Laboratory-scale monitoring of CO_2 sequestration using complex electrical conductivity and seismic property changes derived from seismic interferometry

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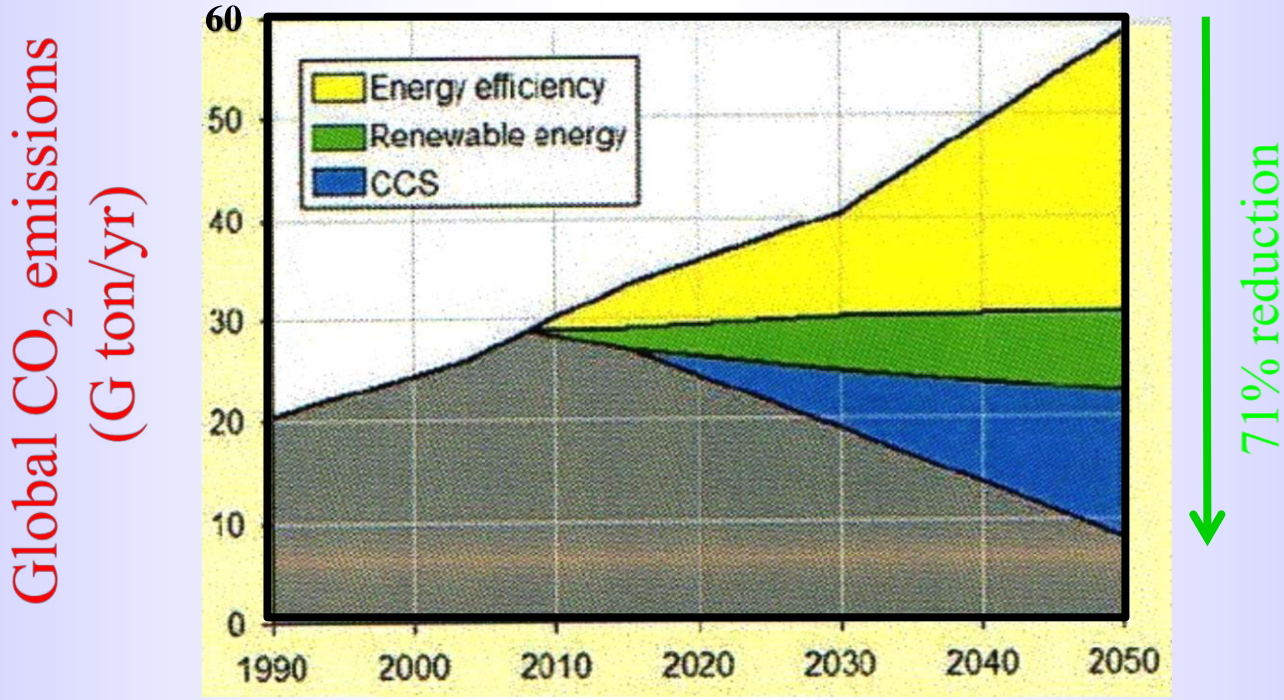
The strategy to reduce greenhouse gas emission must combine:

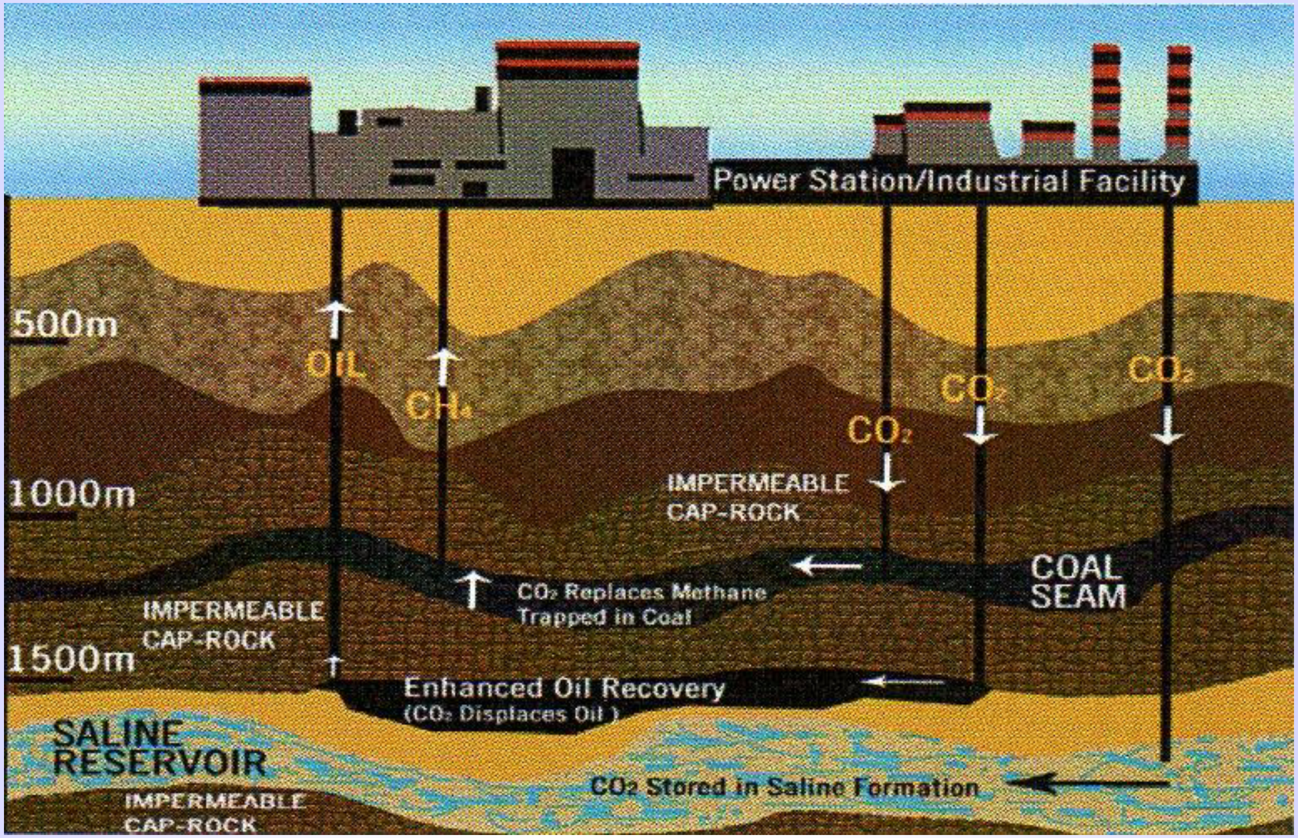
1. Increased Energy Efficiency
2. More renewable energy production
   (incl. wind, solar, geothermal)
3. A wise implementation of Carbon Capture and Storage (CCS)



(Bellona Report, 2007)

Three storage options:

1. Deep unminable coal seams
2. Depleted oil and gas reservoirs
3. Deep saline aquifers



Reasons/Need for monitoring:

1. For process efficiency (for site development, track the migration)
2. For storage verification (containment: mass balance, saturation)
3. For safety (seal or cap rock integrity, leakage)

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Monitoring techniques:

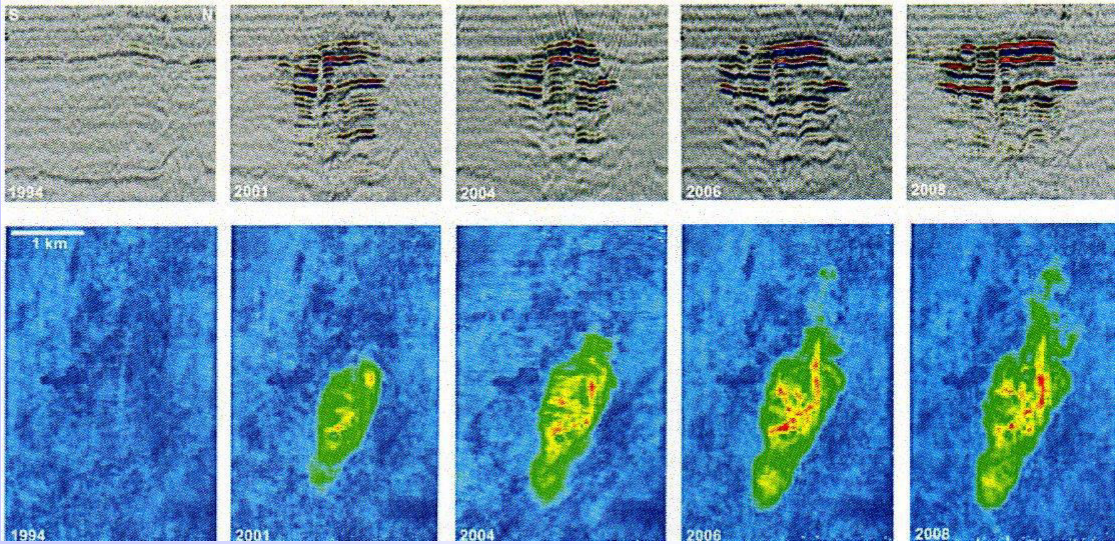
1. Direct sampling methods (chemical sensors, monitoring in wells)
2. Remote sensing methods (spaceborne satellites, geophysical methods)

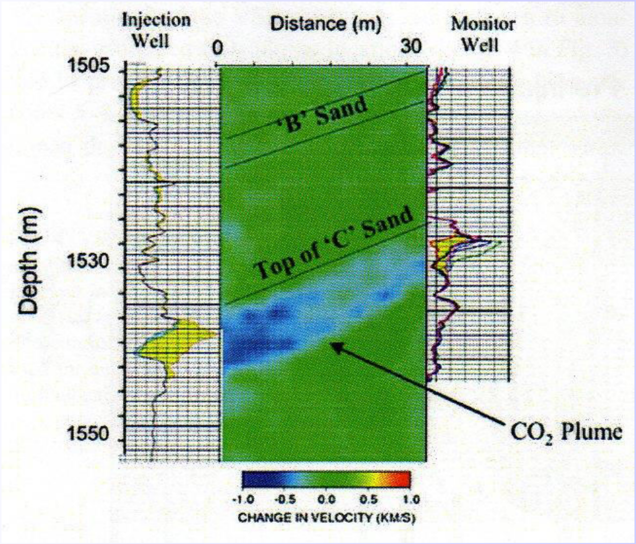
Geophysical methods for monitoring CCS:

- Seismic
- Electromagnetic
- Gravity
- Geodetic

Seismic methods have the broadest applicability !

1994 2001 2004 2006 2008





Sleipner Field, North Sea
(Chadwick et al., 2009)

Frio Formation, Texas
(Daley et al., 2008)

Four major issues that remain unresolved are:

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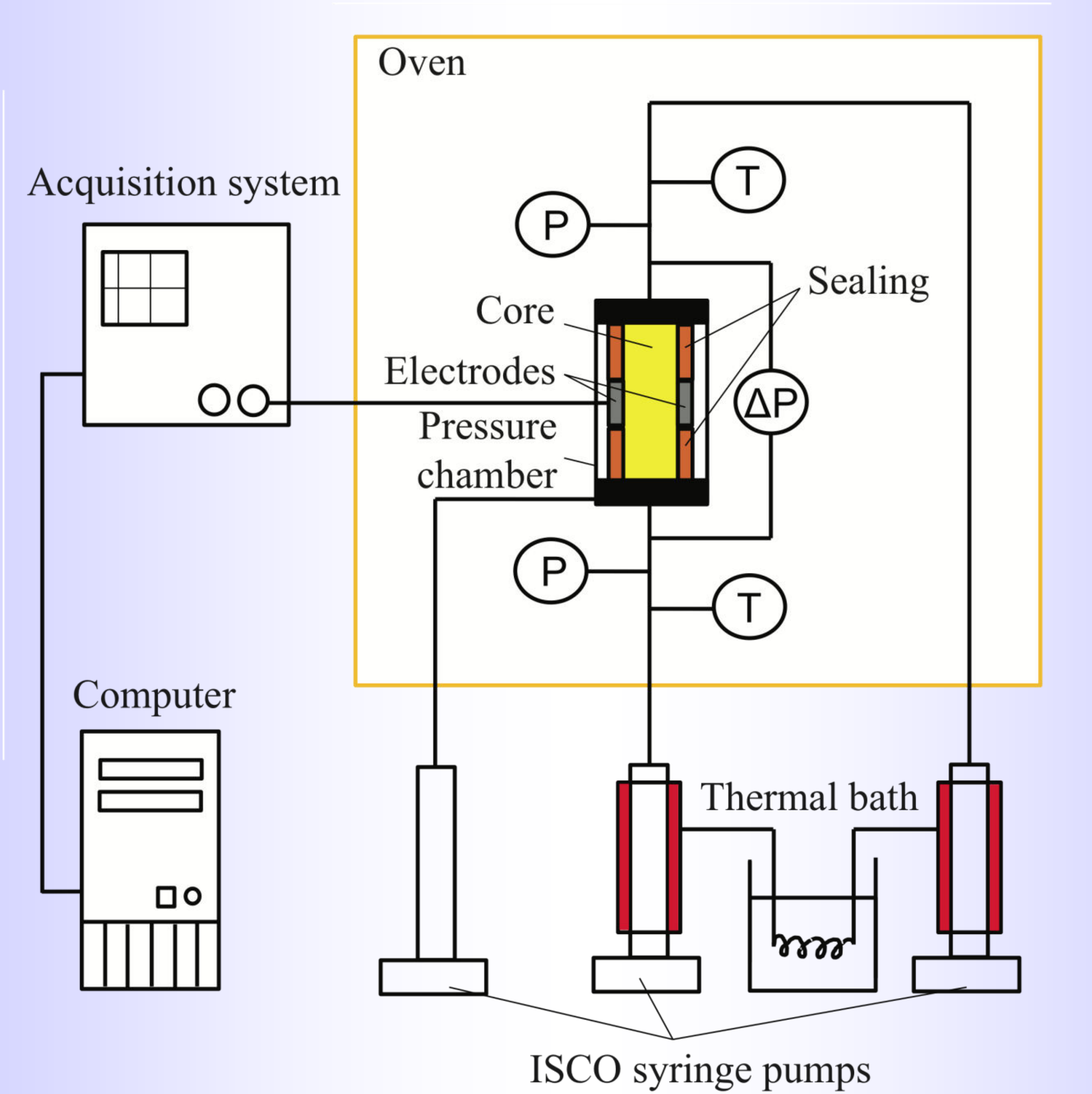
CCS monitoring: use of complex electrical measurements



