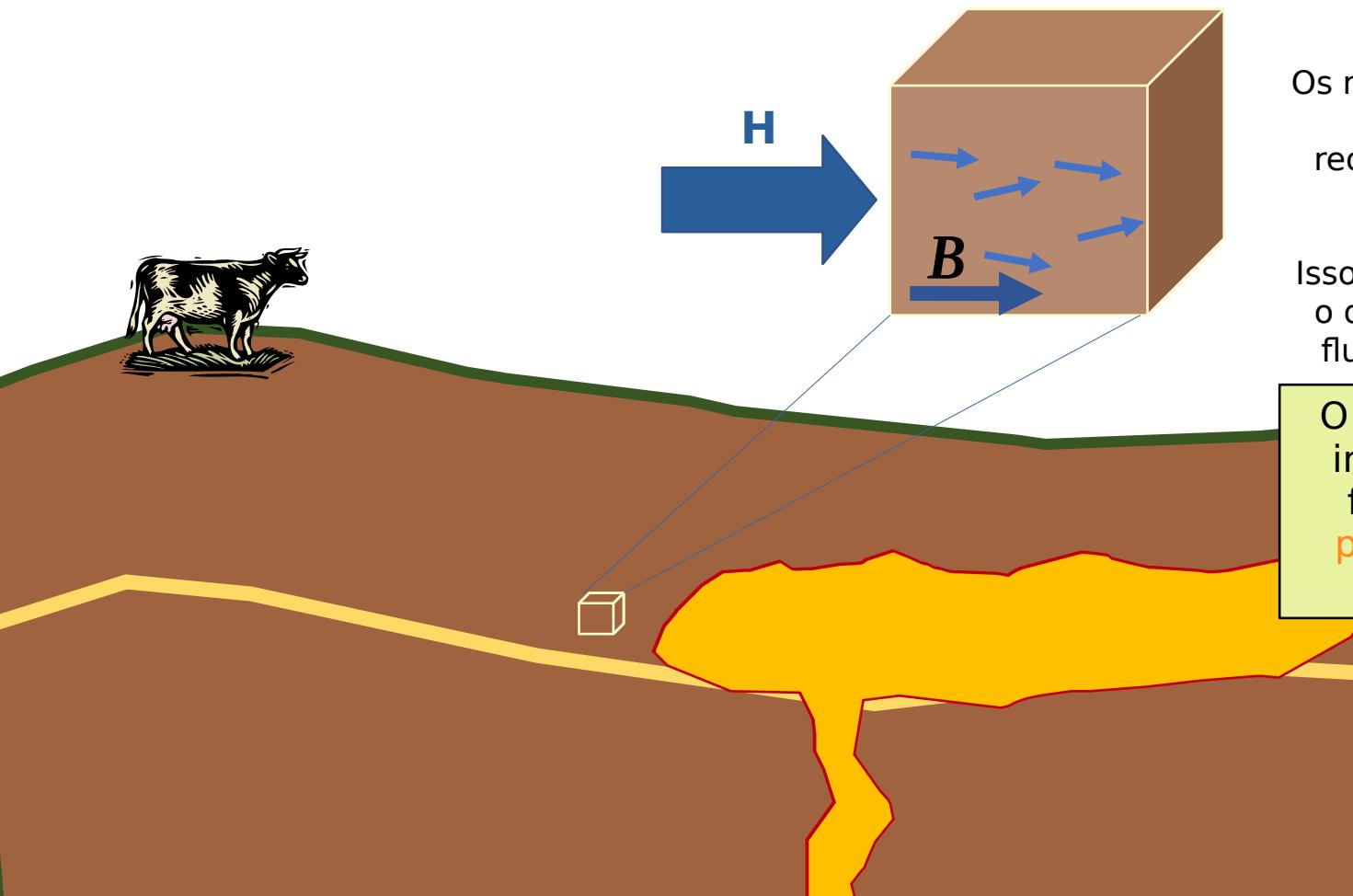
Momentos de dipolo magnéticos individuais

Os momentos de dipolo magnéticos na maioria dos materiais tentarão reorientar-se ao longo da direção do campo.

Isso gera uma magnetização induzida, o que contribui para a densidade de fluxo magnético dentro do material

O grau em que a magnetização induzida afeta a densidade do fluxo magnético depende da **permeabilidade magnética** do material.

$$\mathbf{B} = \mu \mathbf{H}$$



Momentos de dipolo magnéticos individuais

Importância na geofísica

Na maioria dos ambientes geológicos, as variações na permeabilidade magnética da Terra são insignificantes ($\mu \sim \mu_0$) e as pesquisas são sensíveis apenas aos contrastes na condutividade elétrica da Terra.

Entretanto, há uma variedade de casos em que a permeabilidade magnética se torna uma importante propriedade física de diagnóstico. Por exemplo, algumas rochas que contêm minério (magnetita, pirrotita) têm permeabilidade magnética muito alta.

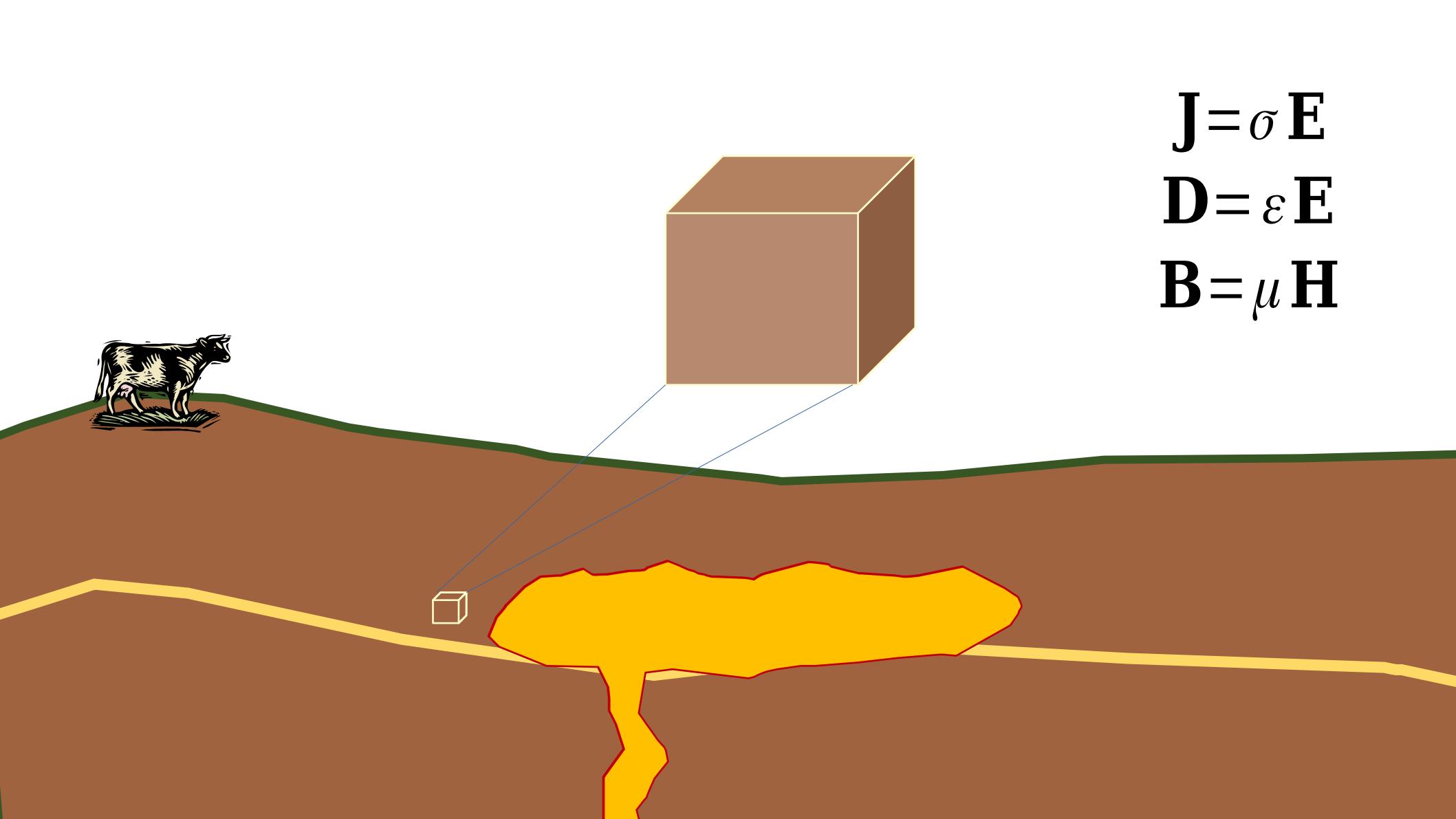
Ao utilizar sistemas EM no domínio de frequência (FDEM) e do tempo (TDEM), foi demonstrado que grandes permeabilidades magnéticas têm impacto na resposta medida.

Os momentos de dipolo magnéticos na maioria dos materiais tentarão reorientar-se ao longo da direção do campo.

Isso gera uma magnetização induzida, o que contribui para a densidade de fluxo magnético dentro do material

O grau em que a magnetização induzida afeta a densidade do fluxo magnético depende da **permeabilidade magnética** do material.

$$\mathbf{B} = \mu \mathbf{H}$$

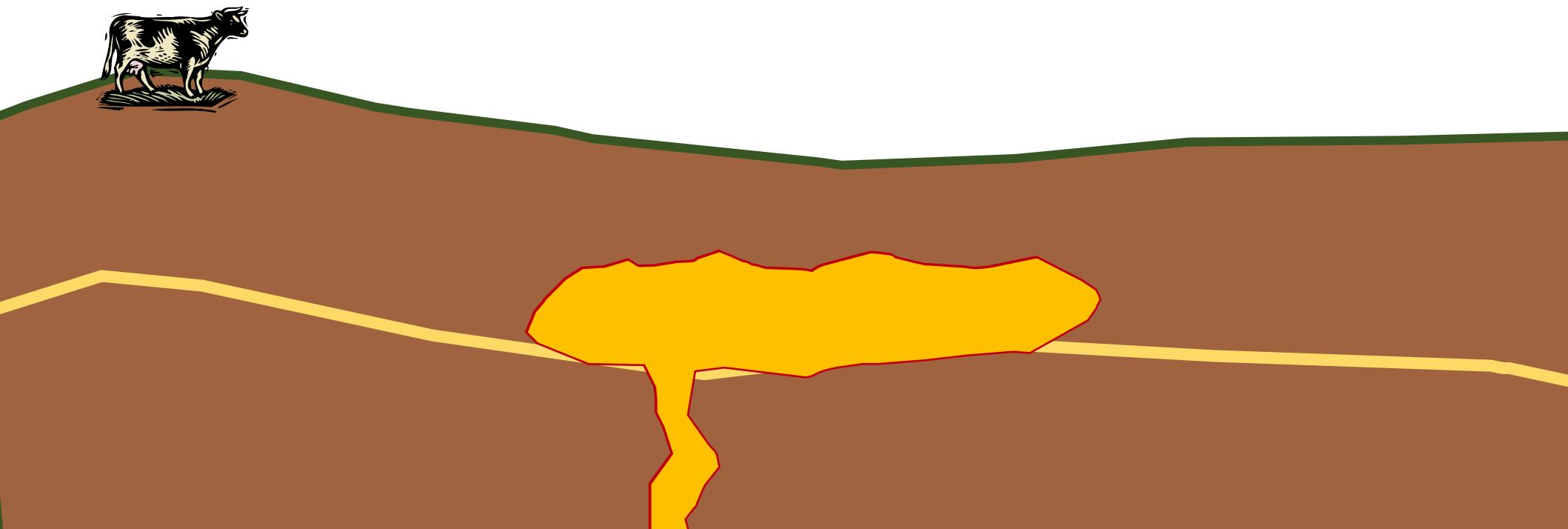

$$\mathbf{J} = \sigma \mathbf{E}$$

$$\mathbf{D} = \epsilon \mathbf{E}$$

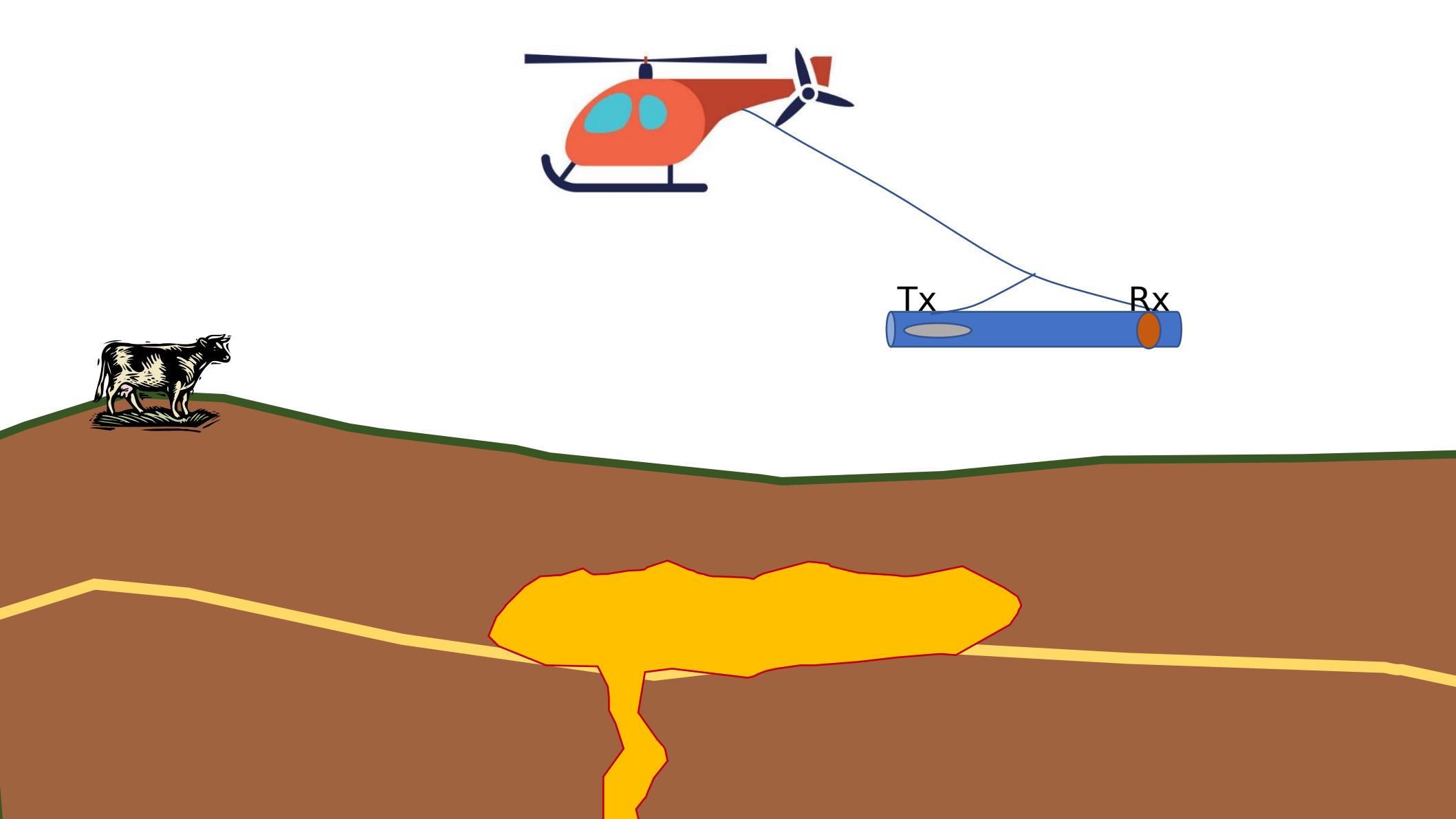
$$\mathbf{B} = \mu \mathbf{H}$$

Dado uma subsuperfície e suas propriedades, como os métodos EM interagem?

$$\begin{aligned} \mathbf{J} &= \sigma \mathbf{E} \\ \mathbf{D} &= \epsilon \mathbf{E} \\ \mathbf{B} &= \mu \mathbf{H} \end{aligned}$$



Métodos EM

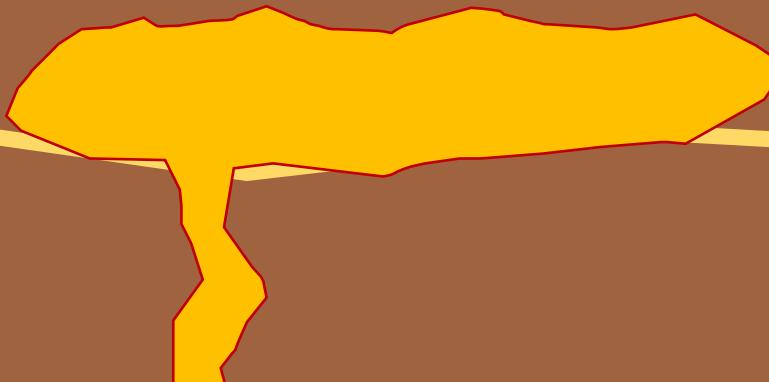


Transmitter

Tx

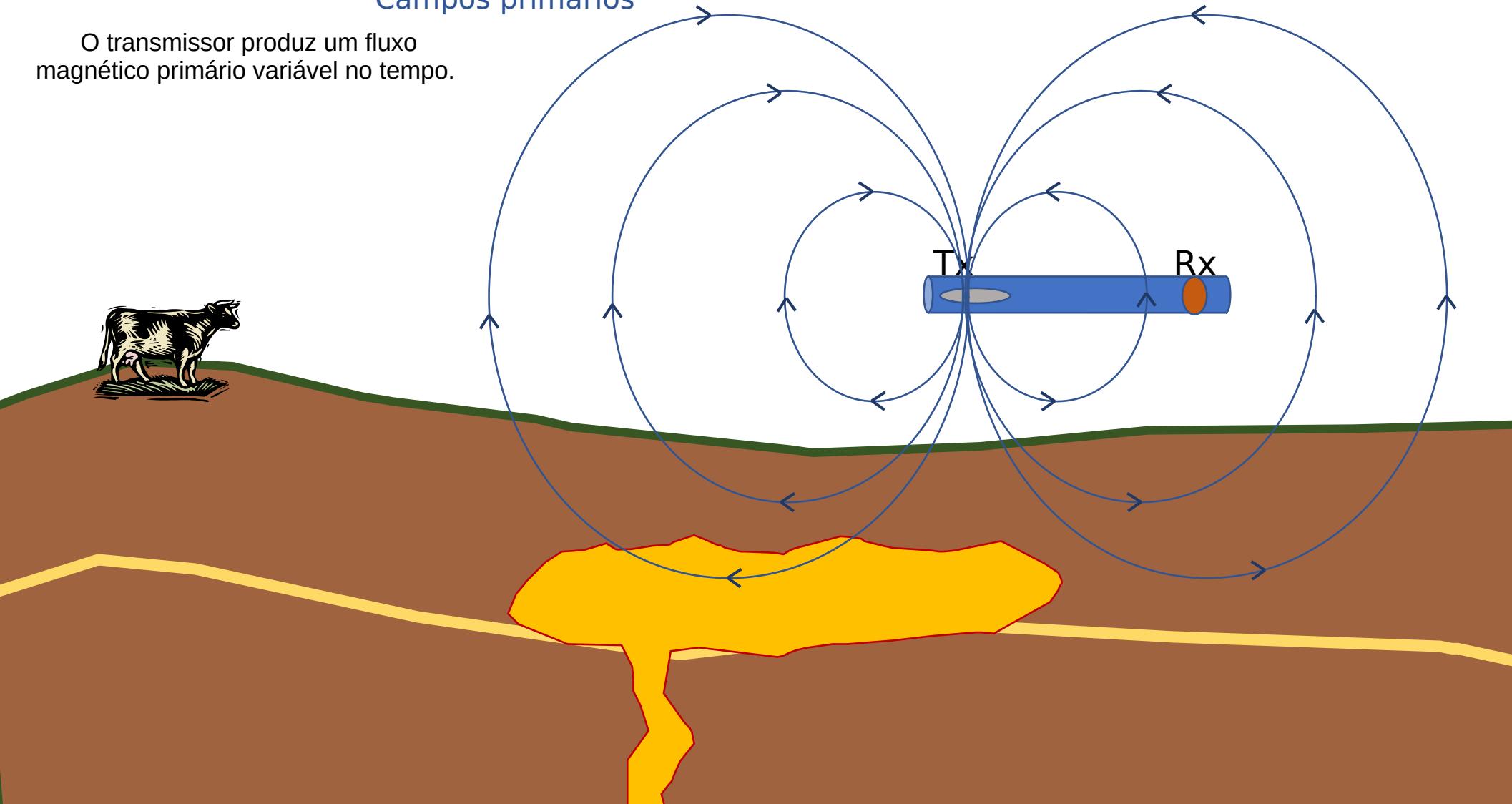
Receptor

Rx

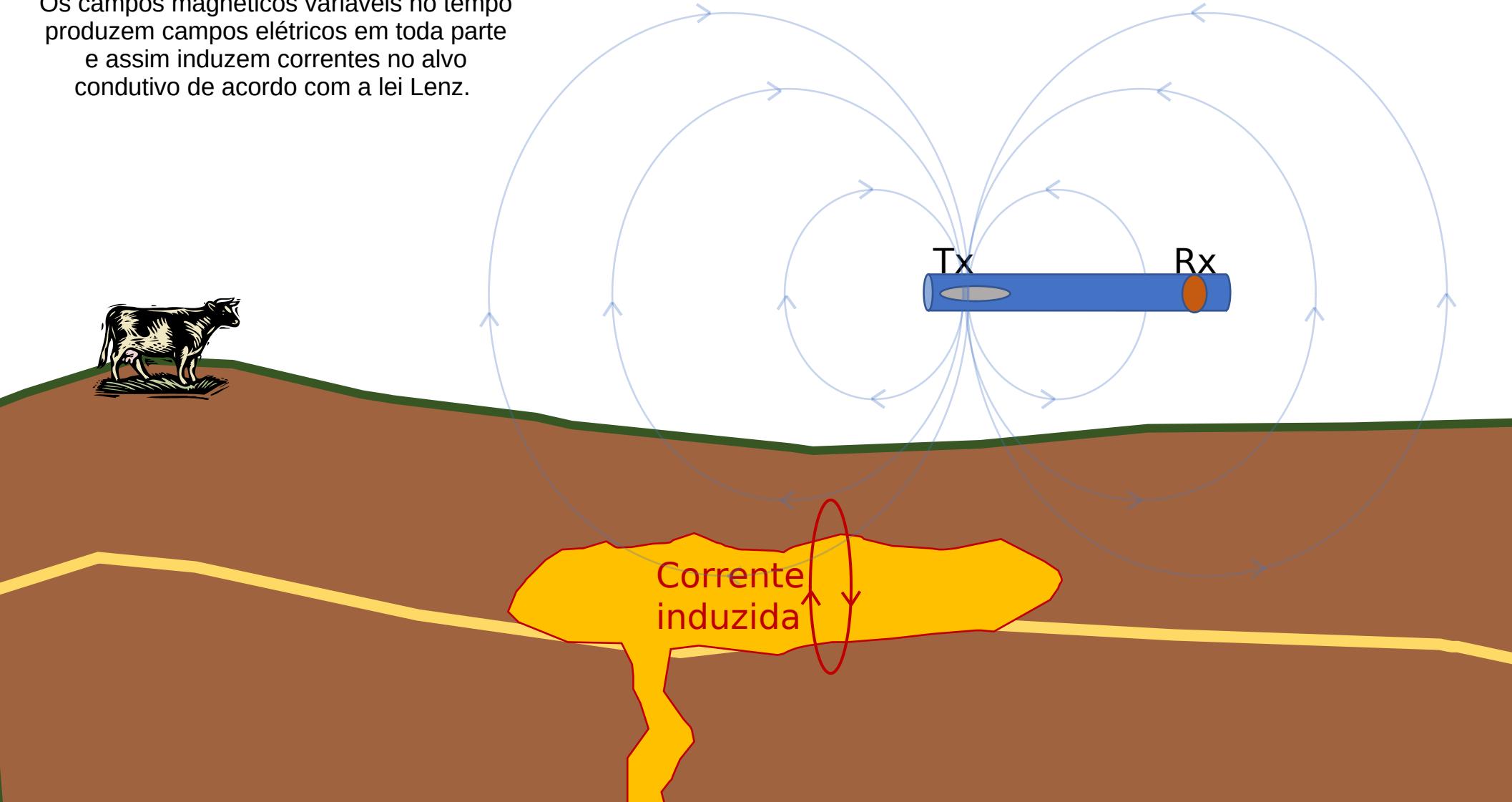


Campos primários

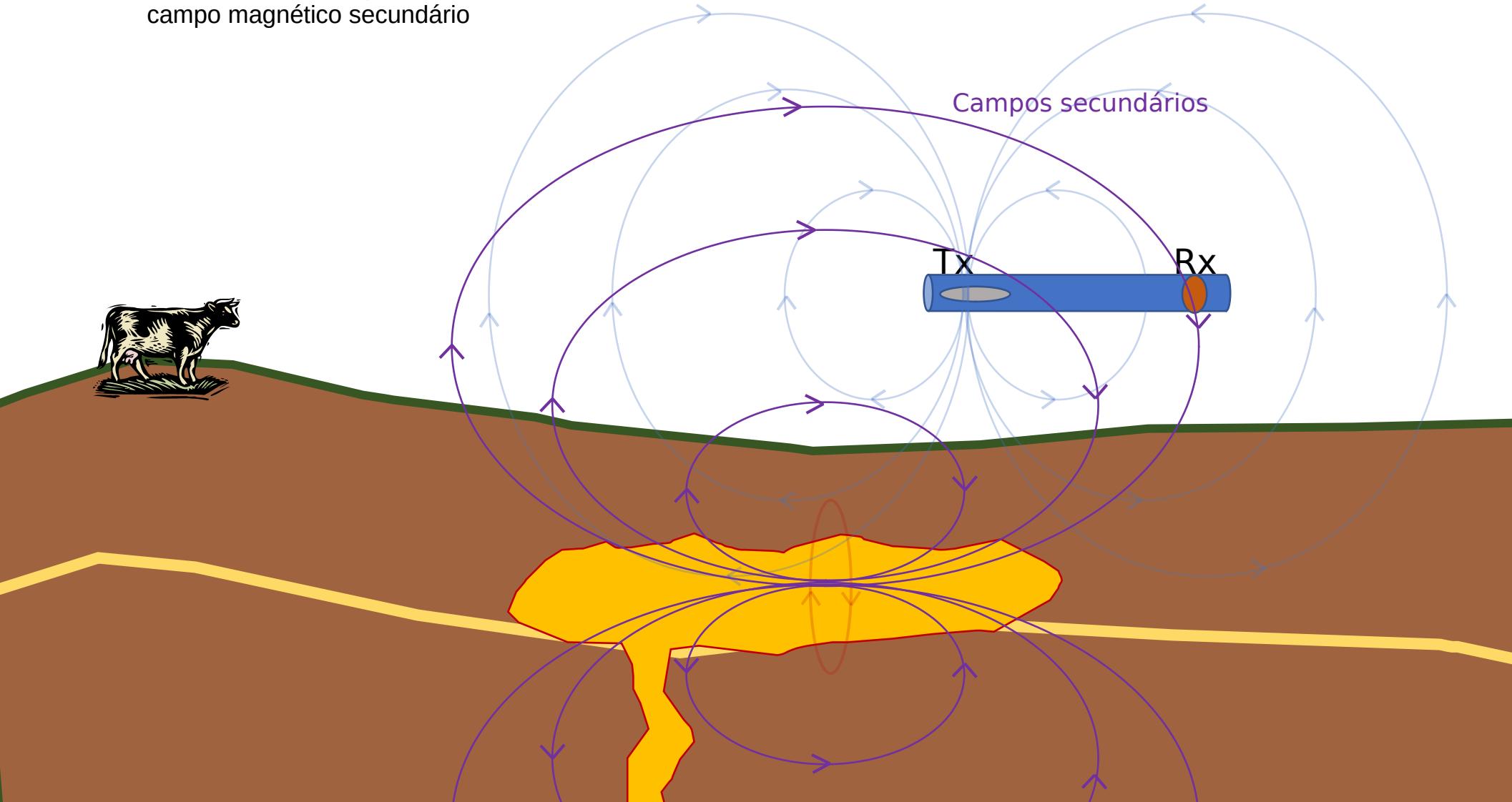
O transmissor produz um fluxo magnético primário variável no tempo.



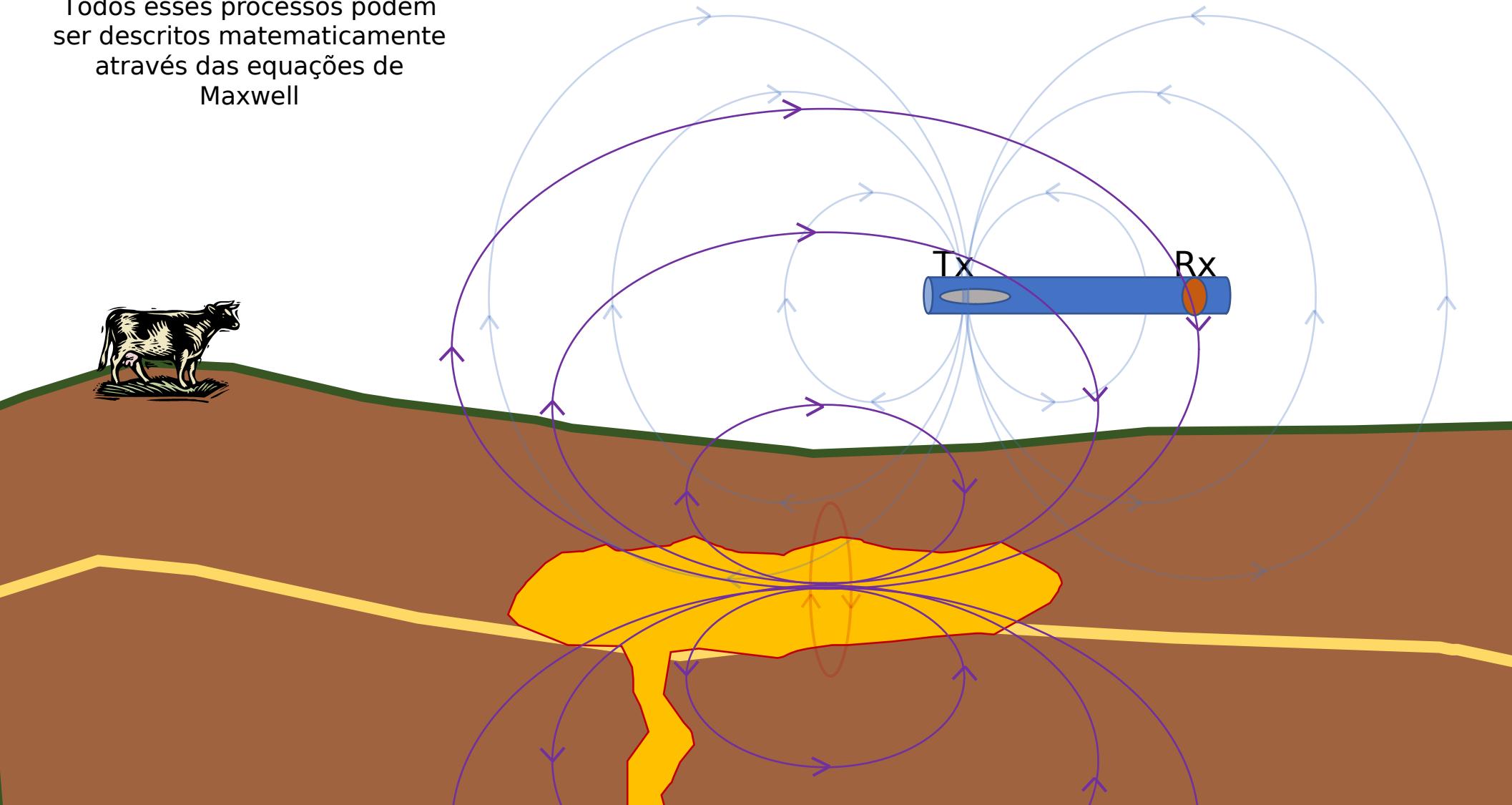
Os campos magnéticos variáveis no tempo produzem campos elétricos em toda parte e assim induzem correntes no alvo condutivo de acordo com a lei Lenz.



As correntes induzidas produzem um campo magnético secundário



Todos esses processos podem ser descritos matematicamente através das equações de Maxwell

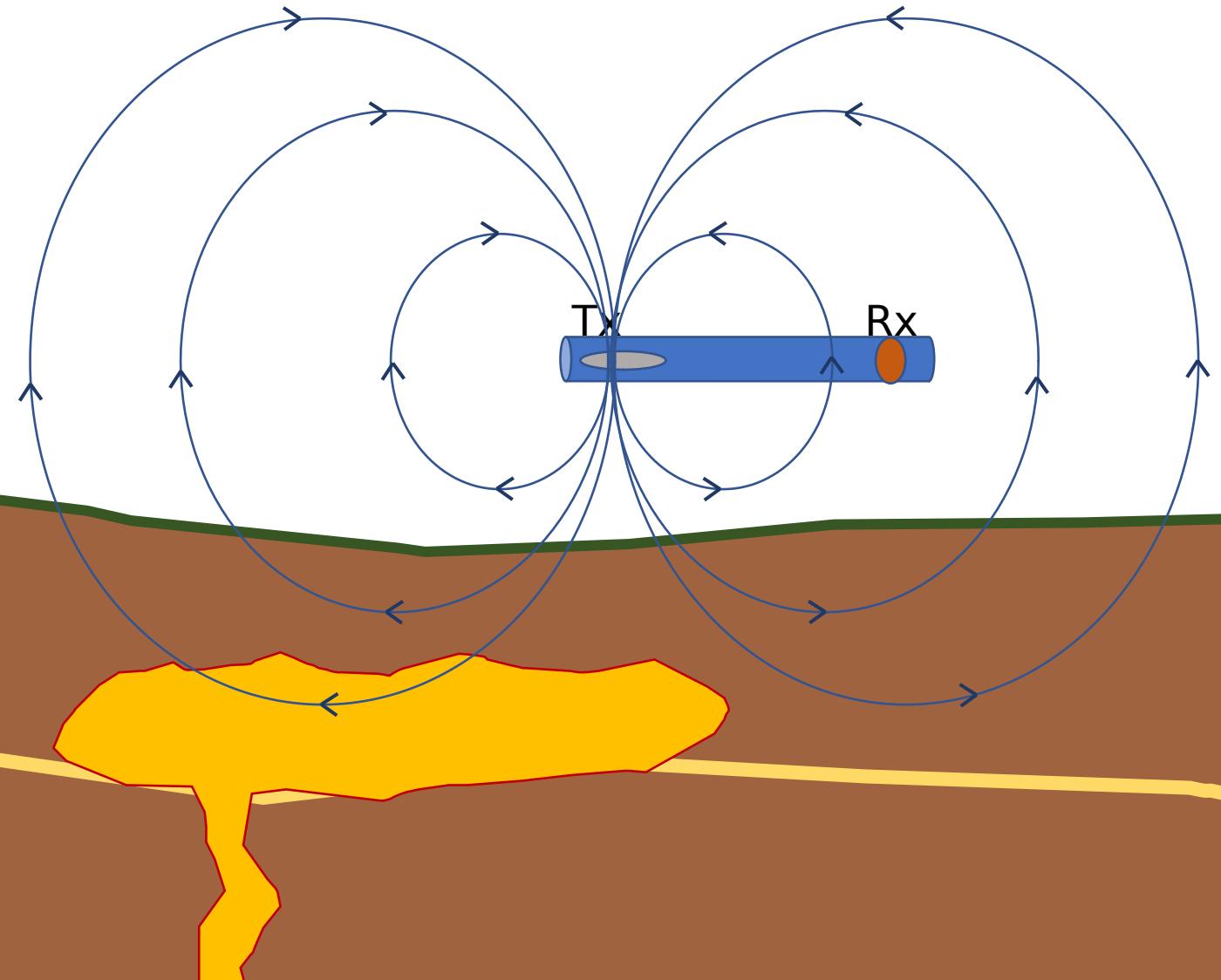


Lei de Ampere

$$\nabla \times \mathbf{H} = \mathbf{J} + i\omega\mathbf{D}$$

Relaciona o campo magnético com a densidade de corrente elétrica e a corrente de deslocamento Eletrico.

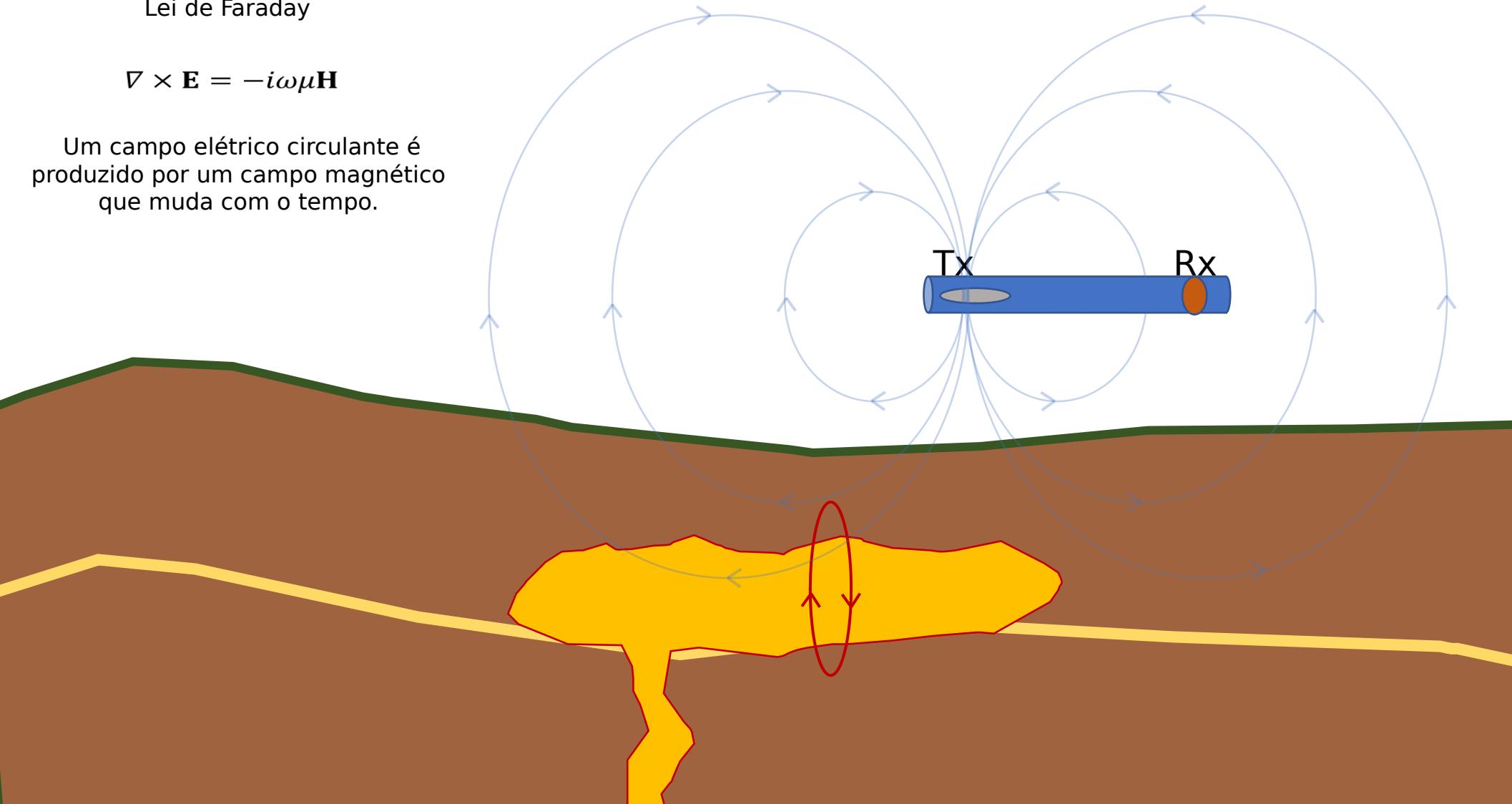
Um campo magnético circulante é produzido por uma corrente elétrica e por um campo elétrico que muda com o tempo.



Lei de Faraday

$$\nabla \times \mathbf{E} = -i\omega\mu\mathbf{H}$$

Um campo elétrico circulante é produzido por um campo magnético que muda com o tempo.



