Coupled seismoelectric wave propagation in porous media

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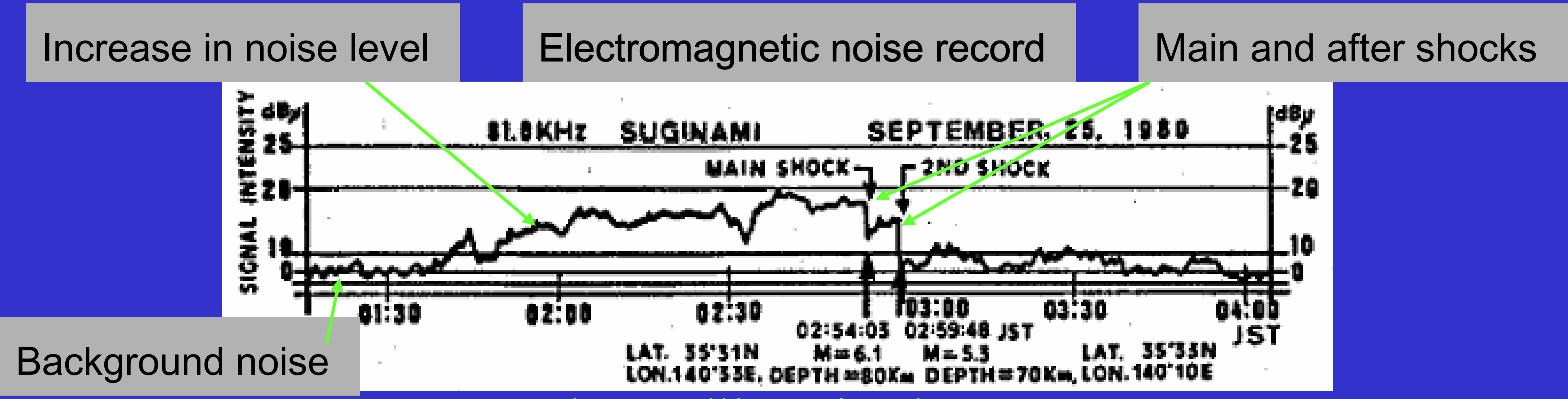
Introduction

- Seismic waves induce electric and magnetic fields.
- Conversion of acoustic energy into electromagnetic energy has been observed since early 1930s.
- Seismo-Electromagnetic phenomena are studied in earthquake seismology as a tool for prediction of earthquakes.



(Source: Gokhberg et al.,1982)

Introduction

Motivations for studying converted-wavefields

- Different properties of poro-elastic media influence the generation and propagation of electromagnetic waves than seismic waves.

- Consequently, we can extract more information about the reservoir and pore fluid from seismic and seismoelectric wave than seismic wave alone.

Introduction

Motivations for studying converted-wavefields

- Industry needs to directly detect fluids
- Seismoelectric and seismomagnetic (SeEM) effects are attached to fluid content
- SeEM waves are another converted wave – especially connected to P & S seismic waves
- Fertile research area, potential step-change for hydrocarbon exploration

Introduction

- Electric and magnetic processes in rocks
  - Piezoelectricity
    - when a stress is applied to certain crystals, opposite sides of the crystals become charged.
  - Triboelectricity/triboluminescence
    - when crystals are abraded, indented, or fractured.
  - Contact electrification
    - charge flow across the contact between two materials with different electronic charge densities.
  - Positive holes mechanism
    - holes or defect electrons in local lattice are generated in microfracturing and act as charge carrier.

  and

  - **Electrokinetic (streaming) potentials**
    - Displacement of the pore fluid relative to the porous solid grains in presence of electrical double layer.

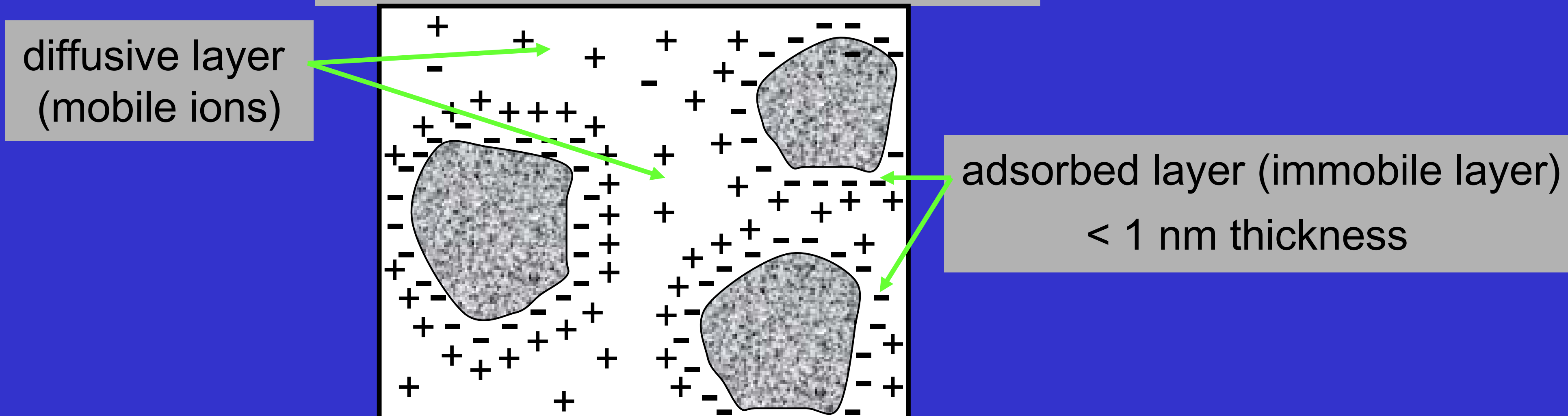
Electrokinetic potentials

- Grains of porous materials are formed by minerals such as silicates, oxides, and carbonates.

- these minerals develop an electrical double layer when in contact with an electrolyte.