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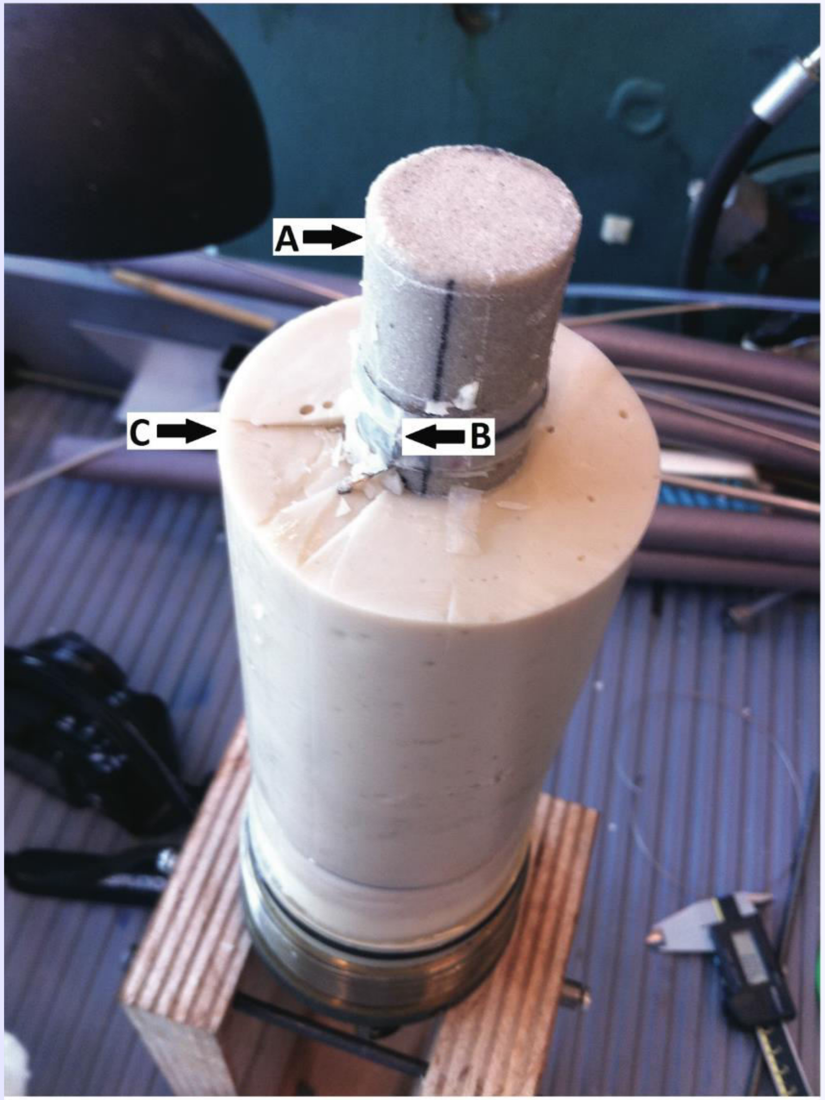

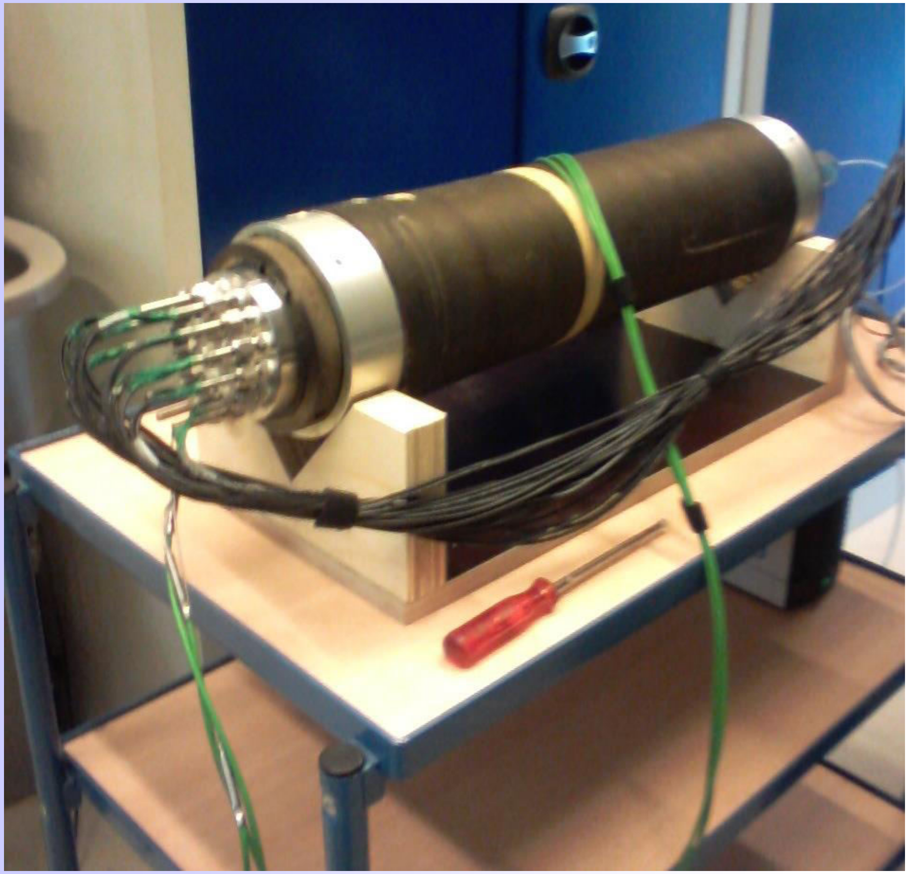

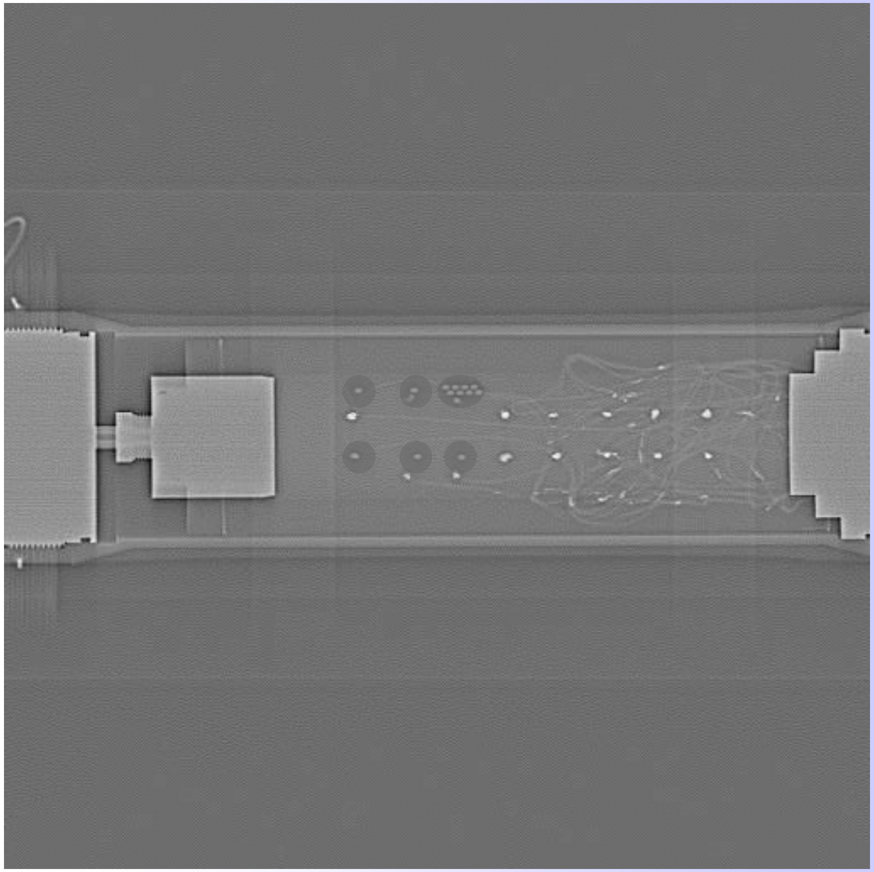

CCS monitoring: use of complex electrical measurements

We measure frequency-dependent impedance: amplitude |Z| and phase ϕ :

We estimate effective complex permittivity :

We get effective complex conductivity :

and are related as :