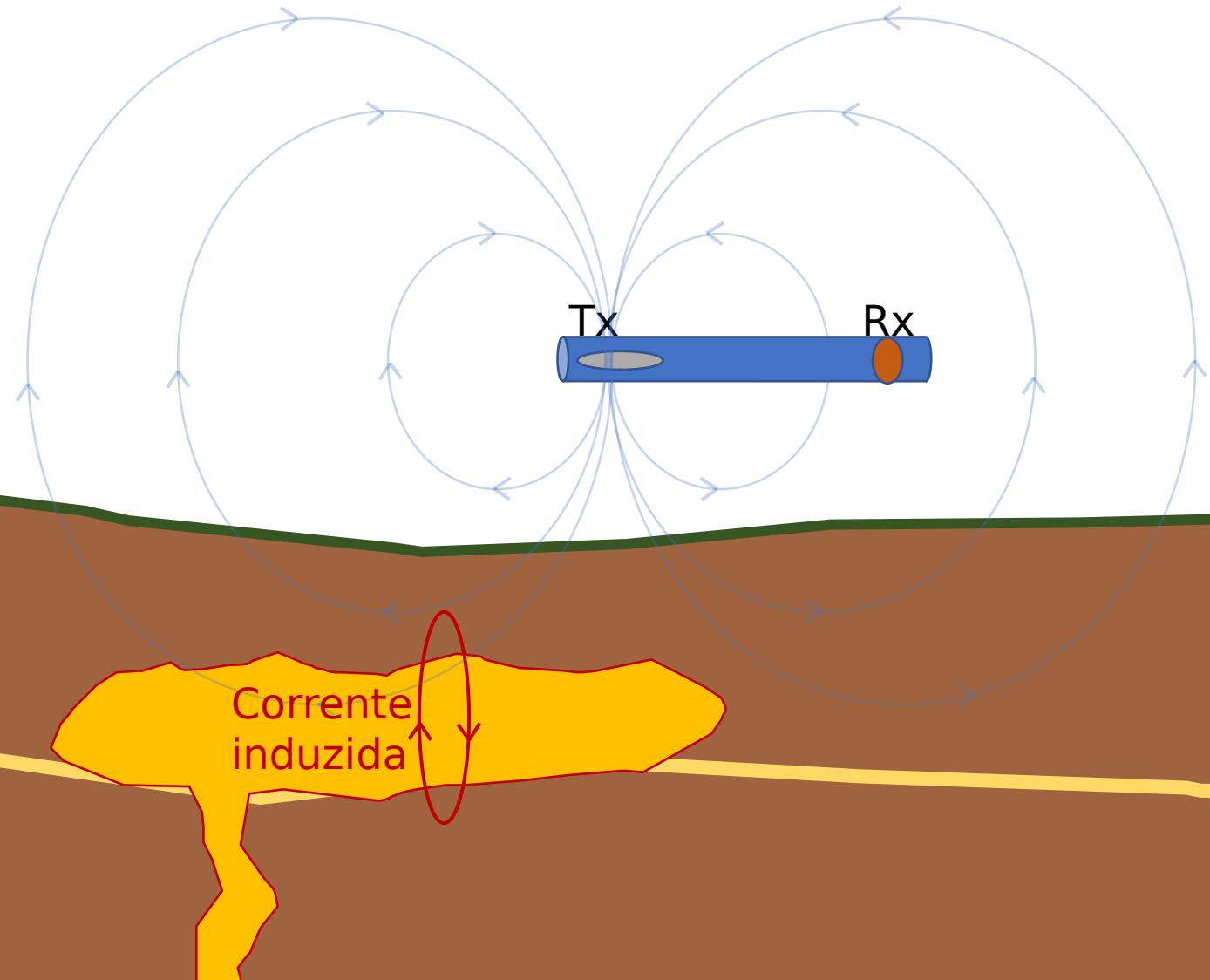
Lei de Faraday

$$\nabla \times \mathbf{E} = -i\omega\mu\mathbf{H}$$

que determina que o campo elétrico rotacional induz campo magnético

Lei de Ohm

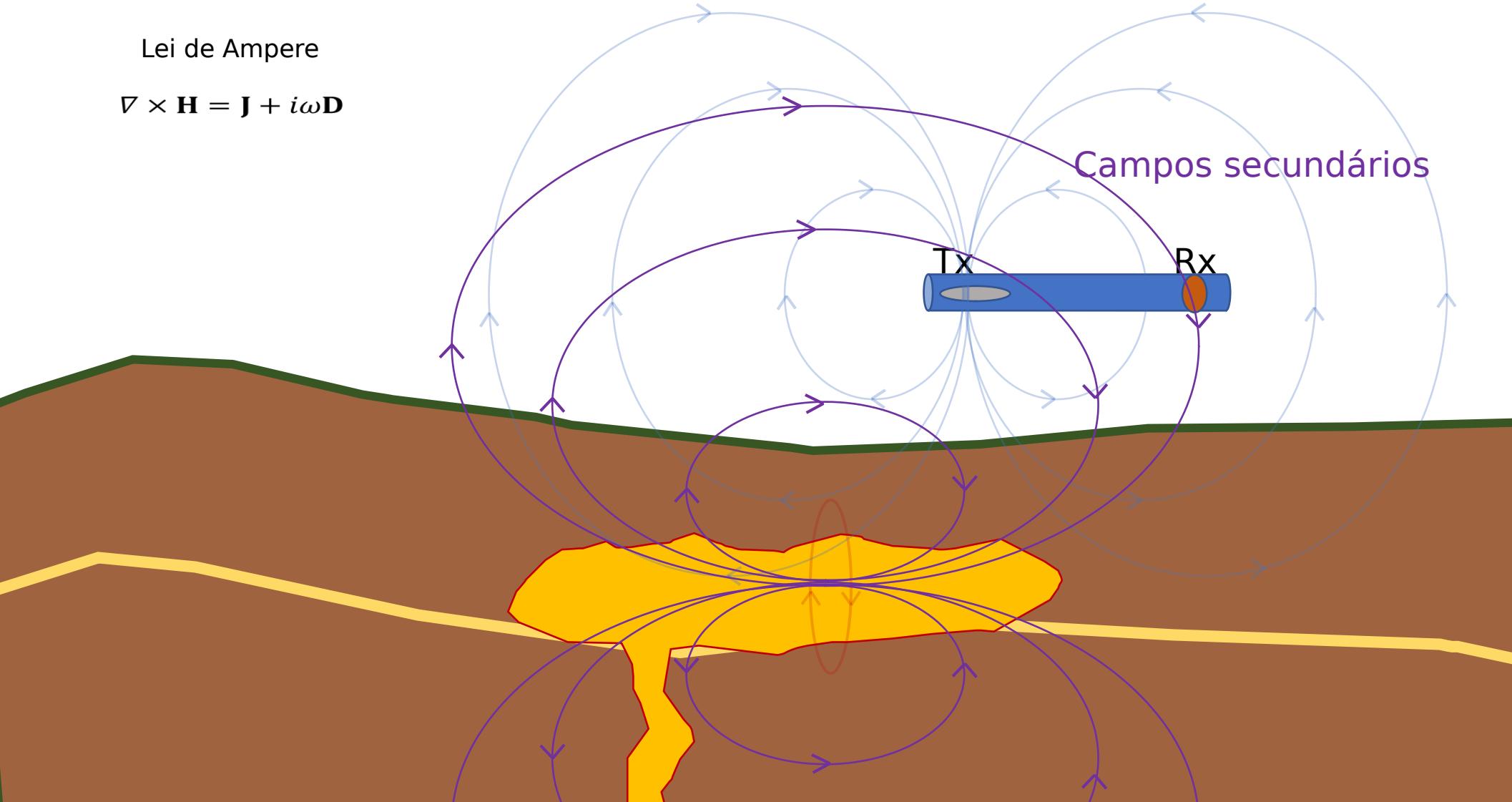
$$\mathbf{J} = \sigma \mathbf{E}$$



Lei de Ampere

$$\nabla \times \mathbf{H} = \mathbf{J} + i\omega\mathbf{D}$$

Campos secundários

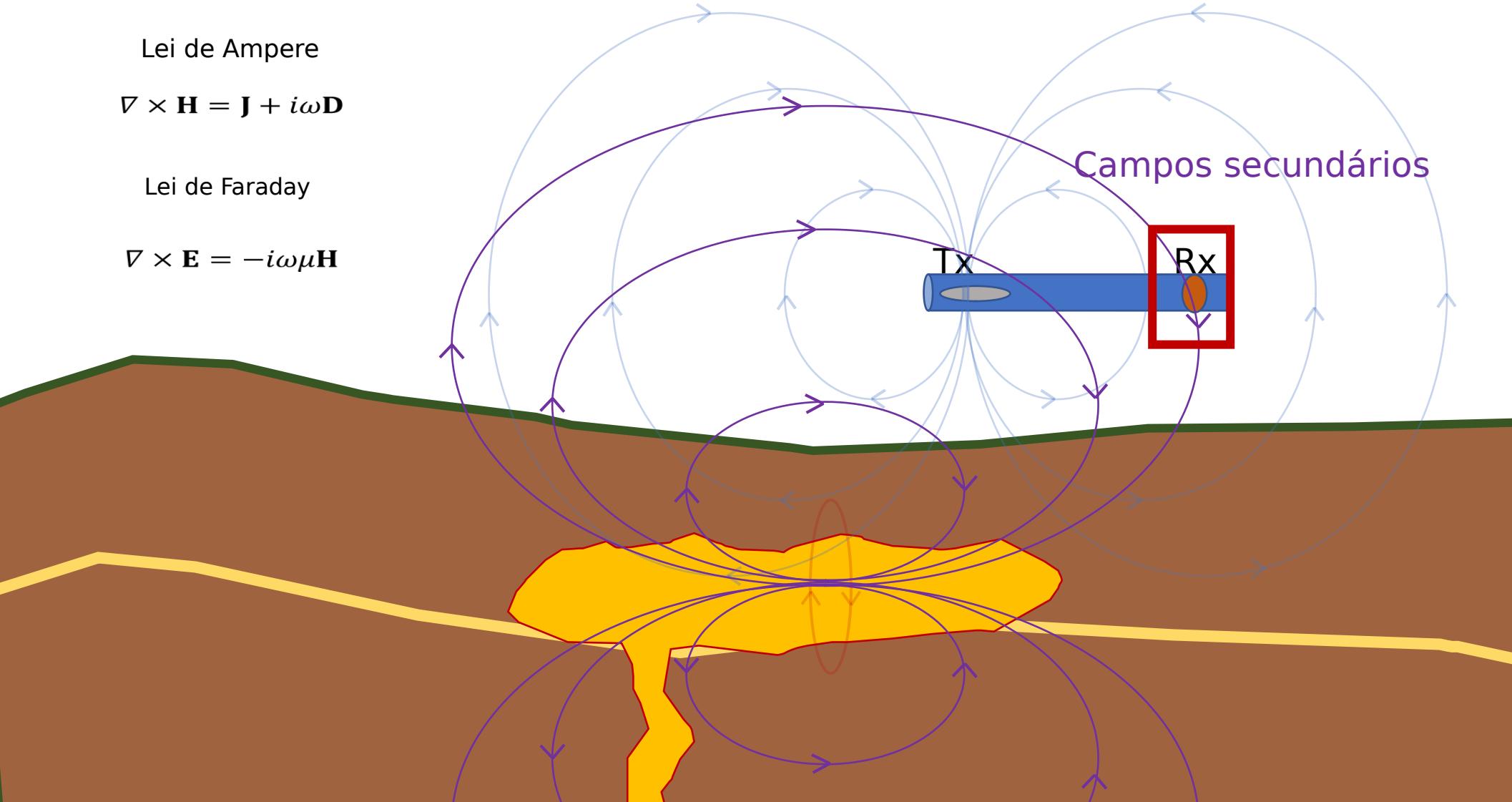


Lei de Ampere

$$\nabla \times \mathbf{H} = \mathbf{J} + i\omega\mathbf{D}$$

Lei de Faraday

$$\nabla \times \mathbf{E} = -i\omega\mu\mathbf{H}$$



Lei de Ampere

$$\nabla \times \mathbf{H} = \mathbf{J} + i\omega \mathbf{D}$$

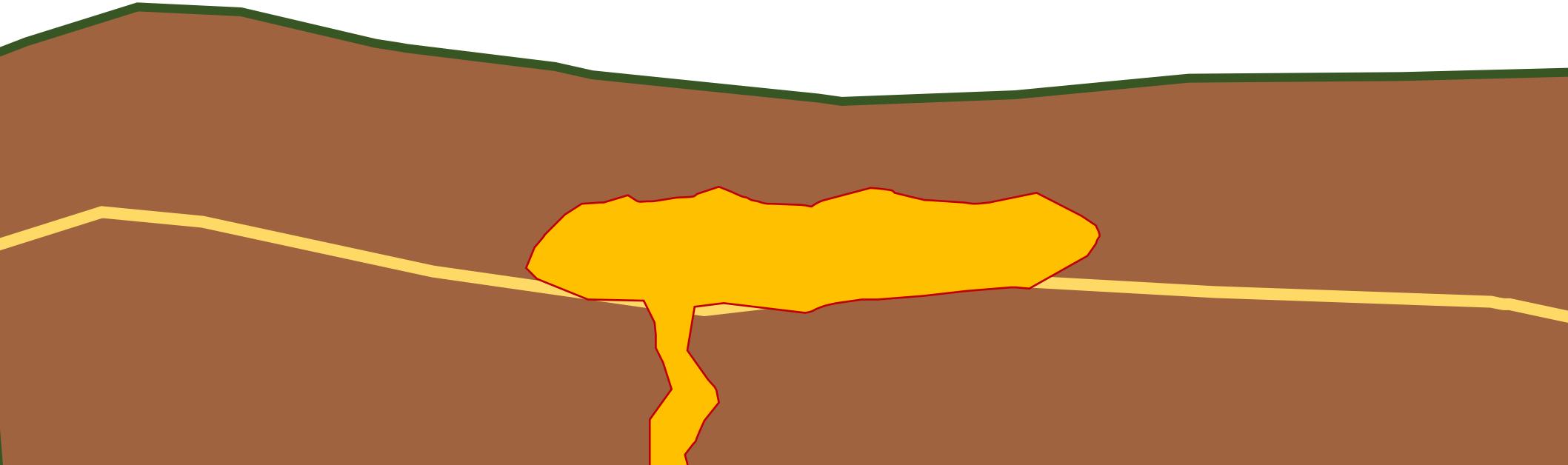
$$\mathbf{J} = \sigma \mathbf{E}$$

$$\mathbf{D} = \epsilon \mathbf{E}$$

Lei de Faraday

$$\mathbf{B} = \mu \mathbf{H}$$

$$\nabla \times \mathbf{E} = -i\omega \mu \mathbf{H}$$



Lei de Ampere

$$\nabla \times \mathbf{H} = \mathbf{J} + i\omega \mathbf{D}$$

$$\mathbf{J} = \sigma \mathbf{E}$$

$$\mathbf{D} = \epsilon \mathbf{E}$$

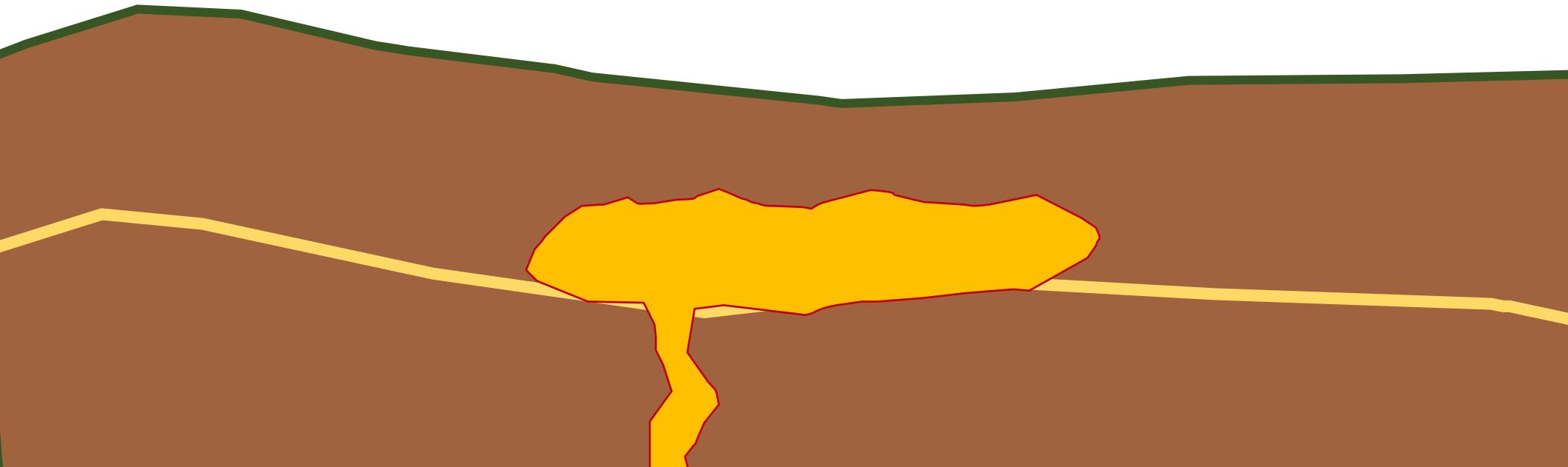
$$\nabla^2 \mathbf{E} + k^2 \mathbf{E} = 0$$

Lei de Faraday

$$\mathbf{B} = \mu \mathbf{H}$$

$$\nabla^2 \mathbf{H} + k^2 \mathbf{H} = 0$$

$$\nabla \times \mathbf{E} = -i\omega \mu \mathbf{H}$$



Lei de Ampere

$$\nabla \times \mathbf{H} = \mathbf{J} + i\omega \mathbf{D}$$

$$\mathbf{J} = \sigma \mathbf{E}$$

$$\nabla^2 \mathbf{E} + k^2 \mathbf{E} = 0$$

Lei de Faraday

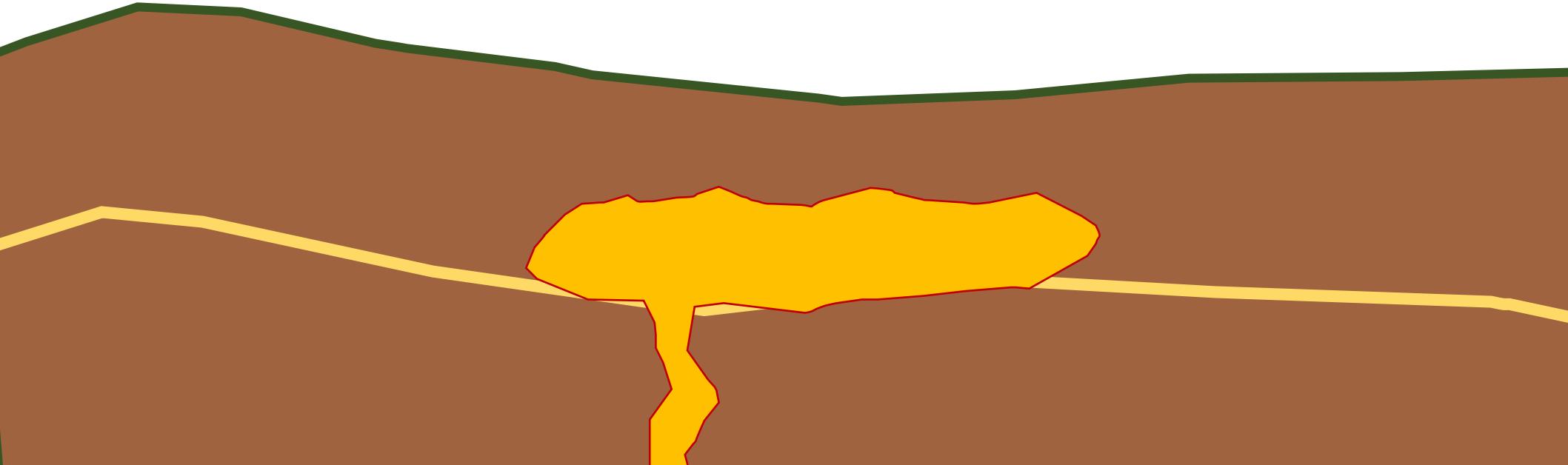
$$\nabla \times \mathbf{E} = -i\omega \mu \mathbf{H}$$

$$\mathbf{D} = \epsilon \mathbf{E}$$

$$\mathbf{B} = \mu \mathbf{H}$$

$$\nabla^2 \mathbf{H} + k^2 \mathbf{H} = 0$$

$$k = \sqrt{\mu \epsilon \omega^2 - i \mu \sigma \omega}$$



Lei de Ampere

$$\nabla \times \mathbf{H} = \mathbf{J} + i\omega\mathbf{D}$$

$$\mathbf{J} = \sigma \mathbf{E}$$

$$\mathbf{D} = \epsilon \mathbf{E}$$

$$\mathbf{B} = \mu \mathbf{H}$$

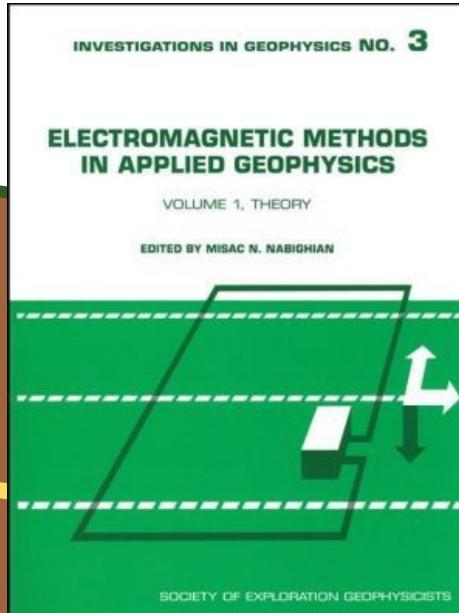
$$\nabla^2 \mathbf{E} + k^2 \mathbf{E} = 0$$

$$\nabla^2 \mathbf{H} + k^2 \mathbf{H} = 0$$

$$k = \sqrt{\mu \epsilon \omega^2 - i \mu \sigma \omega}$$

Lei de Faraday

$$\nabla \times \mathbf{E} = -i\omega\mu\mathbf{H}$$



Misac N. Nabighian, (1988),
Electromagnetic Methods in Applied Geophysics: Volume 1, Theory

Lei de Ampere

$$\nabla \times \mathbf{H} = \mathbf{J} + i\omega \mathbf{D}$$

$$\mathbf{J} = \sigma \mathbf{E}$$

$$\nabla^2 \mathbf{E} + k^2 \mathbf{E} = 0$$

Lei de Faraday

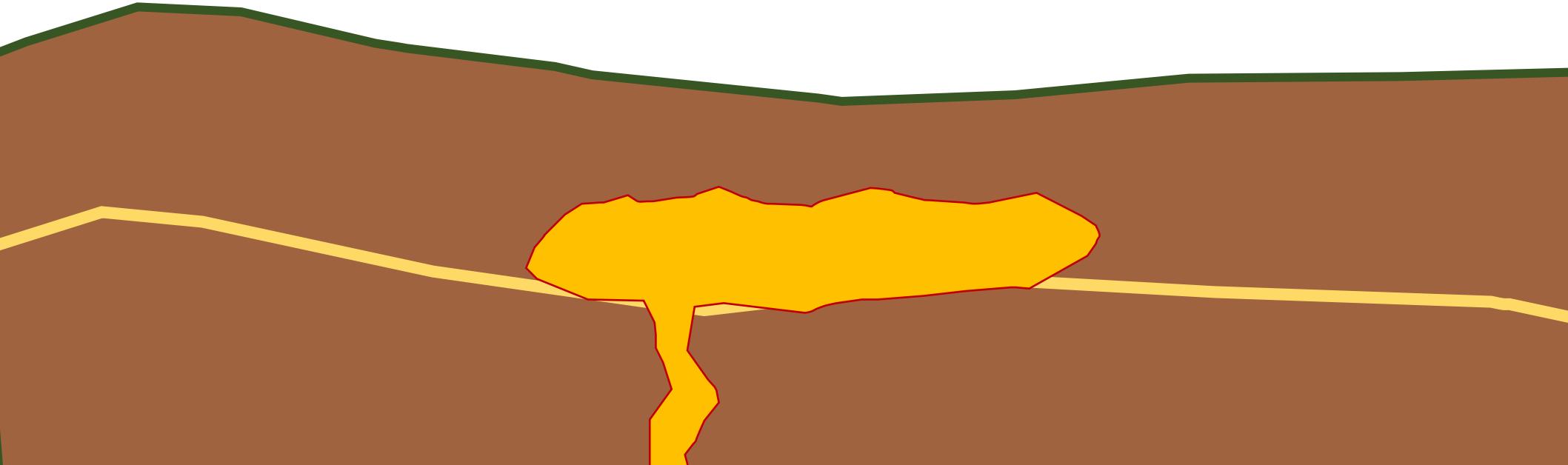
$$\nabla \times \mathbf{E} = -i\omega \mu \mathbf{H}$$

$$\mathbf{D} = \epsilon \mathbf{E}$$

$$\mathbf{B} = \mu \mathbf{H}$$

$$\nabla^2 \mathbf{H} + k^2 \mathbf{H} = 0$$

$$k = \sqrt{\mu \epsilon \omega^2 - i \mu \sigma \omega}$$



Lei de Ampere

$$\nabla \times \mathbf{H} = \mathbf{J} + i\omega \mathbf{D}$$

$$\mathbf{J} = \sigma \mathbf{E}$$

$$\nabla^2 \mathbf{E} + k^2 \mathbf{E} = 0$$

Lei de Faraday

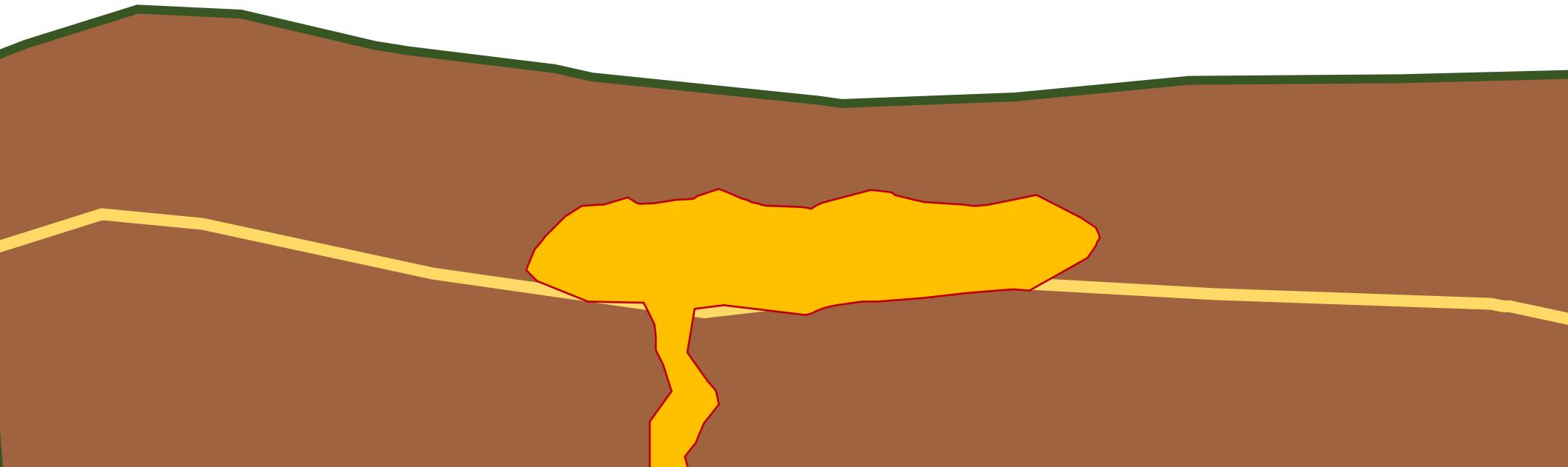
$$\nabla \times \mathbf{E} = -i\omega \mu \mathbf{H}$$

$$\mathbf{D} = \epsilon \mathbf{E}$$

$$\mathbf{B} = \mu \mathbf{H}$$

$$\nabla^2 \mathbf{H} + k^2 \mathbf{H} = 0$$

$$k = \sqrt{\mu \epsilon \omega^2 - i \mu \sigma \omega}$$



Lei de Ampere

$$\nabla \times \mathbf{H} = \mathbf{J} + i\omega \mathbf{D}$$

$$\mathbf{J} = \sigma \mathbf{E}$$

$$\nabla^2 \mathbf{E} + k^2 \mathbf{E} = 0$$

Lei de Faraday

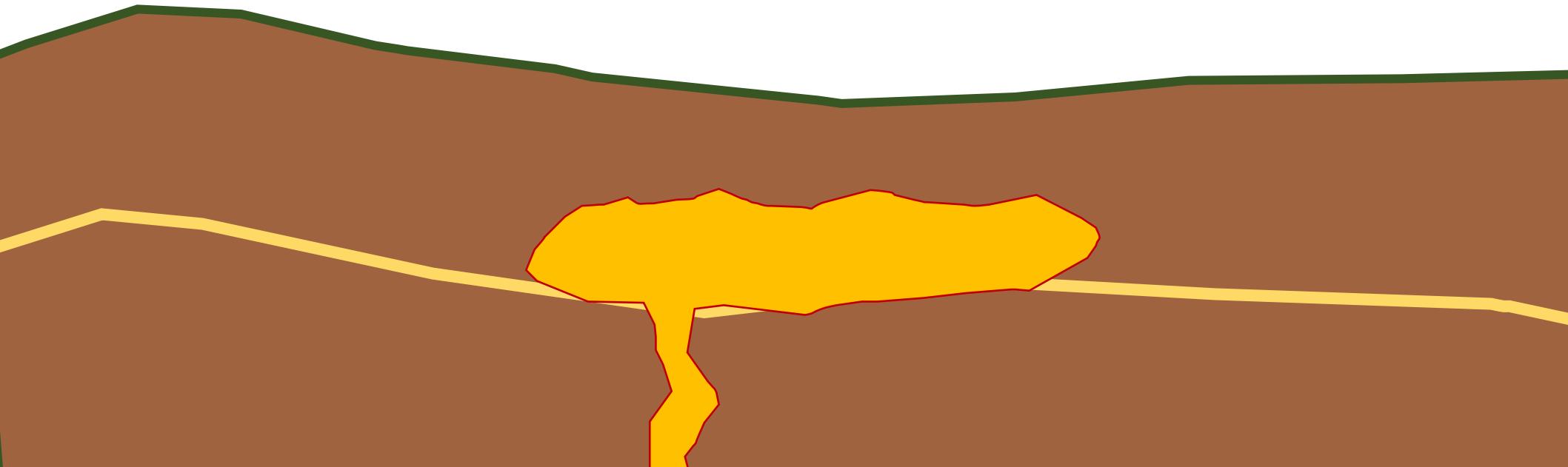
$$\nabla \times \mathbf{E} = -i\omega \mu \mathbf{H}$$

$$\mathbf{D} = \epsilon \mathbf{E}$$

$$\mathbf{B} = \mu \mathbf{H}$$

$$\nabla^2 \mathbf{H} + k^2 \mathbf{H} = 0$$

$$k = \sqrt{\mu \epsilon \omega^2 - i \mu \sigma \omega}$$



Lei de Ampere

$$\nabla \times \mathbf{H} = \mathbf{J} + i\omega \mathbf{D}$$

Lei de Faraday

$$\nabla \times \mathbf{E} = -i\omega \mu \mathbf{H}$$

$$\mathbf{J} = \sigma \mathbf{E}$$

$$\mathbf{D} = \epsilon \mathbf{E}$$

$$\mathbf{B} = \mu \mathbf{H}$$

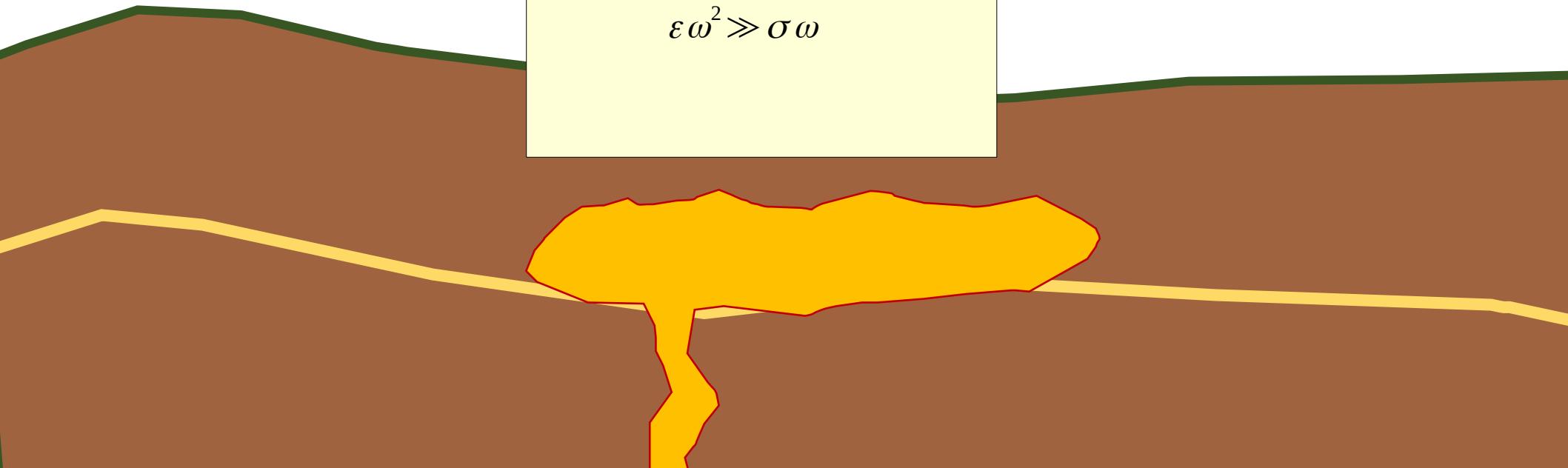
$$\nabla^2 \mathbf{E} + k^2 \mathbf{E} = 0$$

$$\nabla^2 \mathbf{H} + k^2 \mathbf{H} = 0$$

$$k = \sqrt{\mu \epsilon \omega^2 - i \mu \sigma \omega}$$

Para as altas frequências

$$\epsilon \omega^2 \gg \sigma \omega$$



Lei de Ampere

$$\nabla \times \mathbf{H} = \mathbf{J} + i\omega \mathbf{D}$$

Lei de Faraday

$$\nabla \times \mathbf{E} = -i\omega \mu \mathbf{H}$$

$$\mathbf{J} = \sigma \mathbf{E}$$

$$\mathbf{D} = \epsilon \mathbf{E}$$

$$\mathbf{B} = \mu \mathbf{H}$$

$$\nabla^2 \mathbf{E} + k^2 \mathbf{E} = 0$$

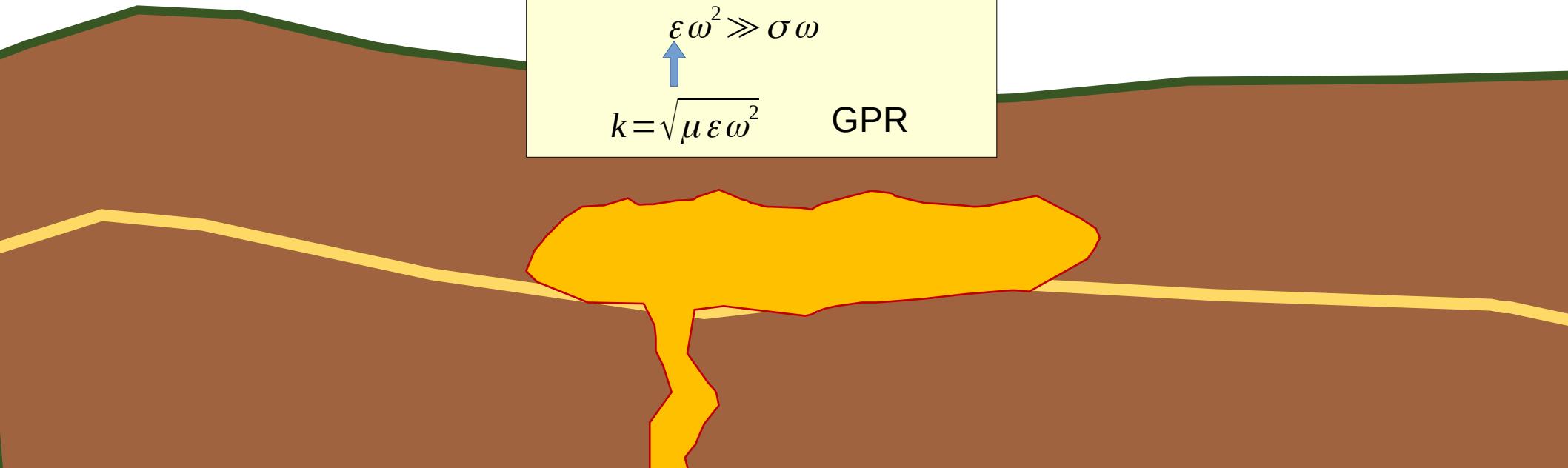
$$\nabla^2 \mathbf{H} + k^2 \mathbf{H} = 0$$

$$k = \sqrt{\mu \epsilon \omega^2 - i \mu \sigma \omega}$$

Para as altas frequências

$$\epsilon \omega^2 \gg \sigma \omega$$

$$k = \sqrt{\mu \epsilon \omega^2} \quad \text{GPR}$$



Lei de Ampere

$$\nabla \times \mathbf{H} = \mathbf{J} + i\omega\mathbf{D}$$

Lei de Faraday

$$\nabla \times \mathbf{E} = -i\omega\mu\mathbf{H}$$

$$\mathbf{J} = \sigma \mathbf{E}$$

$$\mathbf{D} = \epsilon \mathbf{E}$$

$$\mathbf{B} = \mu \mathbf{H}$$

$$\nabla^2 \mathbf{E}$$

$$\nabla^2 \mathbf{H}$$

$$k = \sqrt{\mu \epsilon}$$

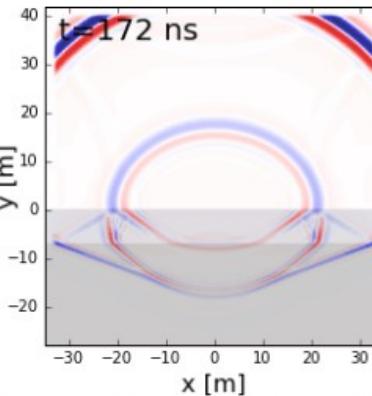


Fig. 223 GPR signal as it propagates through a 2-layer Earth.

Para as altas frequências

$$\epsilon \omega^2 \gg \sigma \omega$$

$$k = \sqrt{\mu \epsilon \omega^2} \quad \text{GPR}$$

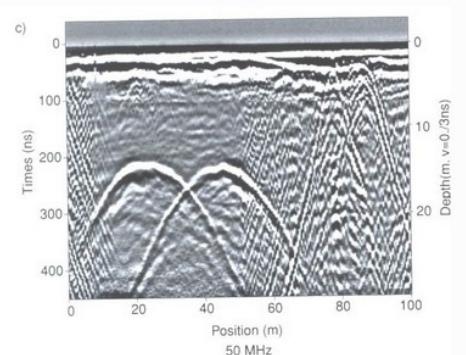
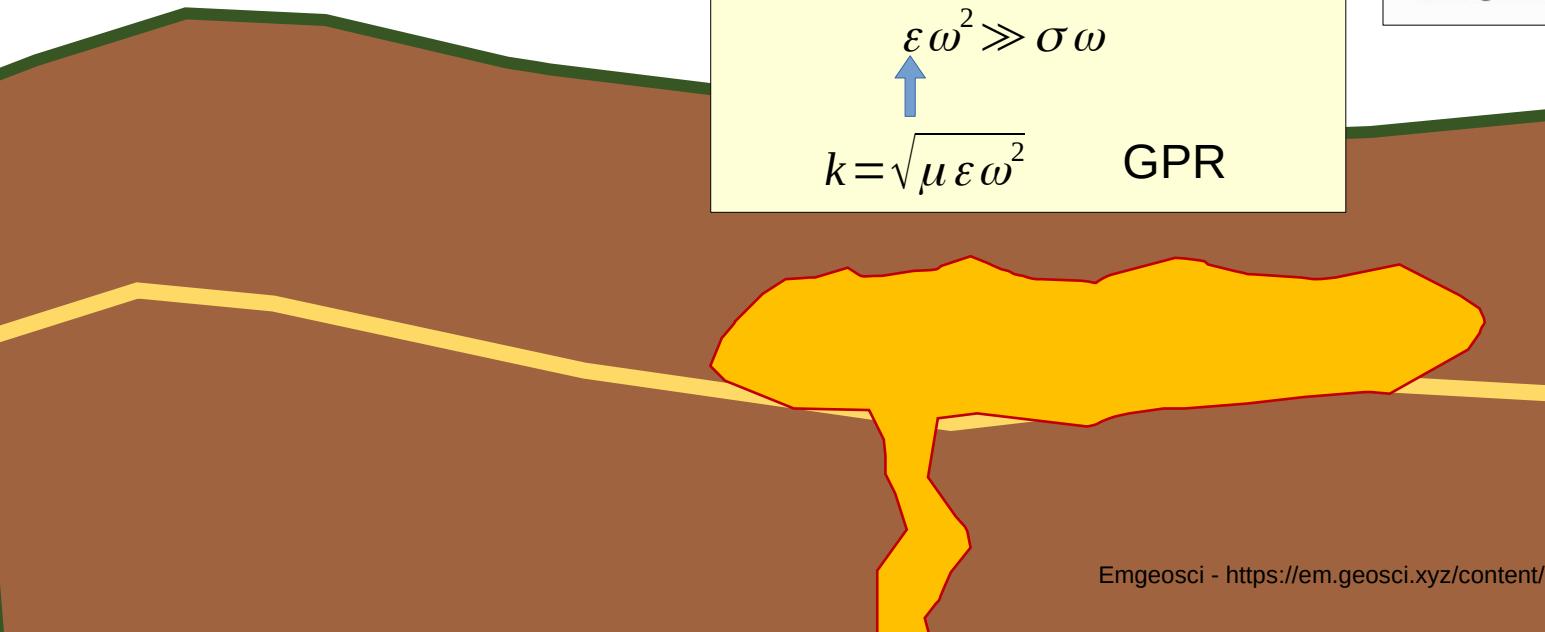


Fig. 236 Radargram showing hyperbolic signatures from two buried pipes.