- This electrical double layer is made up of a layer of immobile ions on the surface of the solid matrix and a diffusive layer of mobile ions extending into liquid phase

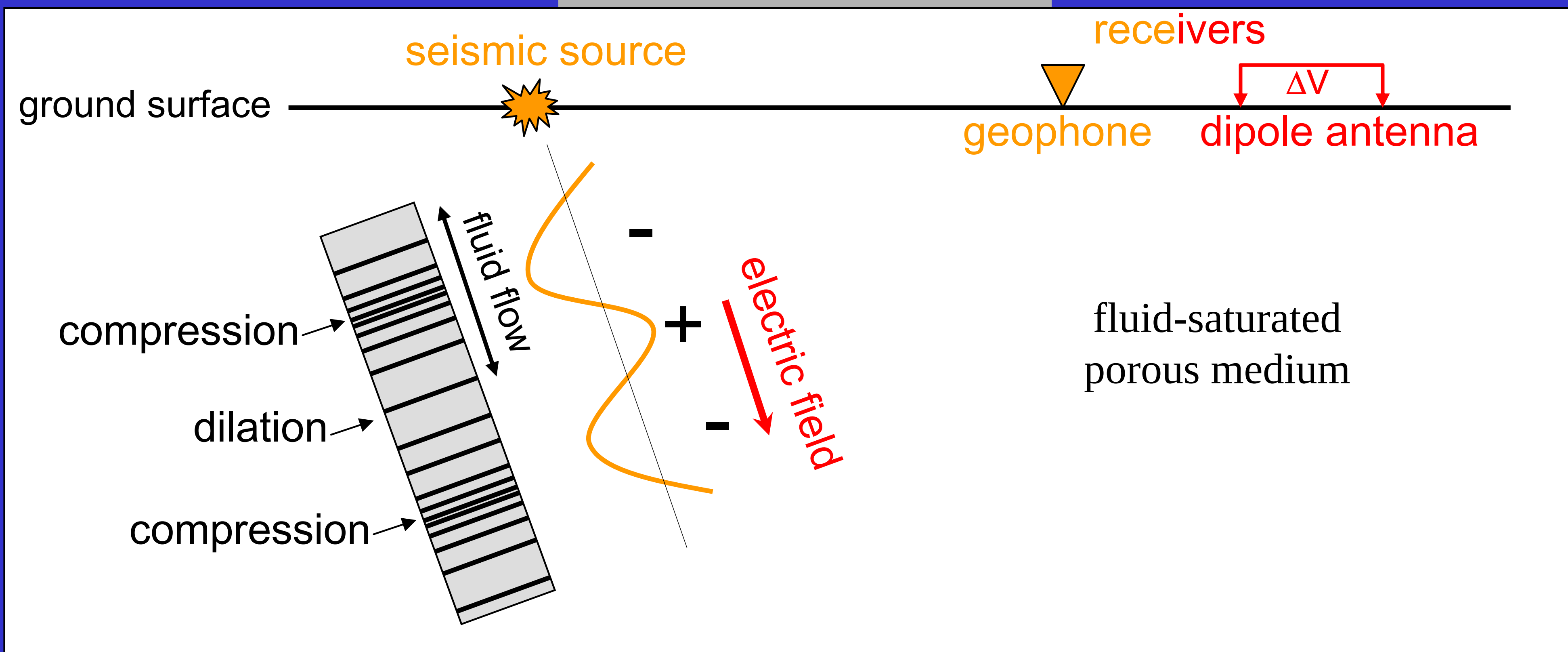
Electrical double layer in porous medium at the grain scale



Electrokinetic potentials

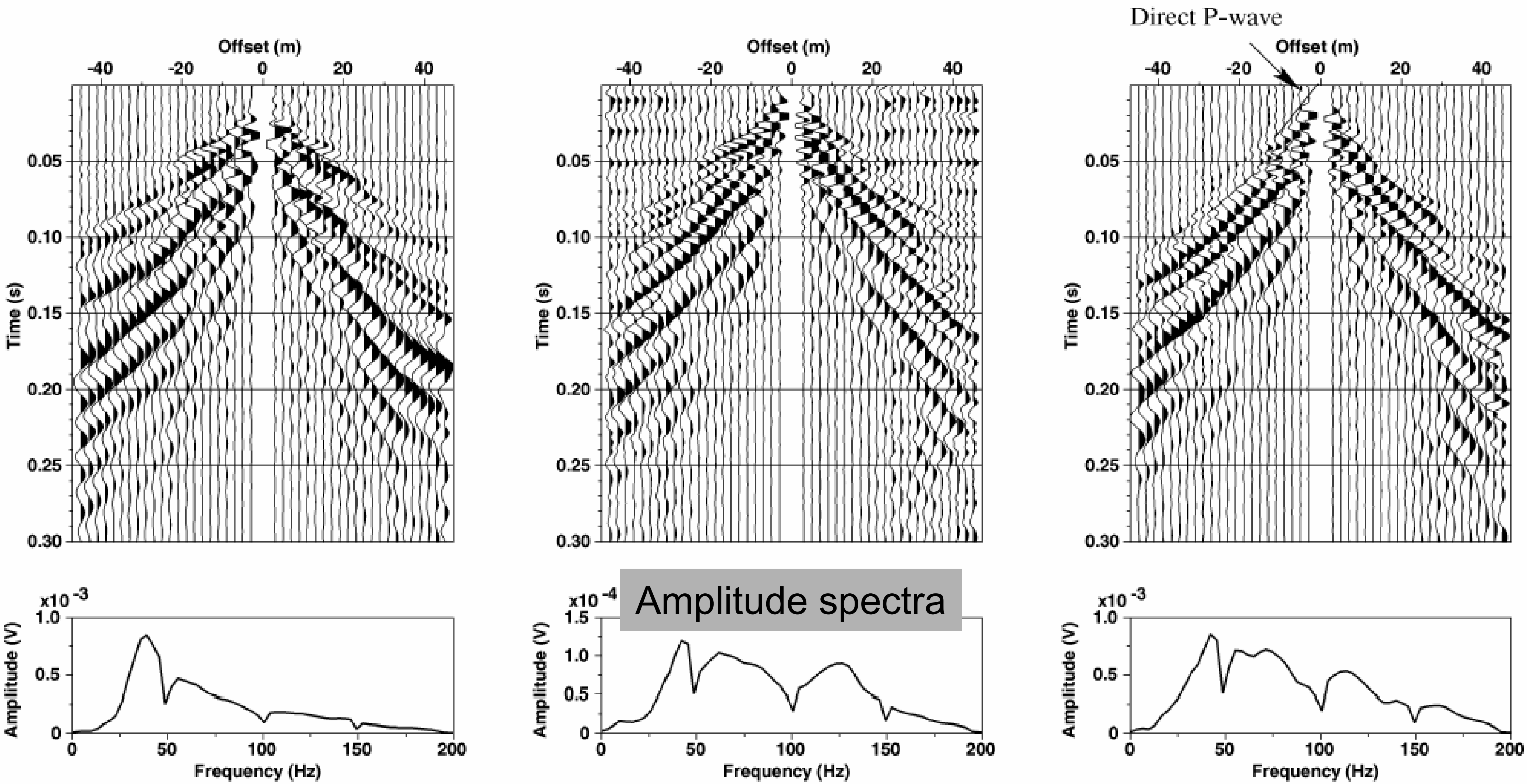
• A passing seismic wave causes displacement of the pore fluid and mobile charge relative to the solid grains and immobile charge.
• Electric current and an electric field are generated (**First type response**).