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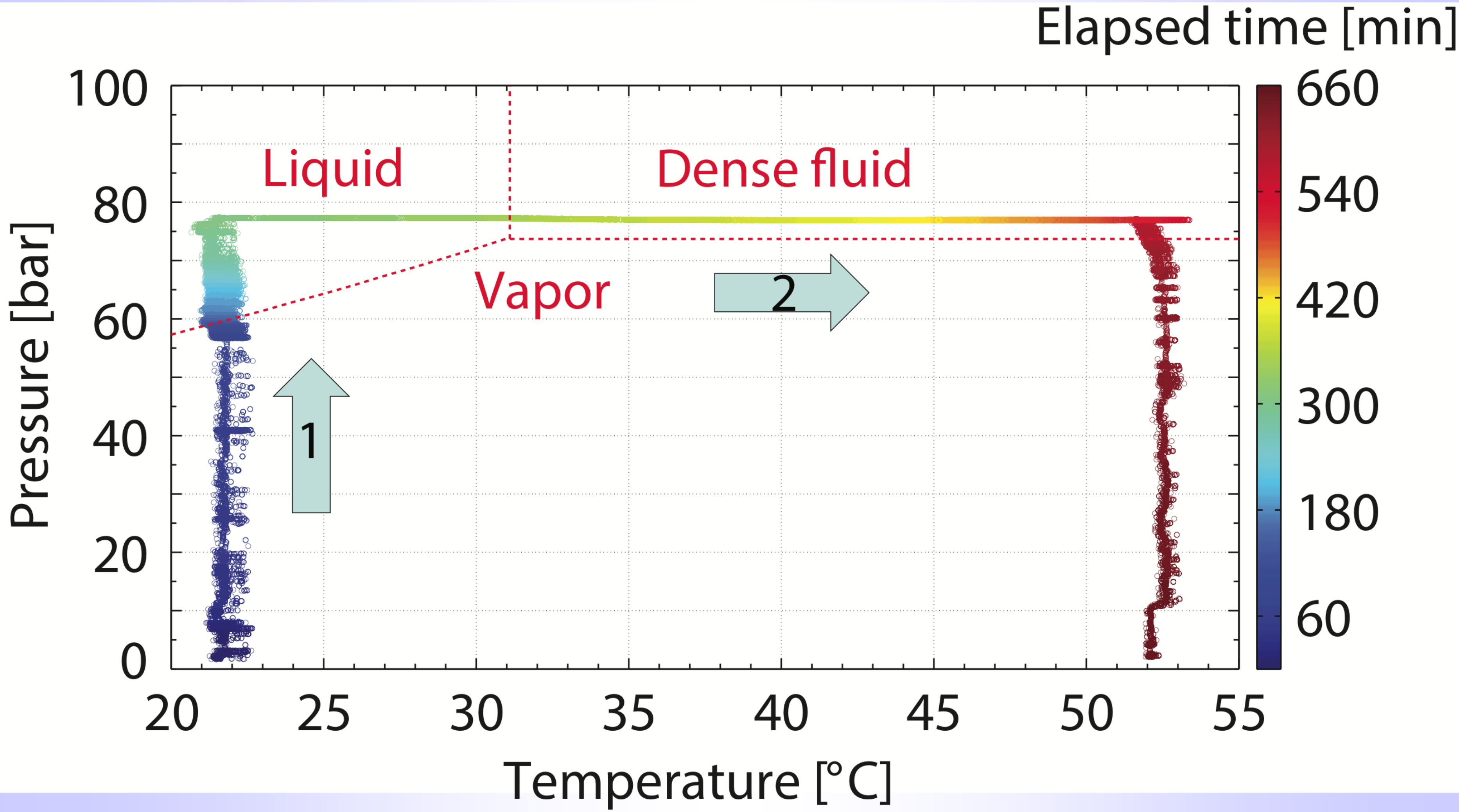

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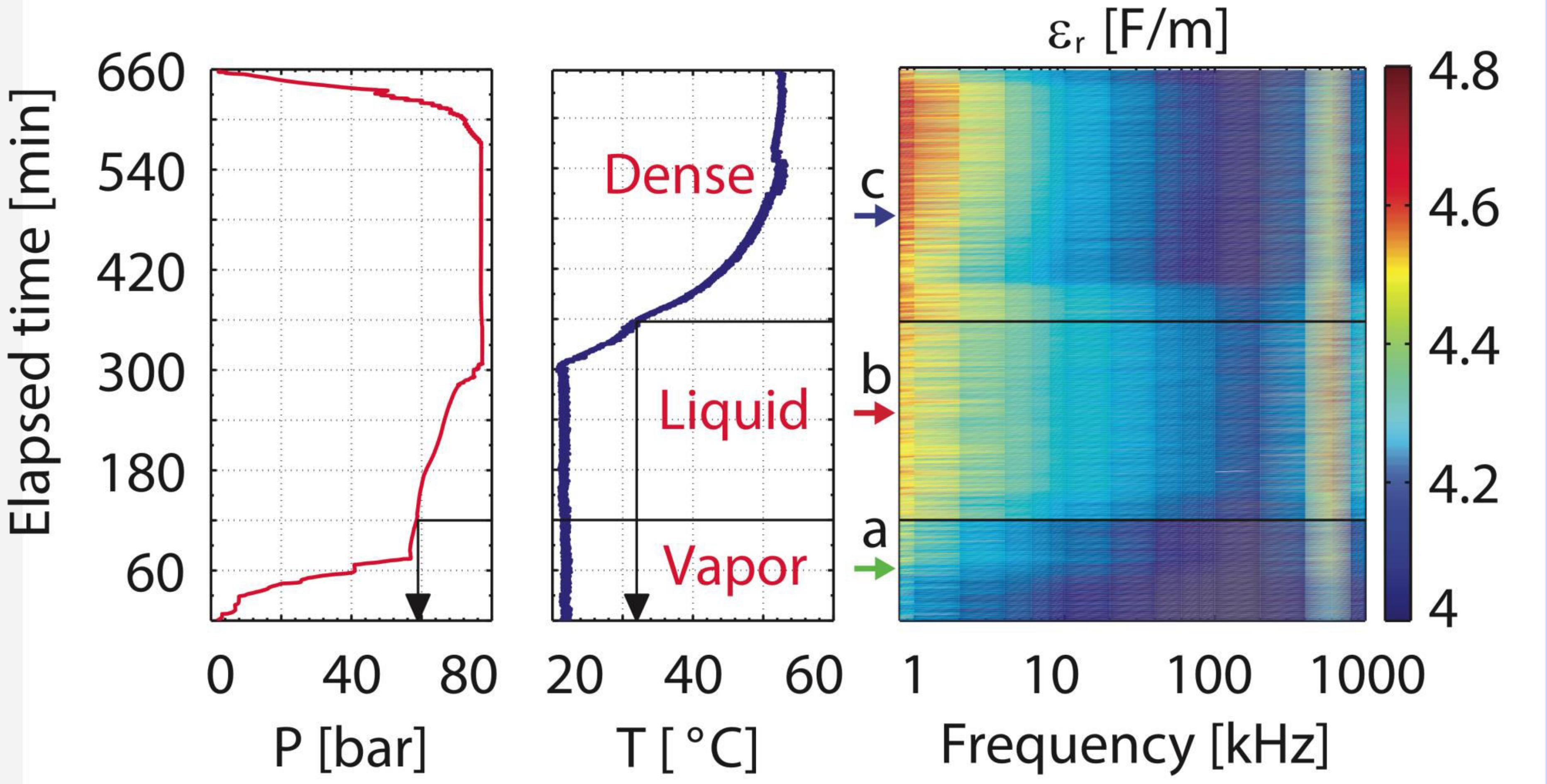