Lei de Ampere

$$\nabla \times \mathbf{H} = \mathbf{J} + i\omega \mathbf{D}$$

Lei de Faraday

$$\nabla \times \mathbf{E} = -i\omega \mu \mathbf{H}$$

$$\mathbf{J} = \sigma \mathbf{E}$$

$$\mathbf{D} = \epsilon \mathbf{E}$$

$$\mathbf{B} = \mu \mathbf{H}$$

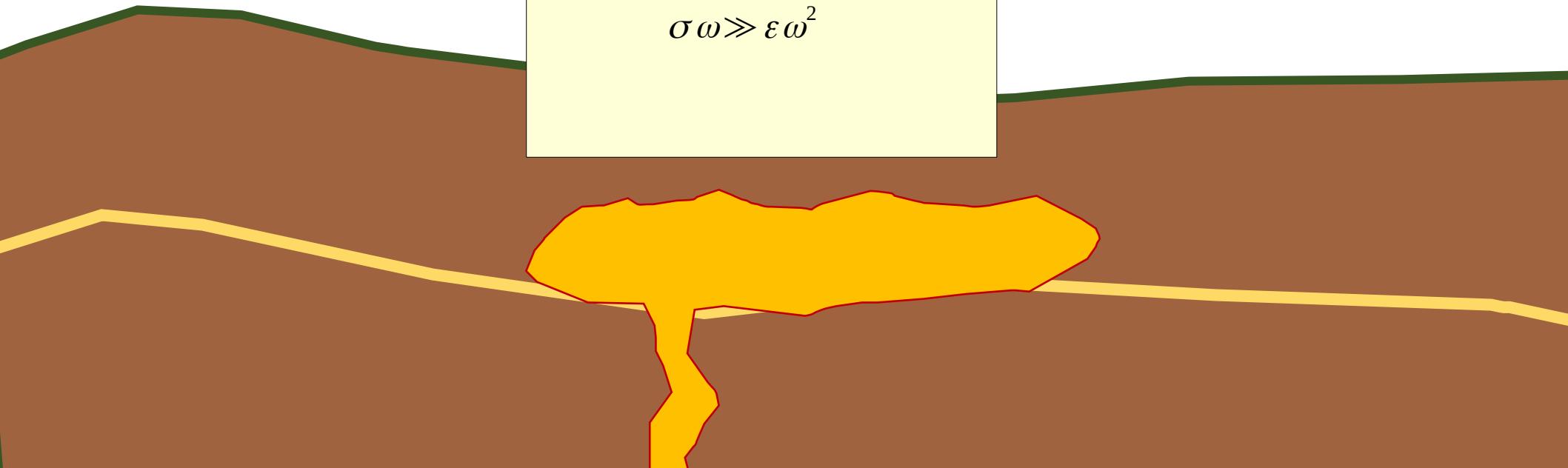
$$\nabla^2 \mathbf{E} + k^2 \mathbf{E} = 0$$

$$\nabla^2 \mathbf{H} + k^2 \mathbf{H} = 0$$

$$k = \sqrt{\mu \epsilon \omega^2 - i \mu \sigma \omega}$$

Para as baixas frequências

$$\sigma \omega \gg \epsilon \omega^2$$



Lei de Ampere

$$\nabla \times \mathbf{H} = \mathbf{J} + i\omega \mathbf{D}$$

Lei de Faraday

$$\nabla \times \mathbf{E} = -i\omega \mu \mathbf{H}$$

$$\mathbf{J} = \sigma \mathbf{E}$$

$$\mathbf{D} = \epsilon \mathbf{E}$$

$$\mathbf{B} = \mu \mathbf{H}$$

$$\nabla^2 \mathbf{E} + k^2 \mathbf{E} = 0$$

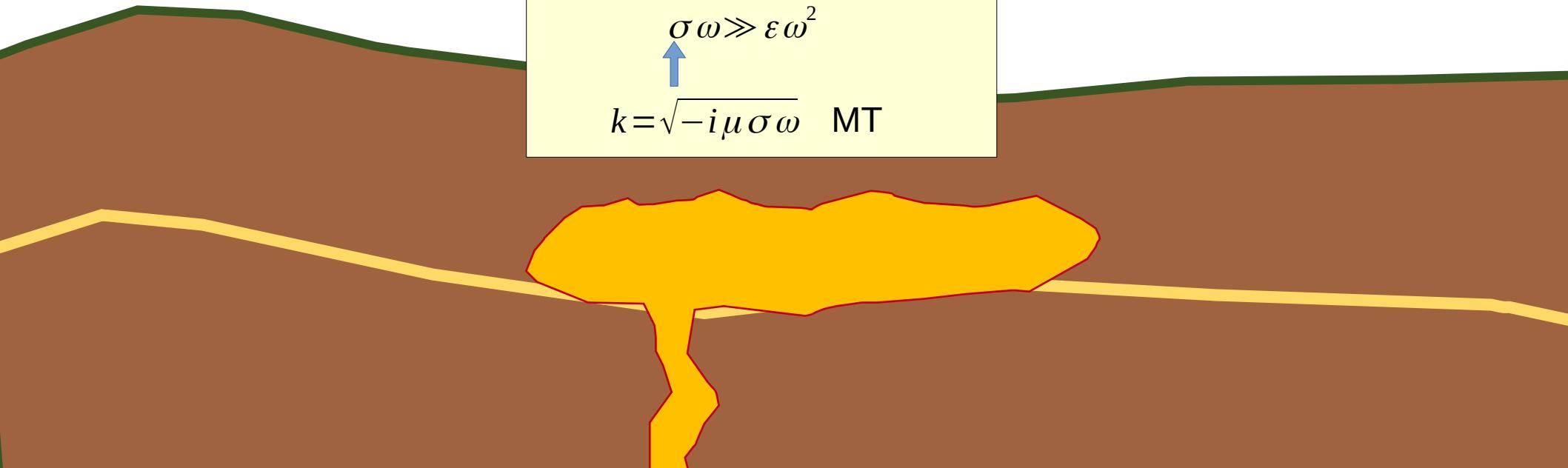
$$\nabla^2 \mathbf{H} + k^2 \mathbf{H} = 0$$

$$k = \sqrt{\mu \epsilon \omega^2 - i \mu \sigma \omega}$$

Para as baixas frequências

$$\sigma \omega \gg \epsilon \omega^2$$

$$k = \sqrt{-i \mu \sigma \omega} \quad \text{MT}$$



Lei de Ampere

$$\nabla \times \mathbf{H} = \mathbf{J} + i\omega\mathbf{D}$$

Lei de Faraday

$$\nabla \times \mathbf{E} = -i\omega\mu\mathbf{H}$$

$$\mathbf{J} = \sigma\mathbf{E}$$

$$\mathbf{D} = \epsilon\mathbf{E}$$

$$\mathbf{B} = \mu\mathbf{H}$$

$$\nabla^2\mathbf{E} + k^2\mathbf{E} = 0$$

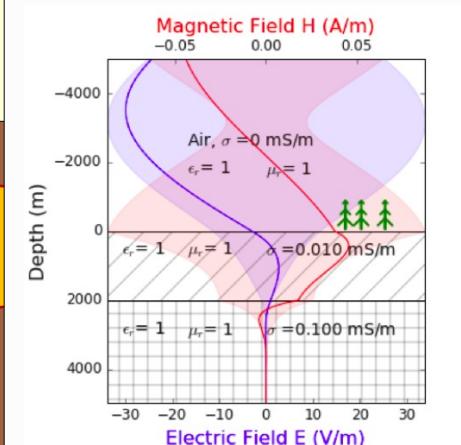
$$\nabla^2\mathbf{H} + k^2\mathbf{H} = 0$$

$$k = \sqrt{\mu\epsilon\omega^2 - i\mu\sigma\omega}$$

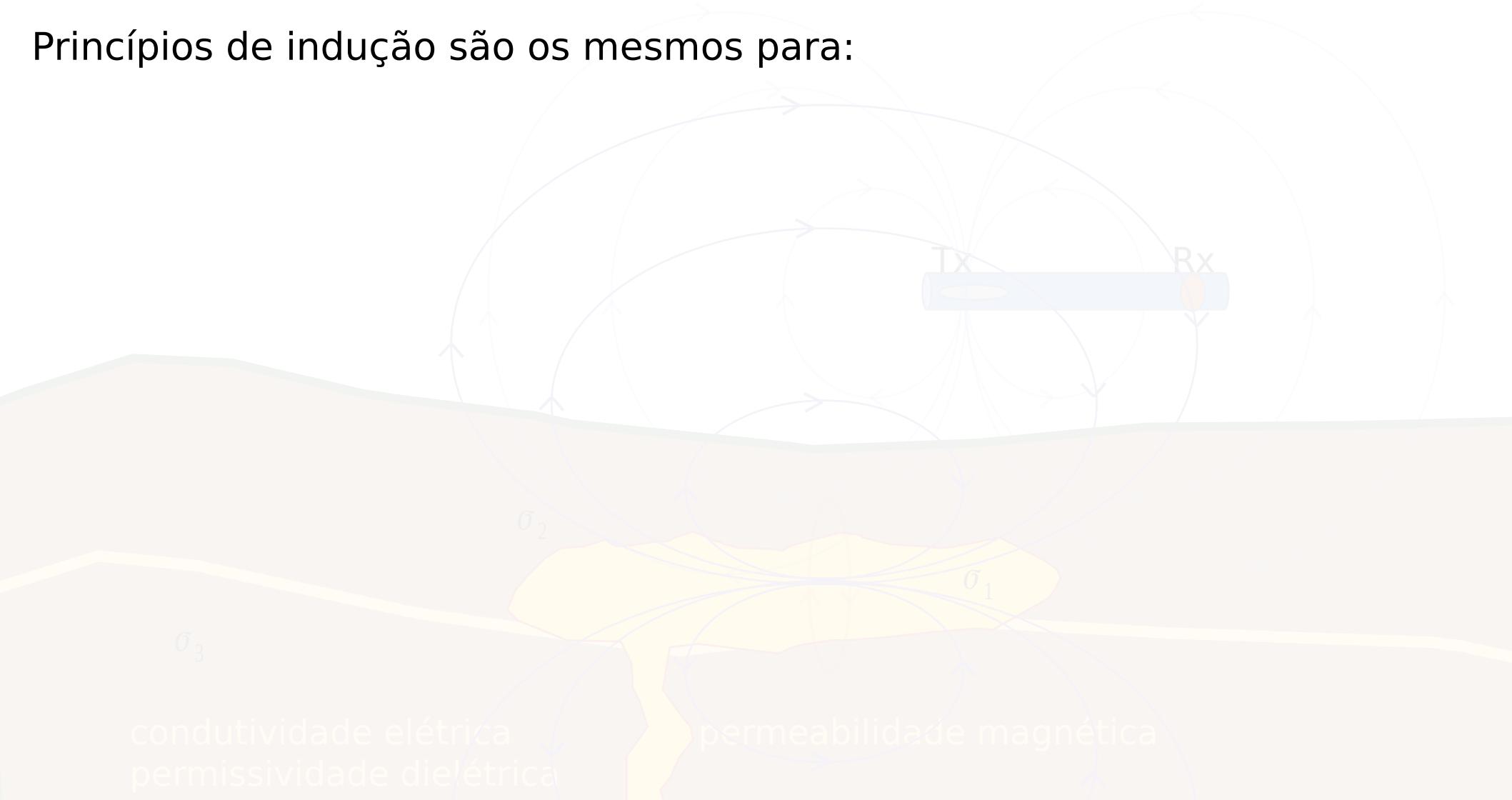
Para as baixas frequências

$$\sigma\omega \gg \epsilon\omega^2$$

$$k = \sqrt{-i\mu\sigma\omega} \quad \text{MT}$$



Princípios de indução são os mesmos para:



Princípios de indução são os mesmos para:

- TDEM: domínio do tempo
- FDEM: domínio da frequência
 - Fontes naturais
 - Fontes controladas

Princípios de indução são os mesmos para:

- TDEM: domínio do tempo
- FDEM: domínio da frequência
 - **Fontes naturais**  Magnetotelúrico
 - Fontes controladas

Magnetotelúrico



Magnetotelúrico

- Exploração de bacias sedimentares



Magnetotelúrico

- Exploração de bacias sedimentares
- Caracterização de embasamento



Magnetotelúrico

- Exploração de bacias sedimentares
- Caracterização de embasamento
- Intrusões



Magnetotelúrico

- Exploração de bacias sedimentares
- Caracterização de embasamento
- Intrusões
- Exploração de hidrocarbonetos



Magnetotelúrico

- Exploração de bacias sedimentares
- Caracterização de embasamento
- Intrusões
- Exploração de hidrocarbonetos
- Estudos geotermais



Magnetotelúrico

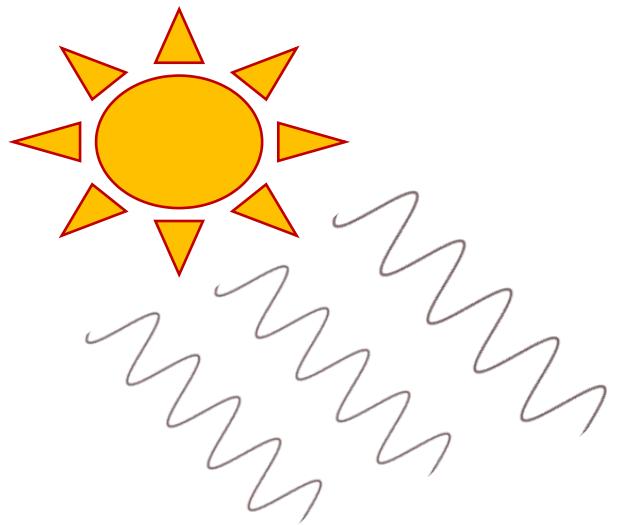
- Exploração de bacias sedimentares
- Caracterização de embasamento
- Intrusões
- Exploração de hidrocarbonetos
- Estudos geotermais
- Mineração

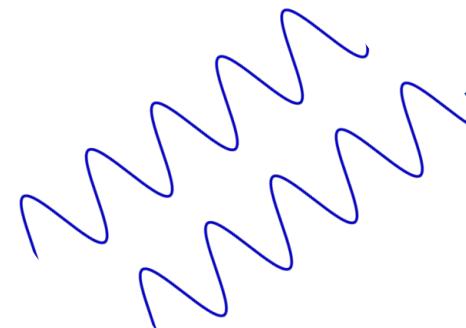
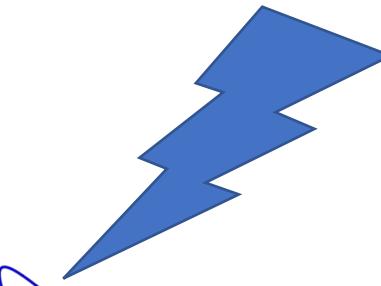
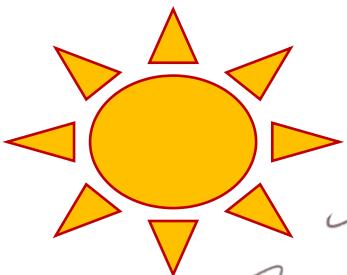


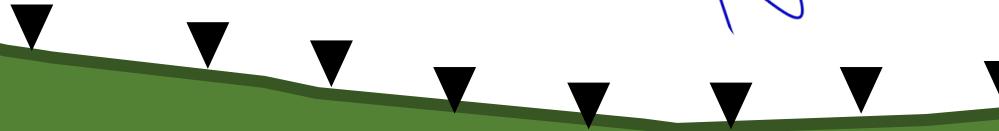
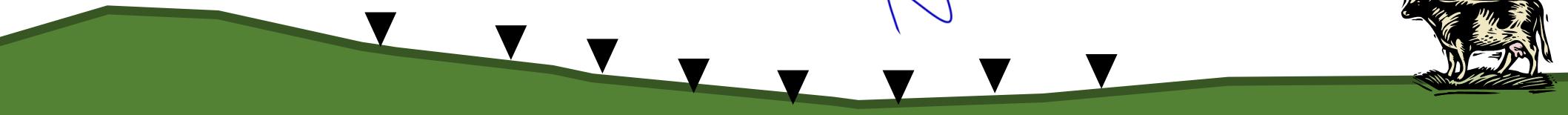
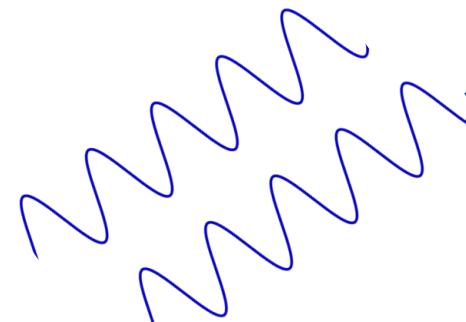
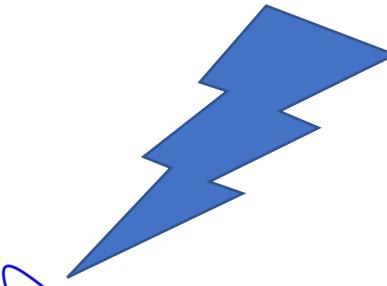
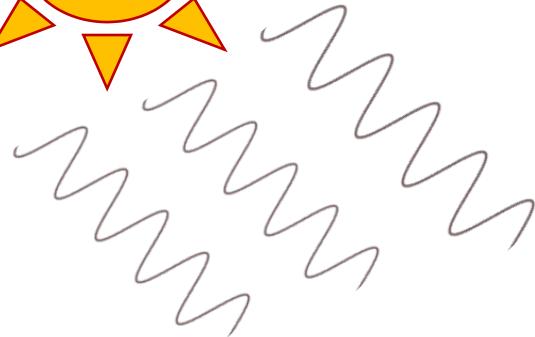
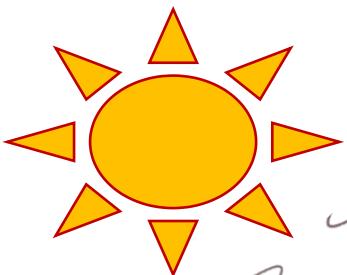
Magnetotelúrico

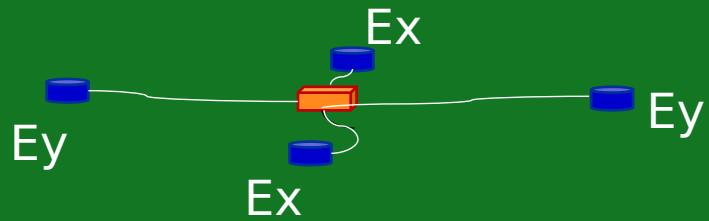
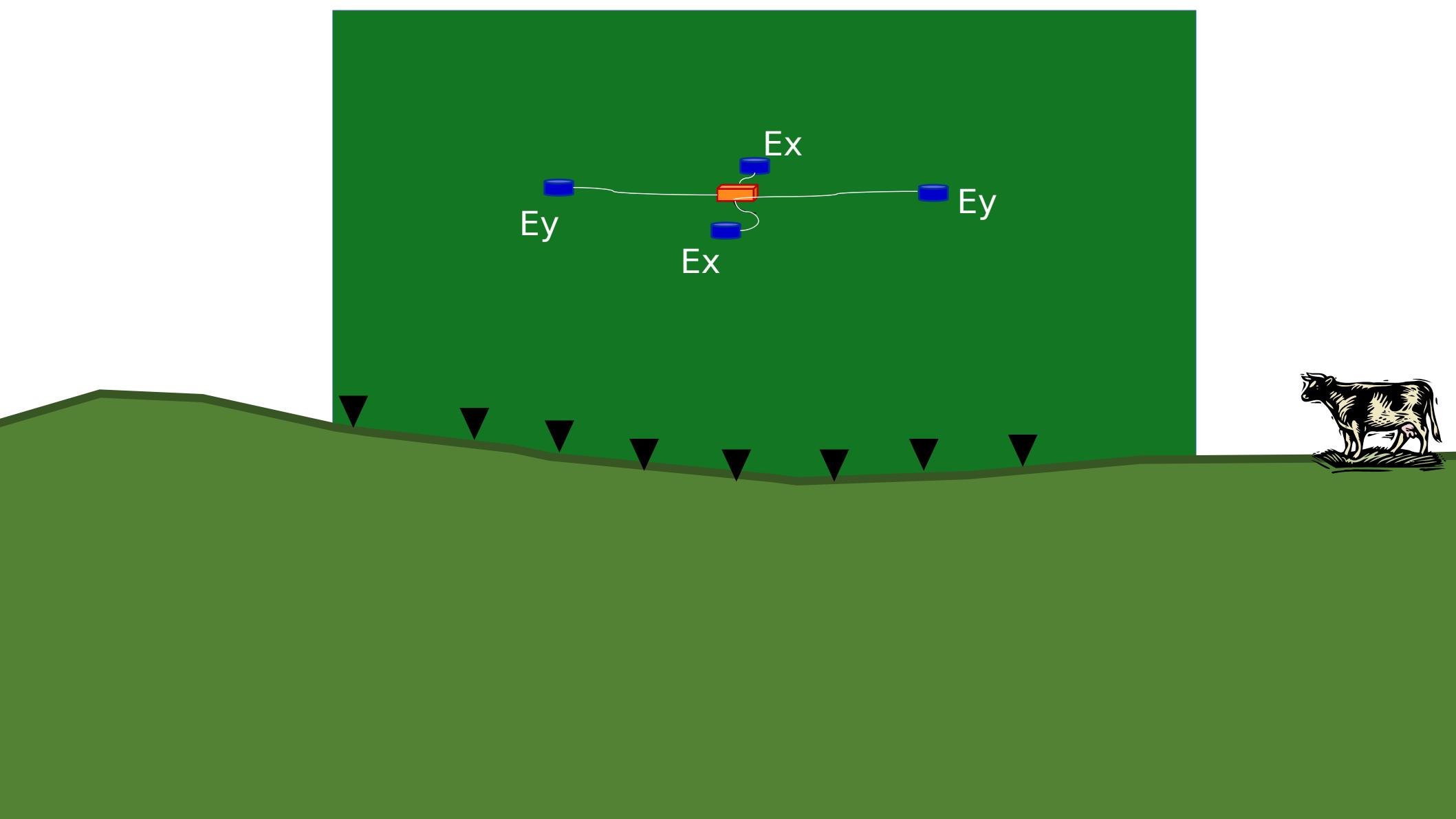
- Exploração de bacias sedimentares
- Caracterização de embasamento
- Intrusões
- Exploração de hidrocarbonetos
- Estudos geotermais
- Mineração
- Estudos tectônicos

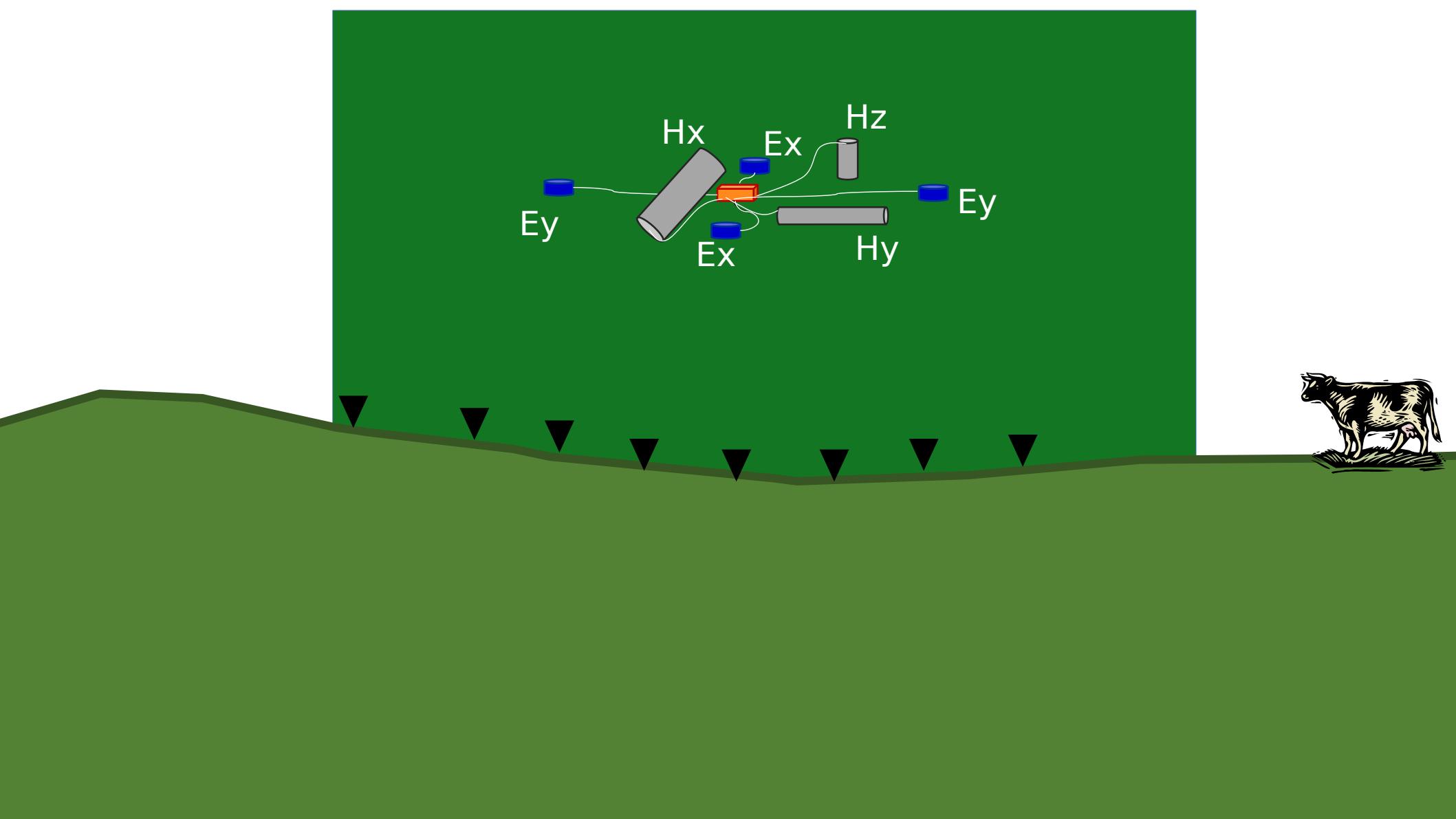


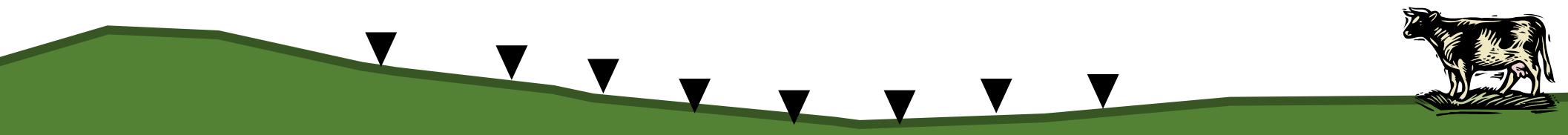
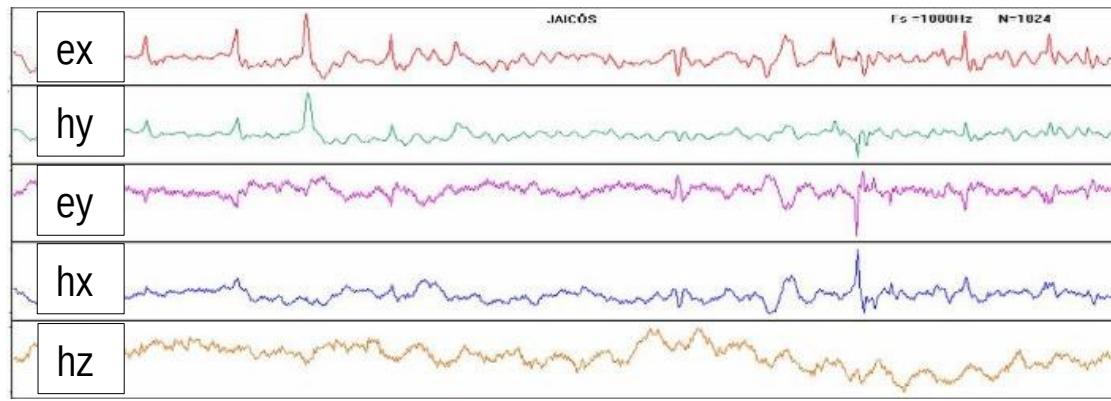


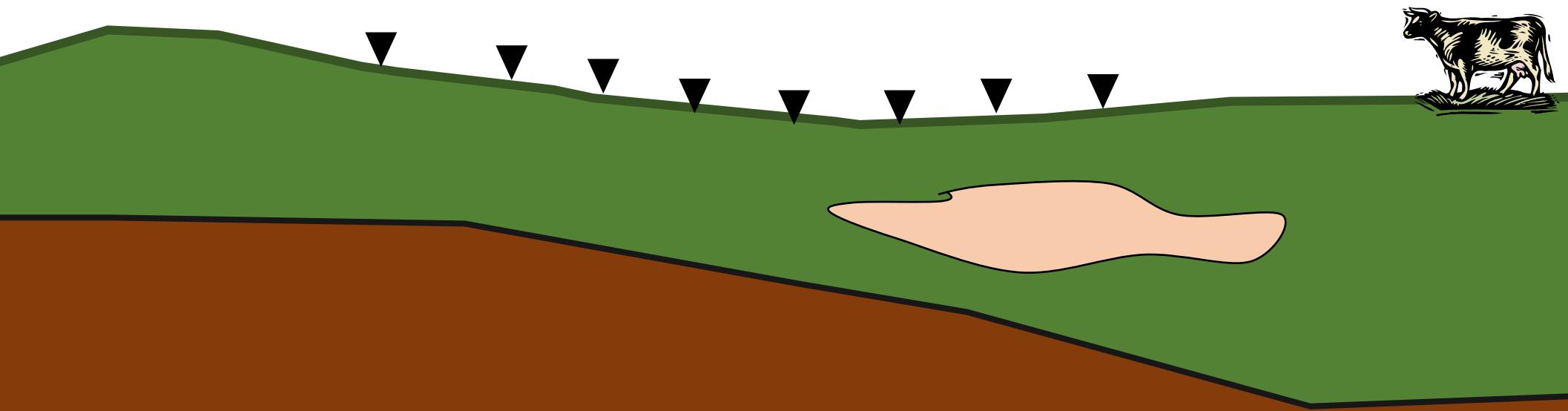
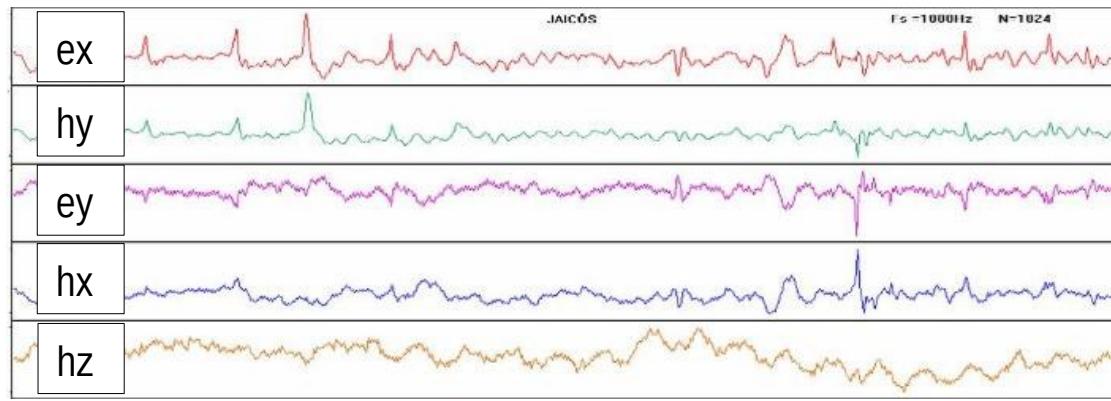












ex

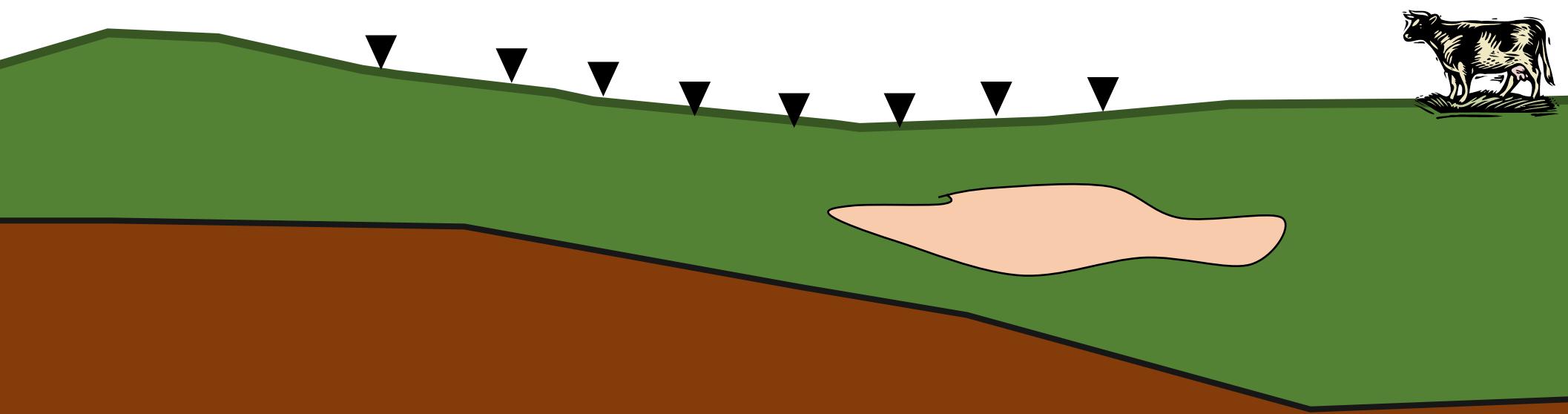
hy

ey

hx

hz

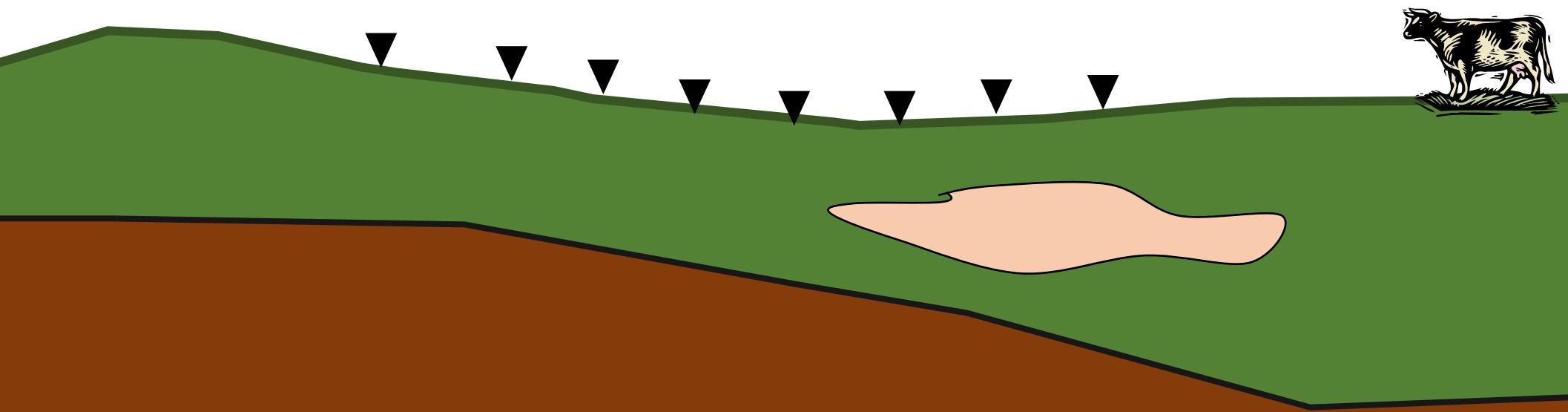
Tempo



ex	Ex
hy	Hy
ey	Ey
hx	Hx
hz	Hz

Fourier

Tempo Frequencia

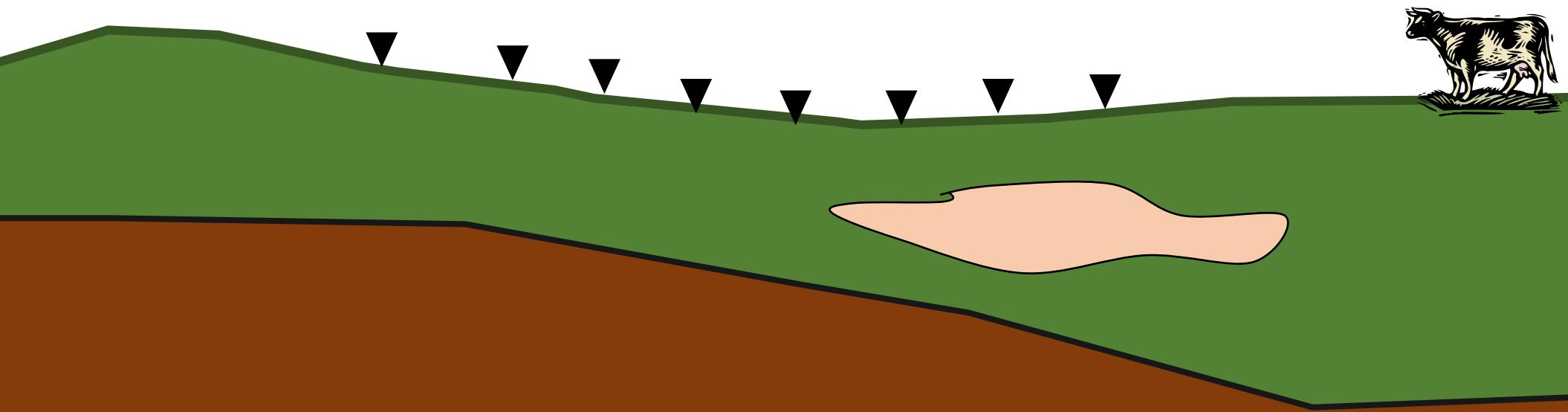


ex	Ex
hy	Hy
ey	Ey
hx	Hx
hz	Hz

Fourier

Equações de Maxwell
descrevem o
comportamento dos
campos EM em meios
geológicos

Tempo Frequencia



ex
hy
ey
hx
hz

Ex
Hy
Ey
Hx
Hz

Fourier

$$\nabla \times \mathbf{E} = -i\omega\mu\mathbf{H}$$

$$\nabla^2 \mathbf{E} + k^2 \mathbf{E} = 0$$

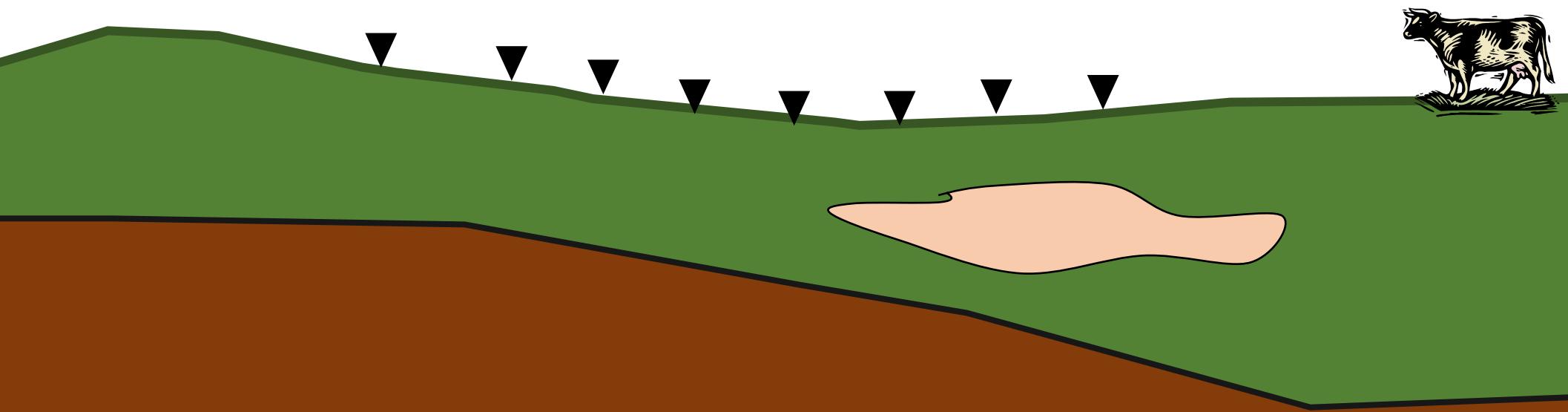
$$\nabla \times \mathbf{H} = \mathbf{J} + i\omega\mathbf{D}$$

$$\nabla^2 \mathbf{H} + k^2 \mathbf{H} = 0$$

$$k = (-i\mu\omega\sigma)^{1/2}$$

Tempo

Frequencia



ex
hy
ey
hx
hz

Ex
Hy
Ey
Hx
Hz

$$\nabla \times \mathbf{E} = -i\omega\mu\mathbf{H}$$

$$\nabla^2 \mathbf{E} + k^2 \mathbf{E} = 0$$

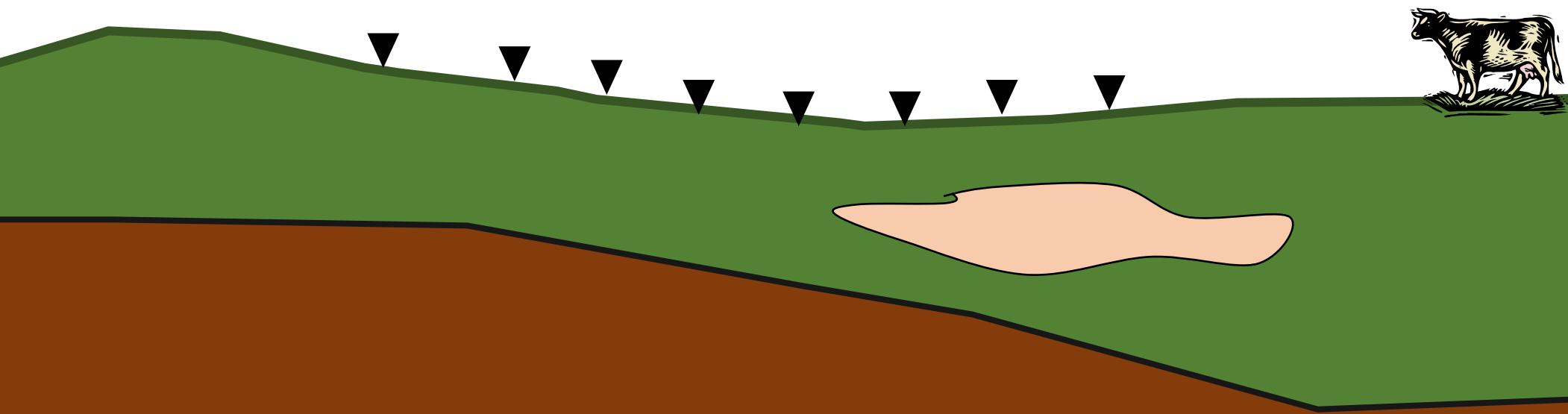
$$\nabla \times \mathbf{H} = \mathbf{J} + i\omega\mathbf{D}$$

$$\nabla^2 \mathbf{H} + k^2 \mathbf{H} = 0$$

$$k = (-i\mu\omega\sigma)^{1/2}$$

Como o campo se
propaga nos meios
geológicos?