Conceptual Model



Example of seismic and electric field data record

Vertical velocity | In-line electric field | In-line horizontal velocity



(source: Garambois and Dietrich 2001)

• **In multi-layer porous media**, traveling seismic wave gives rise to a **second type of seismoelectric response**.

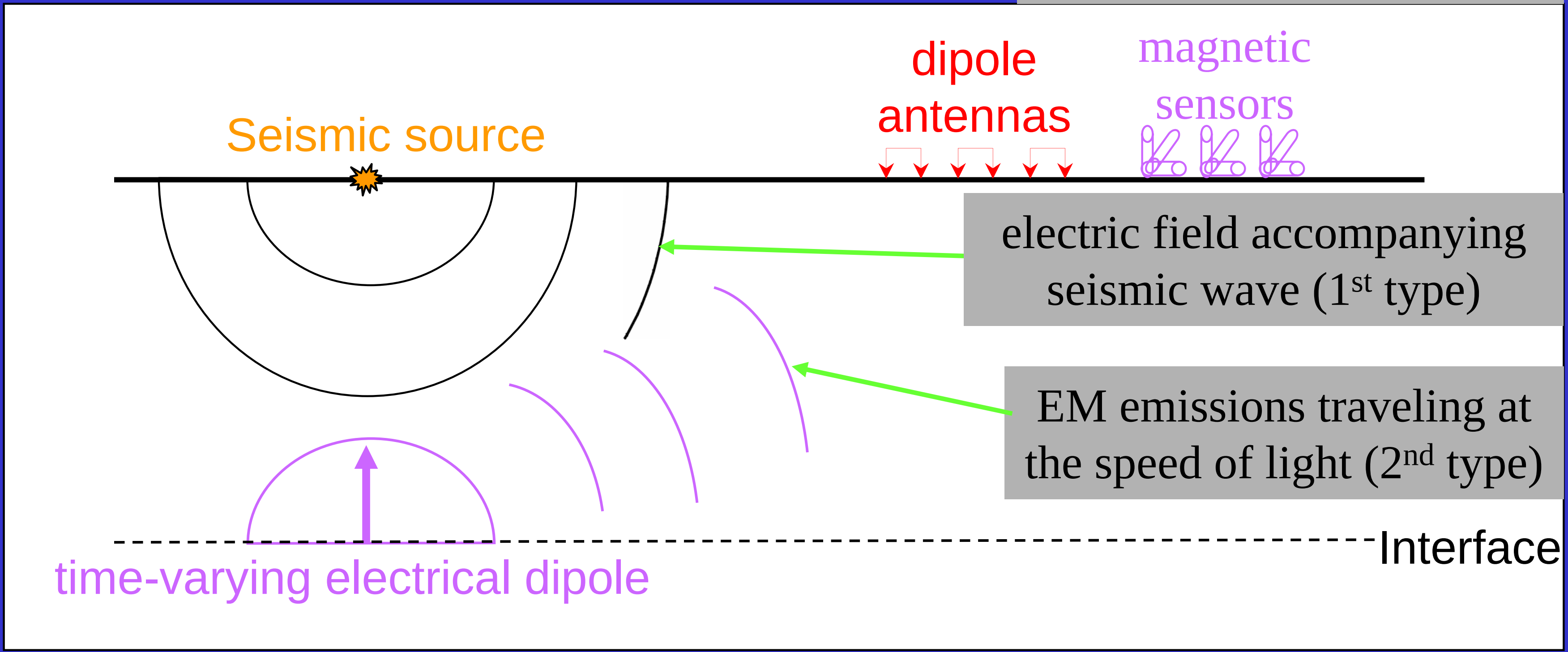
When seismic wave impinges on a layer interface