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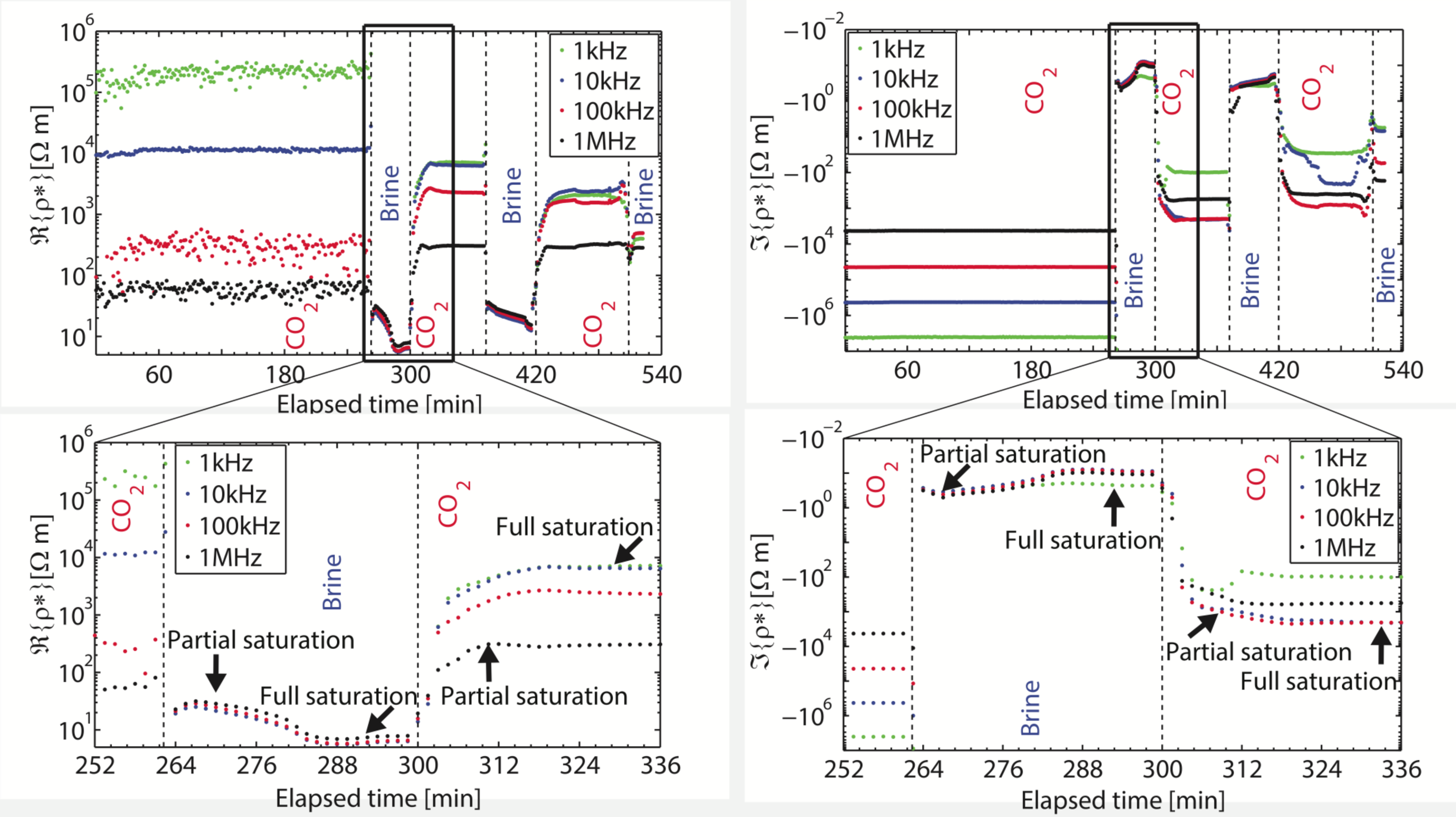
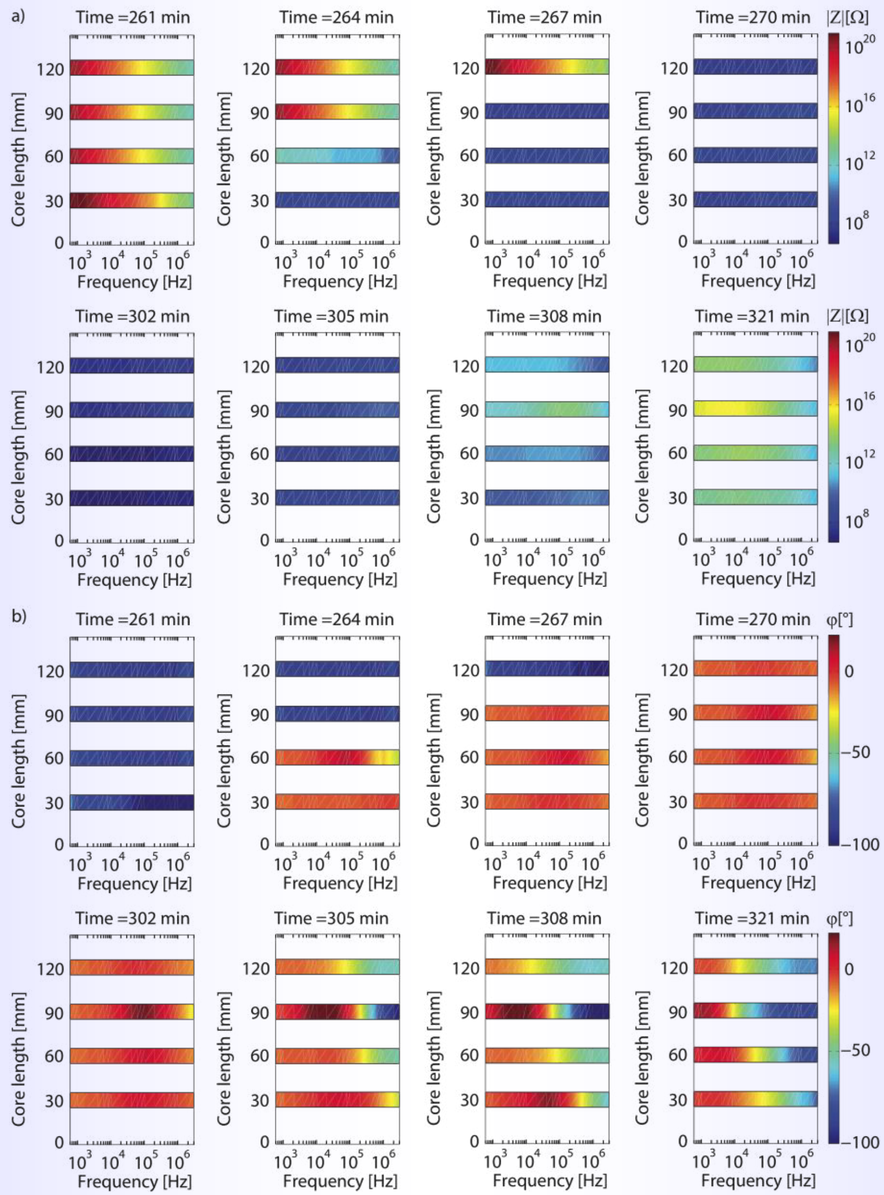


a) b)

CCS monitoring: use of complex electrical measurements

Complex Impedance



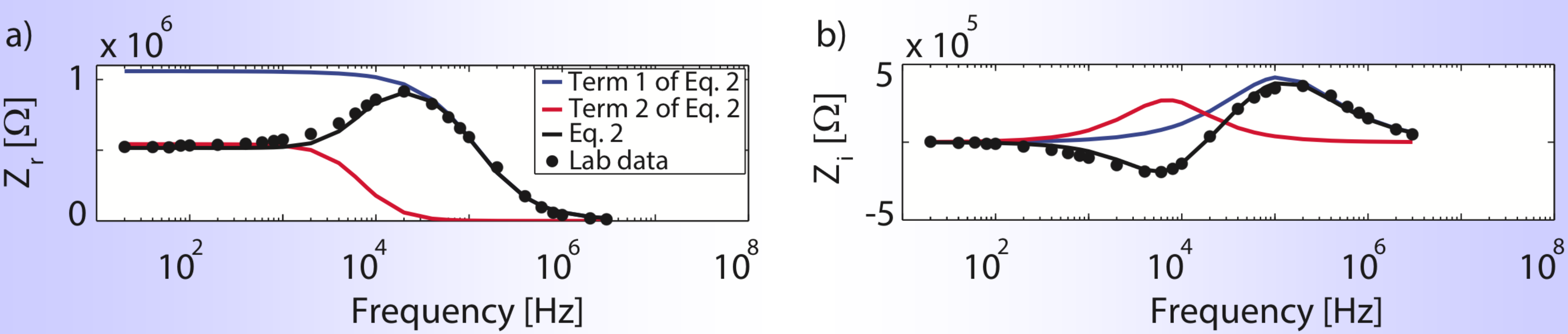
Amplitude

Phase

Equivalent circuit representation for CO2 and brine saturation:

(Kavian et al., 2012)

To estimate the fitting parameters, minimize the residual *R*:



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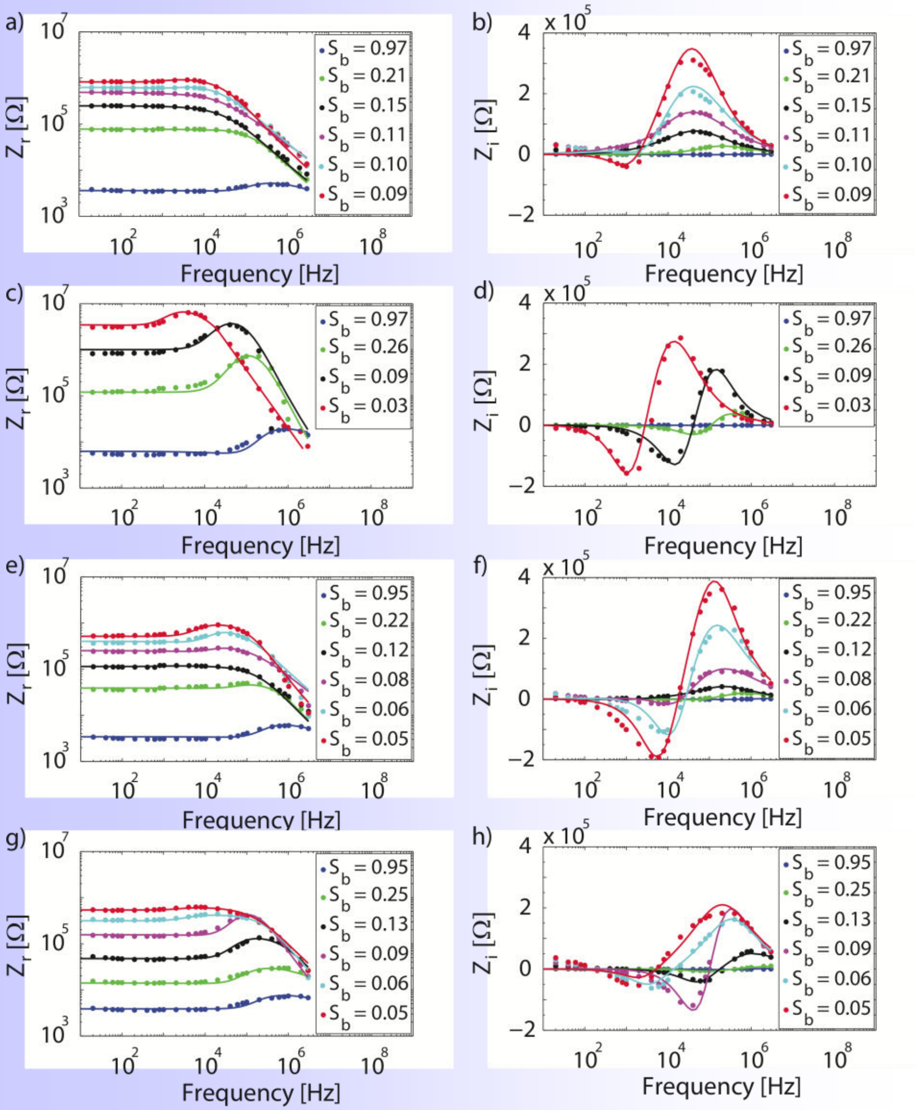