Tempo Frequencia



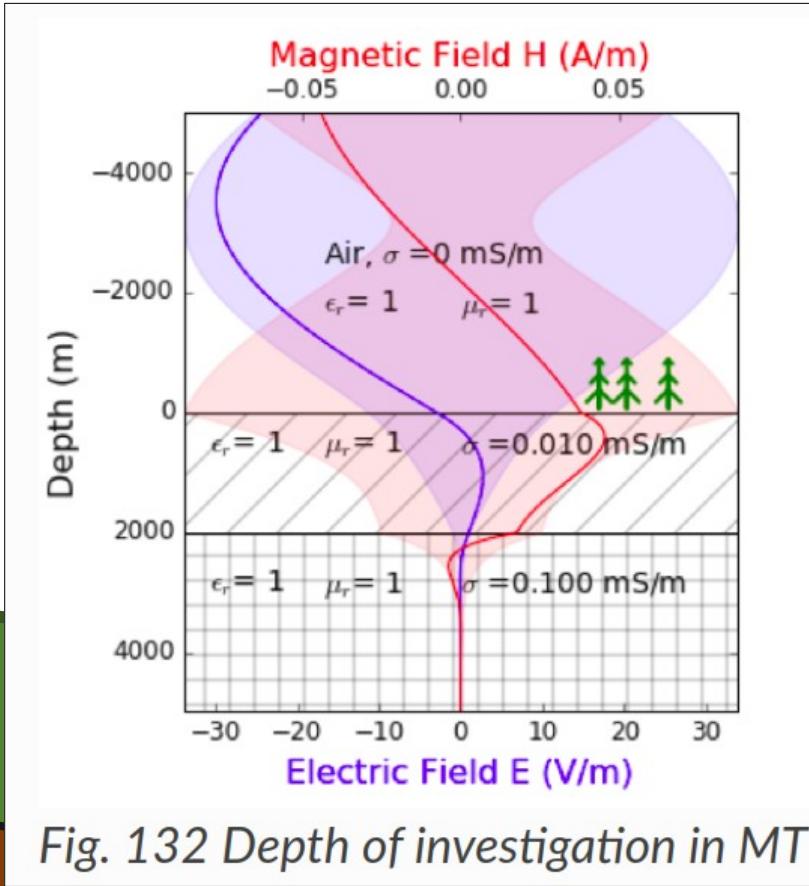
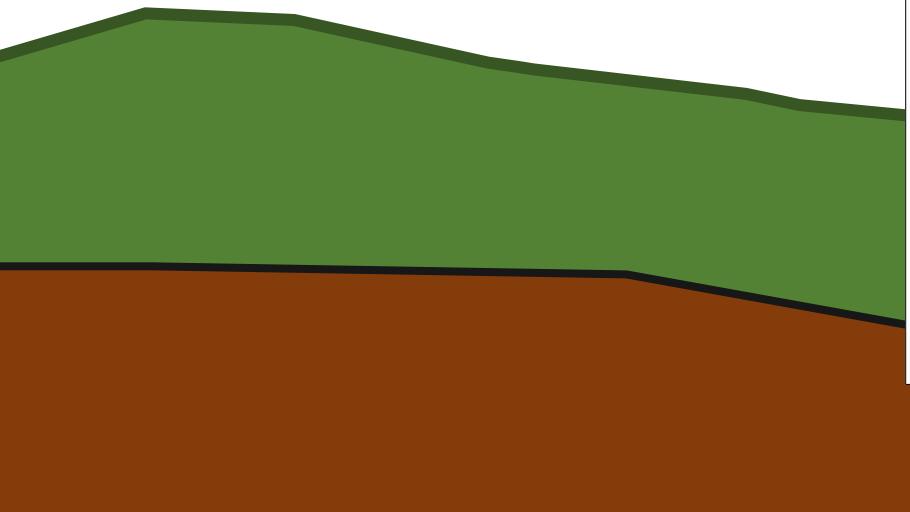
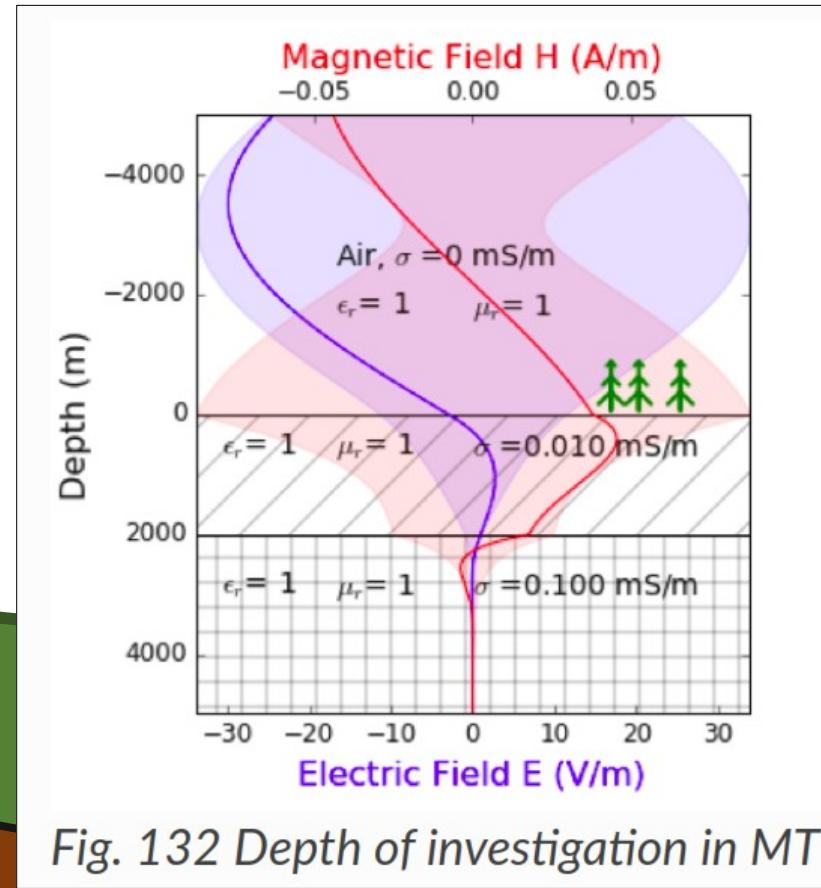


Fig. 132 Depth of investigation in MT

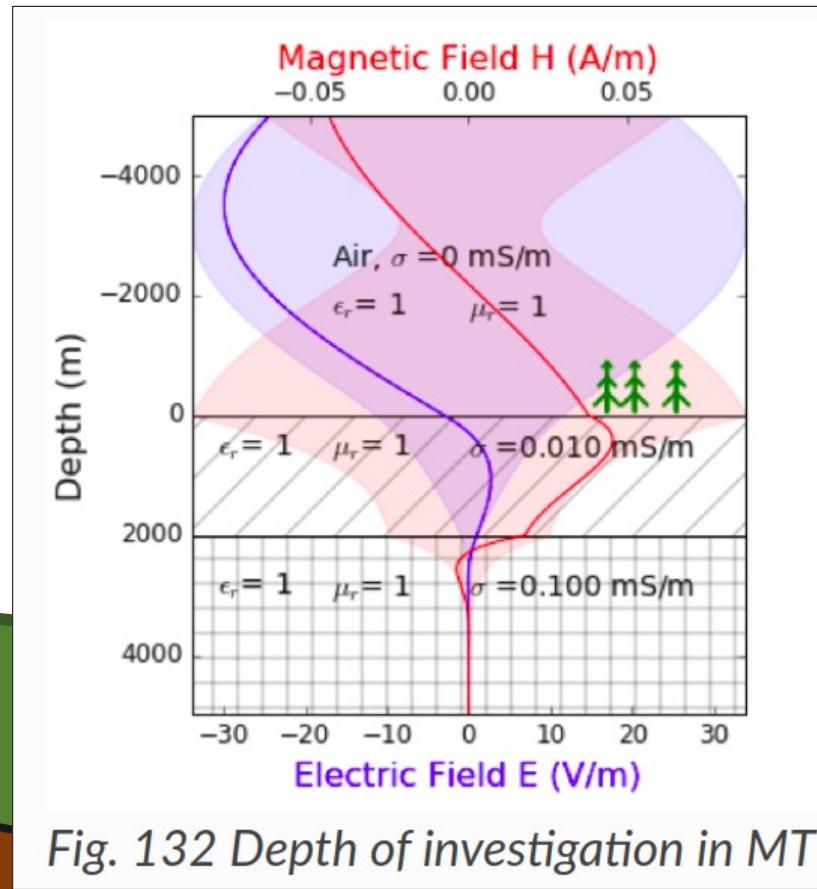


O Skin depth δ é definido como a profundidade em que o sinal decai a um fator $1/e$ ($\approx 36\%$).



O Skin depth δ é definido como a profundidade em que o sinal decai a um fator $1/e$ ($\approx 36\%$).

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}} \approx \frac{500}{\sqrt{\sigma f}}$$



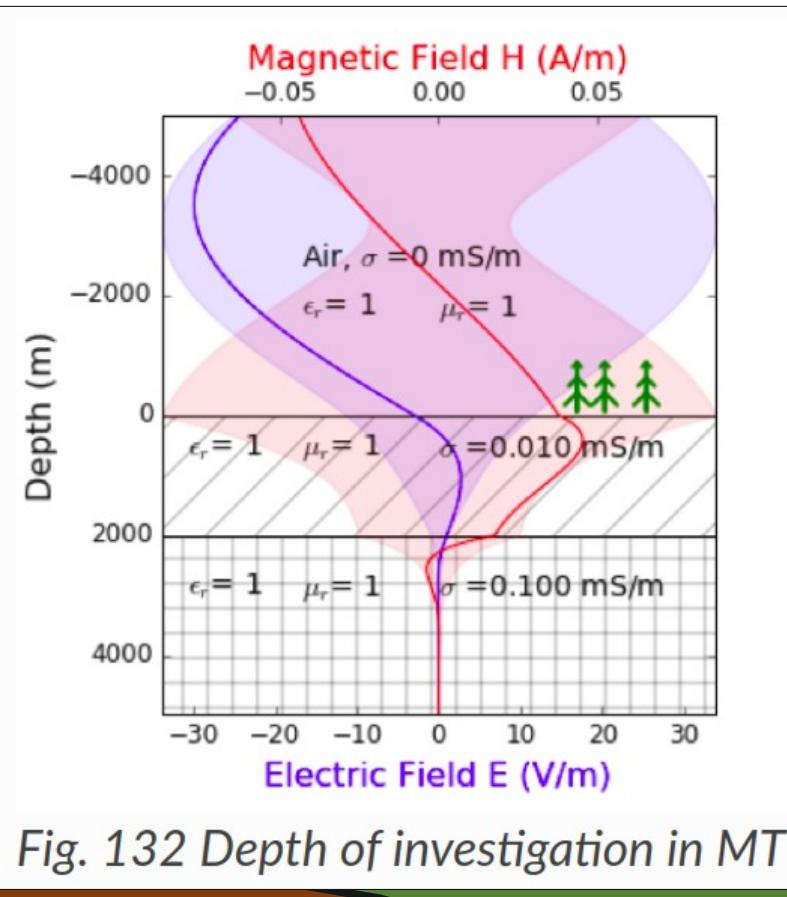
O Skin depth δ é definido como a profundidade em que o sinal decai a um fator $1/e$ ($\approx 36\%$).

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}} \approx \frac{500}{\sqrt{\sigma f}}$$

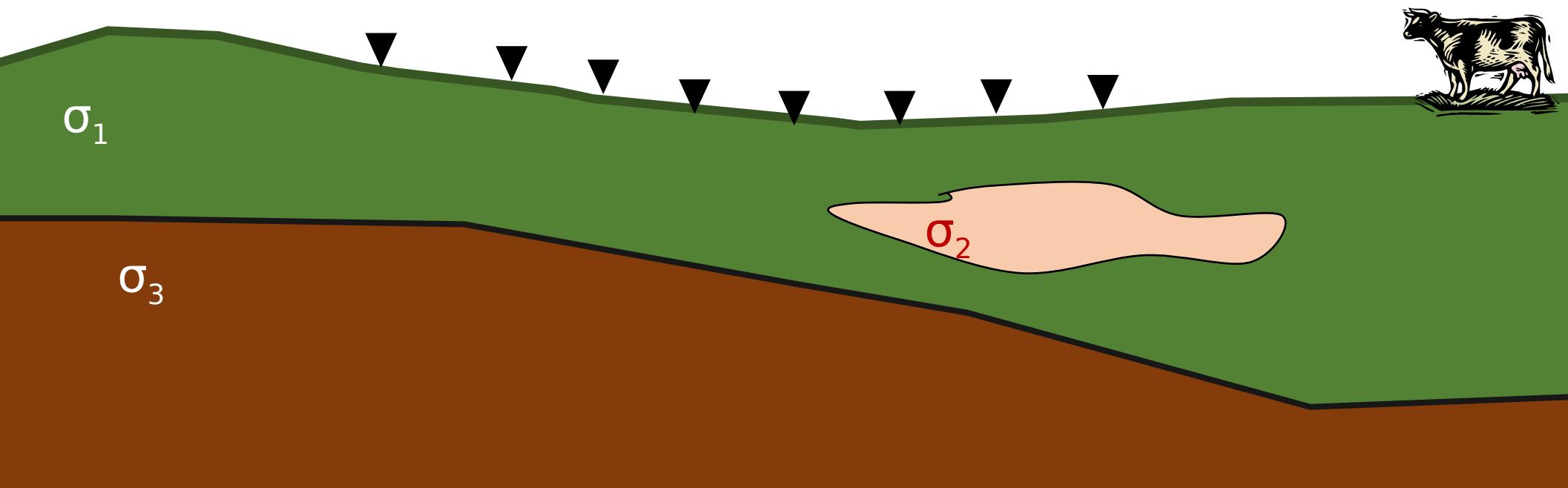
Quanto mais condutivo, mais rápido o decaimento.

Quanto menor a frequência, mais lento é o decaimento.

Frequências mais baixas – mais profundo
Frequências mais altas – mais razo

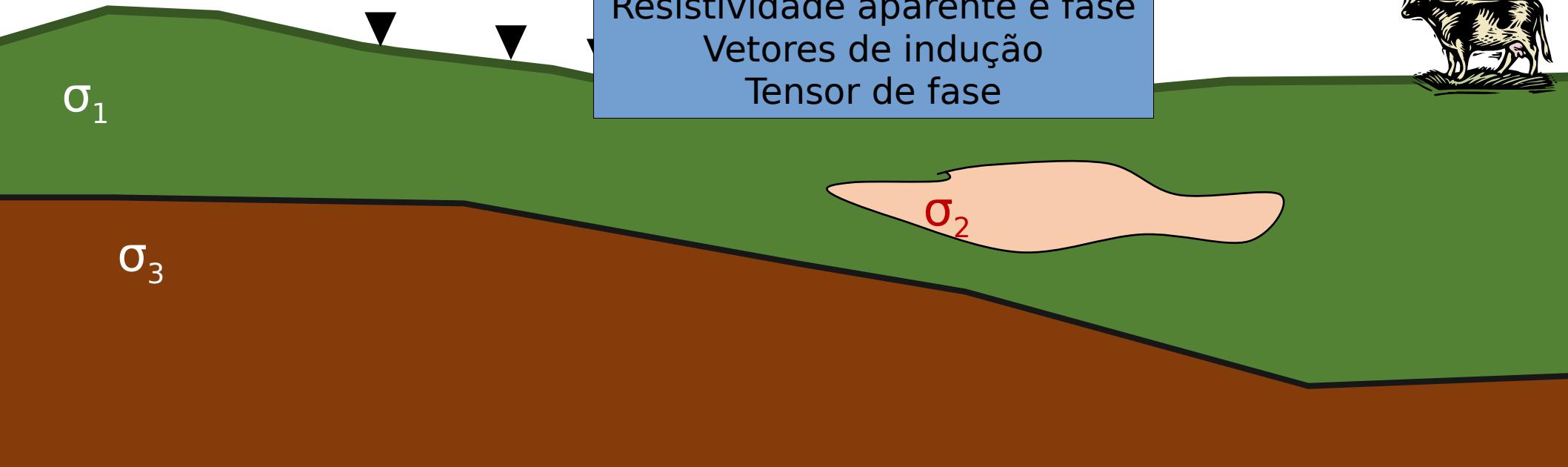


No domínio da frequência podemos calcular algumas quantidades que dependem da distribuição de condutividade



No domínio da frequência podemos calcular algumas quantidades que dependem da distribuição de condutividade

Tensor de impedância
Resistividade aparente e fase
Vetores de indução
Tensor de fase

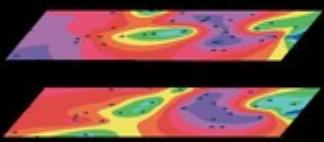


No domínio da frequência podemos calcular algumas quantidades que dependem da distribuição de condutividade

Tensor de impedância
Resistividade aparente e fase
Vetores de indução
Tensor de fase

Practical
Magnetotellurics

Fiona Simpson and Karsten Bahr



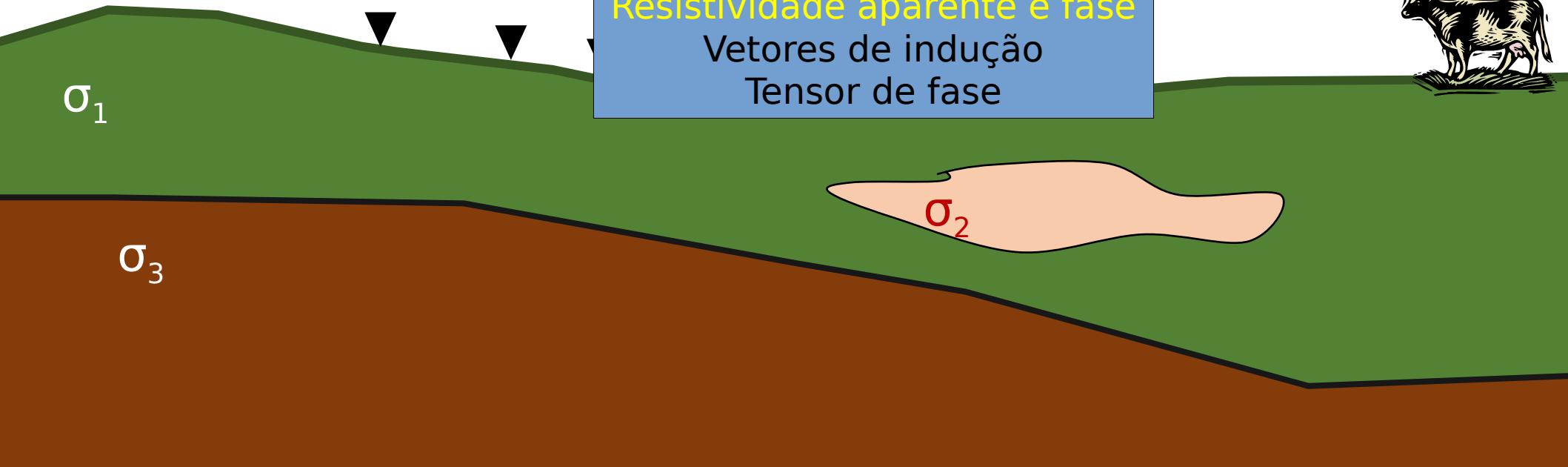
Publisher:
Online publication date:
Print publication year:
Online ISBN:
DOI:

Cambridge University Press
December 2009
2005
9780511614095
<https://doi.org/10.1017/CBO9780511614095>



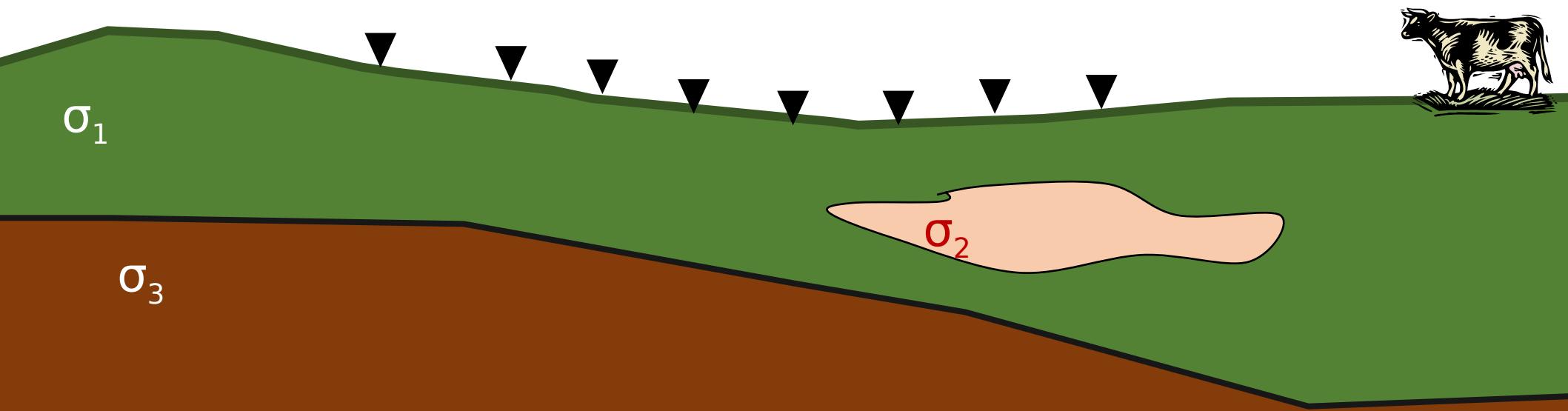
No domínio da frequência podemos calcular algumas quantidades que dependem da distribuição de condutividade

Tensor de impedância
Resistividade aparente e fase
Vetores de indução
Tensor de fase

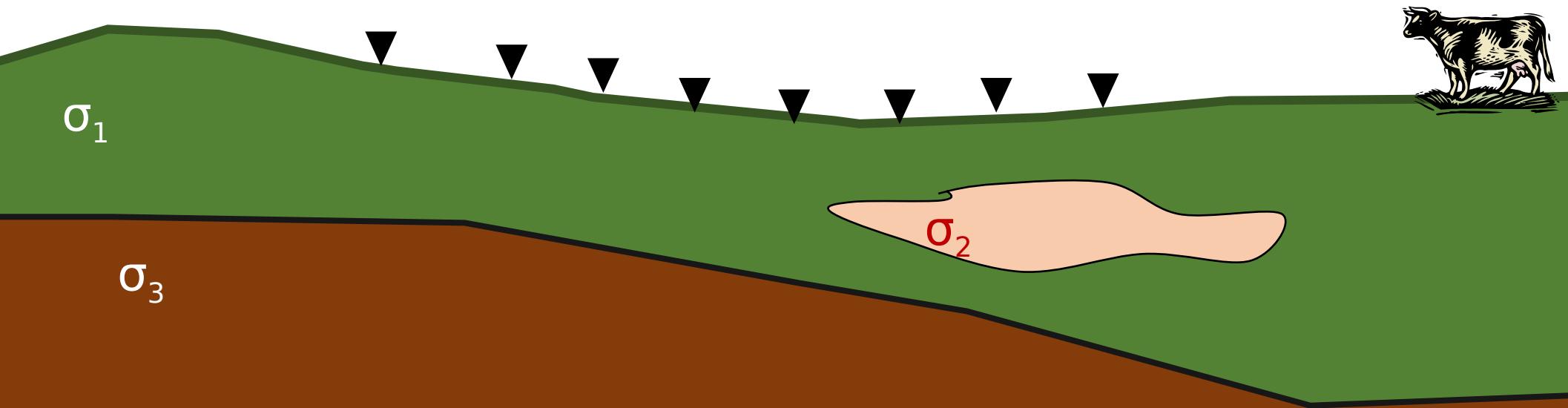


$$\begin{bmatrix} E_x \\ E_y \end{bmatrix}$$

$$\begin{bmatrix} H_x \\ H_y \end{bmatrix}$$



$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix} \begin{bmatrix} H_x \\ H_y \end{bmatrix}$$

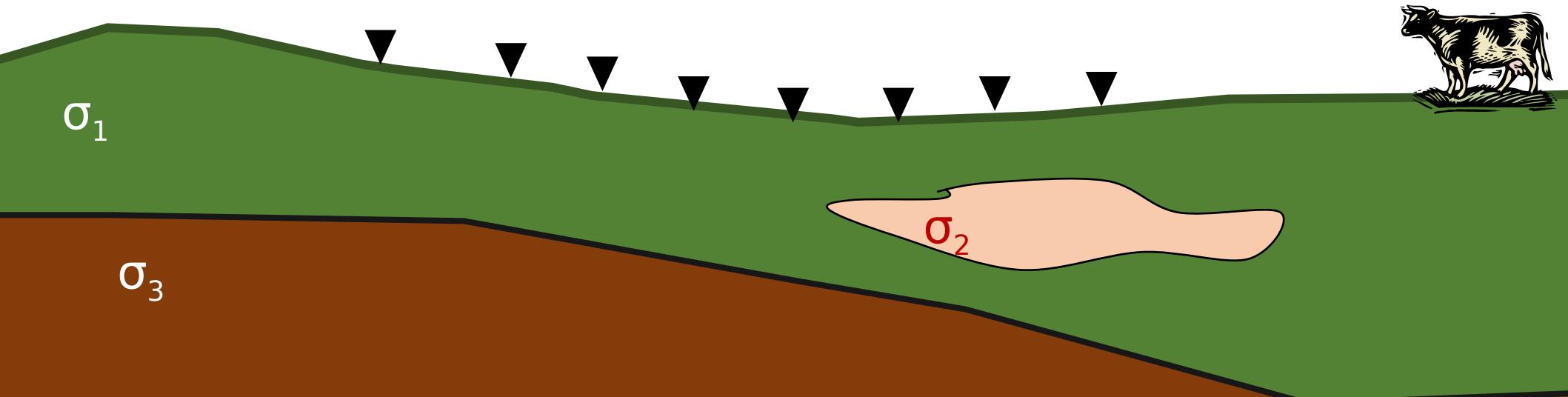
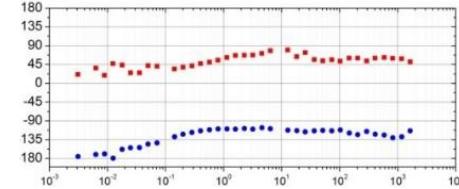
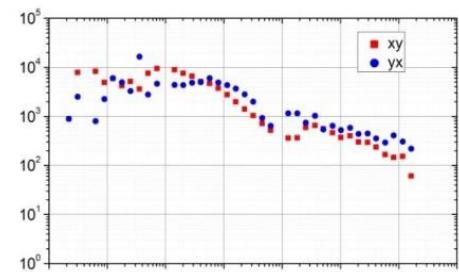


$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix} \begin{bmatrix} H_x \\ H_y \end{bmatrix}$$

Resistividade
aparente e fase

$$\rho_{xy} = \frac{1}{\omega \mu} |Z_{xy}|^2$$

$$\phi_{xy} = \tan^{-1} \left(\frac{\text{imag}(Z_{xy})}{\text{real}(Z_{xy})} \right)$$

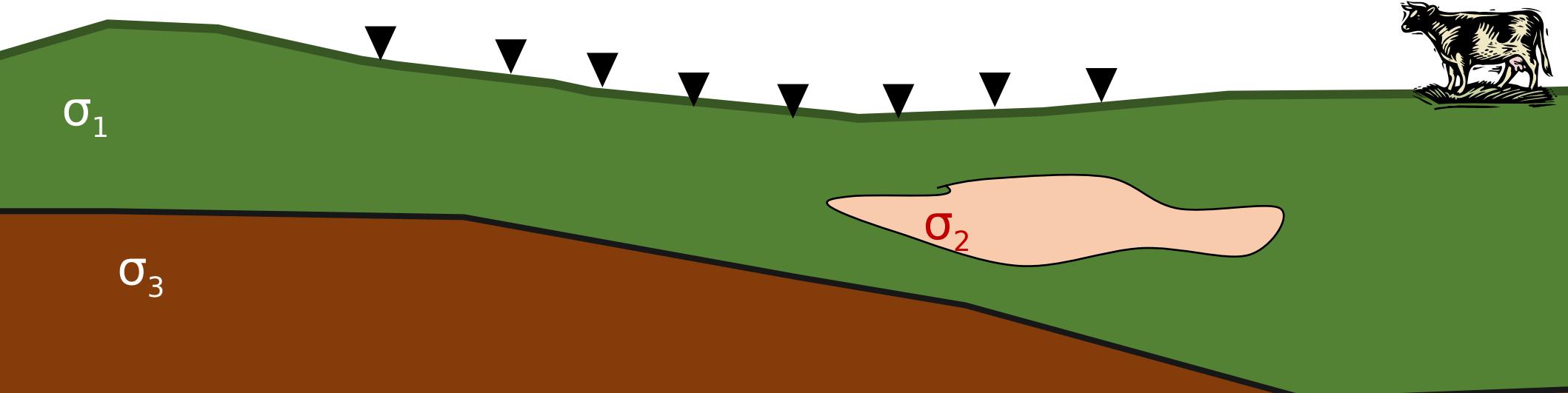
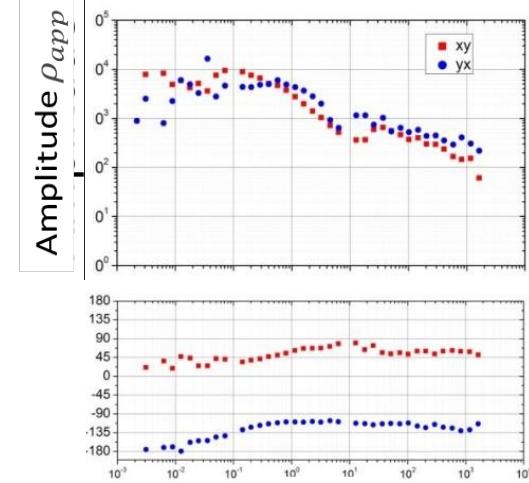


$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix} \begin{bmatrix} H_x \\ H_y \end{bmatrix}$$

Resistividade
aparente e fase

$$\rho_{xy} = \frac{1}{\omega \mu} |Z_{xy}|^2$$

$$\phi_{xy} = \tan^{-1} \left(\frac{\text{imag}(Z_{xy})}{\text{real}(Z_{xy})} \right)$$

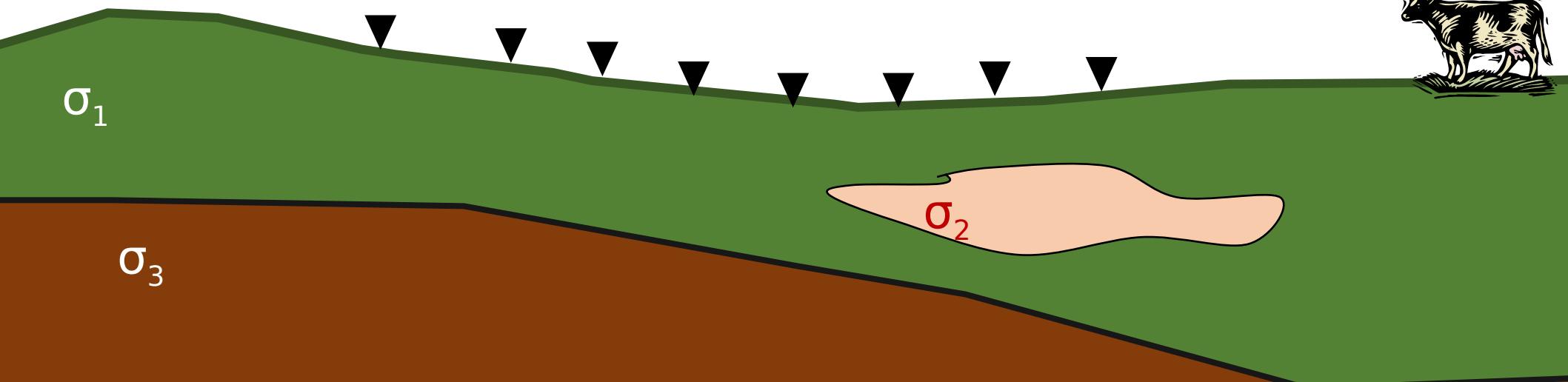
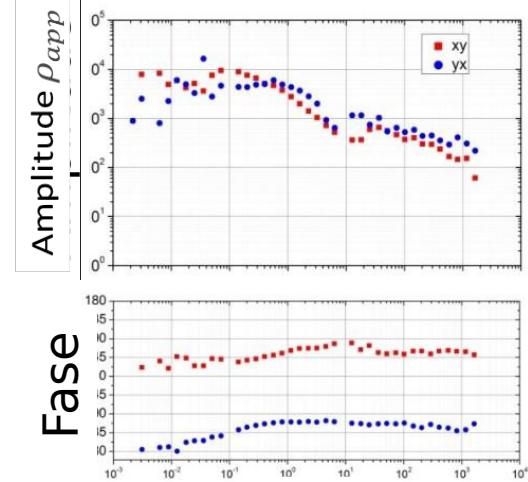


$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix} \begin{bmatrix} H_x \\ H_y \end{bmatrix}$$

Resistividade
aparente e fase

$$\rho_{xy} = \frac{1}{\omega \mu} |Z_{xy}|^2$$

$$\phi_{xy} = \tan^{-1} \left(\frac{\text{imag}(Z_{xy})}{\text{real}(Z_{xy})} \right)$$

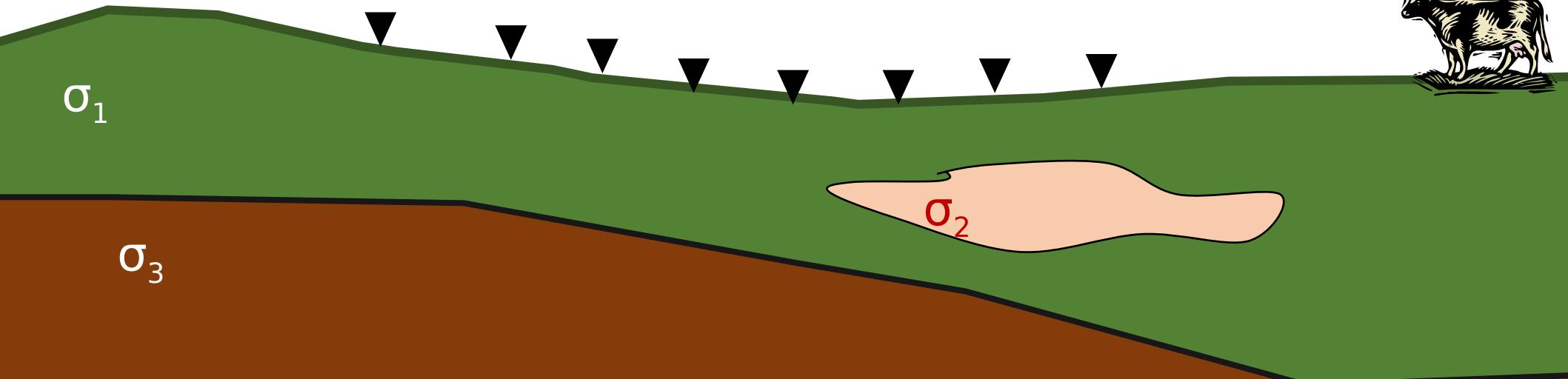
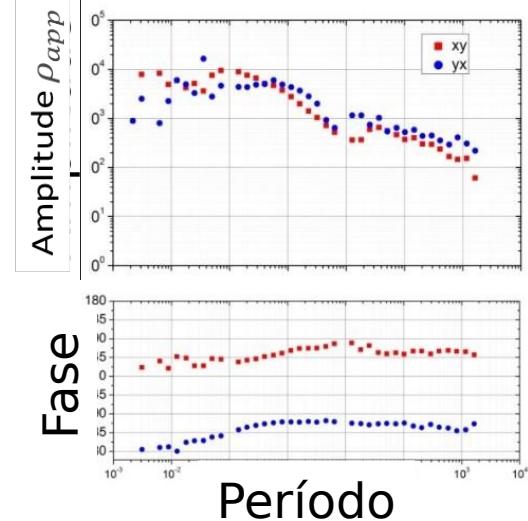


$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix} \begin{bmatrix} H_x \\ H_y \end{bmatrix}$$

Resistividade
aparente e fase

$$\rho_{xy} = \frac{1}{\omega\mu} |Z_{xy}|^2$$

$$\phi_{xy} = \tan^{-1} \left(\frac{\text{imag}(Z_{xy})}{\text{real}(Z_{xy})} \right)$$



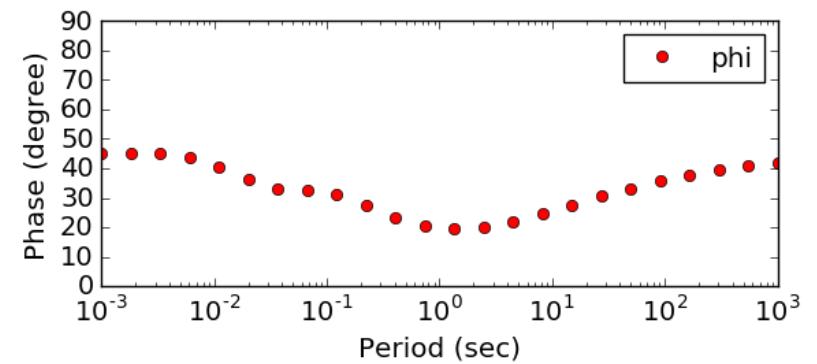
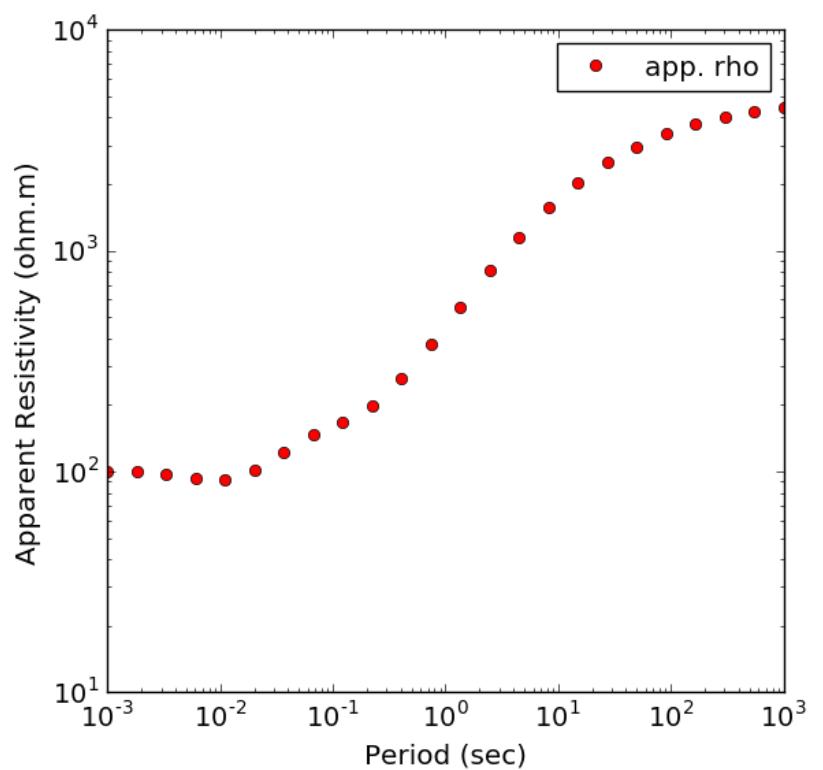
Referências Parte Teórica

- Nabighian, M. Electromagnetic Methods in Applied Geophysics: Volume 1, Theory. Society of Exploration Geophysicists, doi:10.1190/1.9781560802631
- Fitzpatrick, R. Maxwell's Equations and the Principles of Electromagnetism. Physics - Infinity Science Press, 1st Edition
- Cockett, R., Kang, S., Heagy, L. J., Pidlisecky, A., & Oldenburg, D. W. (2015). SimPEG: An open source framework for simulation and gradient based parameter estimation in geophysical applications. Computers & Geosciences.