⇒ partially converts to Biot slow wave

⇒ generates a large time-varying charge separation

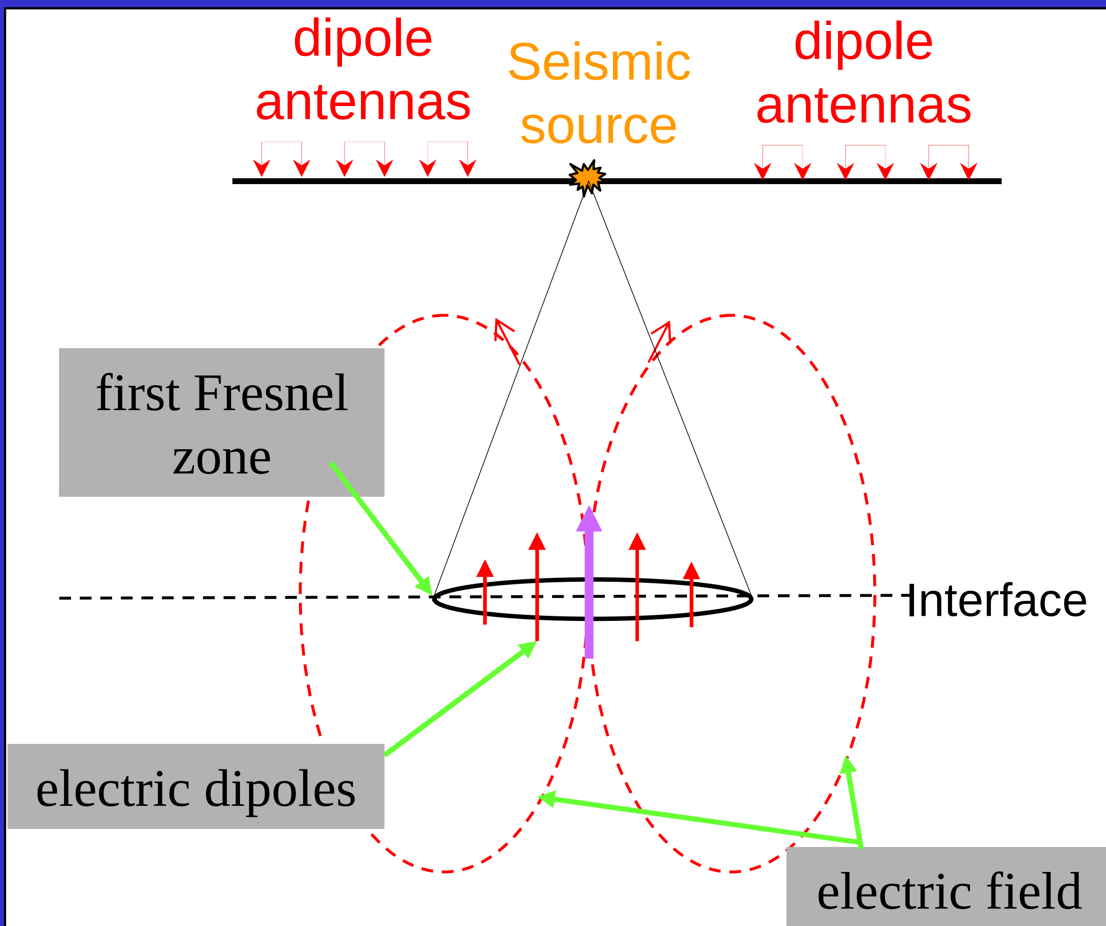
⇒ **radiates electromagnetic wave**

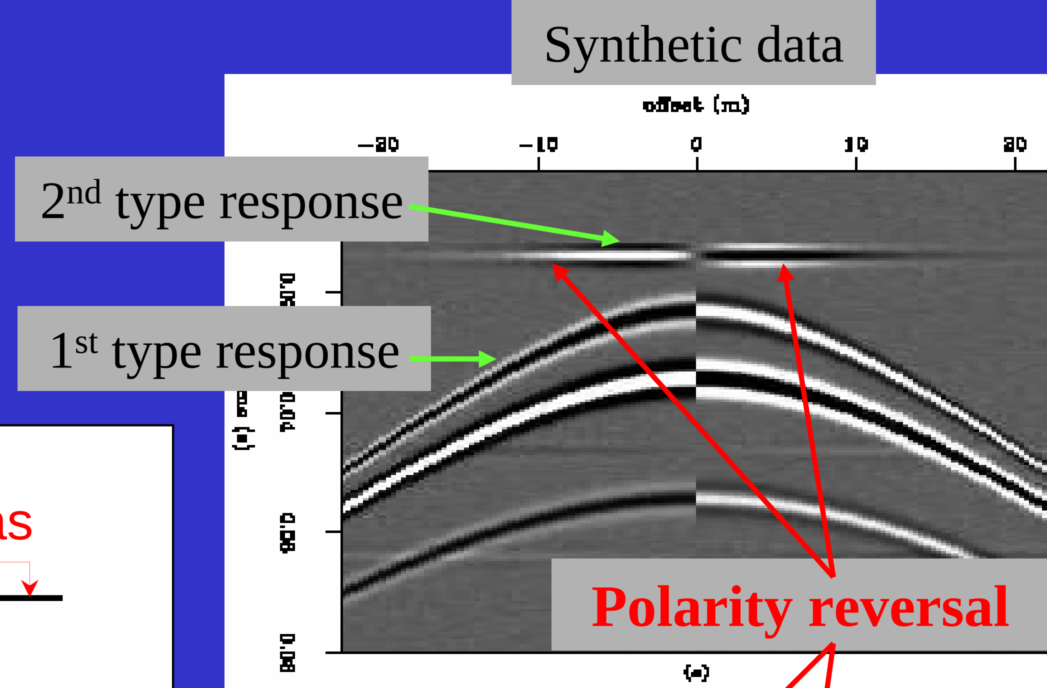
Conceptual Model



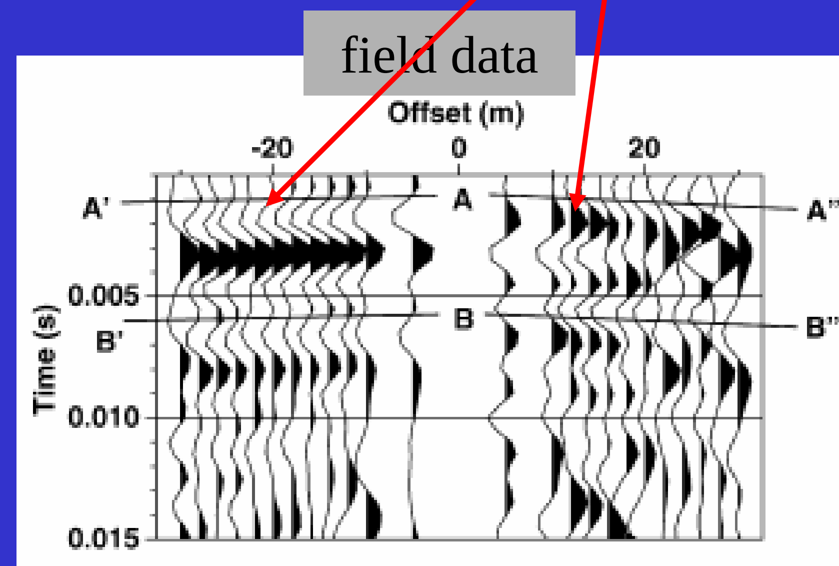
Electromagnetic emission

generated at layer interface





(source: Haines et. al. 2002)



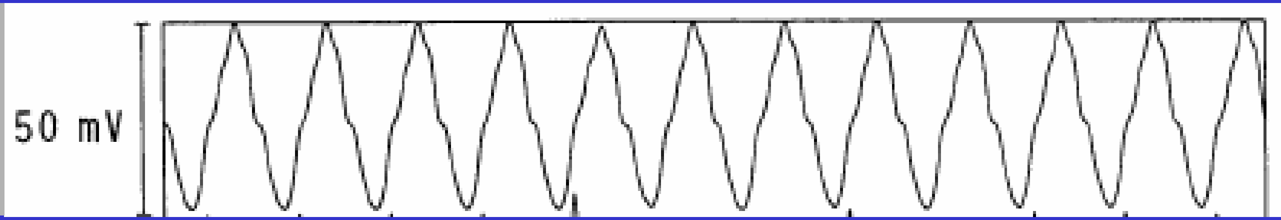
(source: Garambois and Dietrich 2001)

Seismoelectric data processing

Two important steps,

- Powerline harmonics removal.

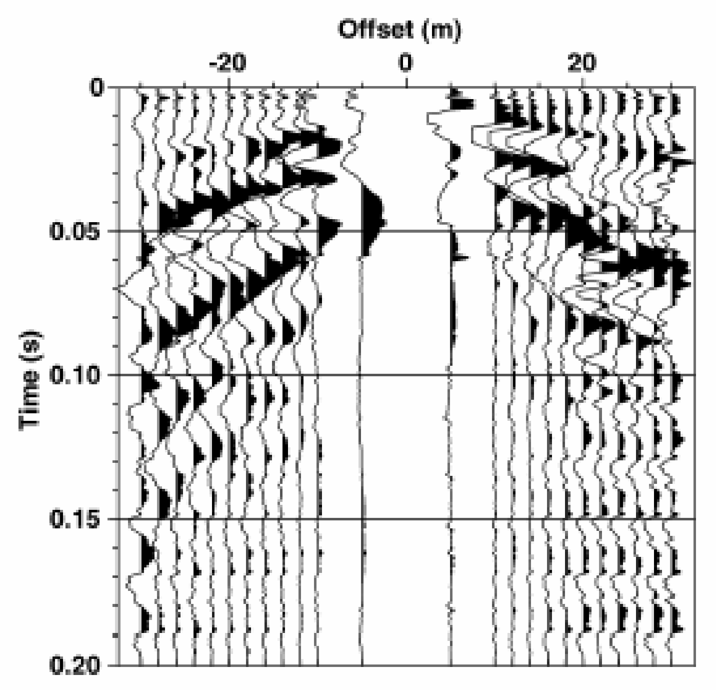
A raw seismoelectric record contaminated by powerline harmonics



(*source: Butler and Russell 1993*)

- Separation of seismoelectric response type.

A raw seismoelectric record. EM interface response has been masked by the first type of the seismoelectric response that travel within the seismic waves.



(*source: Garambois and Dietrich 2001*)

Suppressing of the powerline harmonics

• Sinusoid subtraction technique, subtract 10 to 20 harmonics of the powerline fundamental frequency.

• Amplitude and phase of each of the harmonics are estimated in a least-squares minimization process.