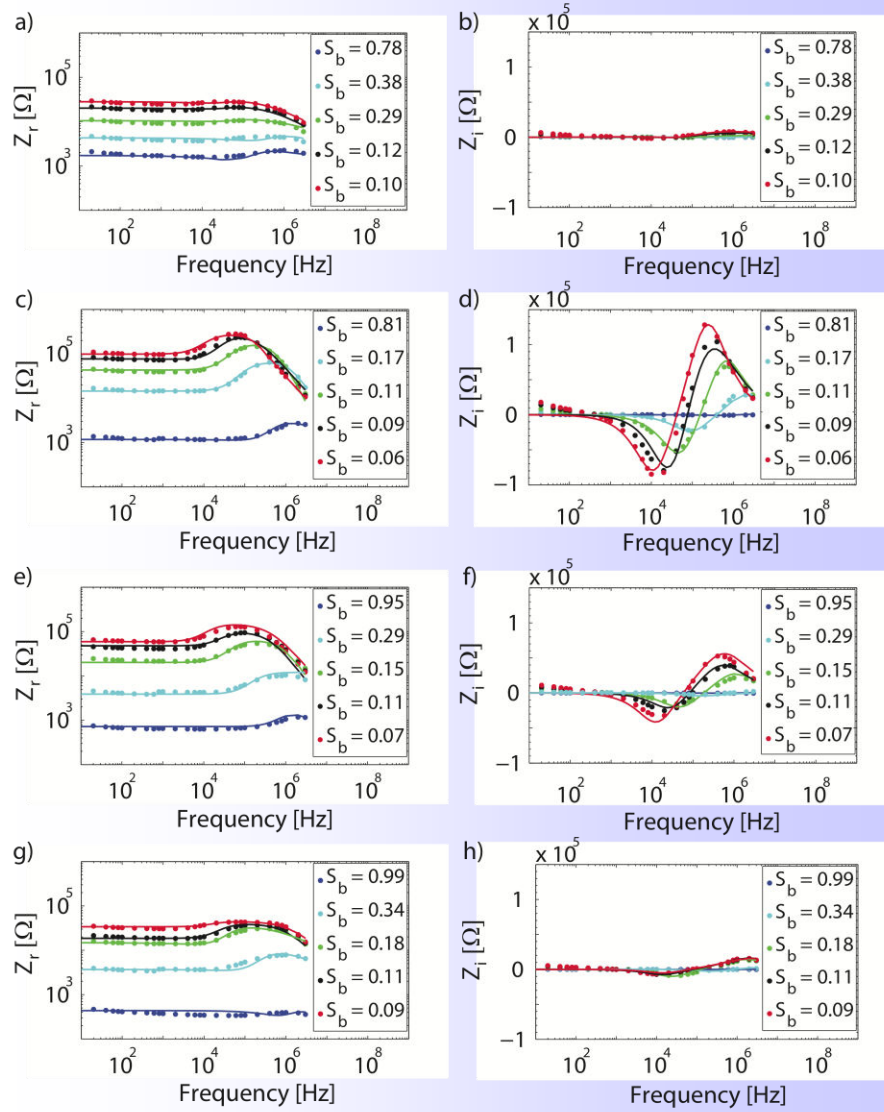

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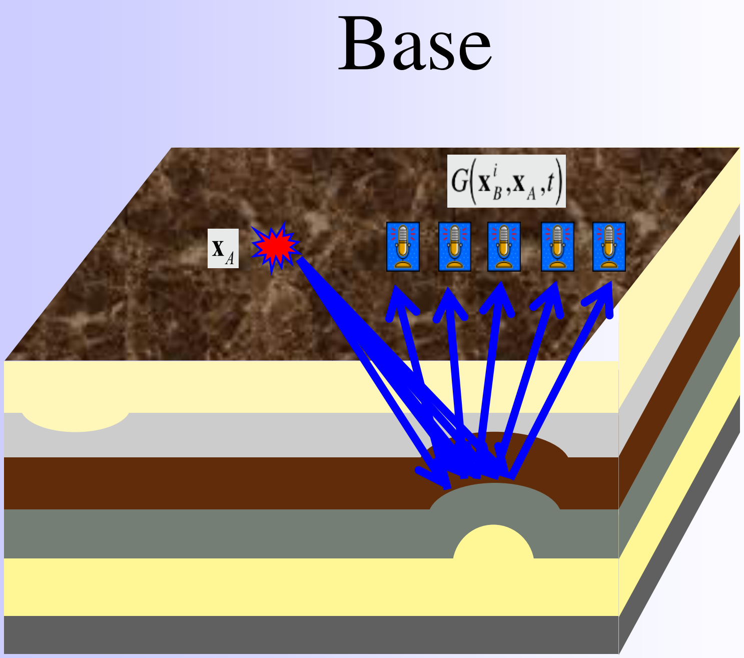
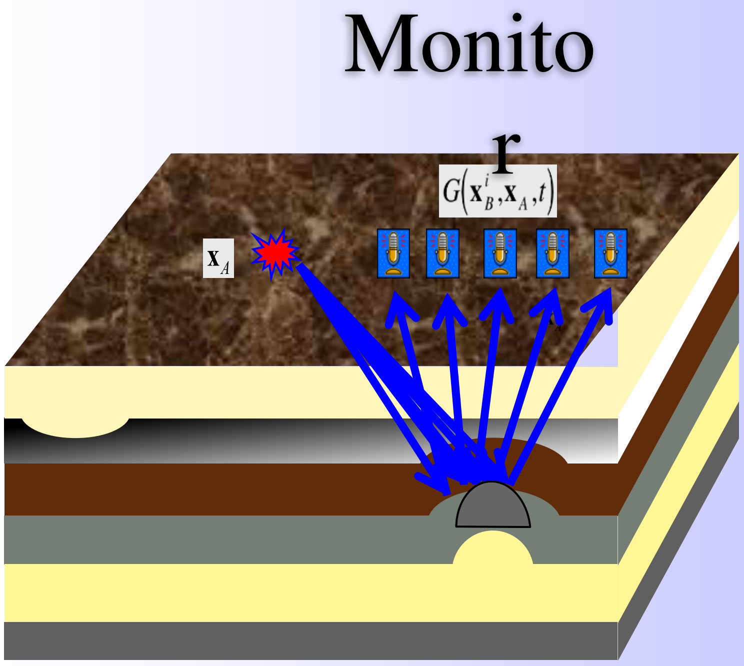

Base
$G(\mathbf{x}_B^i, \mathbf{x}_A, t)$
$\mathbf{x}_A$


Monito
r
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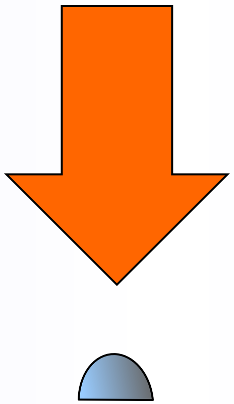

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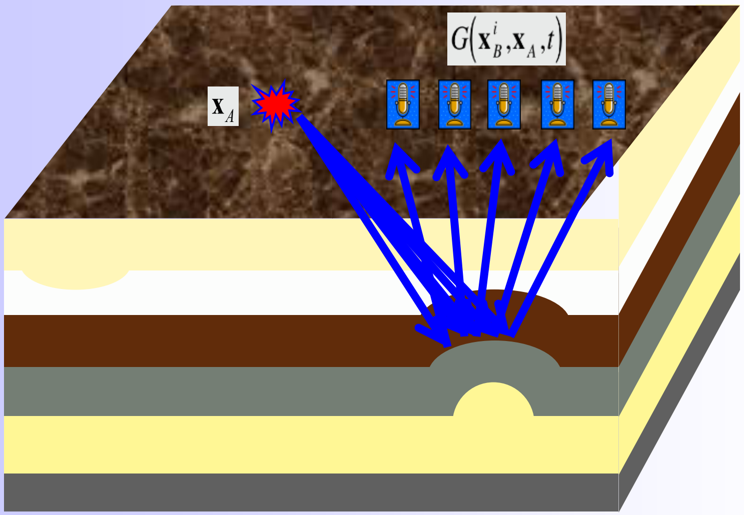

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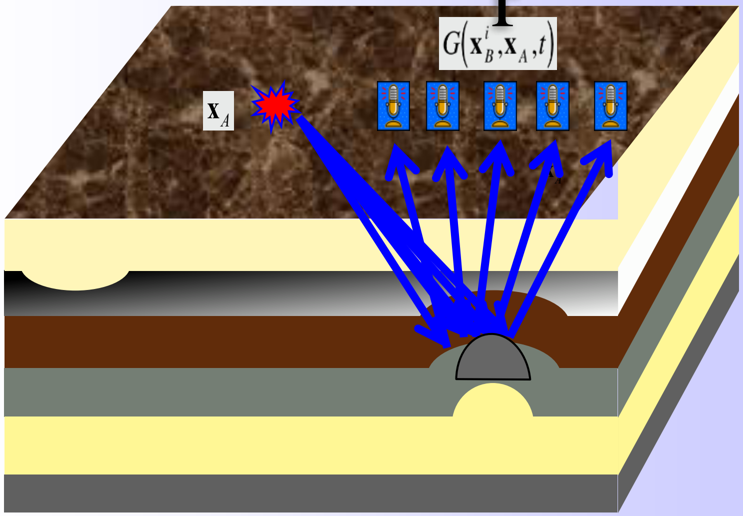