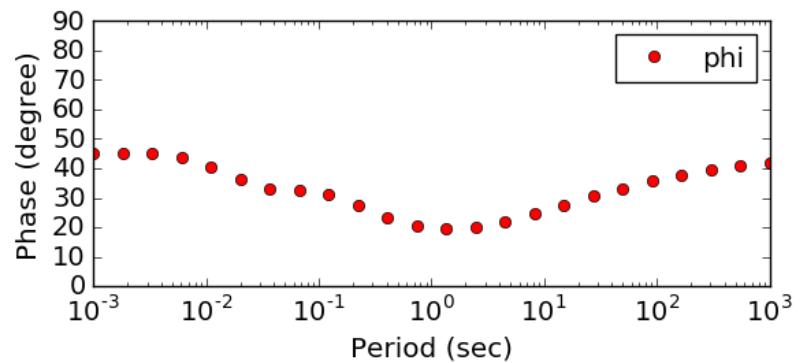
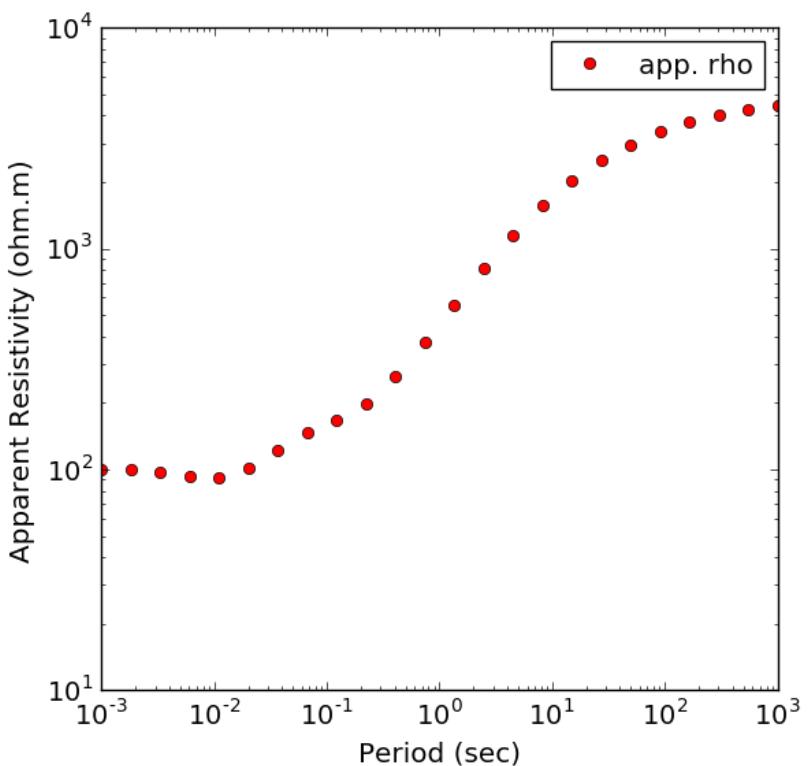
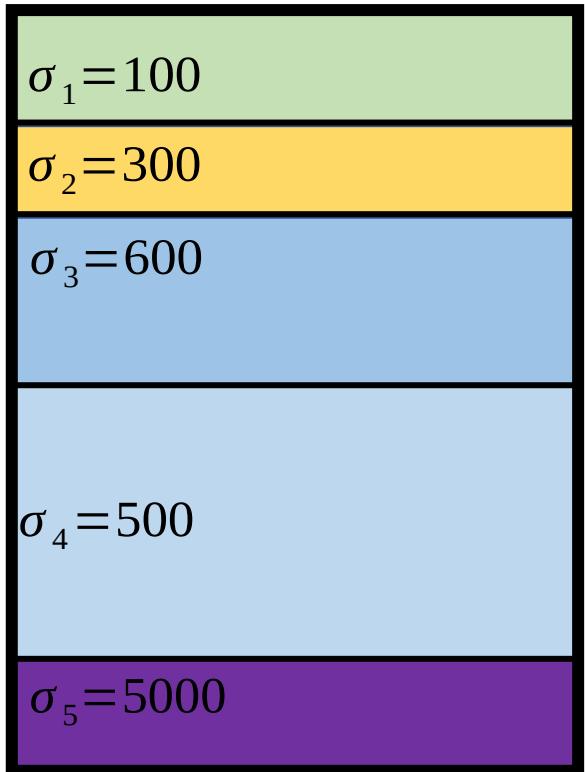
Interpretando ambientes geológicos com MT

Modelagem

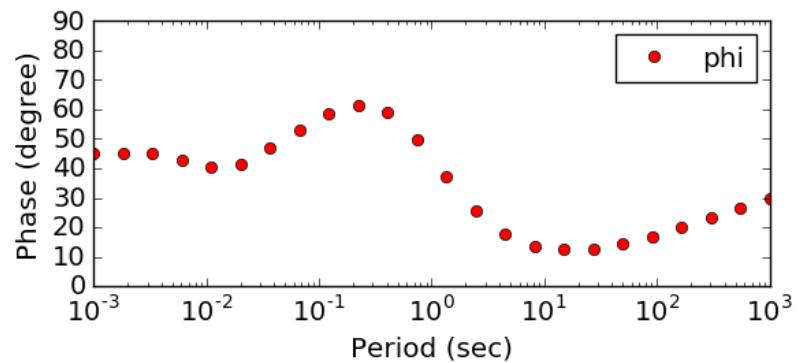
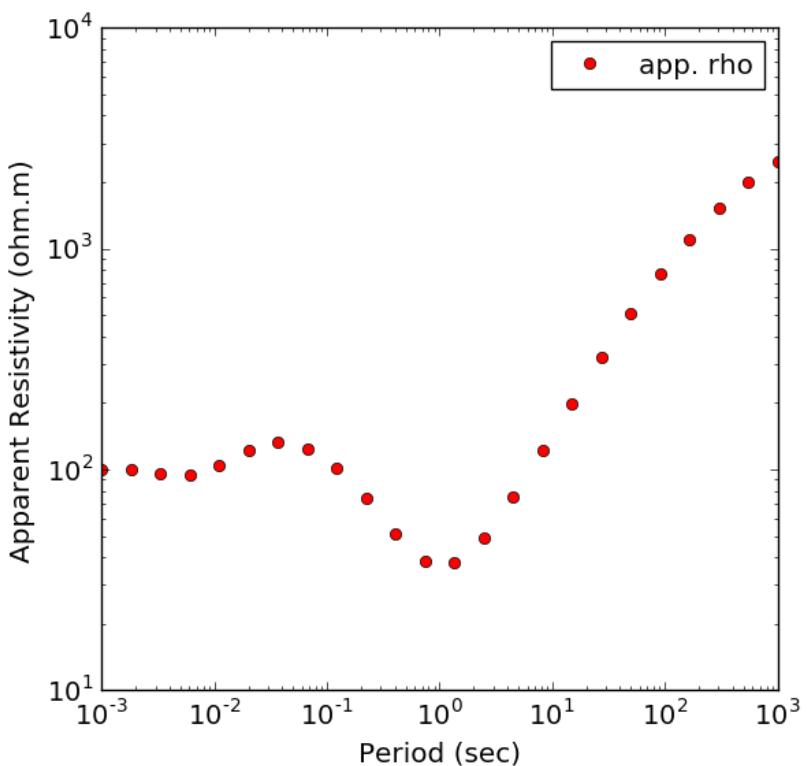
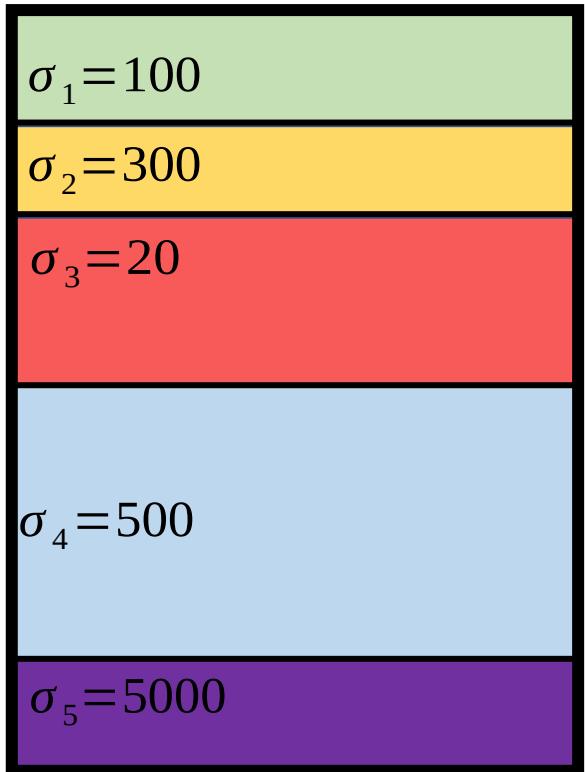
Inversão



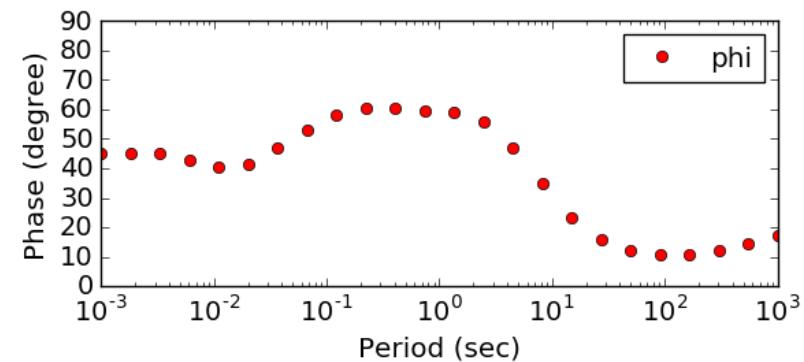
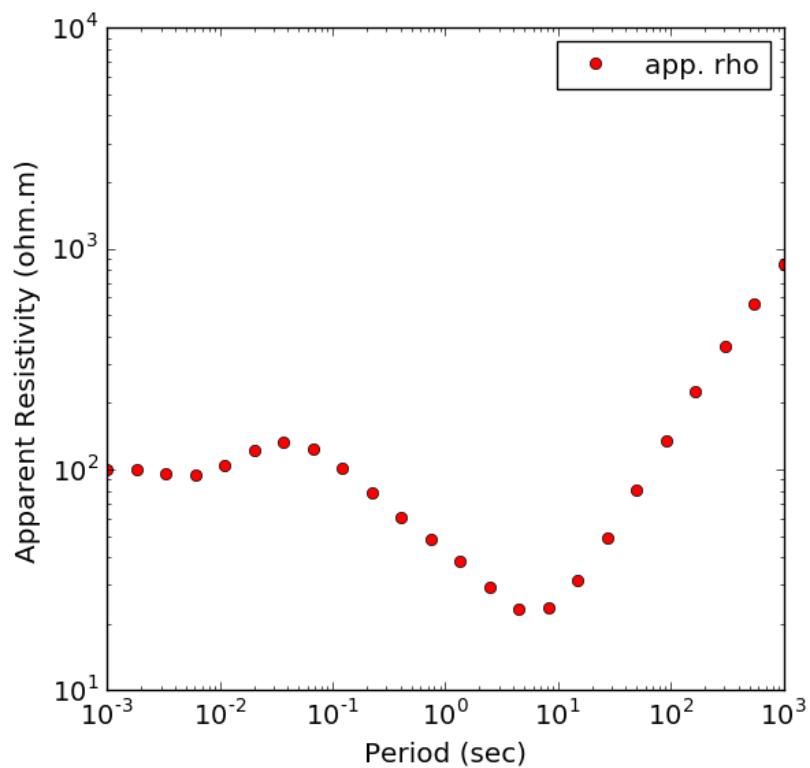
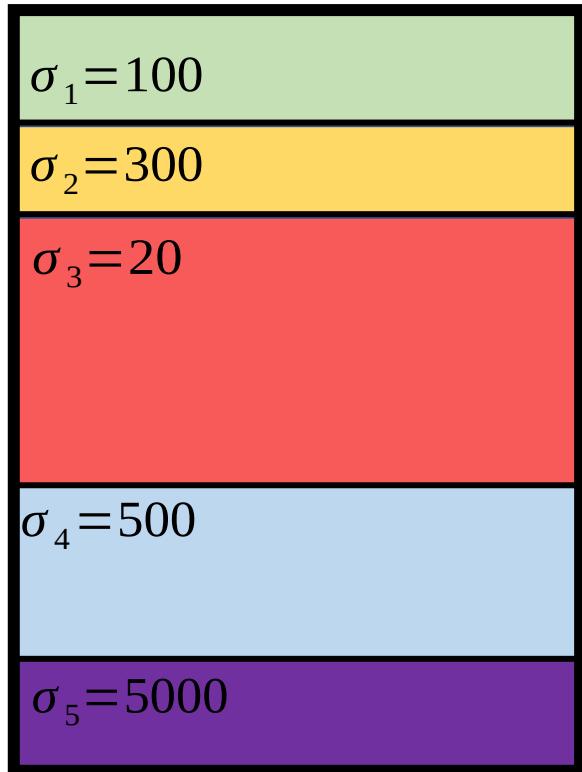
1D



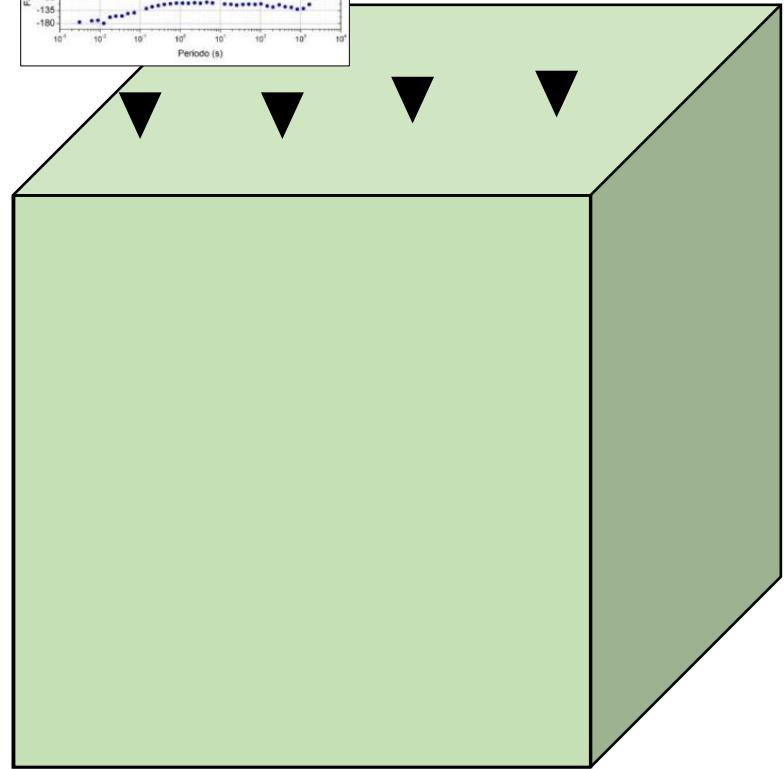
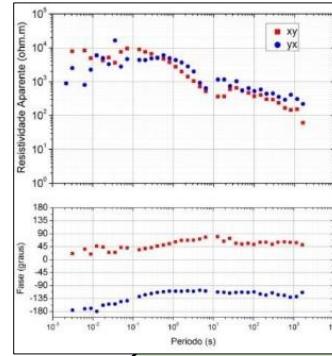
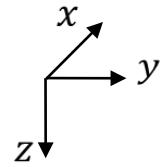
1D



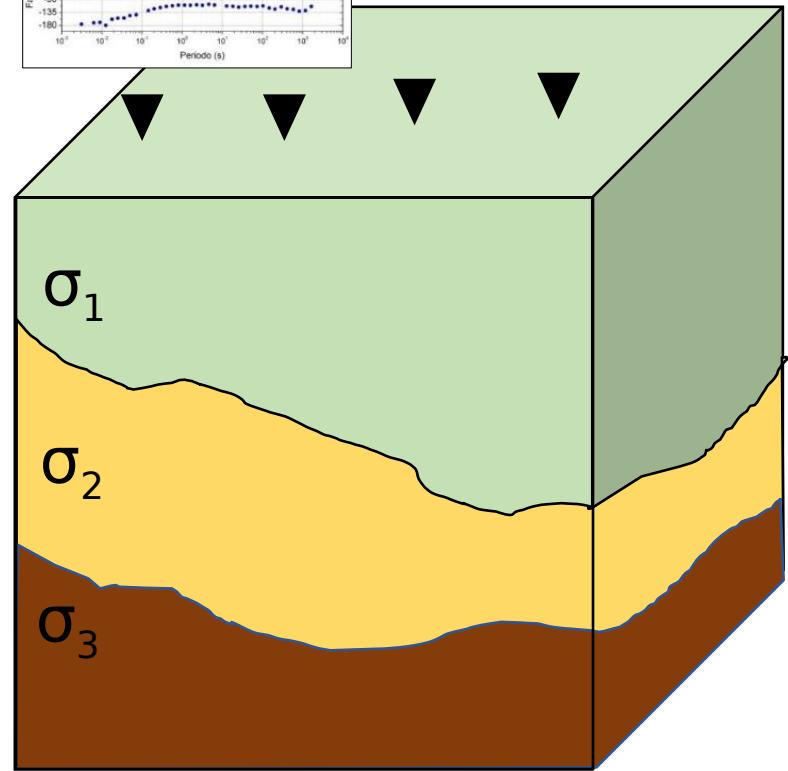
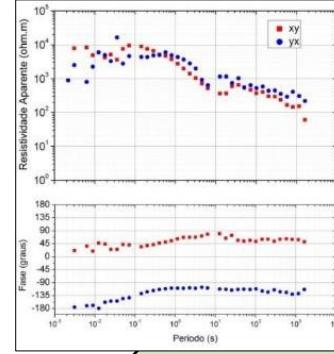
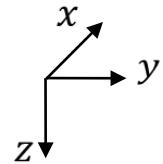
1D



Modelagem

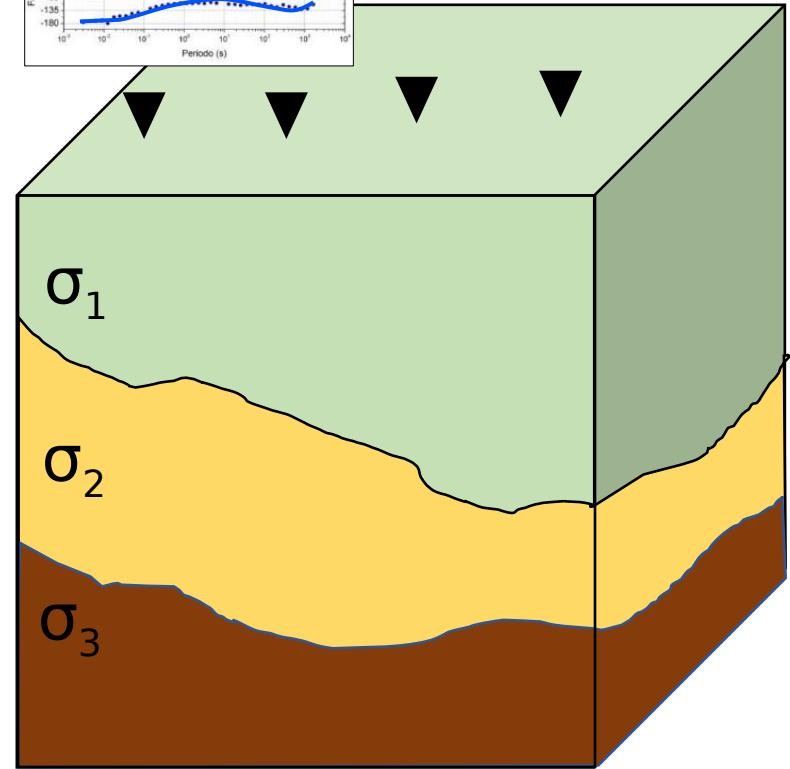
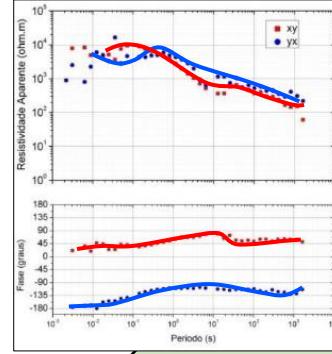


Modelagem



Modelagem

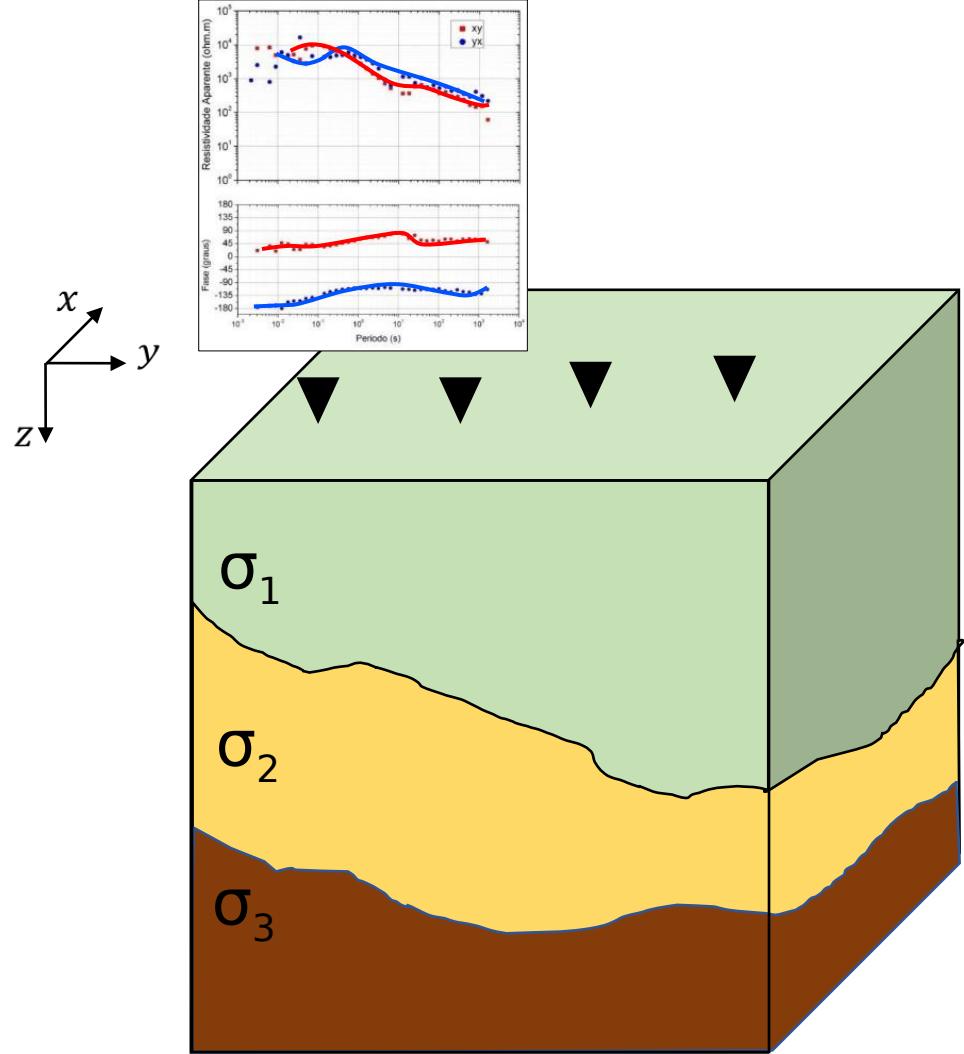
x
 y
 z



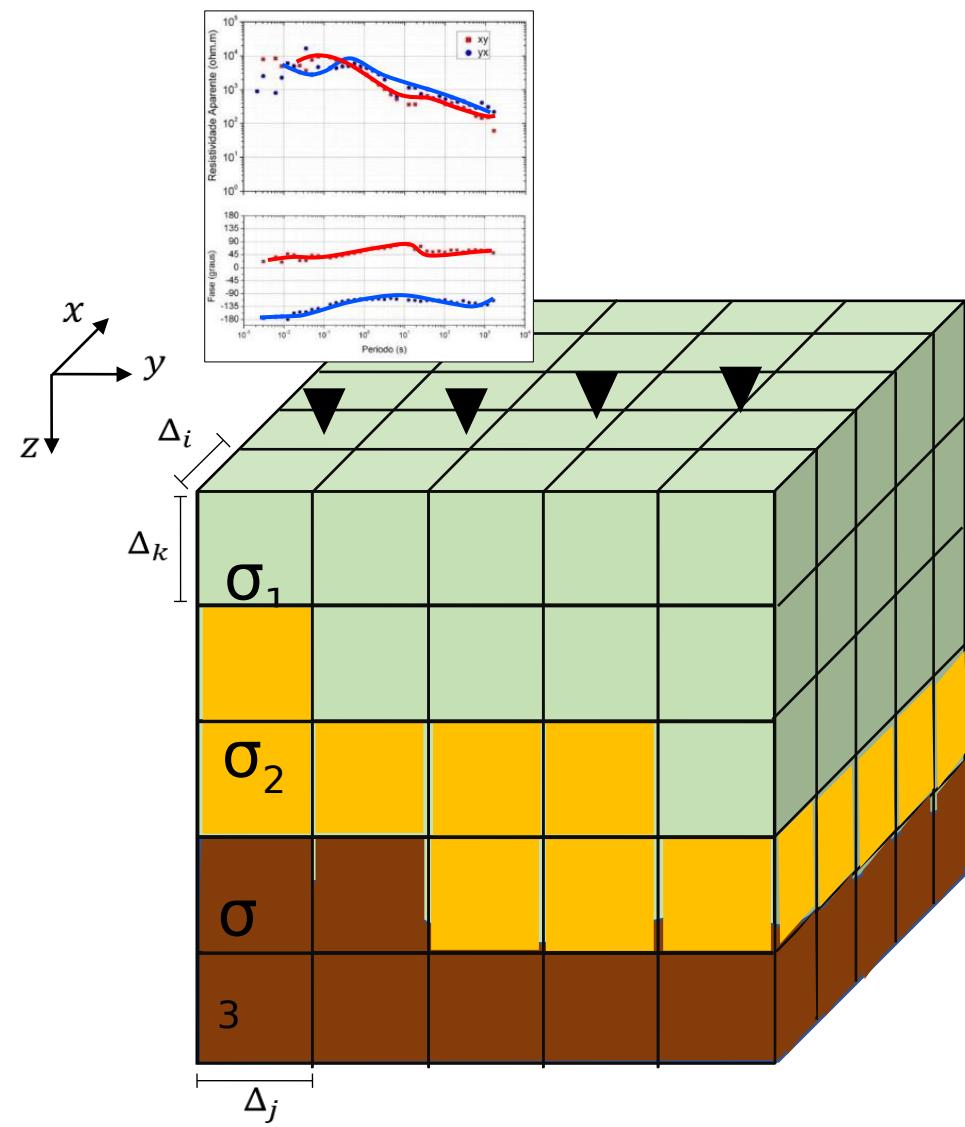
Modelagem

$$\nabla \times \nabla \times \mathbf{E} + i\mu\omega\sigma\mathbf{E} = 0$$

Diferenças Finitas

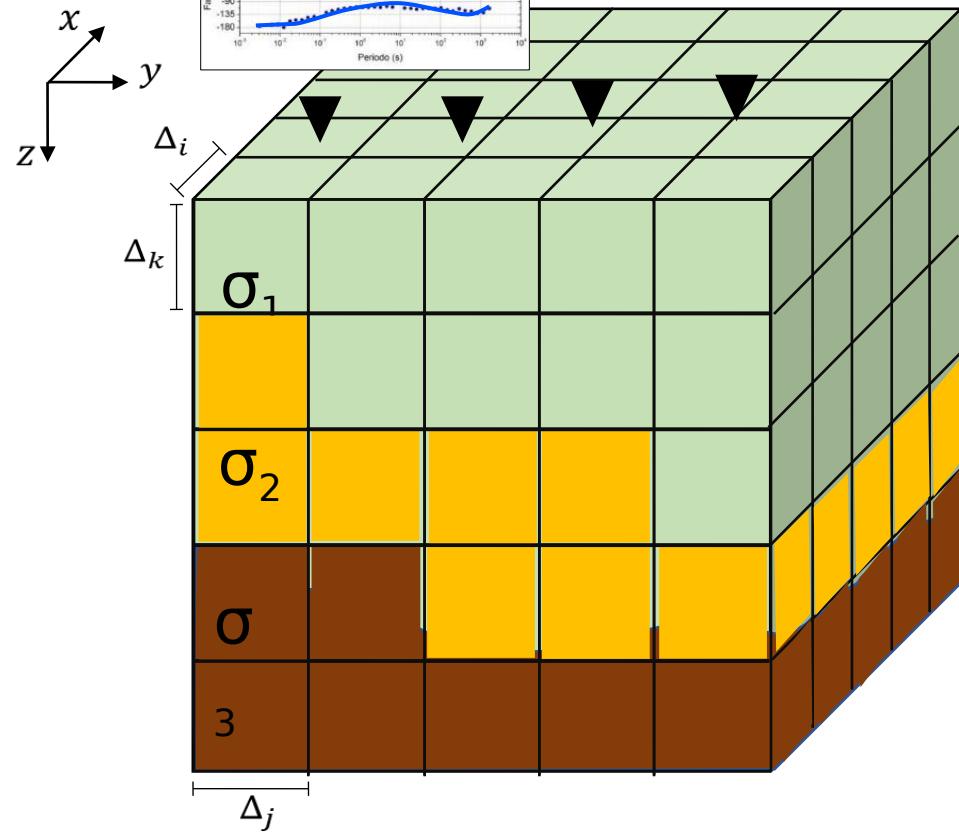


Modelagem



Modelagem

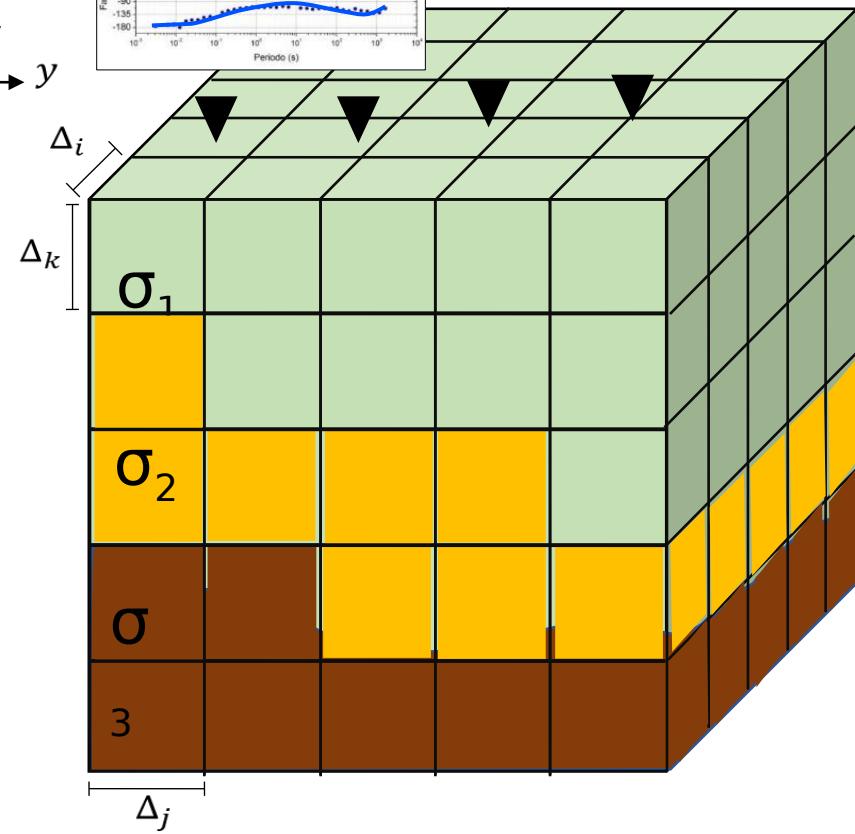
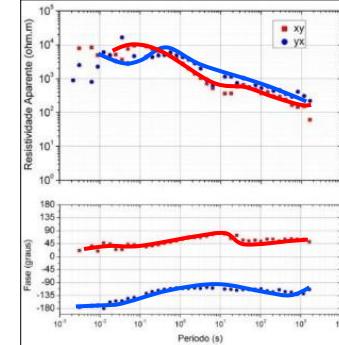
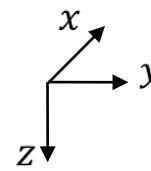
Dimensões e
condutividade
conhecidas



Modelagem

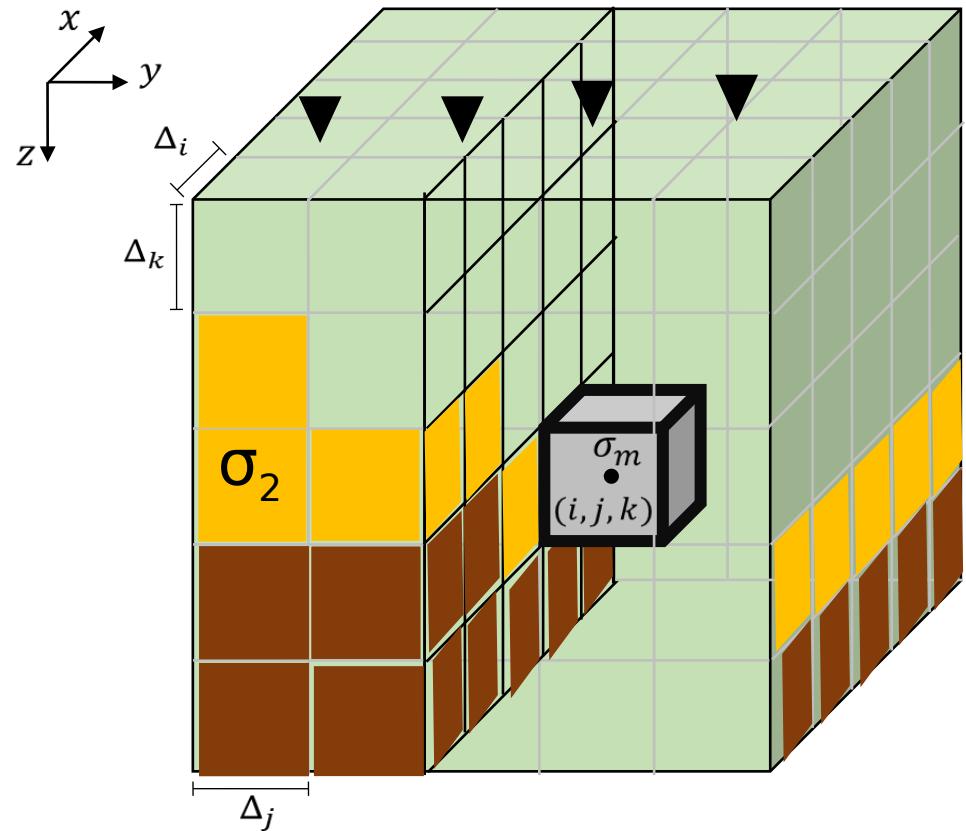
Vetor de parâmetros

$$\boldsymbol{\sigma} = \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \vdots \\ \sigma_M \end{bmatrix}$$

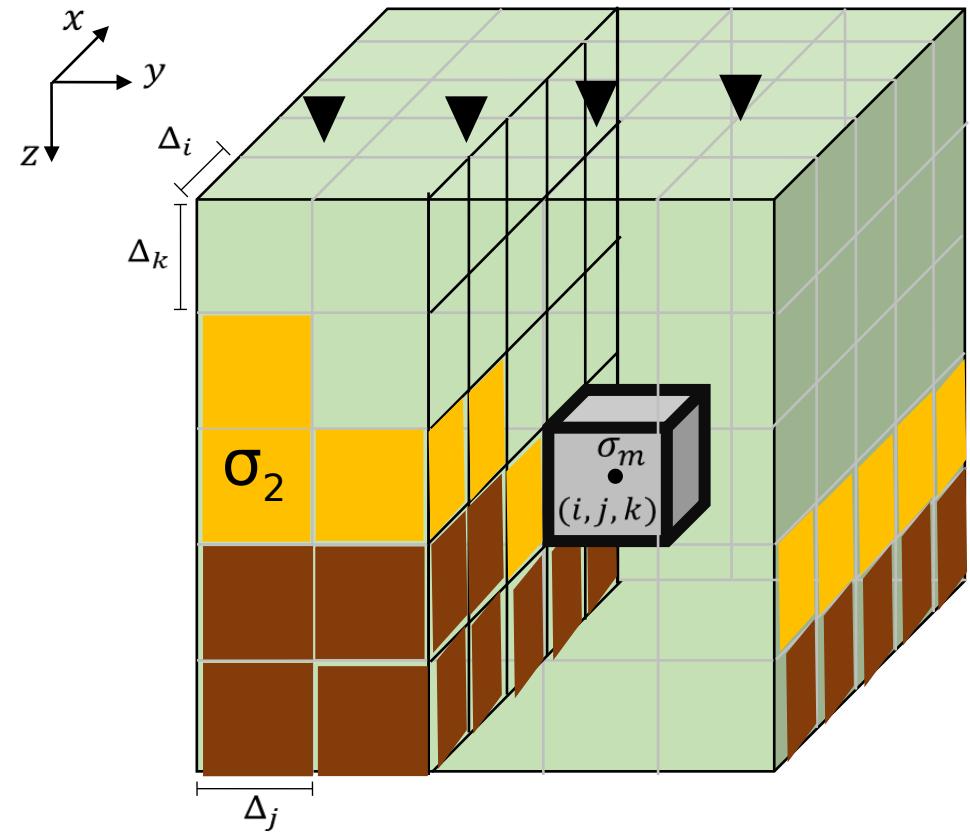
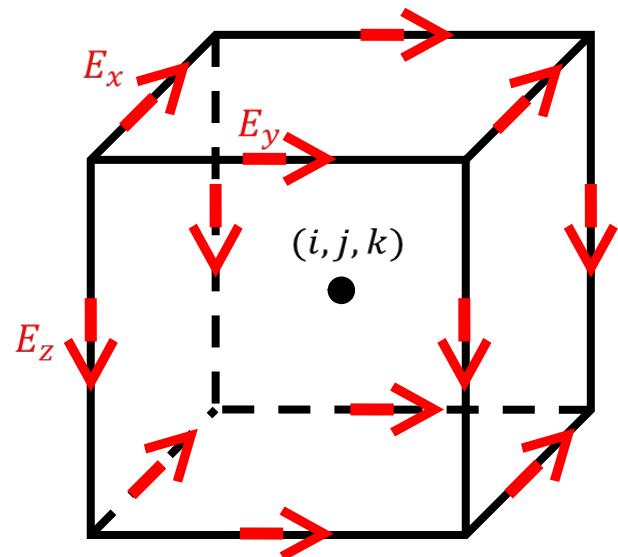