raw seismoelectric record

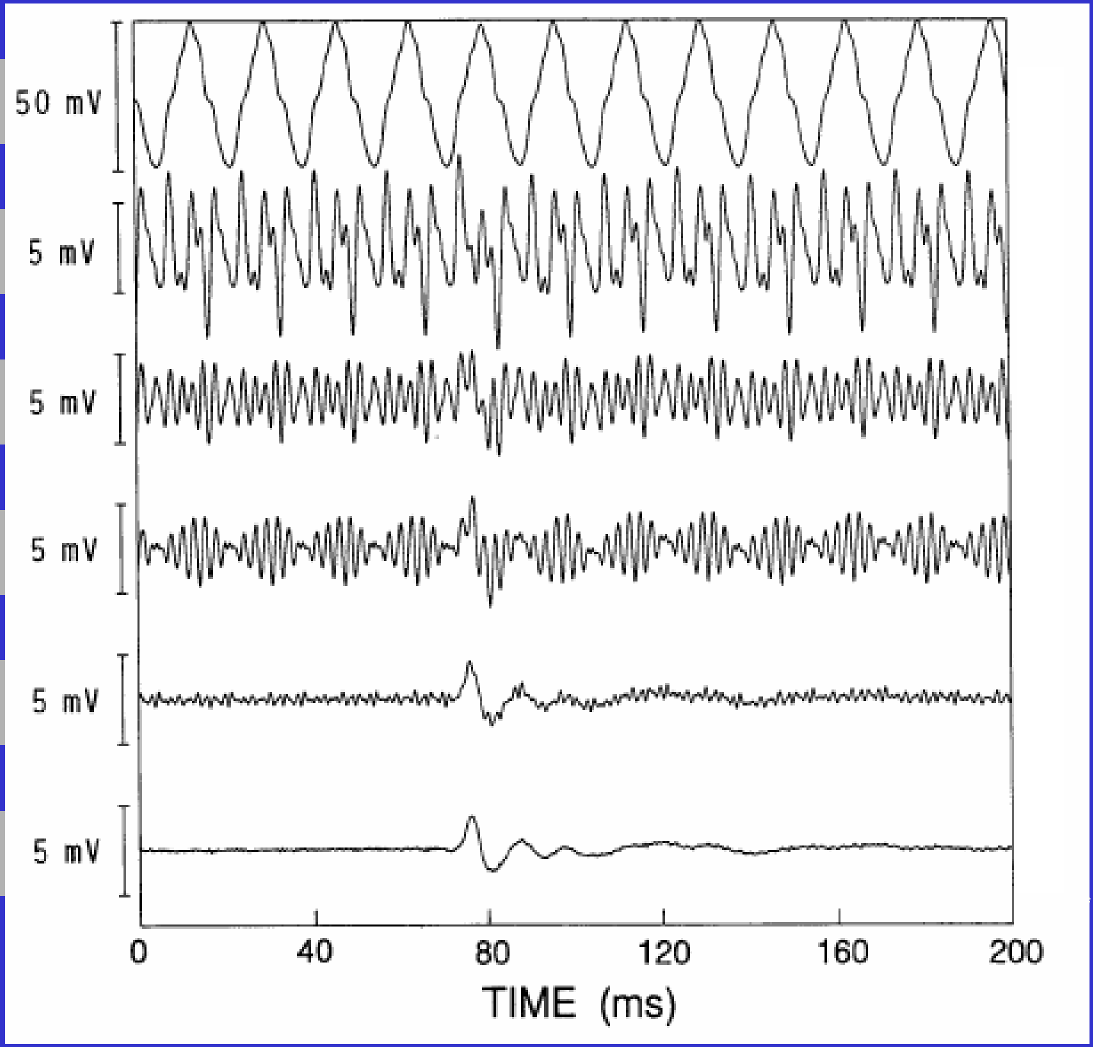
after harmonic 60 Hz removed

after harmonic 180 Hz removed

after harmonic 300 Hz removed

after harmonics 360-420 Hz removed

after harmonics 480-840 Hz removed

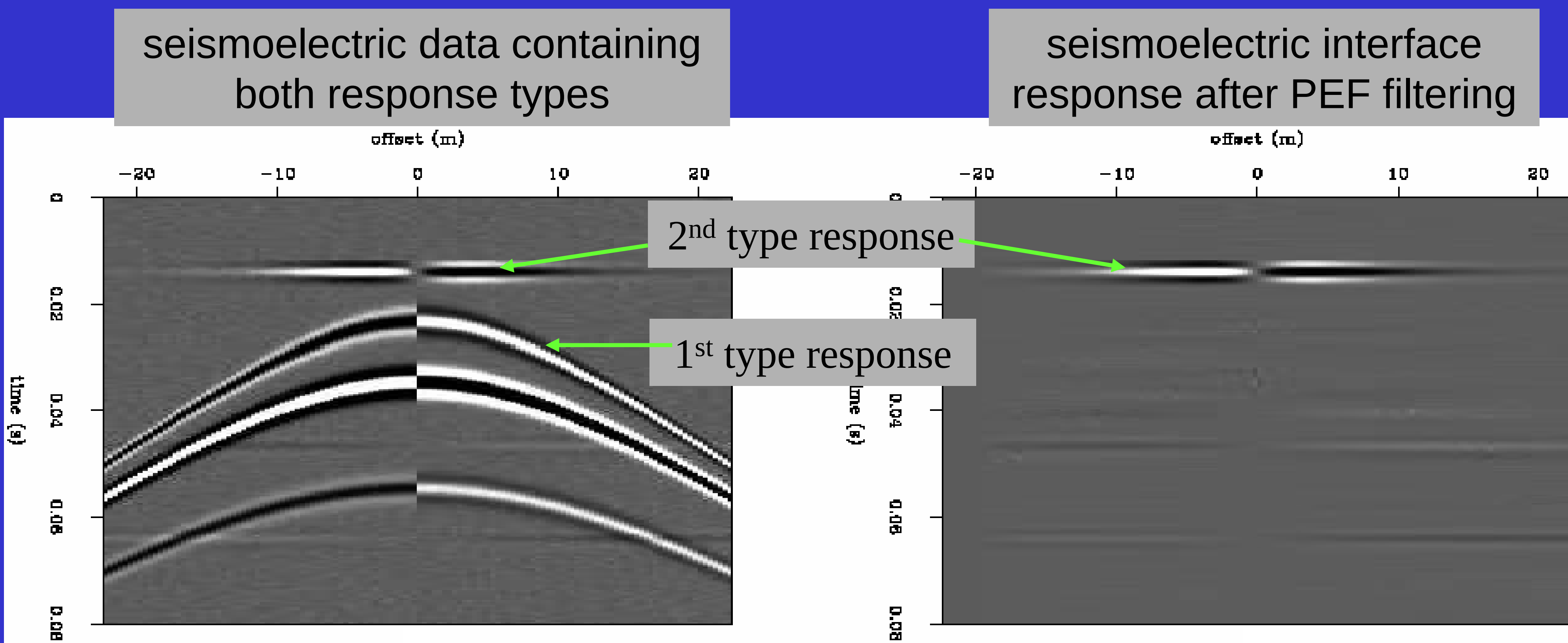


(source: Butler and Russell 1993)

Seismoelectric response types separation

• Seismoelectric data can be considered as sum of interface response and of internal stationary dipole response.

• Prediction Error Filters (PEF) can be used to separate these to seismoelectric responses.

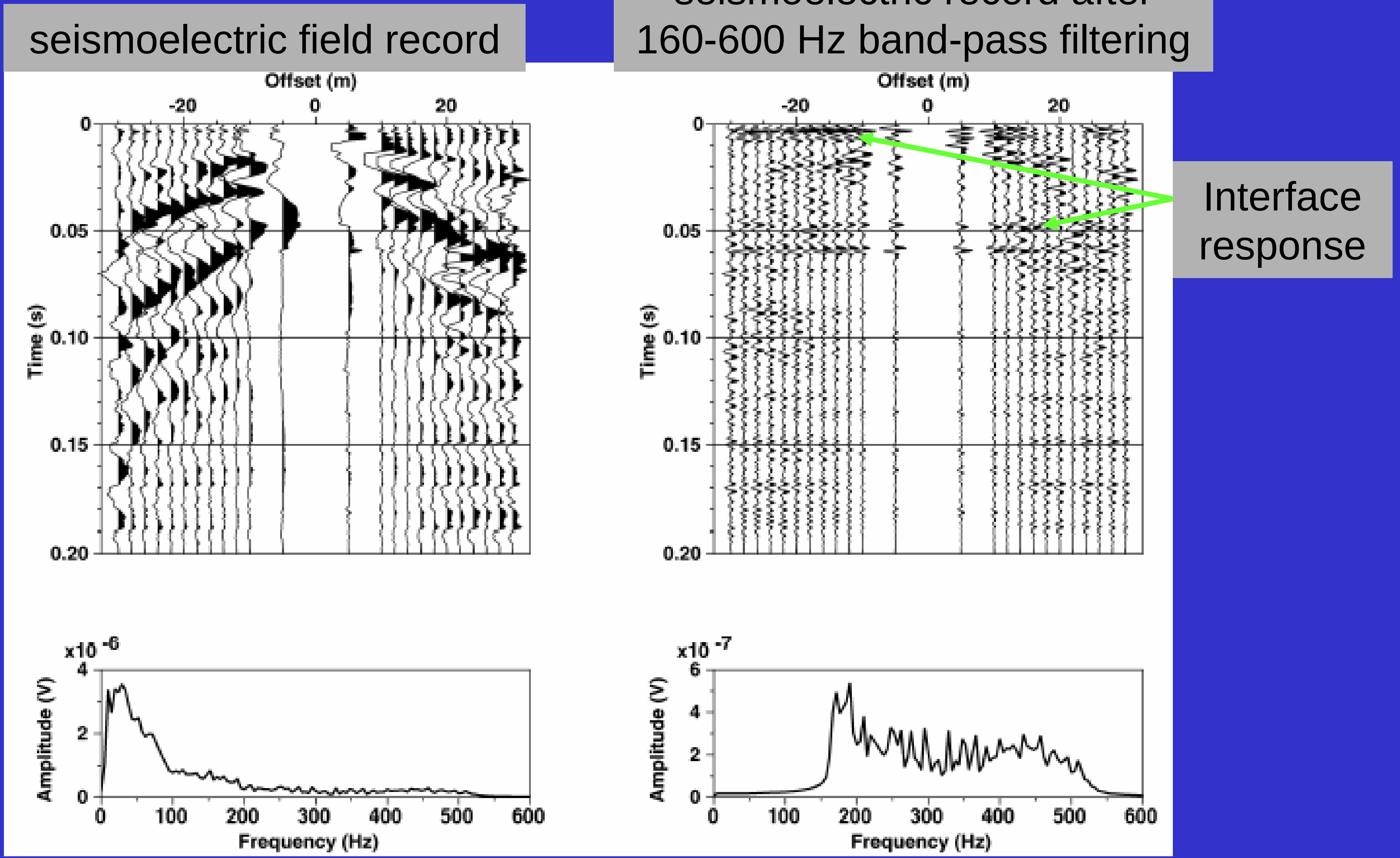


(source: Haines et. al. 2002)

Seismoelectric response types separation

• Seismoelectric interface response contains higher frequency compared to the seismic energy reflected from the same interface.

• Band-pass filtering can be used to separate seismoelectric responses.



Transfer function estimates

- Linear relationship between EM and elastic waveforms

$$E_x \cong L\ddot{u}_x^P \quad \text{,for P-waves}$$

$$E_z \cong L\ddot{u}_z^P \quad \text{,for P-waves}$$

$$\sqrt{H_x^2 + H_z^2} = T\dot{u}_y^S \quad \text{,for SH-waves}$$

$$H_y = T\sqrt{\left(\dot{u}_x^S\right)^2 + \left(\dot{u}_z^S\right)^2} \quad \text{,for SV-waves}$$

E: *electric field*
H: *magnetic field*
U: *grain displacement*

***L*(σ,κ,η,ρ,…)** is a function of fluid's electric conductivity (σ), fluid's dielectric constant (κ), shear viscosity (η), and bulk density (ρ).

T*(ϕ,κ,η,ρ,*G*,…)** is a function of porosity (ϕ), fluid's dielectric constant (κ), shear viscosity (η), bulk density (ρ), and shear modulus (G***).