Modelagem

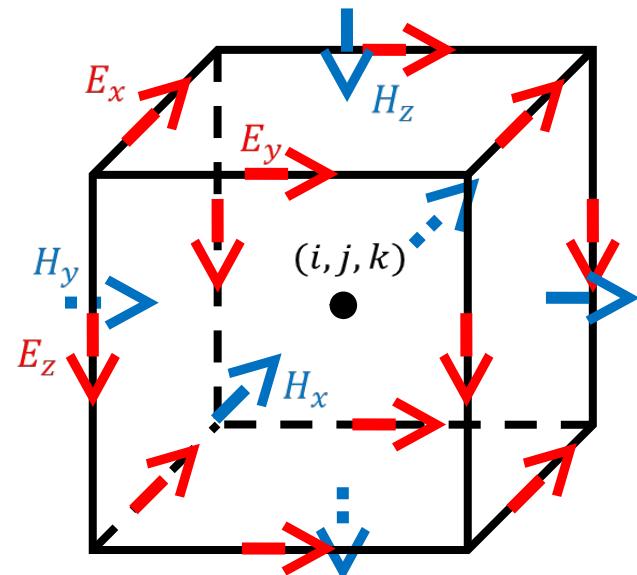
Calcula-se o
campo elétrico
para cada
prisma



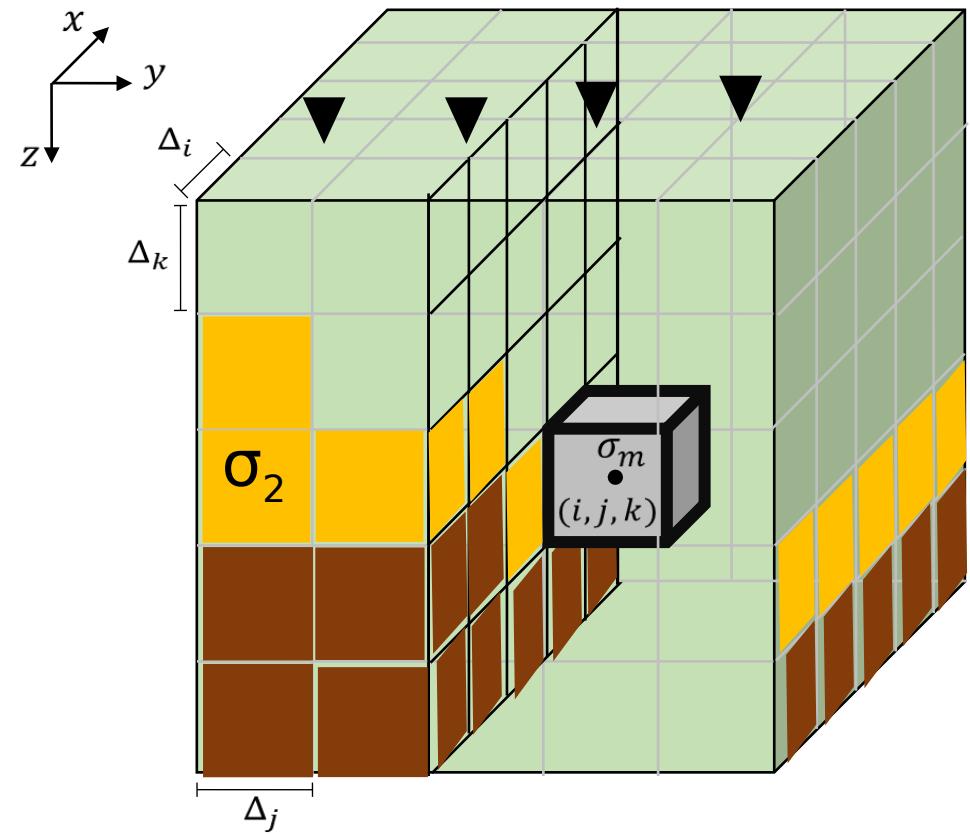
Modelagem



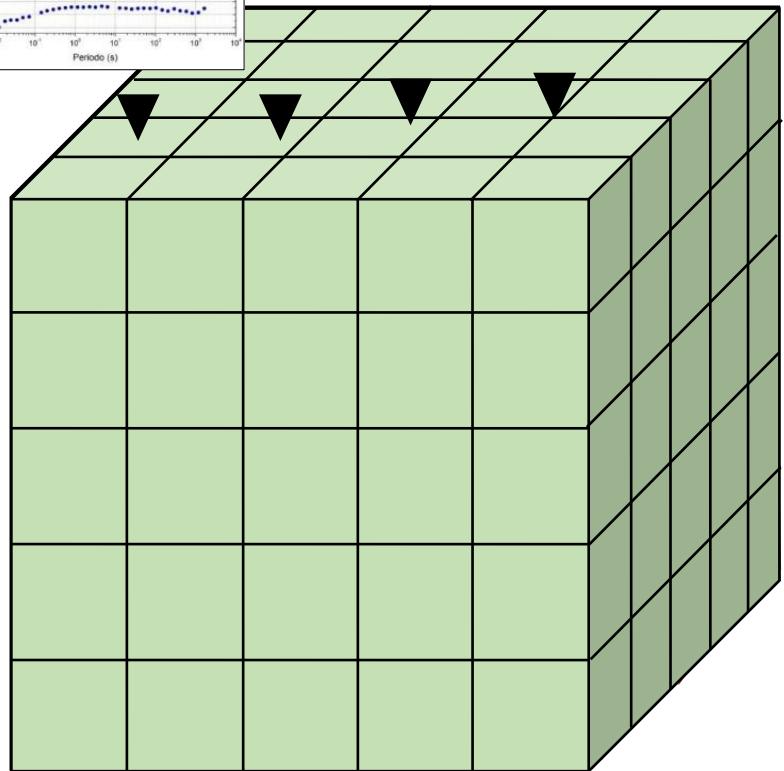
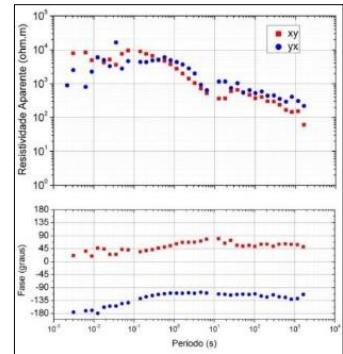
Modelagem



$$\mathbf{H} = (-i\mu\omega)^{-1} \nabla \times \mathbf{E} = 0$$

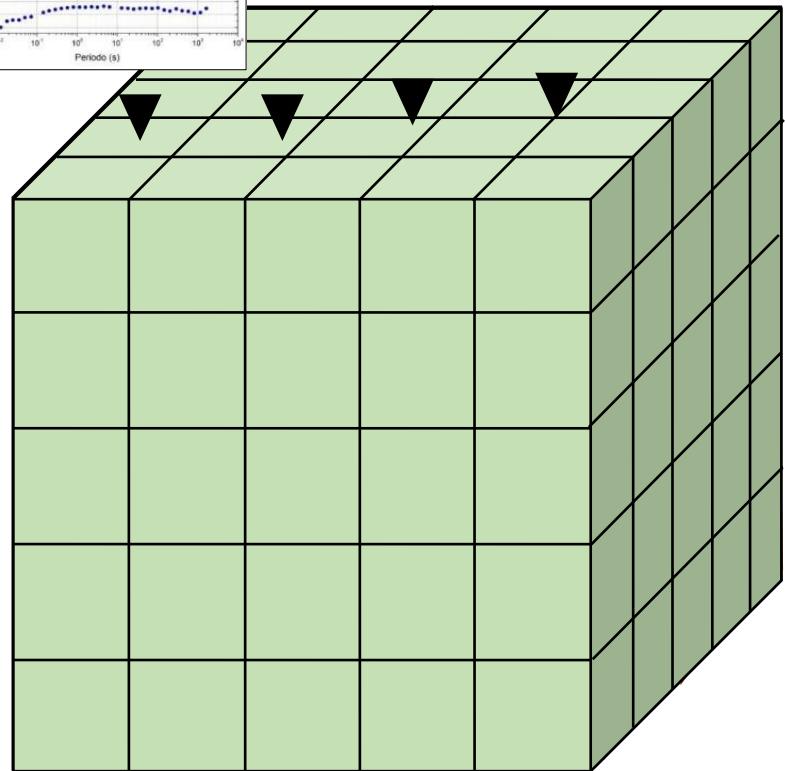
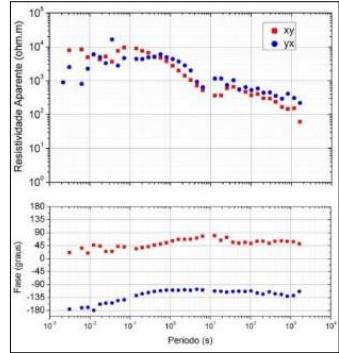


Inversão



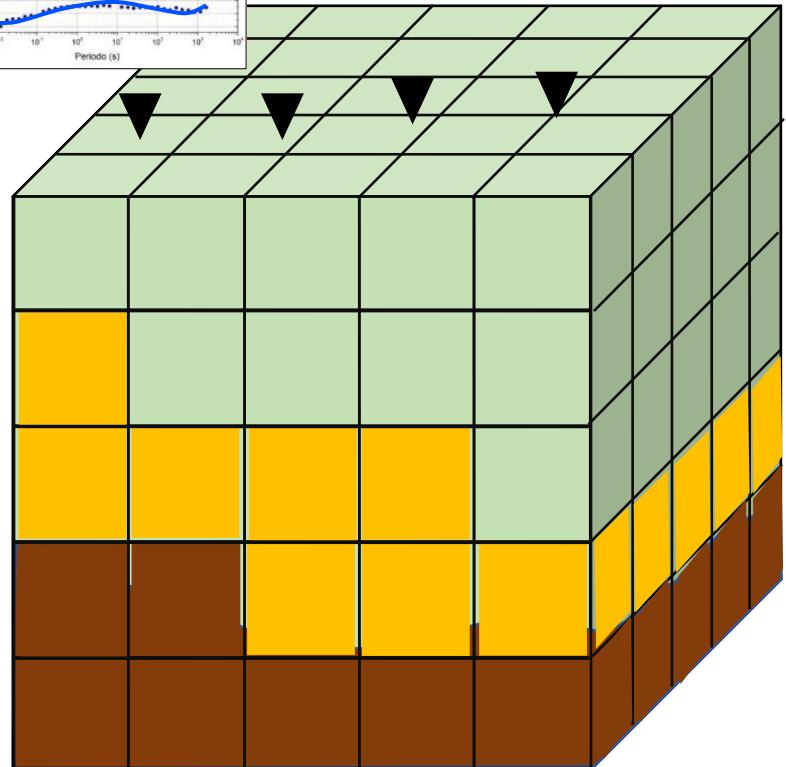
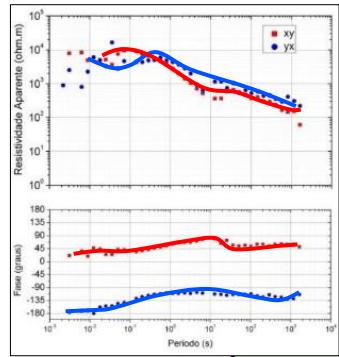
Inversão

$$\mathbf{d} = \begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_N \end{bmatrix}$$

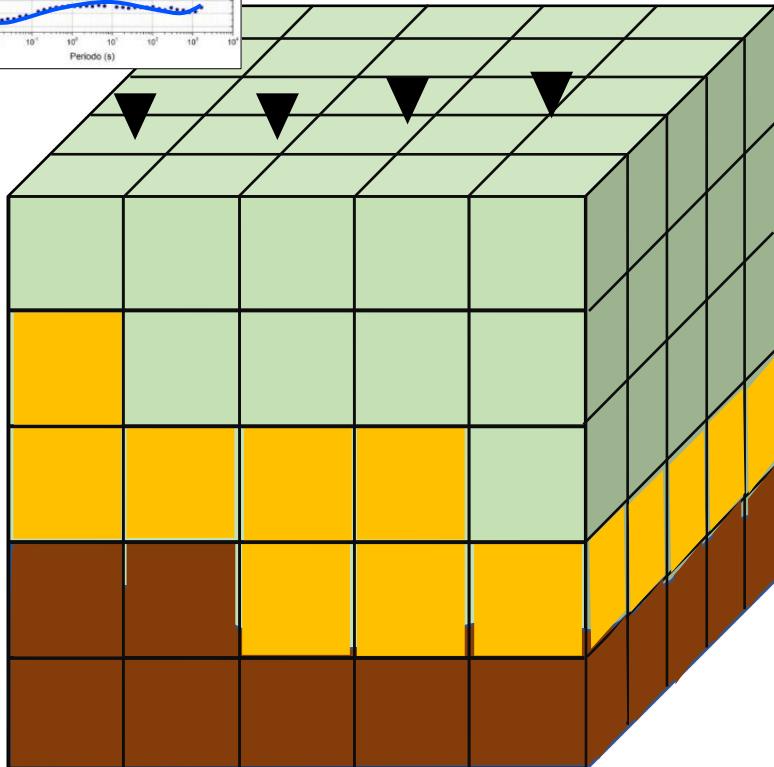
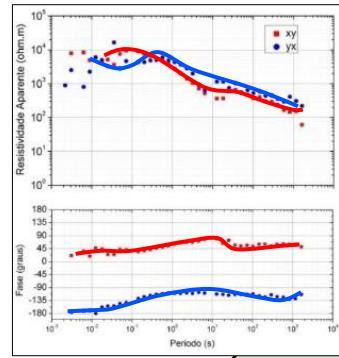


Inversão

$$\mathbf{d} = \begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_N \end{bmatrix} \approx \mathbf{d}(\sigma) = \begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_N \end{bmatrix}$$

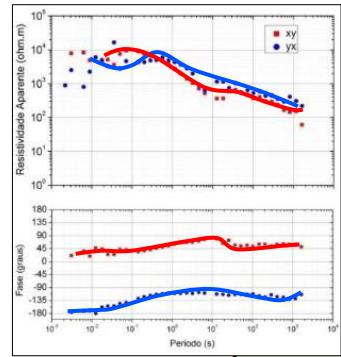


Inversão



$$\Phi(\boldsymbol{\sigma}) = [\mathbf{d} - \mathbf{d}(\boldsymbol{\sigma})]^T \mathbf{C}_d^{-1} [\mathbf{d} - \mathbf{d}(\boldsymbol{\sigma})] - \nu [\boldsymbol{\sigma} - \boldsymbol{\sigma}_0]^T \mathbf{C}_{\boldsymbol{\sigma}}^{-1} [\boldsymbol{\sigma} - \boldsymbol{\sigma}_0]$$

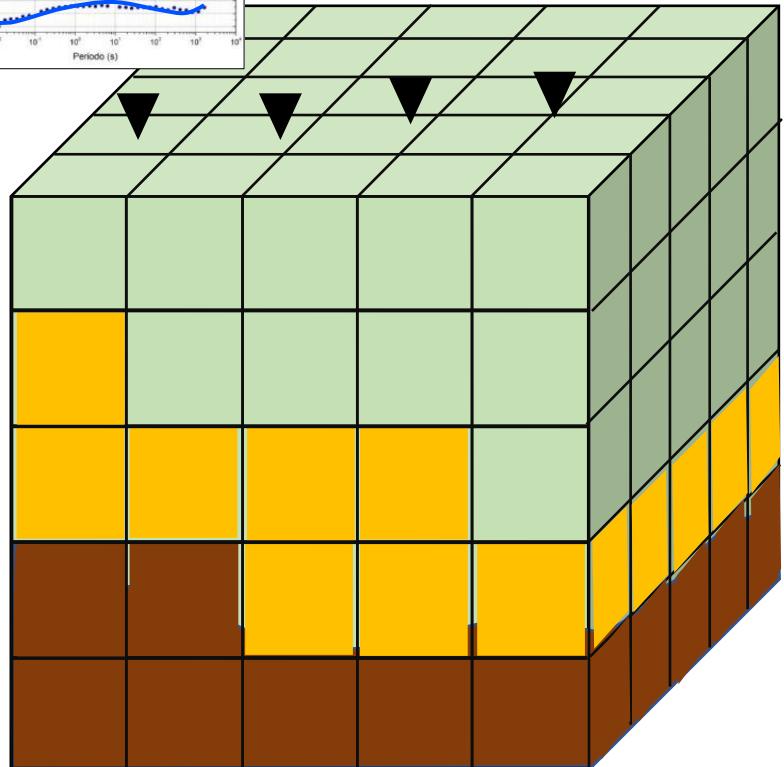
Inversão



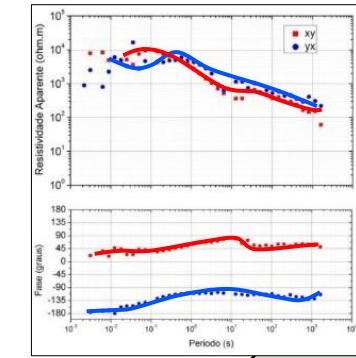
$$\Phi(\boldsymbol{\sigma}) = [\mathbf{d} - \mathbf{d}(\boldsymbol{\sigma})]^T \mathbf{C}_d^{-1} [\mathbf{d} - \mathbf{d}(\boldsymbol{\sigma})] - \nu [\boldsymbol{\sigma} - \boldsymbol{\sigma}_0]^T \mathbf{C}_{\boldsymbol{\sigma}}^{-1} [\boldsymbol{\sigma} - \boldsymbol{\sigma}_0]$$



Vetor de
dados
observad
os



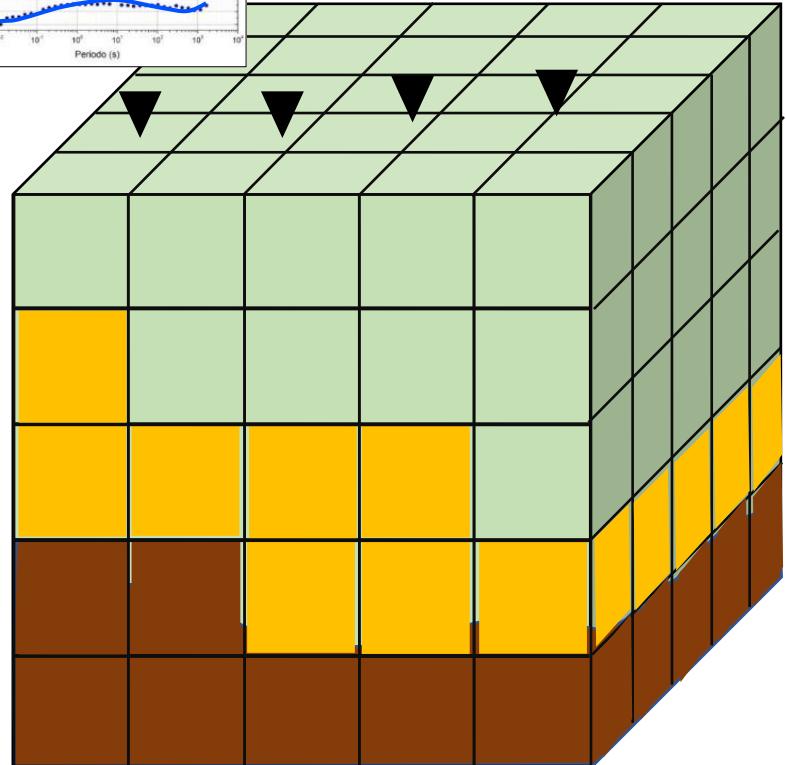
Inversão



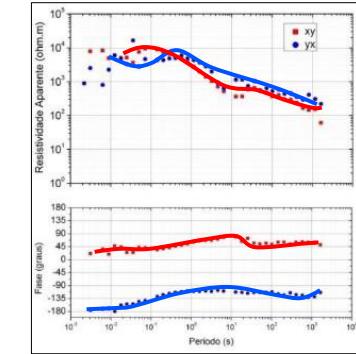
$$\Phi(\boldsymbol{\sigma}) = [\mathbf{d} - \mathbf{d}(\boldsymbol{\sigma})]^T \mathbf{C}_d^{-1} [\mathbf{d} - \mathbf{d}(\boldsymbol{\sigma})] - \nu [\boldsymbol{\sigma} - \boldsymbol{\sigma}_0]^T \mathbf{C}_{\boldsymbol{\sigma}}^{-1} [\boldsymbol{\sigma} - \boldsymbol{\sigma}_0]$$



Vetor de
dados
preditos



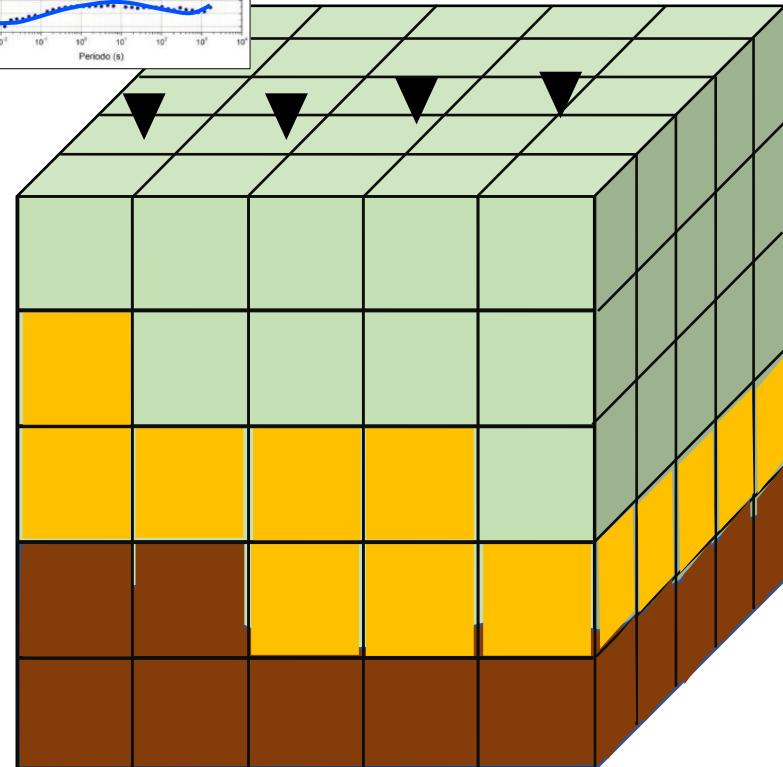
Inversão



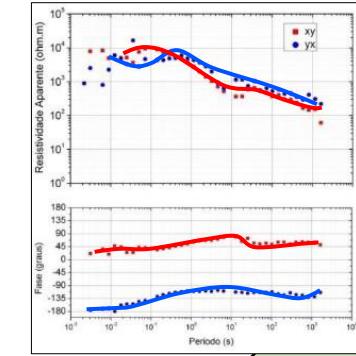
$$\Phi(\boldsymbol{\sigma}) = [\mathbf{d} - \mathbf{d}(\boldsymbol{\sigma})]^T \mathbf{C}_d^{-1} [\mathbf{d} - \mathbf{d}(\boldsymbol{\sigma})] - \nu [\boldsymbol{\sigma} - \boldsymbol{\sigma}_0]^T \mathbf{C}_{\boldsymbol{\sigma}}^{-1} [\boldsymbol{\sigma} - \boldsymbol{\sigma}_0]$$



Matriz de covariânc
ia



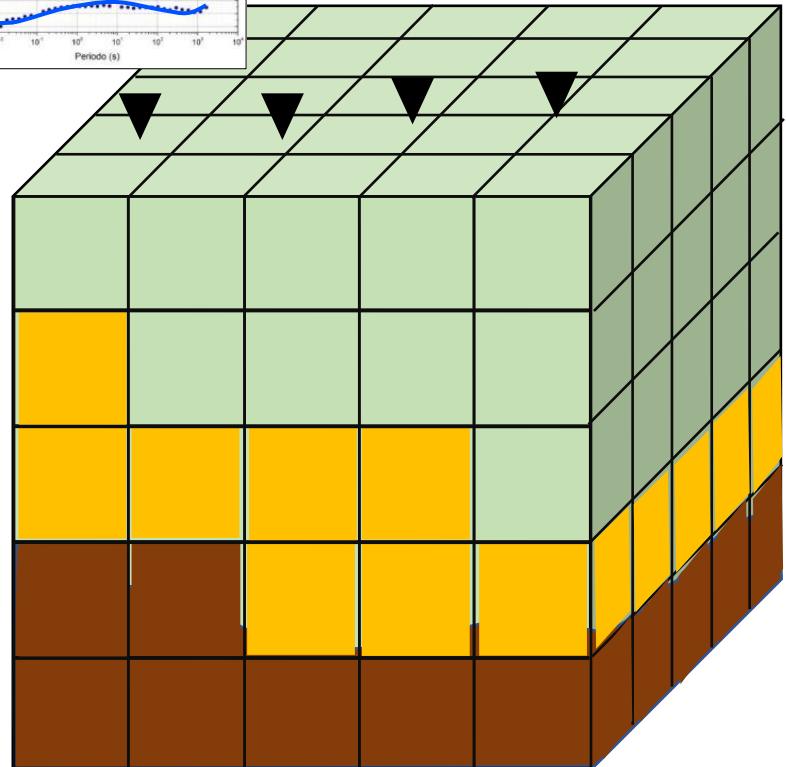
Inversão



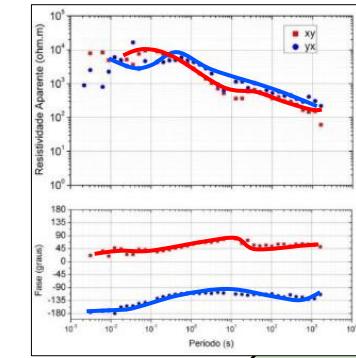
$$\Phi(\boldsymbol{\sigma}) = [\mathbf{d} - \mathbf{d}(\boldsymbol{\sigma})]^T \mathbf{C}_d^{-1} [\mathbf{d} - \mathbf{d}(\boldsymbol{\sigma})] - \nu [\boldsymbol{\sigma} - \boldsymbol{\sigma}_0]^T \mathbf{C}_{\boldsymbol{\sigma}}^{-1} [\boldsymbol{\sigma} - \boldsymbol{\sigma}_0]$$



Vetor de
parâmetr
os

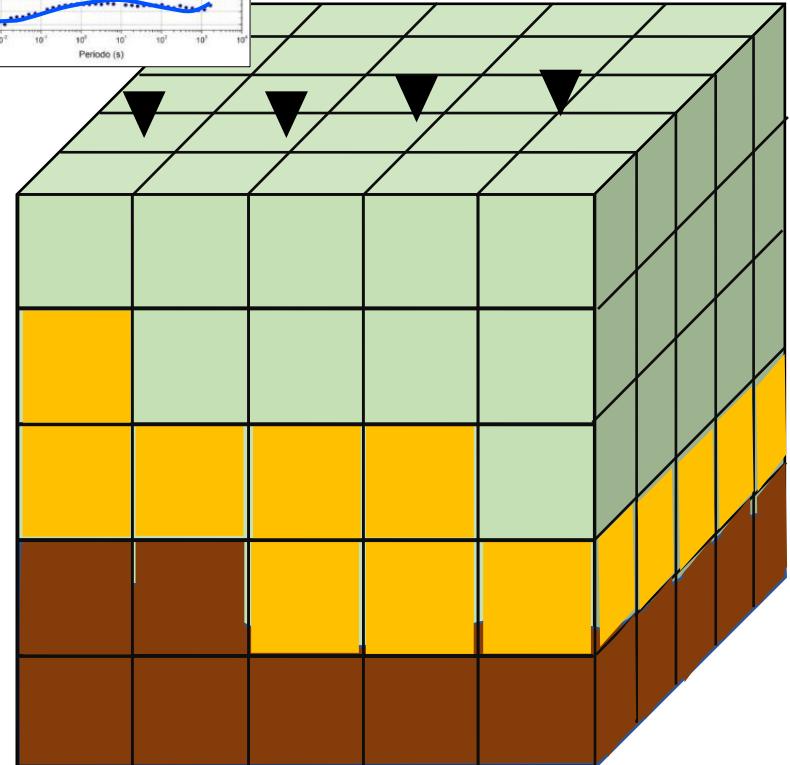


Inversão

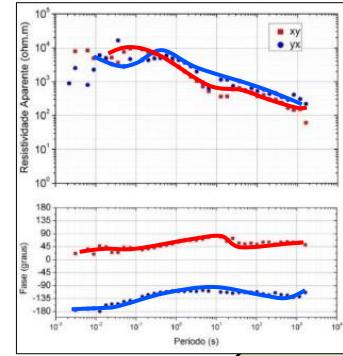


$\Phi(\sigma) = [\mathbf{d} - \mathbf{d}(\sigma)]^T \mathbf{C}_d^{-1} [\mathbf{d} - \mathbf{d}(\sigma)] - \nu [\sigma - \sigma_0]^T \mathbf{C}_\sigma^{-1} [\sigma - \sigma_0]$

↑
Modelo a priori ou chute inicial



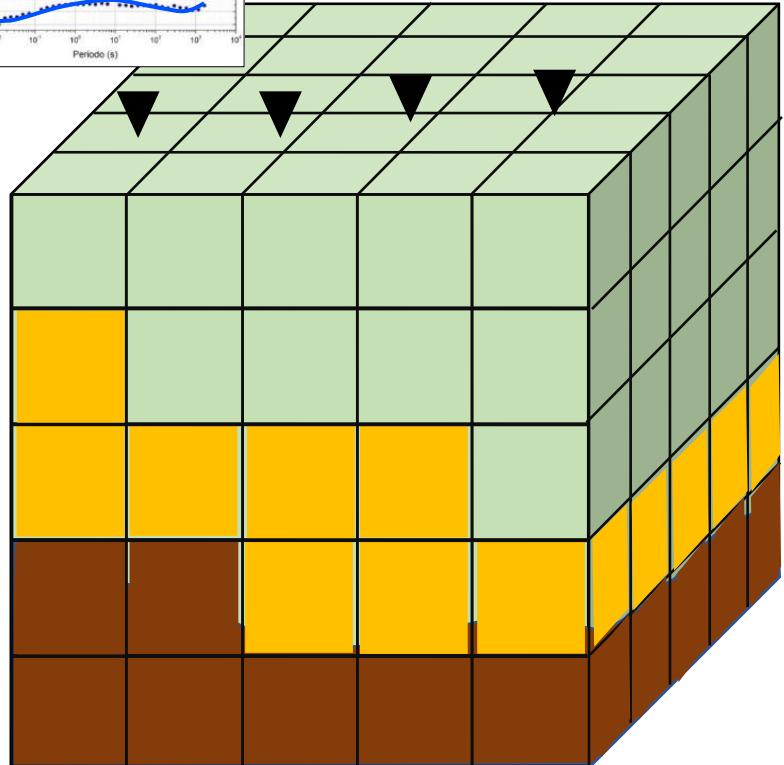
Inversão



$$\Phi(\boldsymbol{\sigma}) = [\mathbf{d} - \mathbf{d}(\boldsymbol{\sigma})]^T \mathbf{C}_d^{-1} [\mathbf{d} - \mathbf{d}(\boldsymbol{\sigma})] - \nu [\boldsymbol{\sigma} - \boldsymbol{\sigma}_0]^T \mathbf{C}_{\boldsymbol{\sigma}}^{-1} [\boldsymbol{\sigma} - \boldsymbol{\sigma}_0]$$



Matriz de covariânci a dos parâmetro s

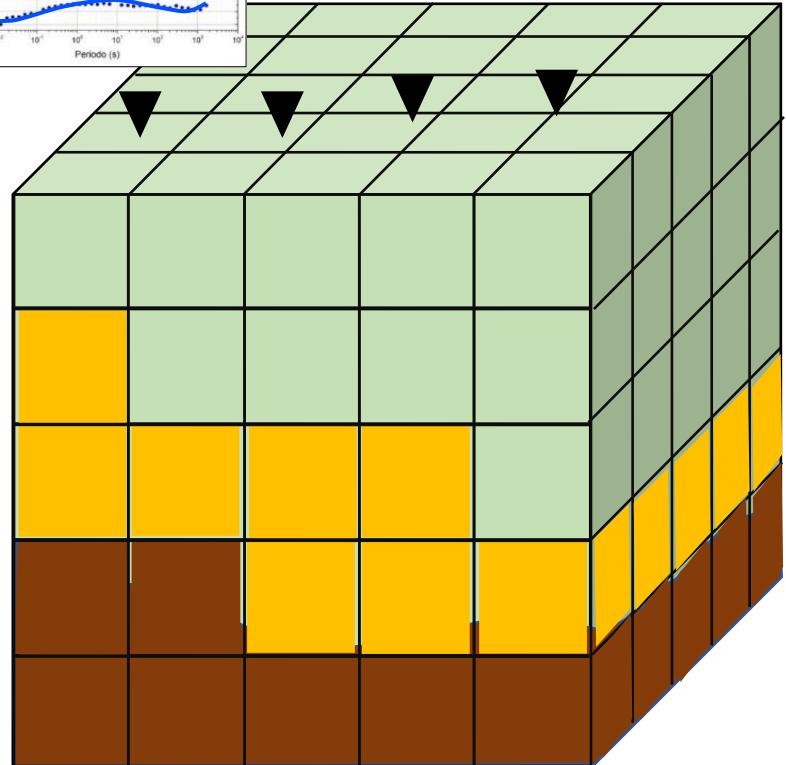
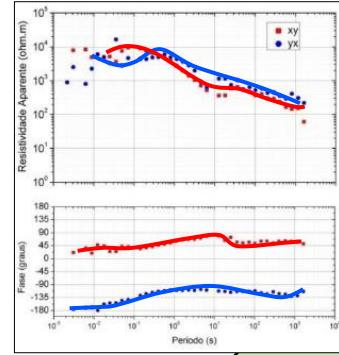


Inversão

$$\Phi(\sigma) = [\mathbf{d} - \mathbf{d}(\sigma)]^T \mathbf{C}_d^{-1} [\mathbf{d} - \mathbf{d}(\sigma)] - \nu [\sigma - \sigma_0]^T \mathbf{C}_{\sigma}^{-1} [\sigma - \sigma_0]$$



Parâmetro
de
regulariza-
ção



Inversão

1D

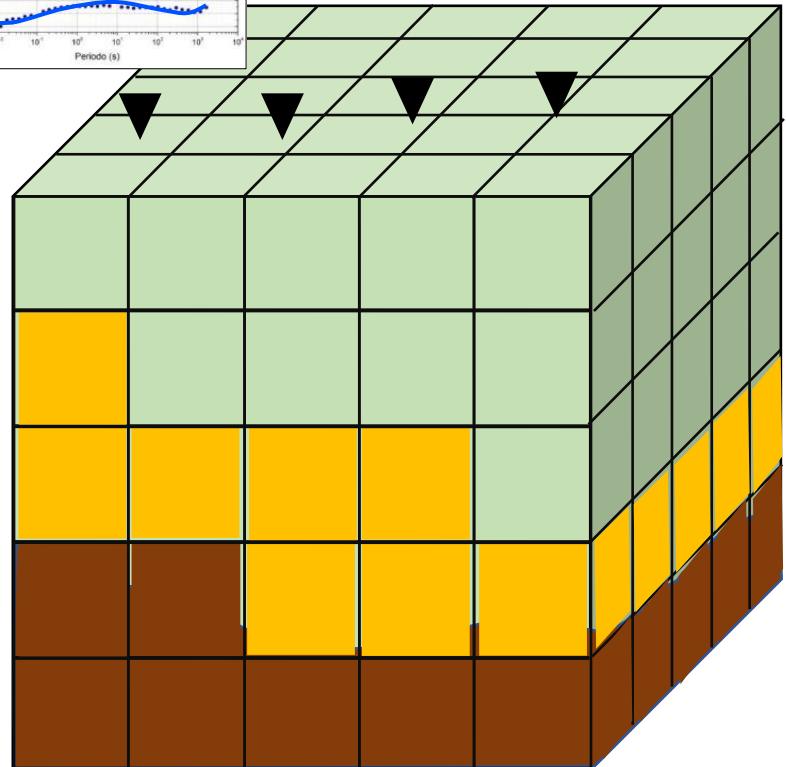
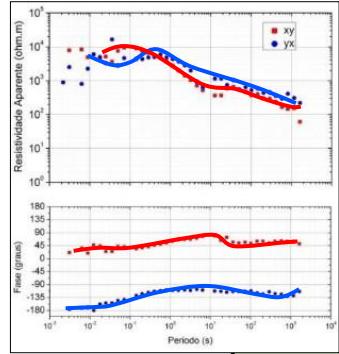
- Constable, S.C., R.L. Parker, and C.G. Constable, 1987. Occam's inversion: A practical algorithm for generating smooth models from electromagnetic sounding data, *Geophysics*, 52, 289-300.
- Smith, J.T., and J.R. Booker, 1988. Magnetotelluric inversion for minimum structure, *Geophysics*, 53, 1565-1576.

2D

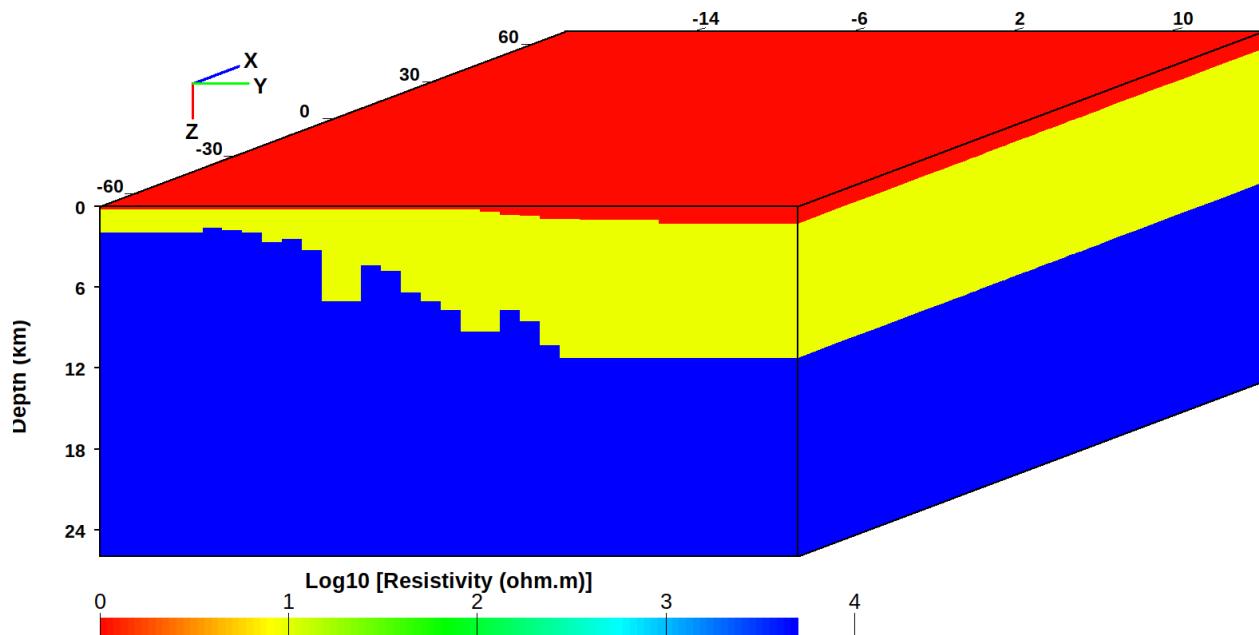
- Rodi, W., and R.L. Mackie, 2001. Nonlinear conjugate gradients algorithm for 2-D magnetotelluric inversion, *Geophysics*, 66, 174-187.

3D

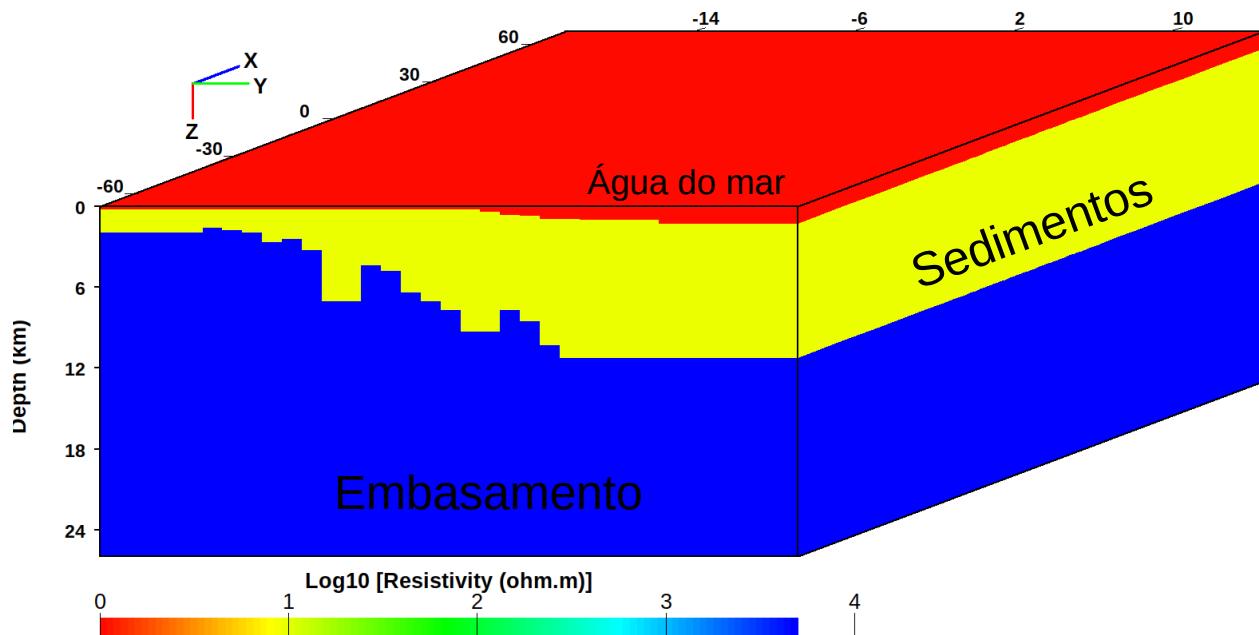
- Egbert, G. D., Kelbert, A., 2012, Computational recipes for electromagnetic inverse problems, *Geophysical Journal International*, v. 189, n. 1 (abr.), pp. 251–267. ISSN: 1365-246X. doi: 10.1111/j.1365-246X.2011.05347.x.



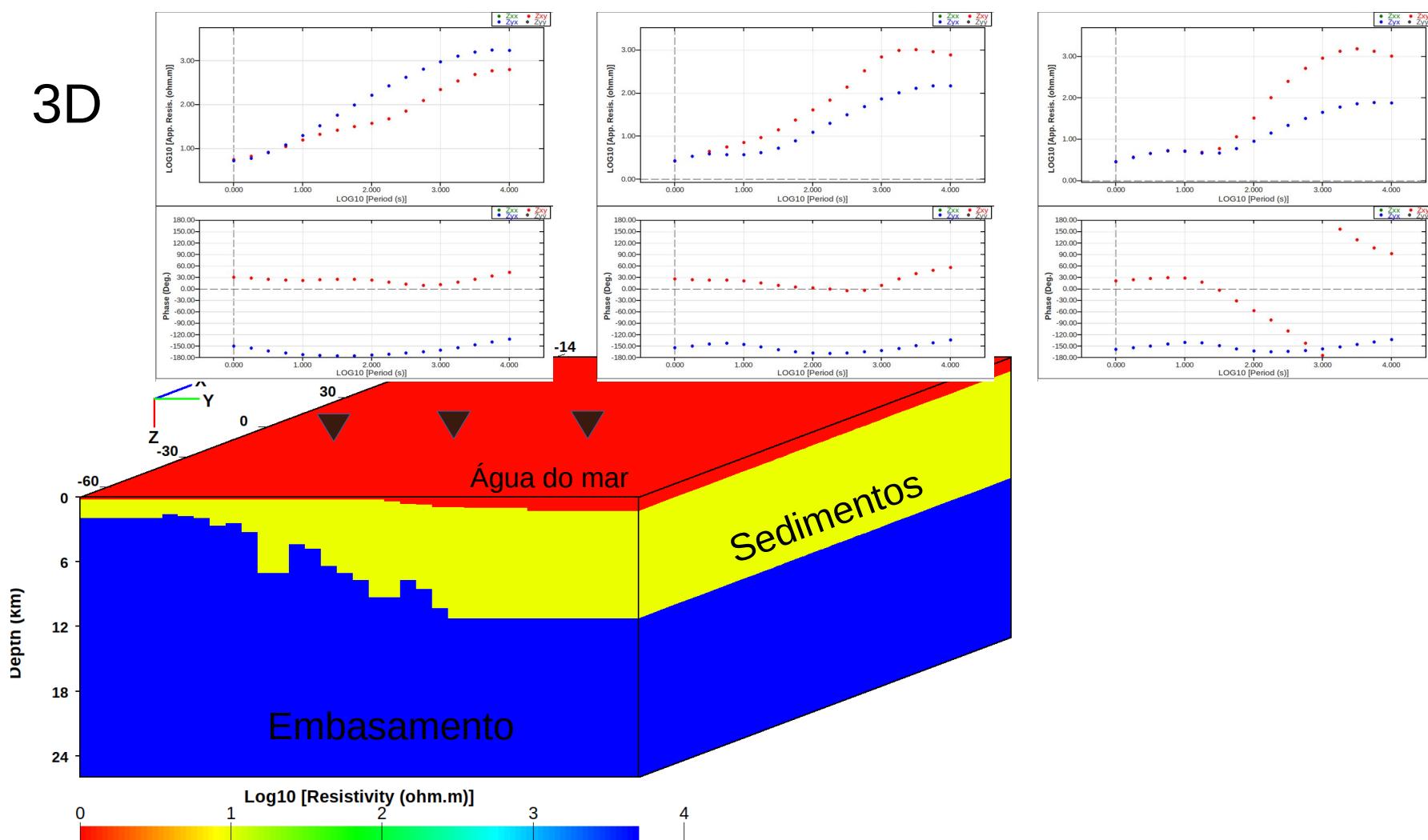
3D



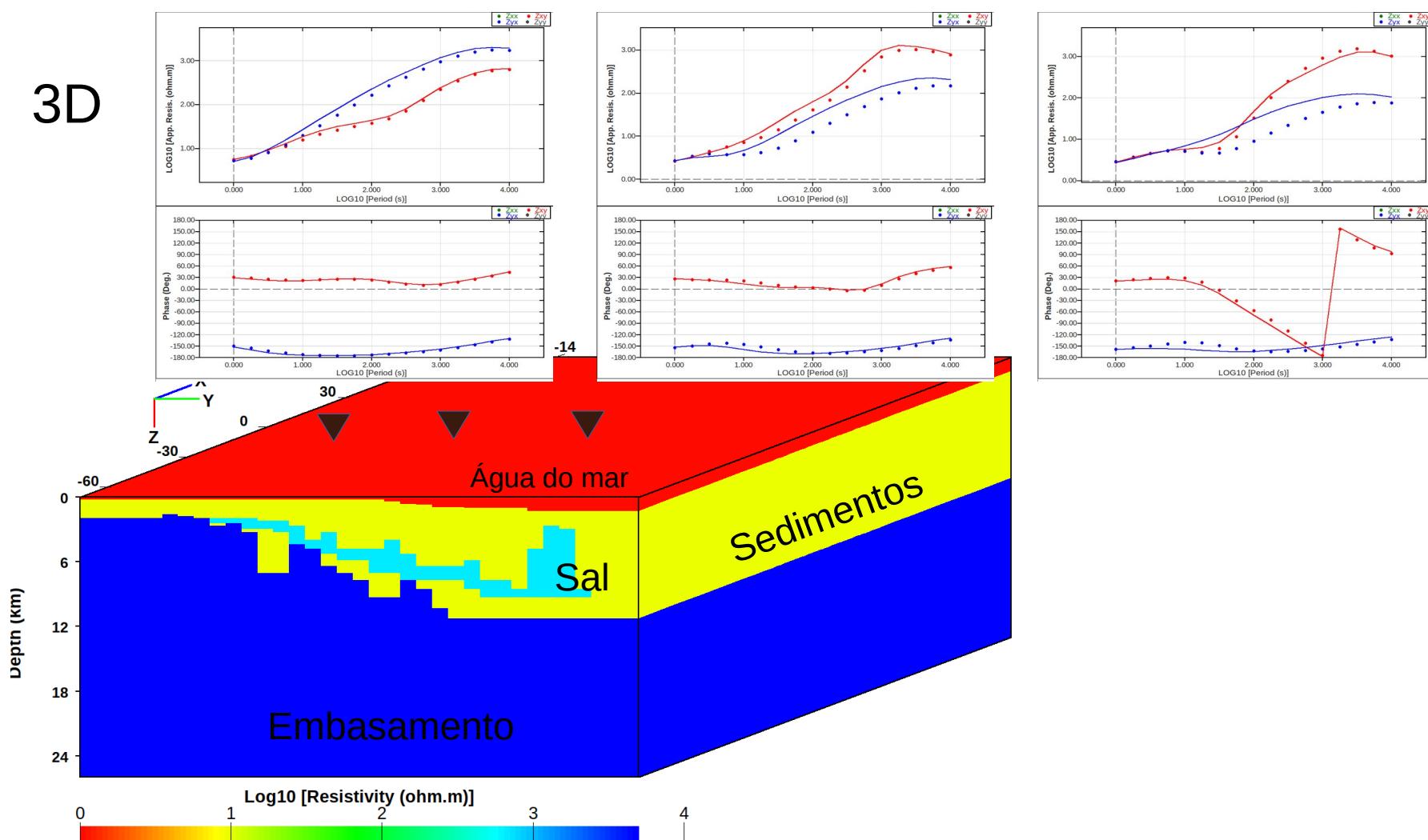
3D



3D



3D



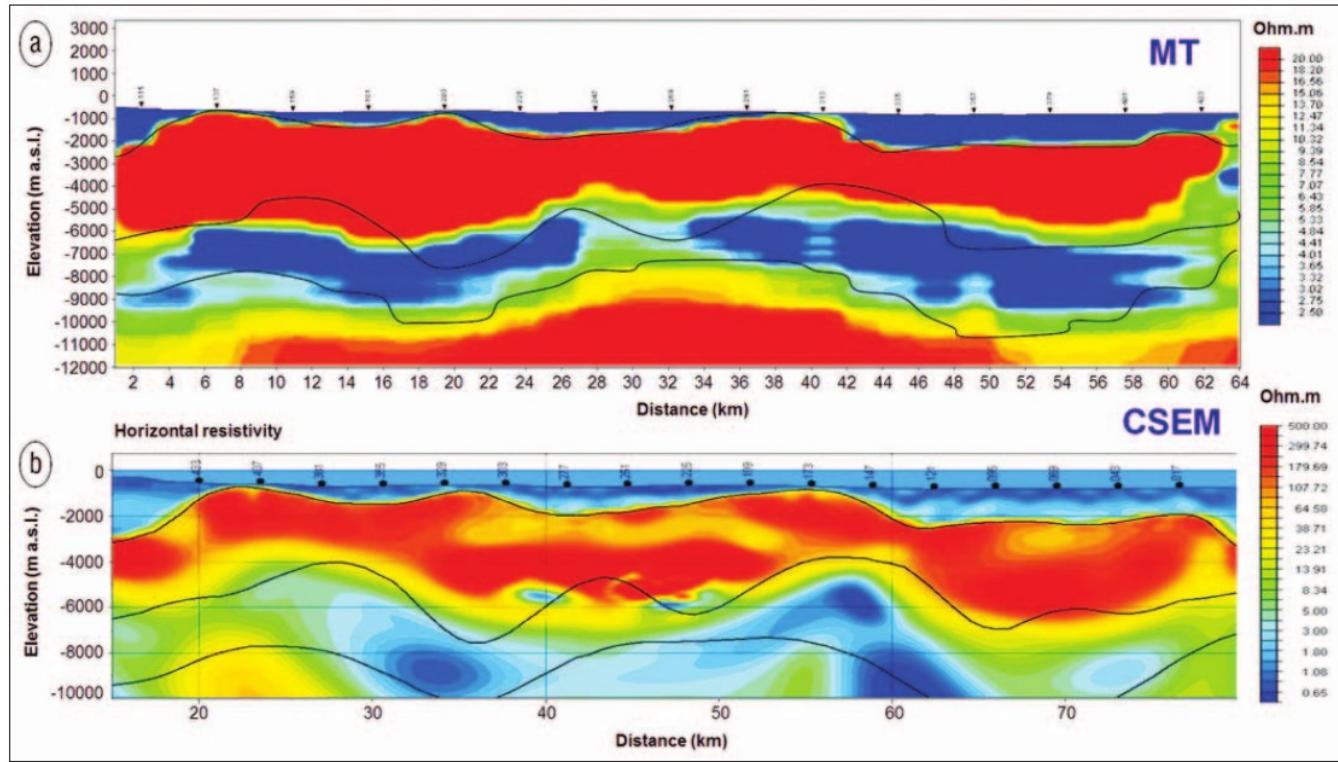


Figure 3. Inversion results for the synthetic MT (a) and CSEM (b) data sets along the profile shown in Figure 2. Both inversions resolve the base of salt, while only MT resolves the basement (black lines are used to indicate from top to bottom: top LES, base of salt and top of basement surfaces).

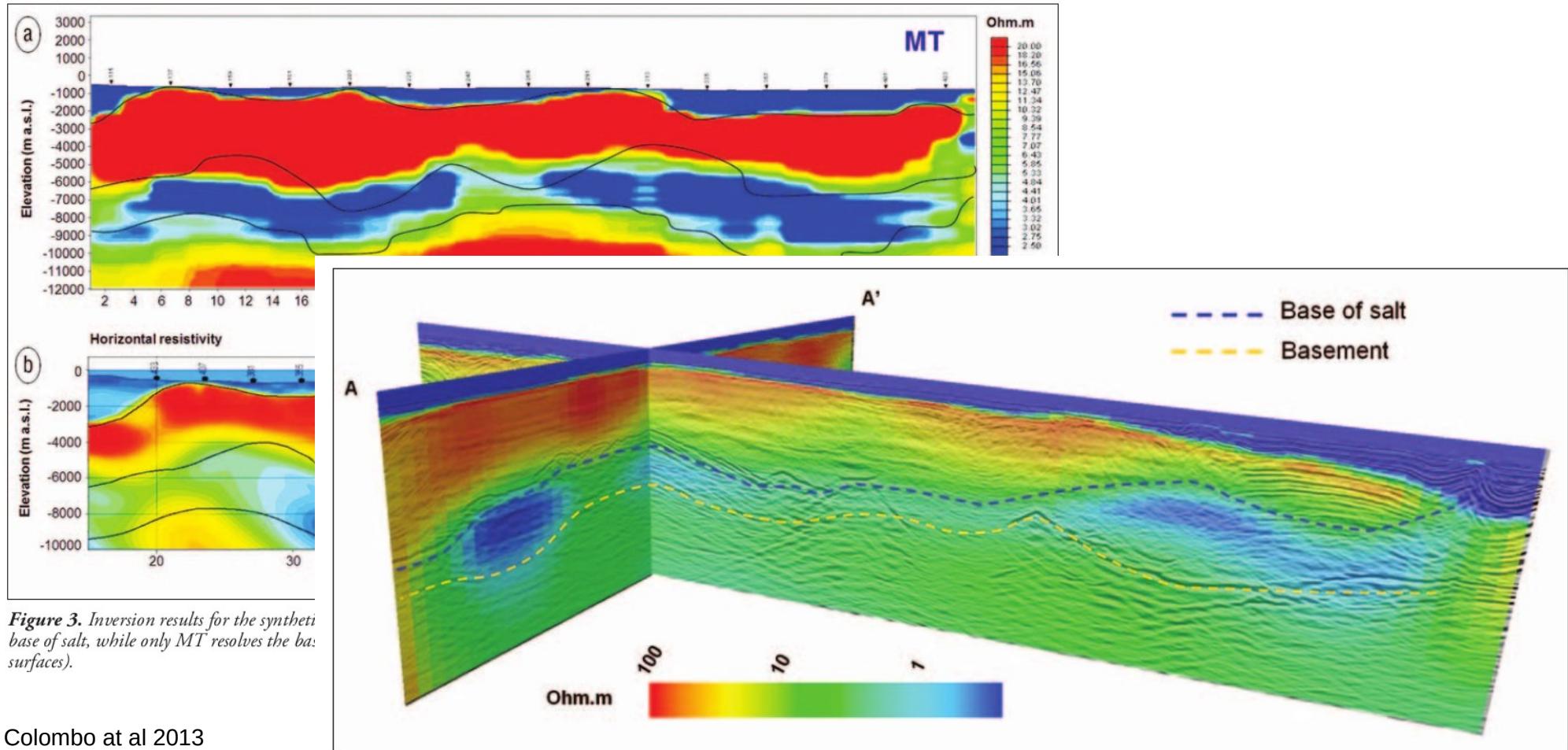


Figure 3. Inversion results for the synthetic base of salt, while only MT resolves the basement surfaces).

Colombo et al 2013

Figure 9. 3D MT inversion results. The seismic volume is depth-migrated to 8 km.

Estudos de caso

MMT na Bacia de Santos

first break volume 27, May 2009

special topic 

EM/Potential Methods

Marine magnetotelluric mapping of basement and salt bodies in the Santos Basin of Brazil

Sergio L. Fontes,^{1*} Patricia P. de Lugo,² Max A. Mejú,³ Vinicius R. Pinto,¹ Jean-Marie Flexor,¹ Emin U. Ulugergili,¹ Emanuele F. La Terra,¹ Luis A. Gallardo⁴ and Luiz Rijo⁵ present the first large-scale MMT survey acquired recently in Brazil by WesternGeco Electromagnetics in cooperation with Observatório Nacional/MCT and Petrobras as part of a major project on improving depth imaging by integrating multiple geophysical measurements in the Santos Basin.

Recent subsalt oil discoveries in the deep waters of the Santos basin in Brazil have received considerable attention due to the extent of the resource reserves and the challenges in exploration and production in such environment. This paper presents the first large-scale marine magnetotelluric (MMT) survey in an area of the Santos Basin suggested by magnetic and gravity data to be approximately 2D regionally. The resulting 2D MMT inversion model clearly shows resistivity anomalies that correctly delimit the position and depth extent of the known salt bodies. This study thus provides an important practical validation of the MMT method in the deep marine environment of Santos Basin, and demonstrates the feasibility of economically developing a reliable image of subsurface resistivity in the depth range of current interest in hydrocarbon development in offshore Brazil. We are currently working on a joint interpretation (Gallardo & Mejú, 2007) that combines the available seismic, MMT, and gravity data using structural constraints.

ern seismic interpretation has mapped, through high resolution imaging, the stratigraphy of hydrocarbon-producing turbidite reservoirs in these basins. Seismic interpretation has posted correct geometries of salt structures and, beneath the salt, has uncovered the structures of the underlying syn-rift sequences that encompass most oil-bearing source rocks. The offshore seismic data acquisition targets the mapping of new reservoirs in deep water and their relationship with rift sequences source rocks (Fainstein, 2005). Seismic prestack depth migration (PSDM) processing has identified a thick pre-salt sedimentary sequence above the syn-rift mega sequence. However, the lithology of the syn-rift mega sequence was not known until the drilling of the first discovery well of the Tupi field (Fainstein, 2007).

The Santos Basin block BMS-11 was the site of the subsalt light oil discovery by Petrobras with exploration well 1-RJS-628A drilled in 2140 m water depth reaching a total vertical depth (TVD) of 6000 m. It passed through an evaporitic salt sequence more than 2000 m thick. These

MMT na Bacia de Santos

first break volume 27, May 2009

special topic 

EM/Potential Methods

Marine magnetotelluric mapping of basement and salt bodies in the Santos Basin of Brazil

Sergio L. Fontes,^{1*} Patricia P. de Lugo,² Max A. Meju,³ Vinicius R. Pinto,¹ Jean-Marie Flexor,¹ Emin U. Ulugergili,¹ Emanuele F. La Terra,¹ Luis A. Gallardo⁴ and Luiz Rijo⁵ present the first large-scale MMT survey acquired recently in Brazil by WesternGeco Electromagnetics in cooperation with Observatório Nacional/MCT and Petrobras as part of a major project on improving depth imaging by integrating multiple geophysical measurements in the Santos Basin.

Recent subsalt oil discoveries in the deep waters of the Santos basin in Brazil have received considerable attention due to the extent of the resource reserves and the challenges in exploration and production in such environment. This paper presents the first large-scale marine magnetotelluric (MMT) survey in an area of the Santos Basin suggested by magnetic and gravity data to be approximately 2D regionally. The resulting 2D MMT inversion model clearly shows resistivity anomalies that correctly delimit the position and depth extent of the known salt bodies. This study thus provides an important practical validation of the MMT method in the deep marine environment of Santos Basin, and demonstrates the feasibility of economically developing a reliable image of subsurface resistivity in the depth range of current interest in hydrocarbon development in offshore Brazil. We are currently working on a joint interpretation (Gallardo & Meju, 2007) that combines the available seismic, MMT, and gravity data using structural constraints.

ern seismic interpretation has mapped, through high resolution imaging, the stratigraphy of hydrocarbon-producing turbidite reservoirs in these basins. Seismic interpretation has posted correct geometries of salt structures and, beneath the salt, has uncovered the structures of the underlying syn-rift sequences that encompass most oil-bearing source rocks. The offshore seismic data acquisition targets the mapping of new reservoirs in deep water and their relationship with rift sequences source rocks (Fainstein, 2005). Seismic prestack depth migration (PSDM) processing has identified a thick pre-salt sedimentary sequence above the syn-rift mega sequence. However, the lithology of the syn-rift mega sequence was not known until the drilling of the first discovery well of the Tupi field (Fainstein, 2007).

The Santos Basin block BMS-11 was the site of the subsalt light oil discovery by Petrobras with exploration well 1-RJS-628A drilled in 2140 m water depth reaching a total vertical depth (TVD) of 6000 m. It passed through an evaporitic salt sequence more than 2000 m thick. These

- Primeiro levantamento MMT em 2008

MMT na Bacia de Santos

first break volume 27, May 2009

special topic
fb

EM/Potential Methods

Marine magnetotelluric mapping of basement and salt bodies in the Santos Basin of Brazil

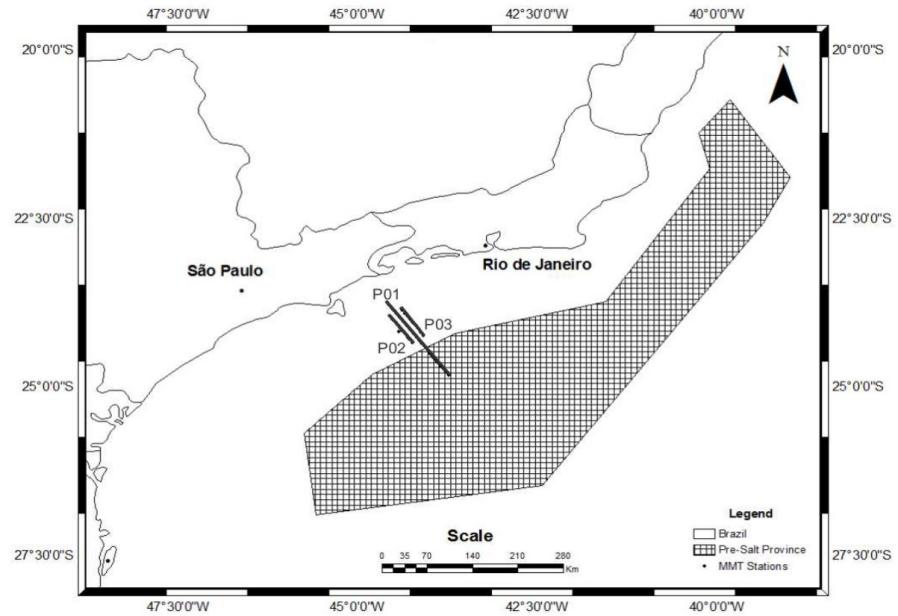
Sergio L. Fontes,^{1*} Patricia P. de Lugo,² Max A. Mejú,³ Vinicius R. Pinto,¹ Jean-Marie Flexor,¹ Emin U. Ulugergeli,¹ Emanuele F. La Terra,¹ Lui A. Gallardo⁴ and Luiz Rijo⁵ present the first large-scale MMT survey acquired recently in Brazil by WesternGeco Electromagnetics in cooperation with Observatório Nacional/MCT and Petrobras as part of a major project on improving depth imaging by integrating multiple geophysical measurements in the Santos Basin.

Recent subsalt oil discoveries in the deep waters of the Santos basin in Brazil have received considerable attention due to the extent of the resource reserves and the challenges in exploration and production in such environment. This paper presents the first large-scale marine magnetotelluric (MMT) survey in an area of the Santos Basin suggested by magnetic and gravity data to be approximately 2D regionally. The resulting 2D MMT inversion model clearly shows resistivity anomalies that correctly delimit the position and depth extent of the known salt bodies. This study thus provides an important practical validation of the MMT method in the deep marine environment of Santos Basin, and demonstrates the feasibility of economically developing a reliable image of subsurface resistivity in the depth range of current interest in hydrocarbon development in offshore Brazil. We are currently working on a joint interpretation (Gallardo & Mejú, 2007) that combines the available seismic, MMT, and gravity data using structural constraints.

ern seismic interpretation has mapped, through high resolution imaging, the stratigraphy of hydrocarbon-producing turbidite reservoirs in these basins. Seismic interpretation has posted correct geometries of salt structures and, beneath the salt, has uncovered the structures of the underlying syn-rift sequences that encompass most oil-bearing source rocks. The offshore seismic data acquisition targets the mapping of new reservoirs in deep water and their relationship with rift sequences source rocks (Fainstein, 2005). Seismic prestack depth migration (PSDM) processing has identified a thick pre-salt sedimentary sequence above the syn-rift mega sequence. However, the lithology of the syn-rift mega sequence was not known until the drilling of the first discovery well of the Tupi field (Fainstein, 2007).

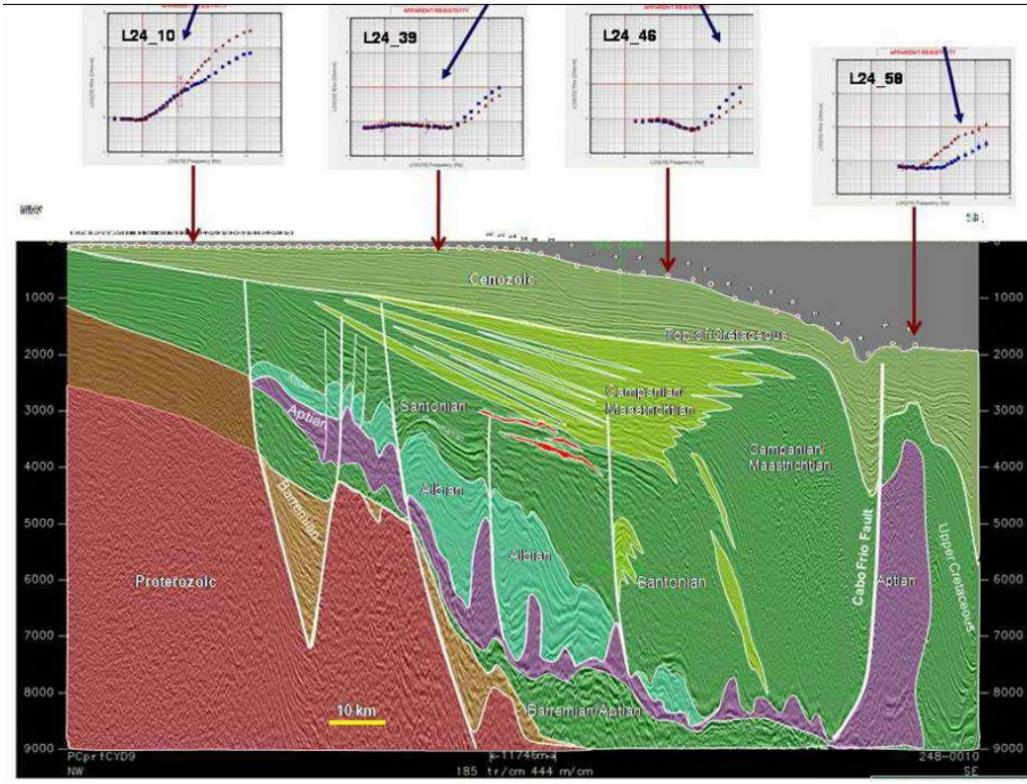
The Santos Basin block BMS-11 was the site of the subsalt light oil discovery by Petrobras with exploration well 1-RJS-628A drilled in 2140 m water depth reaching a total vertical depth (TVD) of 6000 m. It passed through an evaporitic salt sequence more than 2000 m thick. These

- Primeiro levantamento MMT em 2008



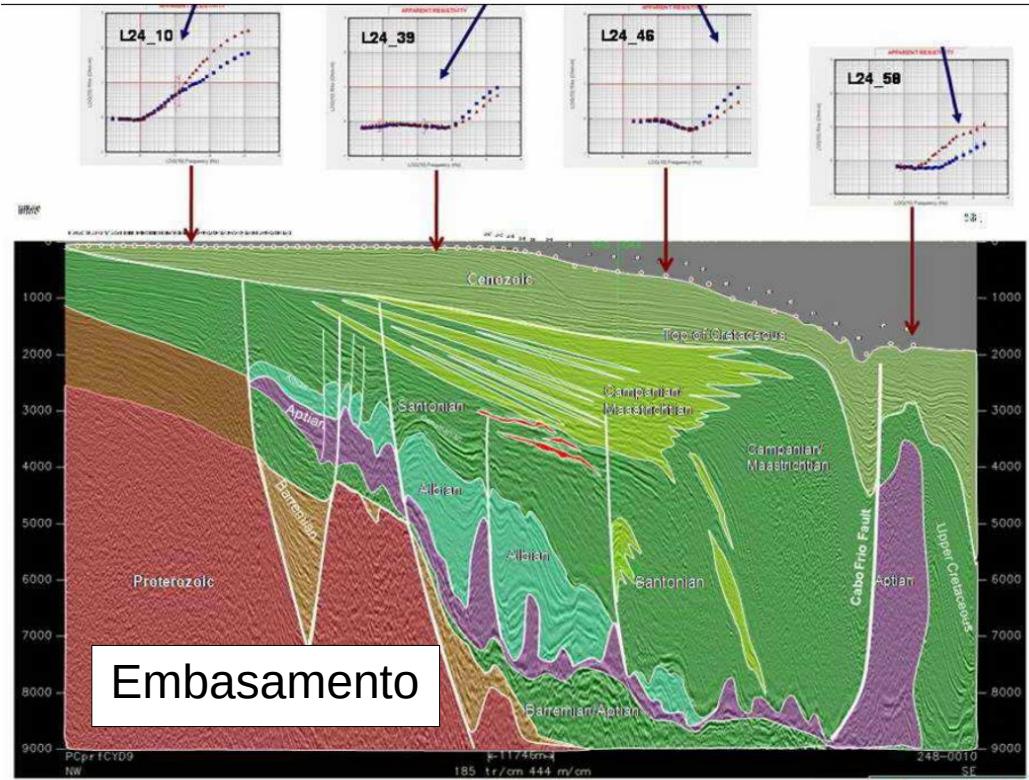
Pinto, V.R. (2013)

MMT na Bacia de Santos



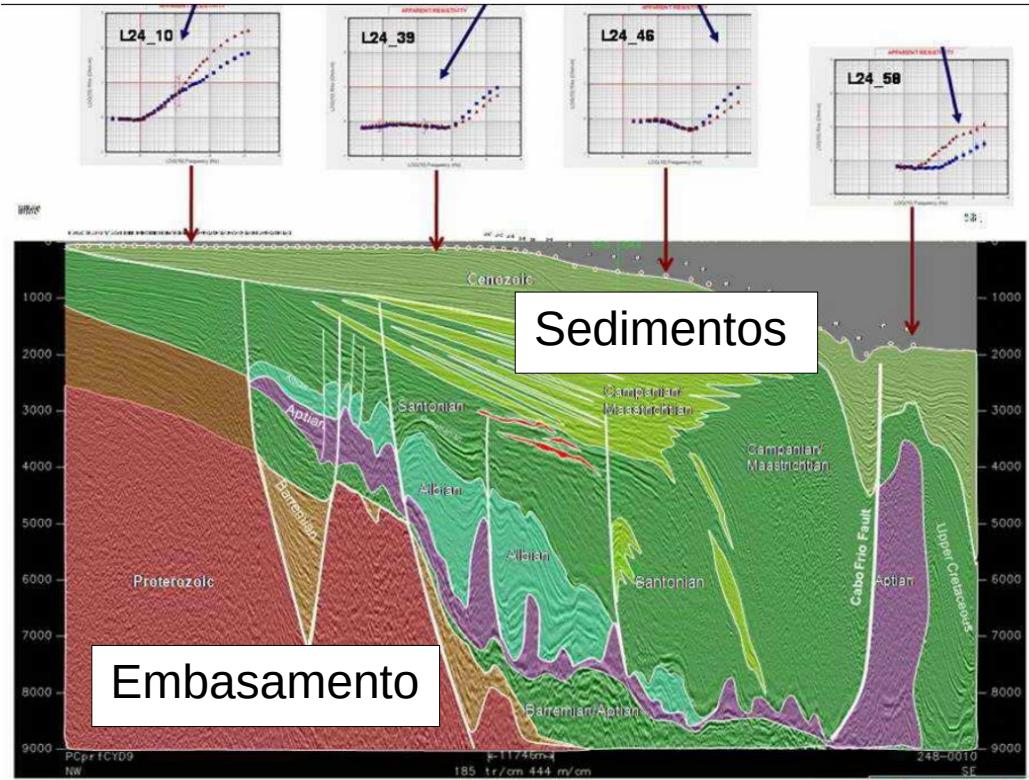
Fontes et al 2009

MMT na Bacia de Santos



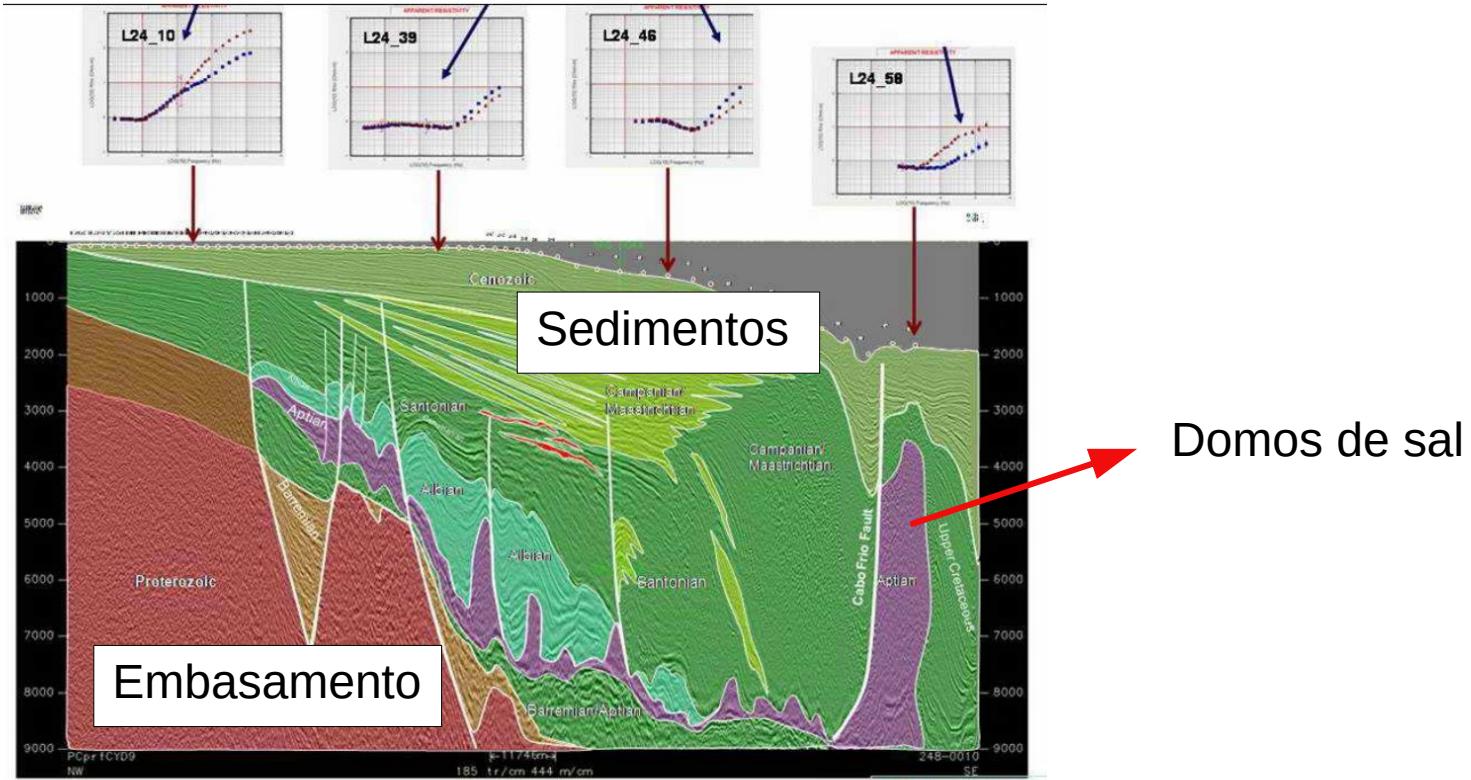
Fontes et al 2009

MMT na Bacia de Santos



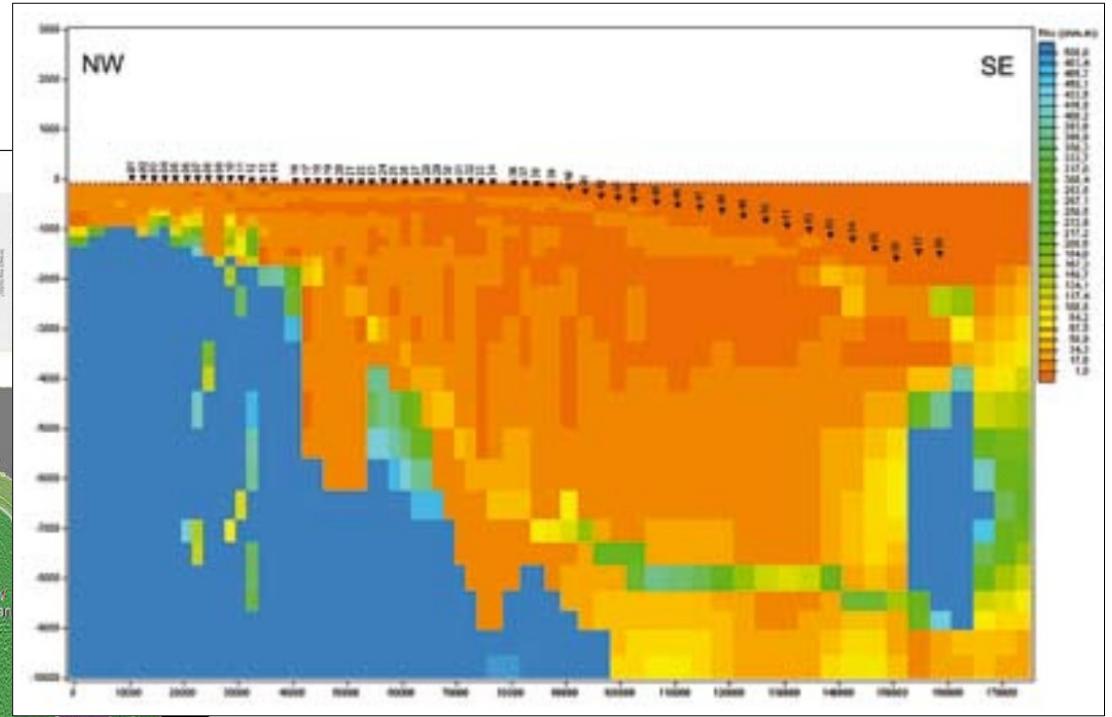
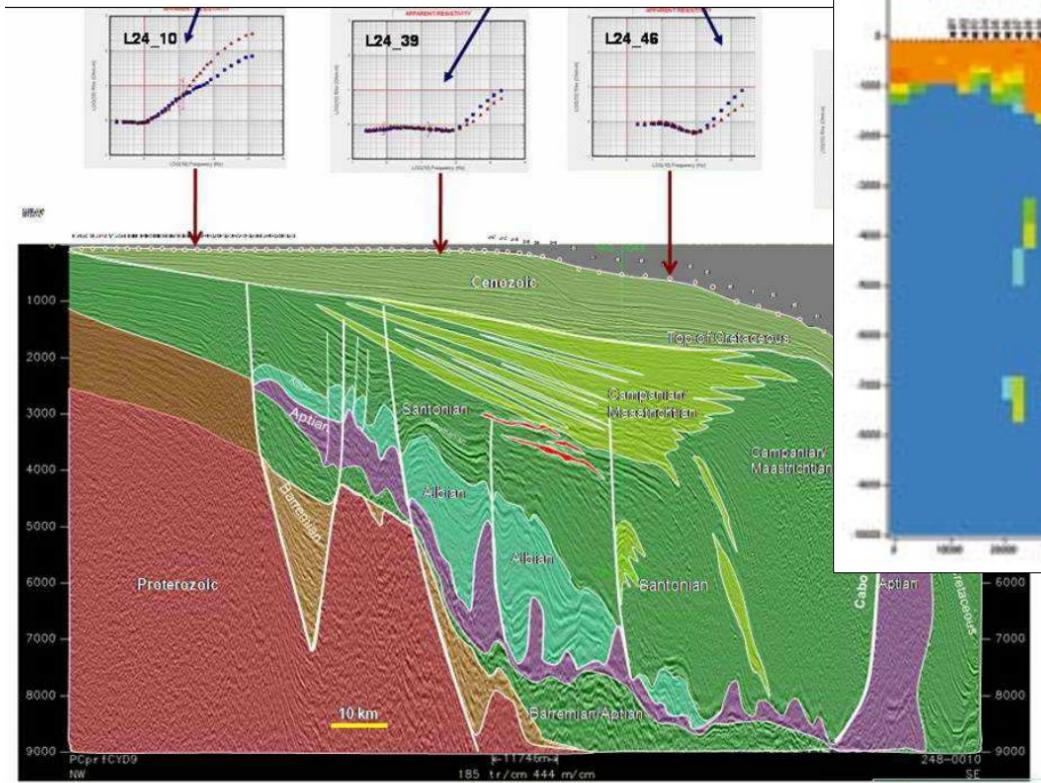
Fontes et al 2009