Estimation of physical properties

Compute *L* using;

$$L = E_x / \ddot{u}_x^P$$

$$\text{or} \quad L = E_z / \ddot{u}_z^P$$

$$\text{or} \quad L = (E_x + E_z)/(\ddot{u}_x^P + \ddot{u}_z^P)$$

Compute *T* using;

$$T = \sqrt{H_x^2 + H_z^2} / \dot{u}_y^S$$

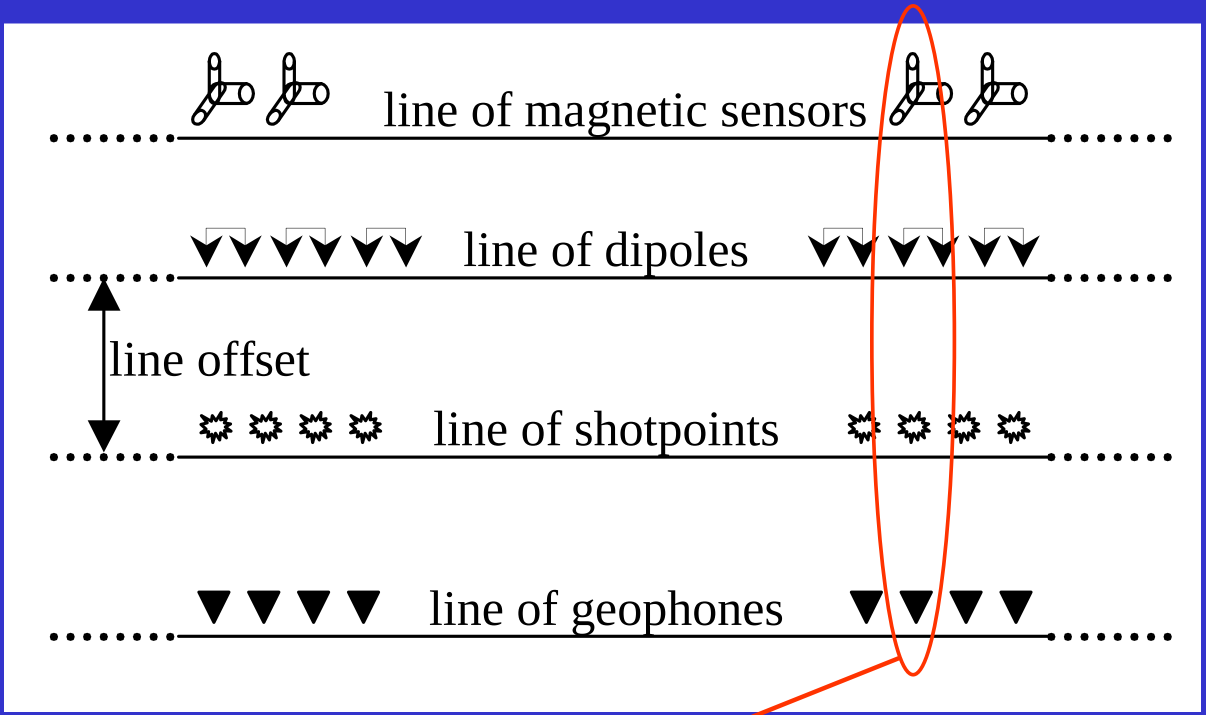
$$\text{or} \quad T = H_y / \sqrt{\left(\dot{u}_x^S\right)^2 + \left(\dot{u}_z^S\right)^2}$$

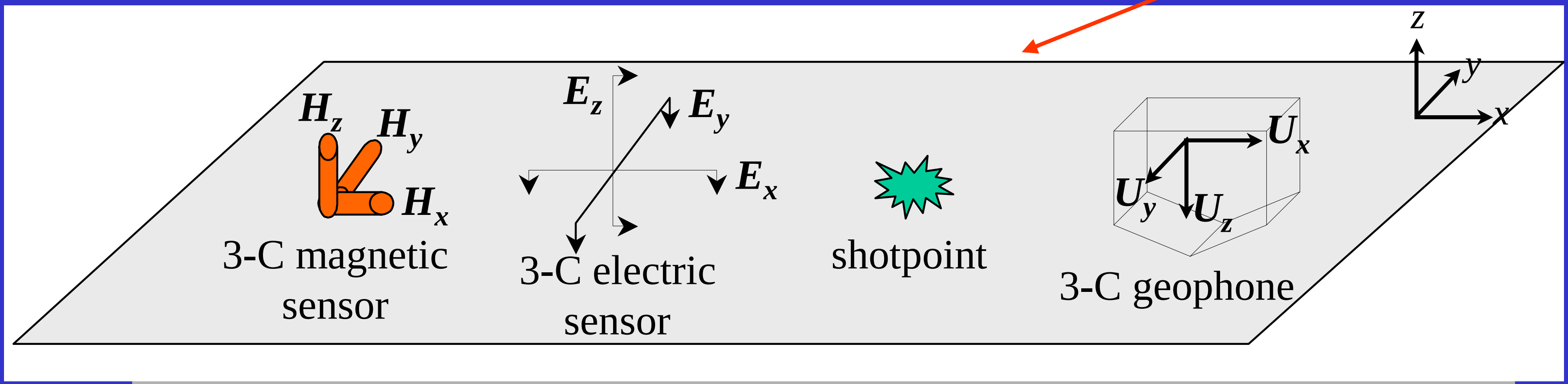
Invert *L* and *T* to estimate;

$$f(L,T) \xrightarrow{\text{inversion}} \sigma, \kappa, \phi, \eta, \rho, \boldsymbol{G}$$

Seismoelectromagnetic survey

- Layout of grounded dipole antennas, magnetic sensors, and geophones about the shotpoints.





Single shot and receiver illustration of simultaneous seismic and seismoelectromagnetic survey.

Summary

- In multi-layer fluid-saturated media, two types of seismoelectric responses are generated:
  - Internal stationary dipole response
  - Interface EM emission response

- Primary seismoelectric data processing includes:
  - Removal of powerline harmonic interferences
  - Response types separation

- Transfer functions between EM fields and elastic waves can be estimated by simultaneous measurements of multi-component electric and magnetic fields and seismic waves.

- Transfer functions composed of physical properties of formation’s pore-fluid and solid matrix: dielectric constant, electrical conductivity, porosity, shear viscosity, bulk density and, salt concentration

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Strategy and the road ahead

- Currently building team;
  - Geophysics (Dr. R. Stewart, Dr. L. Bentley, Dr. M. Gharibi)
  - Mechanical Engineering (Dr. A. Budiman)
  - AERI funding
- Connecting with established groups (e.g., Butler, UNB)
- Theory, numerical modeling then oilfield trial