MMT na Bacia de Santos



Fontes et al 2009

MMT na Bacia de Santos



Fontes et al 2009

mCSEM na Bacia de Santos

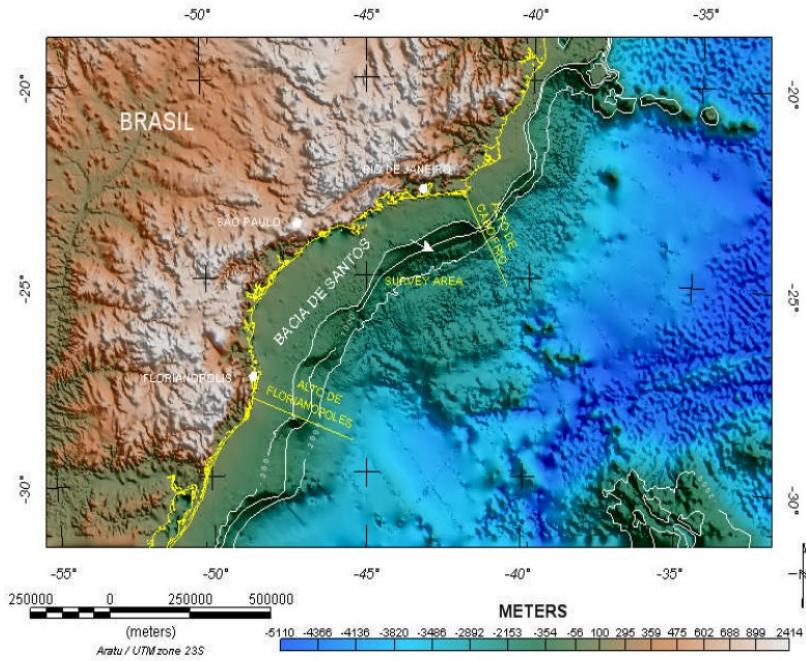


Figure 1: Location of Survey Area

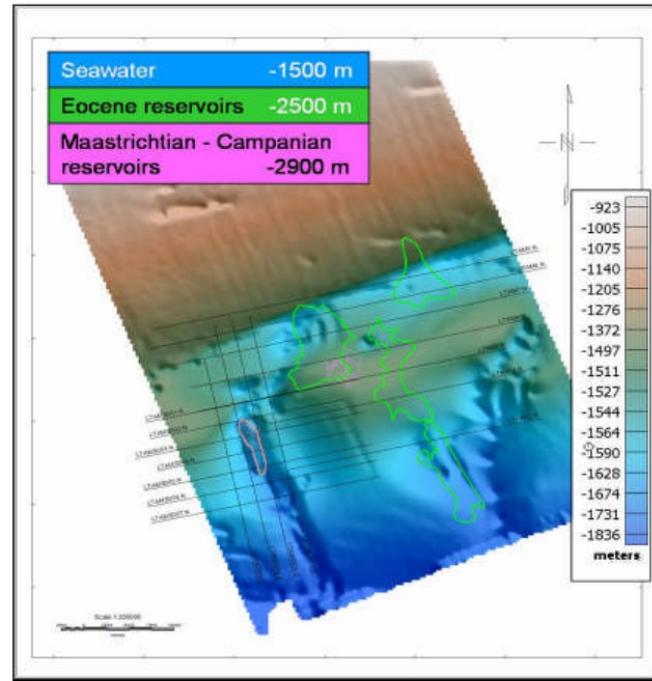
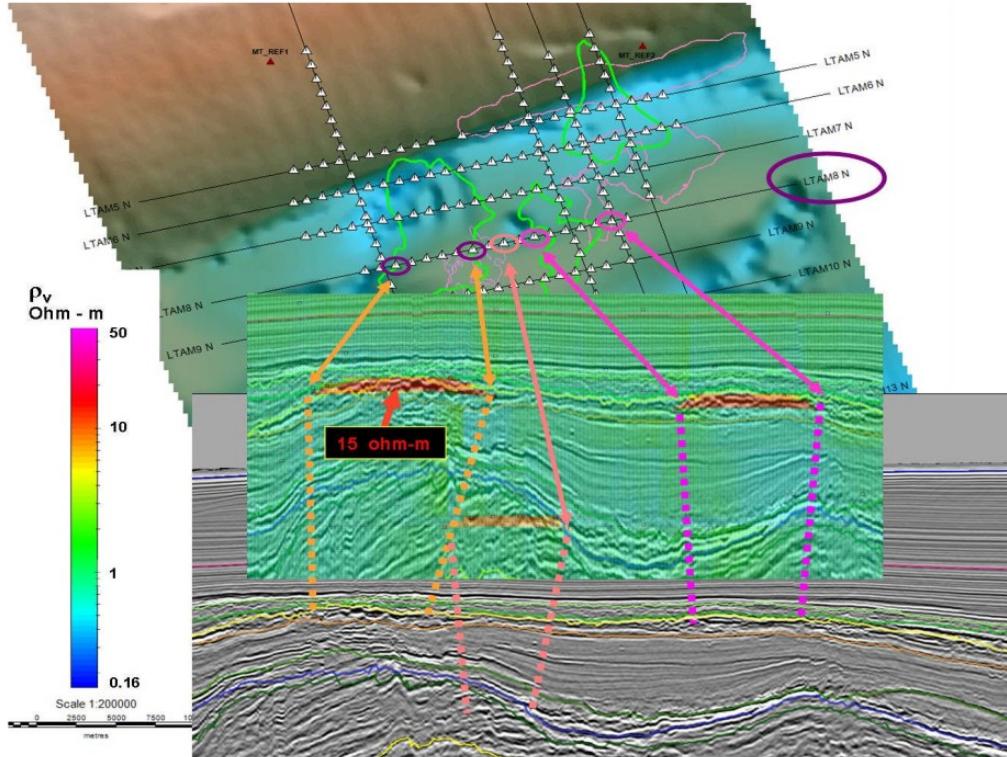


Figure 2: Survey Area. mCSEM Source lines

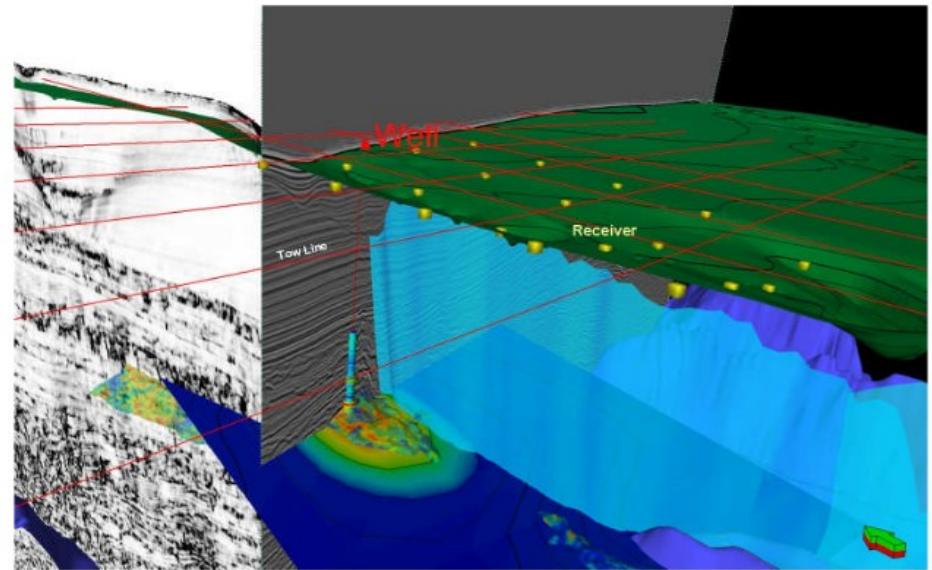
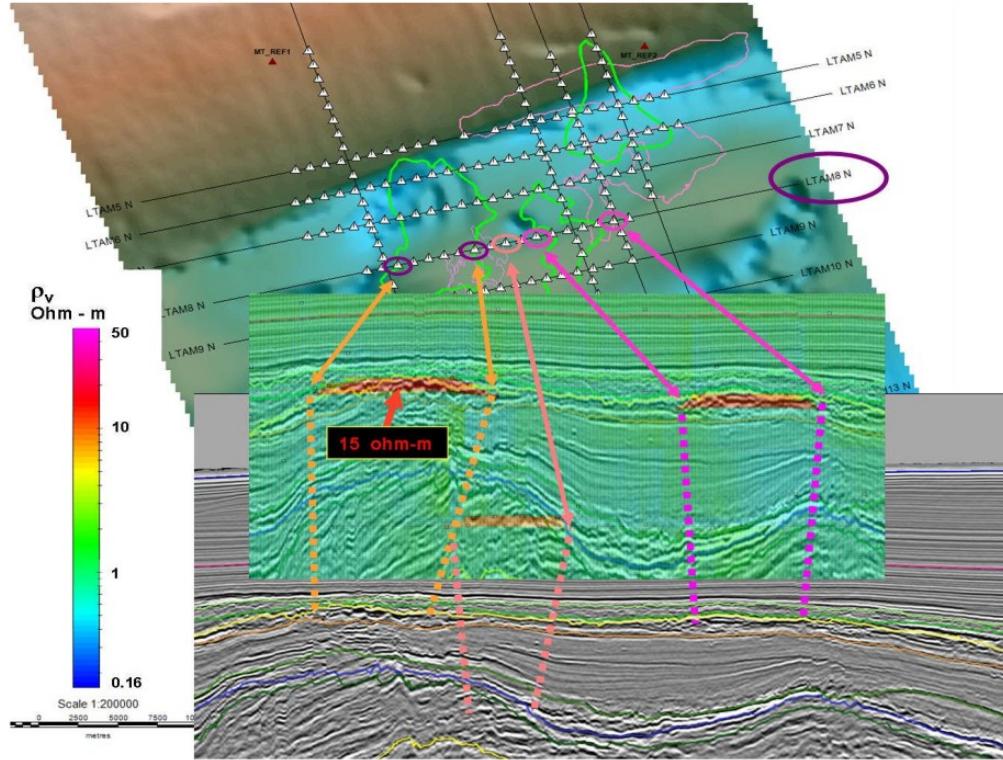
mCSEM na Bacia de Santos



Seção vertical de resistividade a partir da inversão anisotrópica 2.5D com sísmica. A interpretação sísmica foi utilizada como vínculo.

As anomalias de resistividade (vermelho) são coincidentes com a profundidade e extensão lateral de reservatórios conhecidos.

mCSEM na Bacia de Santos



CSEM e MT no Mar Vermelho

Exploration beyond seismic: The role of electromagnetics and gravity gradiometry in deep water subsalt plays of the Red Sea

Daniele Colombo¹, Gary McNeice¹, Nickolas Raterman², Mike Zinger², Diego Rovetta¹, and Ernesto Sandoval Curiel¹

ABSTRACT

The Red Sea is characterized by thick salt sequences representing a seal for potential hydrocarbon accumulations within Tertiary formations deposited over deep basement structures. The Red Sea “salt” is characterized by halite concentrations embedded in layered evaporite sequences composed of evaporite and clastic lithologies. Salt complicates seismic exploration efforts in the Red Sea by generating vertical and lateral velocity variations that are difficult to estimate by seismic methods alone. In these conditions, the exploration challenges of independently imaging the subsalt section and provide enhanced velocity model building capabilities were addressed by a multigeophysics strategy involving marine electromagnetics (magnetotellurics and controlled source electromagnetics [CSEM]) and gravity gradiometry surveys colocated with wide azimuth seismic. Three-dimensional inversion of MT and CSEM is performed first with minimal a priori constraints and then by including variable amounts of interpretation in the starting models. The internal variations in the evaporitic overburden, the subsalt, and the basement structures are independently imaged by combined electromagnetic methods and confirmed by new drilling results. CSEM, in particular, provides unprecedented detail of the internal structures within the salt overburden while magnetotellurics provides excellent reconstruction of the base of salt and basement. Gravity gradiometry shows primary sensitivity to the basement and the corresponding 3D inversion provides density distributions structurally consistent with the resistivity volumes. The common-structure, multi-parameter models obtained from 3D inversion deliver additional aid to seismic interpreters to further derisk exploration in the Red Sea and provide additional detail to depth imaging velocity models. The reciprocal consistency of the obtained results show promises for extending the work to more analytical integration with seismic such as provided by joint geophysical inversion.

CSEM e MT no Mar Vermelho

Exploration beyond seismic: The role of electromagnetics and gravity gradiometry in deep water subsalt plays of the Red Sea

Daniele Colombo¹, Gary McNeice¹, Nickolas Raterman², Mike Zinger², Diego Rovetta¹, and Ernesto Sandoval Curiel¹

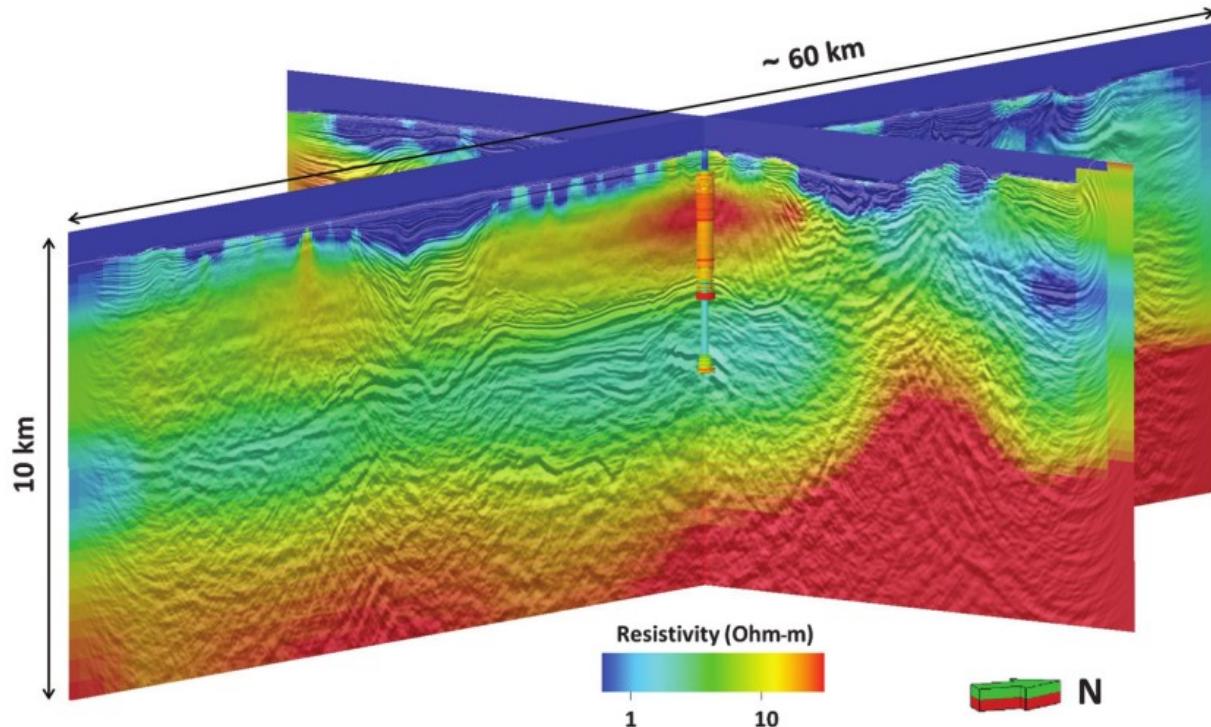
ABSTRACT

The Red Sea is characterized by thick salt sequences representing a seal for potential hydrocarbon accumulations within Tertiary formations deposited over deep basement structures. The Red Sea “salt” is characterized by halite concentrations embedded in layered evaporite sequences composed of evaporite and clastic lithologies. Salt complicates seismic exploration efforts in the Red Sea by generating vertical and lateral velocity variations that are difficult to estimate by seismic methods alone. In these conditions, the exploration challenges of independently imaging the subsalt section and provide enhanced velocity model building capabilities were addressed by a multigeophysics strategy involving marine electromagnetics (magnetotellurics and controlled source electromagnetics [CSEM]) and gravity gradiometry surveys colocated with wide azimuth seismic. Three-dimensional inversion of MT and CSEM is performed first with minimal a priori constraints and then by including variable amounts of interpretation in the starting models. The internal variations in the evaporitic overburden, the subsalt, and the basement structures are independently imaged by combined electromagnetic methods and confirmed by new drilling results. CSEM, in particular, provides unprecedented detail of the internal structures within the salt overburden while magnetotellurics provides excellent reconstruction of the base of salt and basement. Gravity gradiometry shows primary sensitivity to the basement and the corresponding 3D inversion provides density distributions structurally consistent with the resistivity volumes. The common-structure, multi-parameter models obtained from 3D inversion deliver additional aid to seismic interpreters to further derisk exploration in the Red Sea and provide additional detail to depth imaging velocity models. The reciprocal consistency of the obtained results show promises for extending the work to more analytical integration with seismic such as provided by joint geophysical inversion.

Integração

**EM (CSEM e MT)
Sismica
Gradiometria**

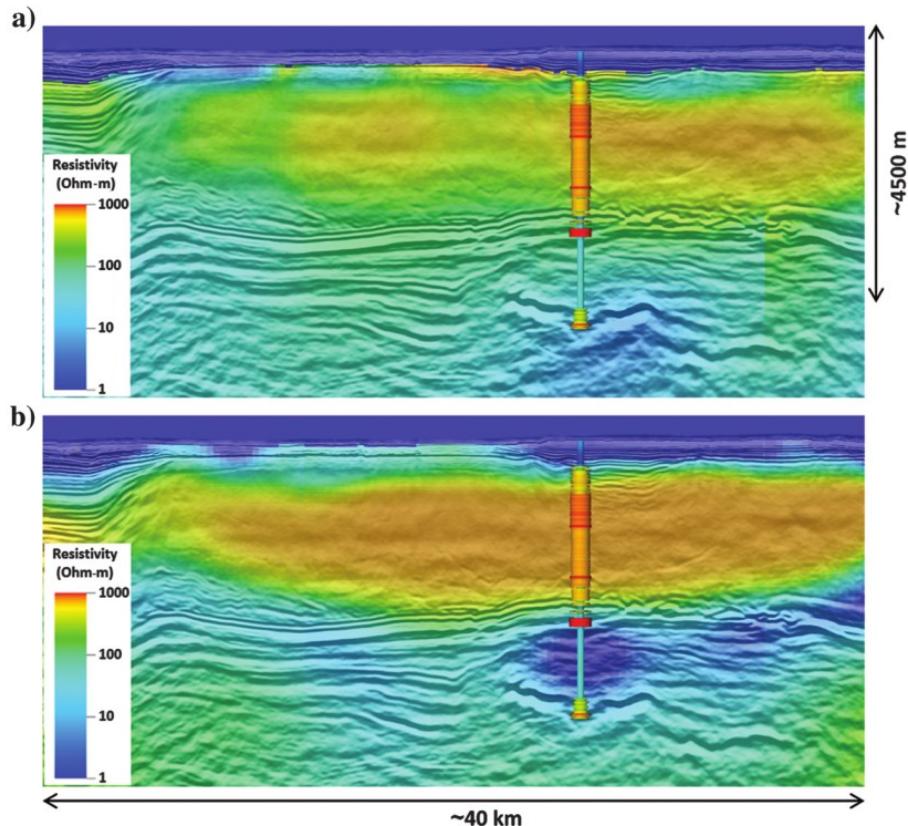
CSEM e MT no Mar Vermelho



MT mostra grande sensibilidade ao corpo principal de sal e embasamento

Figure 7. Data-driven 3D MT inversion results from area 1. Excellent sensitivity to the main salt body (LES+halite bodies) is shown by the recovered resistivity structure and confirmed by the newly drilled well (resistivity log shown). The MT inversion also recovers a deep basement with the definition of an uplifted basement block on the northeast side of the survey area.

CSEM e MT no Mar Vermelho

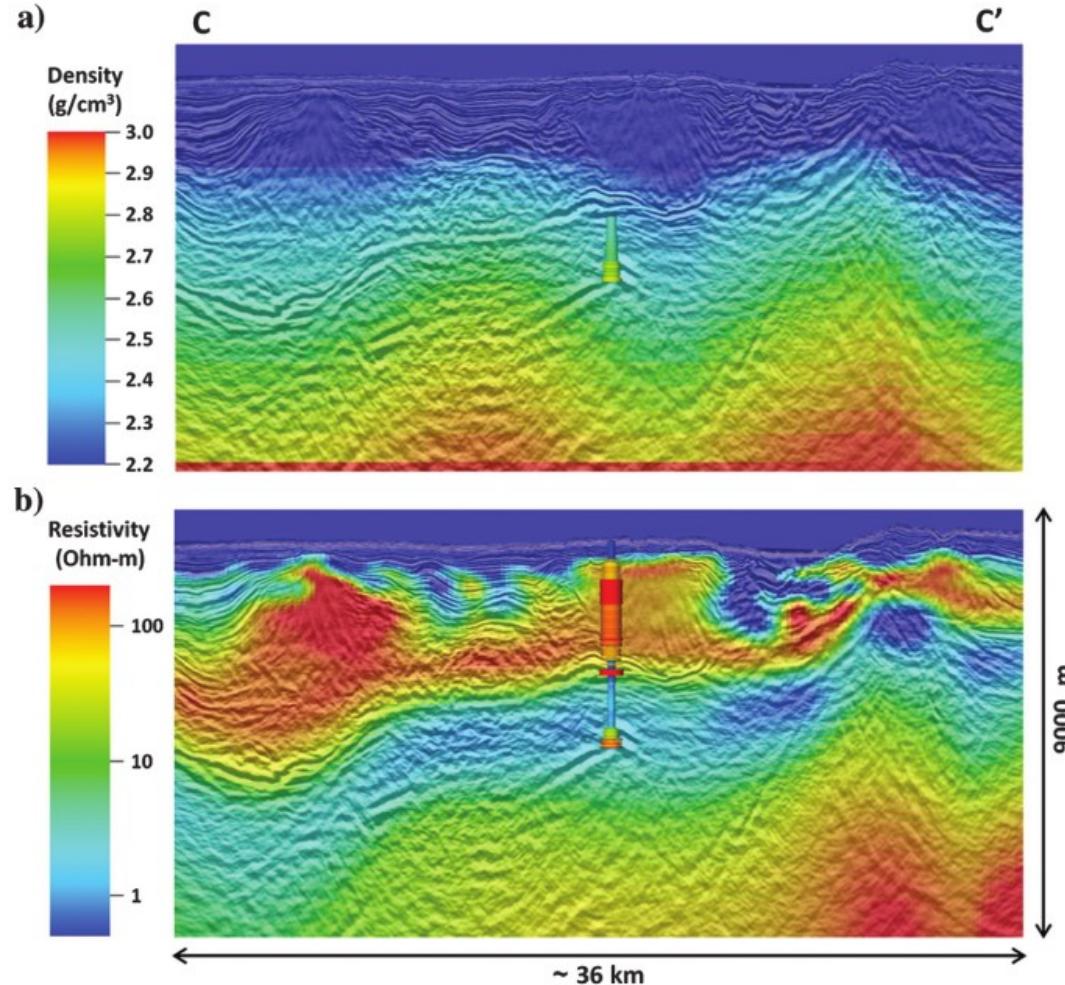


Modelos CSEM fornecem informações sobre as camadas evaporáticas e sedimentos de subsal.

Figure 8. Data-driven 3D CSEM inversion in area 1 from different starting models: (a) half-space resistivity start model, i.e., below top LES; (b) start model is the 3D MT inversion model. In both cases, the background resistivity and the log use the same color scale.

CSEM e MT no Mar Vermelho

Figure 17. Common structure model from area 1: (a) 3D gravity inversion showing primary sensitivity to the basement structures; (b) 3D CSEM inversion from the MT start model detailing the internal structures of the LES and halite.



Magnetotelluric imaging integrated with seismic, gravity, magnetic and well-log data for basement and carbonate reservoir mapping in the São Francisco Basin, Brazil

F. F. Solon^{1*}, S. L. Fontes¹ & M. A. Meju²

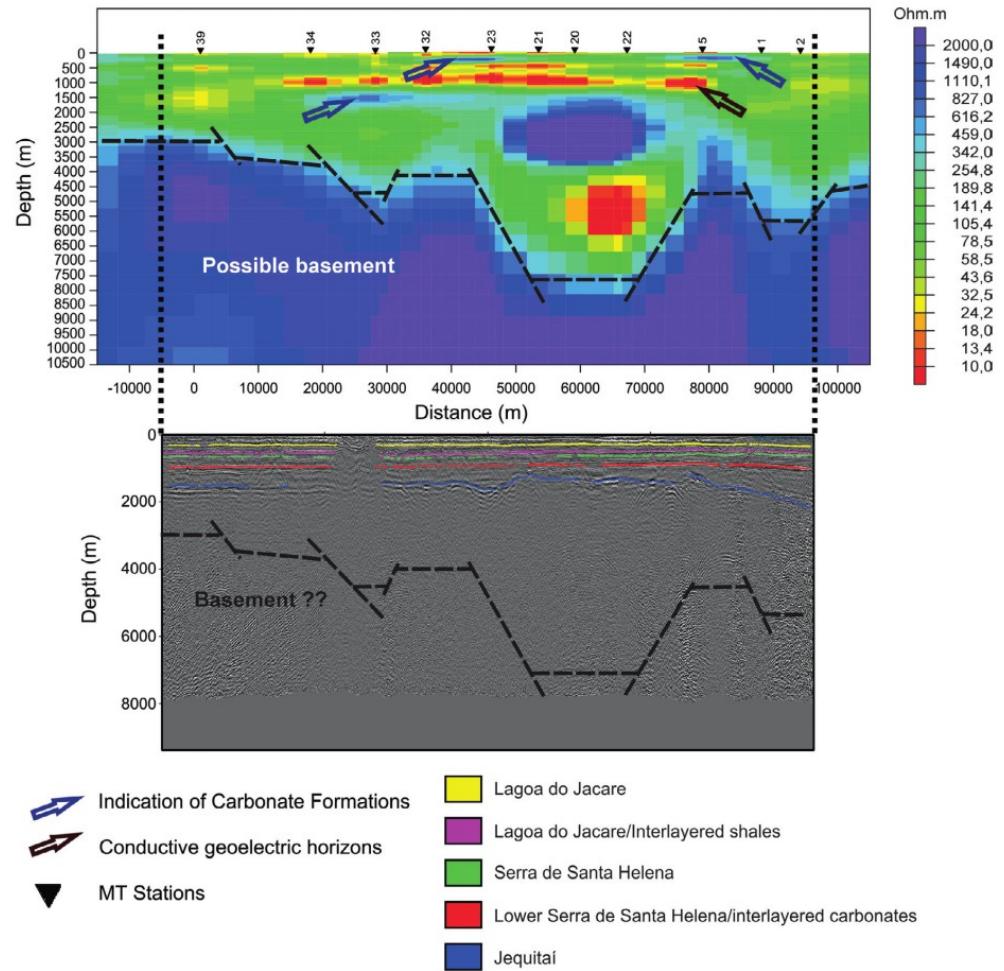
¹ Department of Geophysics, Observatorio Nacional/MCTI, 20921-400 São Cristóvão, Rio de Janeiro, Brazil

² Exploration Technical Services Division, Petronas Carigali, Petronas Twin Towers, 50088 Kuala Lumpur, Malaysia

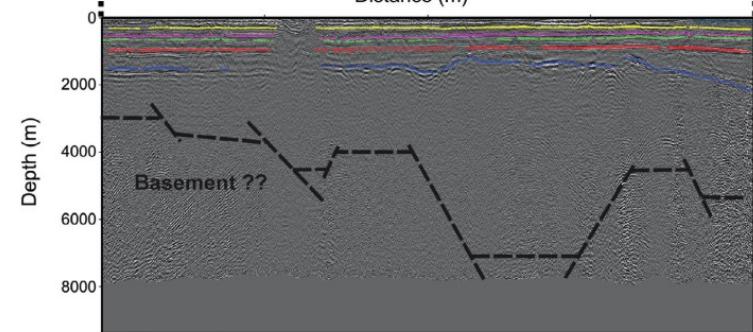
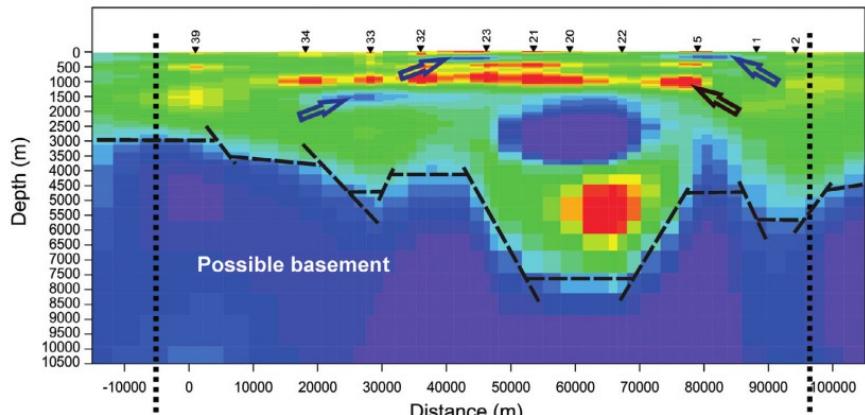
* Correspondence: flora@on.br

Abstract: We evaluate the use of the magnetotelluric (MT) method to locate crystalline basement and overlying carbonate reservoir rocks underneath a thick overburden in the São Francisco basin in Brazil. Mapping the complex basement and the carbonate reservoir using seismic reflection is a major problem in hydrocarbon exploration in this intracratonic basin, and it is expected that MT will provide useful complementary information. In the present study, we analysed 31 MT soundings along four survey lines in the central region of the basin. The MT soundings covered a period range of 0.001–100 s, probing the subsurface resistivity structure down to a maximum depth of about 15 km. The MT data were inverted using a regularized two-dimensional (2D) inversion algorithm with a variety of *a priori* data for comparison. For model appraisal, we analysed well log (gamma ray, deep resistivity and neutron porosity) data as well as seismic, gravity and magnetic profiles coincident with one MT line passing through the well. We found that shallow geological boundaries separating zones of strong resistivity contrasts also coincide with seismic boundaries in the inversion models with or without *a priori* data. Using gravity data, it was also possible to define the compartmentalized basement in this sector of São Francisco Basin, not clear in the seismic section. However, only by integrating all available information were we able to map the Lagoa do Jacaré and Sete Lagoas carbonate member-formations of the Bambuí Group, which are considered to host both the source and reservoir rocks identified from past exploratory history of this basin. We also imaged a basement structural high with thinned or disrupted conductive cover rocks over a known zone of hydrocarbon microseepage and a buried conductive (source rock?) channel at its NW margin, the trace of which coincides with the present-day River Paracatu along which gas bubbles have been observed. This suggests that MT may be fruitfully integrated with gravity, magnetic and seismic data to study the structural controls on hydrocarbon occurrence in this basin.

MT no Remanso do Fogo - Onshore

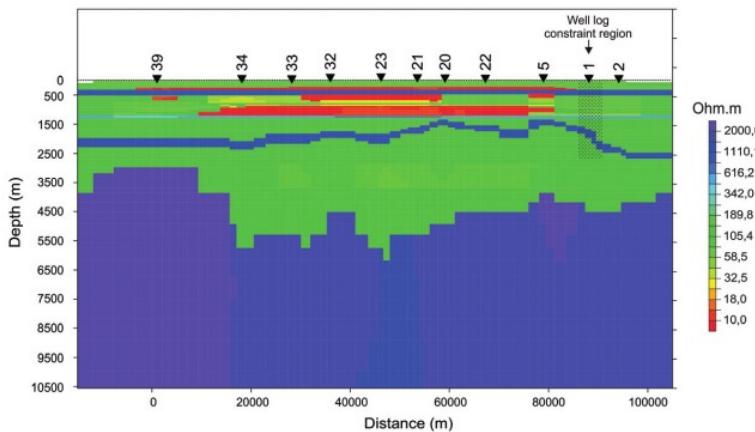


MT no Remanso do Fogo - Onshore

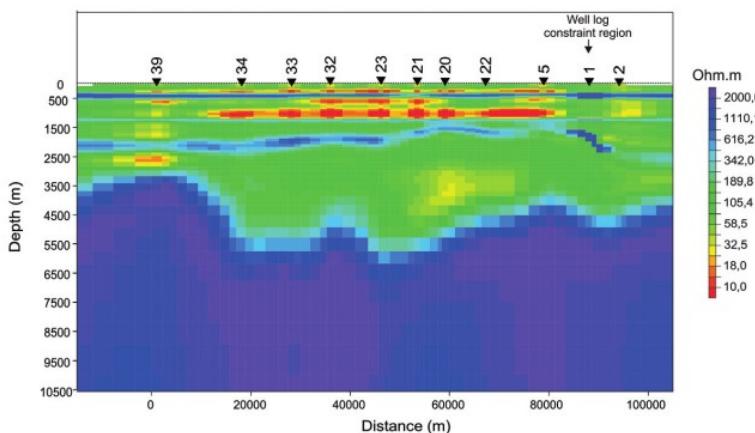


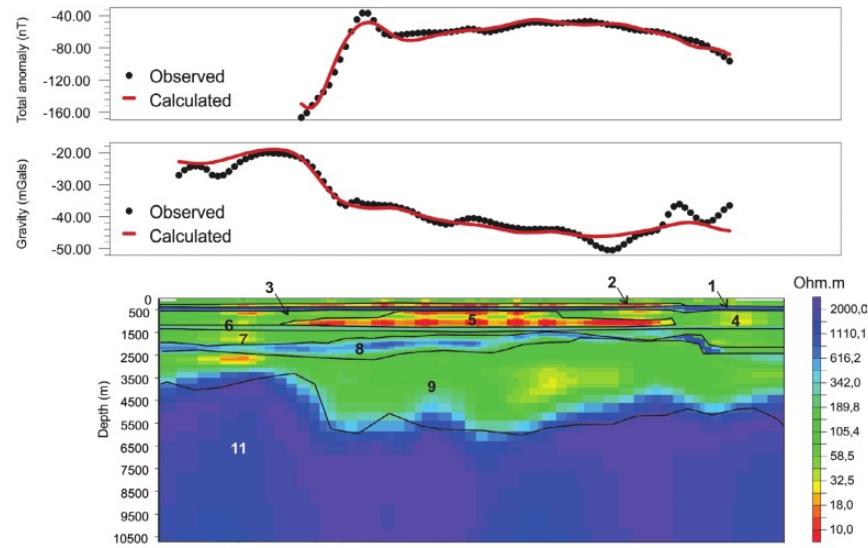
- ➡ Indication of Carbonate Formations
- ➡ Conductive geoelectric horizons
- ▼ MT Stations
- Lagoa do Jacare
- Lagoa do Jacare/Interlayered shales
- Serra de Santa Helena
- Lower Serra de Santa Helena/interlayered carbonates
- Jequitáí

(a)

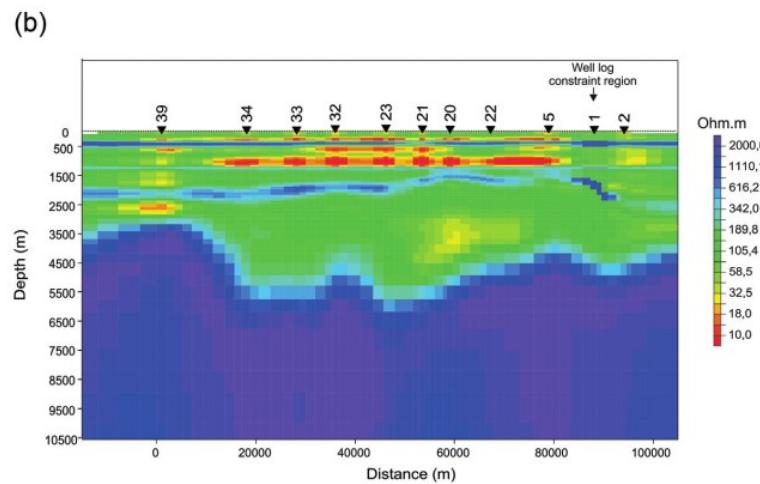
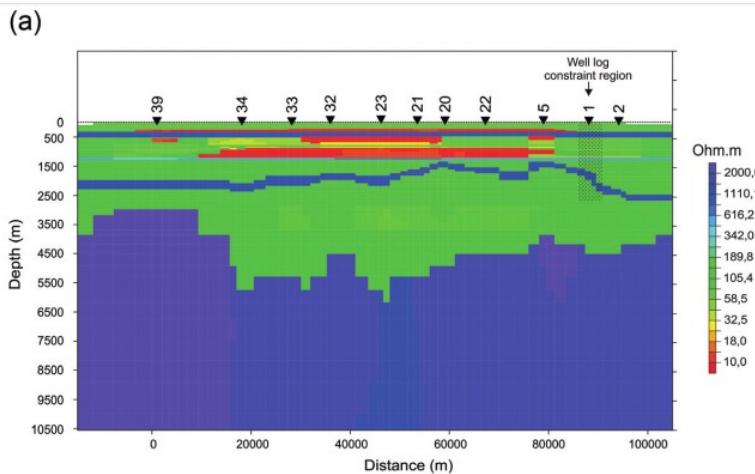


(b)





Geobody Number	Density (g cm^{-3})	Susceptibility (SI)
1 - Serra da Saudade sandstones and shales	2.4	0.0006
2 - Lagoa do Jacaré carbonate	2.5	0.0008
3 - Serra de Santa Helena sandstones	2.3	0.0004
4 - Serra de Santa Helena sandstones	2.3	0.0004
5 - Serra de Santa Helena shale	2.4	0.0006
6 - Sete Lagoas carbonate	2.5	0.0008
7 - Upper Jequitai shales and conglomerates	2.3	0.0004
8 - Upper Jequitai - calcilutites	2.5	0.0008
9 - Sandstone	2.3	0.0004
10 - Basement	2.7	0.07



Referências

- Pinto, V. R., 2013 - Interpretação conjunta semi-quantitativa utilizando vínculos com dados geofísicos na Bacia de Santos. Tese de doutorado, Observatorio Nacional.
- Fontes, S.L., de Lugao,P.P., Meju,M.A., Pinto,V.R., Flexor,J.M., Ulugergerli,E.U., La Terra, E.F., Gallardo, L.A. 2009 - Marine magnetotelluric mapping of basement and salt bodies in the Santos Basin of Brazil. First Break, Volume 27, Issue 5. doi:10.3997/1365-2397.27.1299.28933
- Zerilli,A., Labruzzo, T., Buonora,M.P., Menezes, P.T.L., Rodrigues, L.F., Lovatini, A. 2010 - 3D inversion of total field mCSEM data: The Santos Basin case study, SEG Technical Program Expanded Abstracts : 629-633.
- Colombo,D., McNeice,G., Curiel,E.S., Fox,A. 2013 - Full tensor CSEM and MT for subsalt structural imaging in the Red Sea: Implications for seismic and electromagnetic integration, The Leading Edge 32: 436-449.
- Colombo, D., McNeice, G., Raterman, N., Zinger,M., Rovetta,D., Curiel, E.S. 2014 - Exploration beyond seismic: The role of electromagnetics and gravity gradiometry in deep water subsalt plays of the Red Sea, Interpretation 2: SH33-SH53. Doi: 10.1190/INT-2013-0149.1