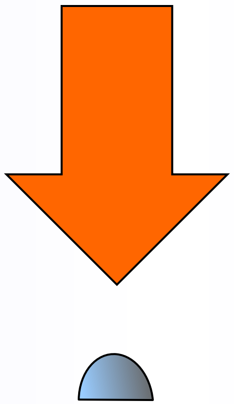

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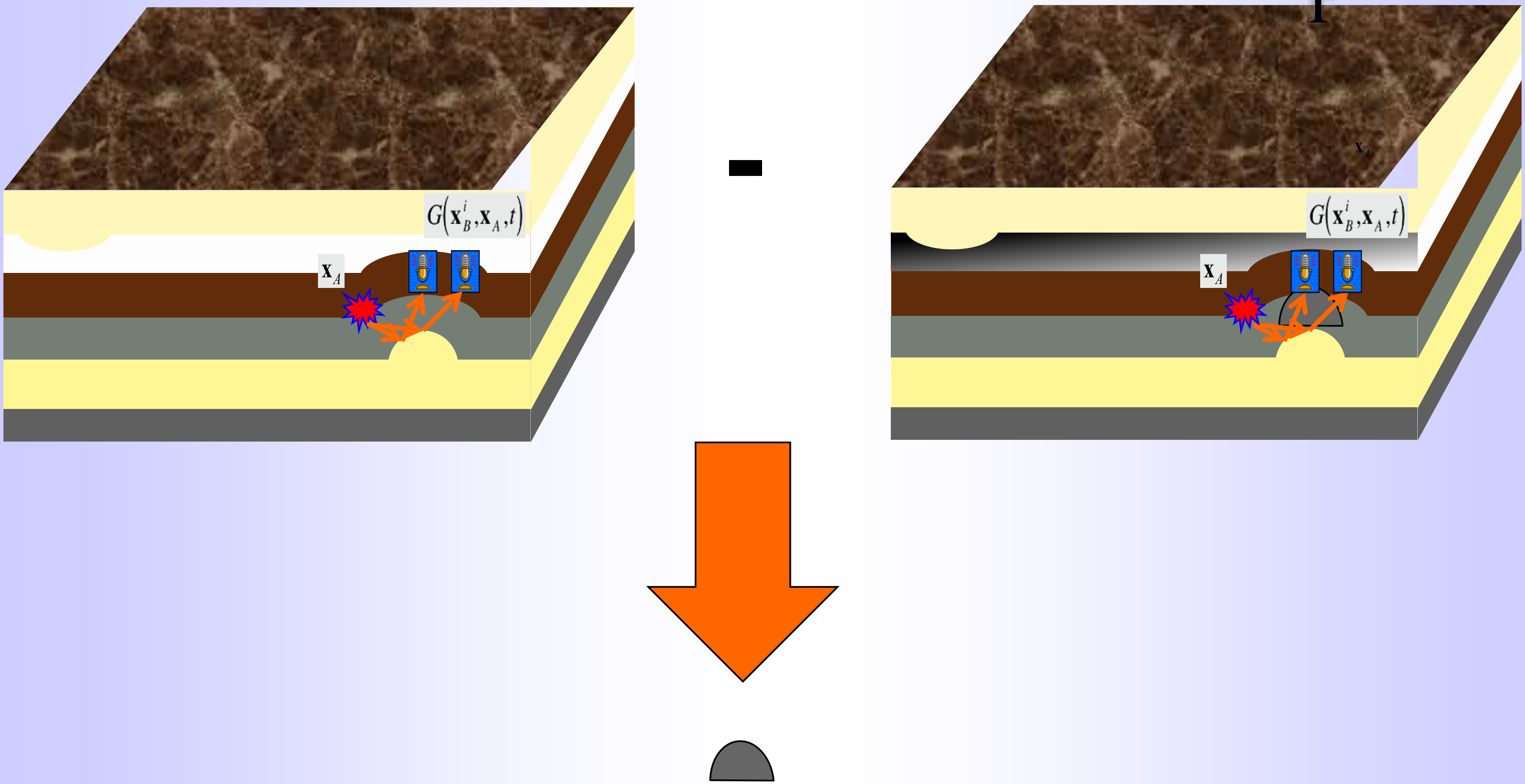
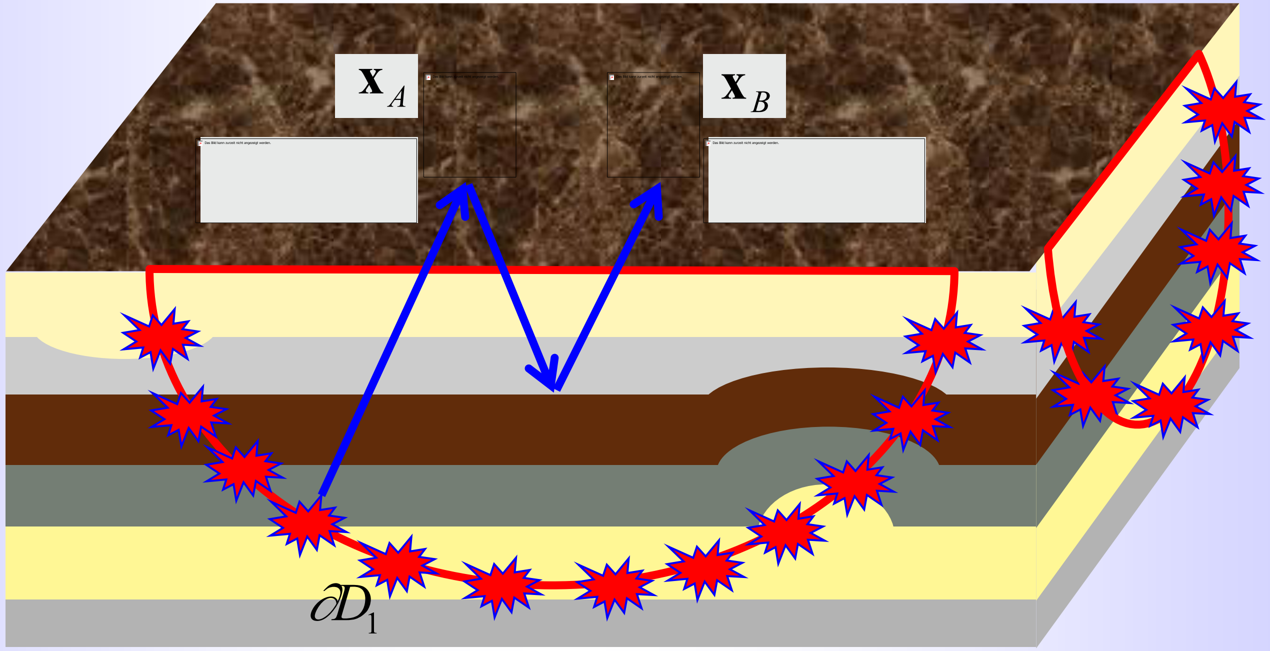


CCS monitoring: use of “ghost” arrivals in seismic interferometry



Wapenaar and Fokkema, 2006

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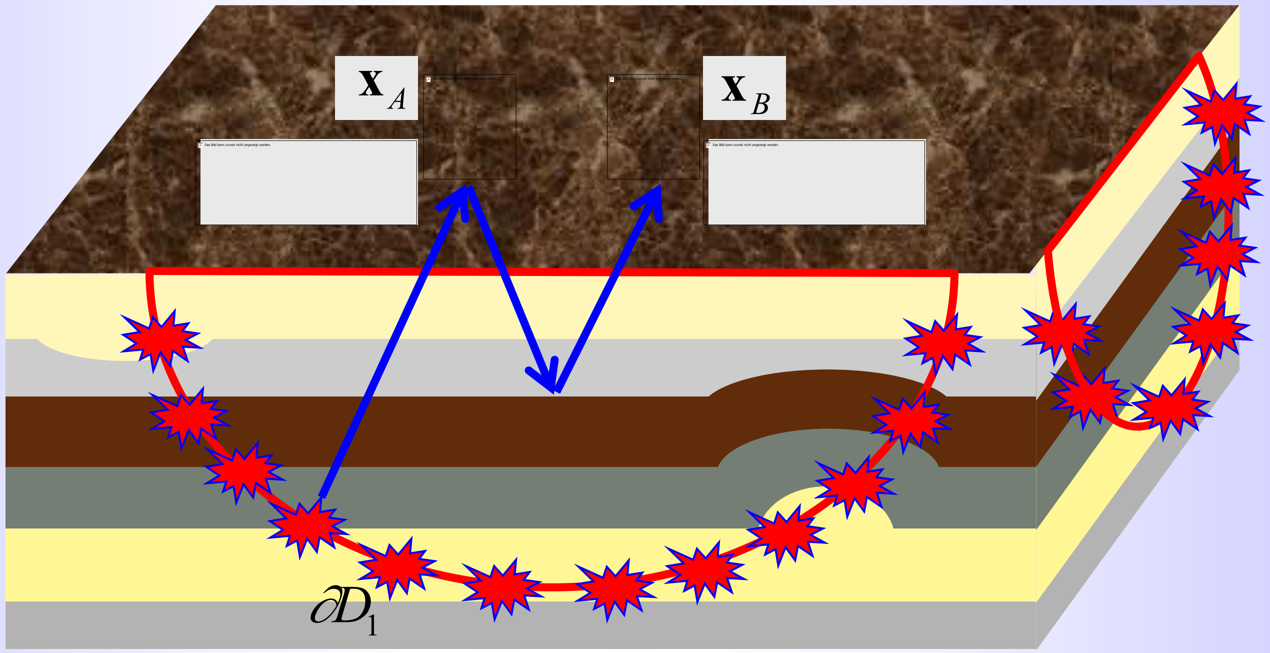
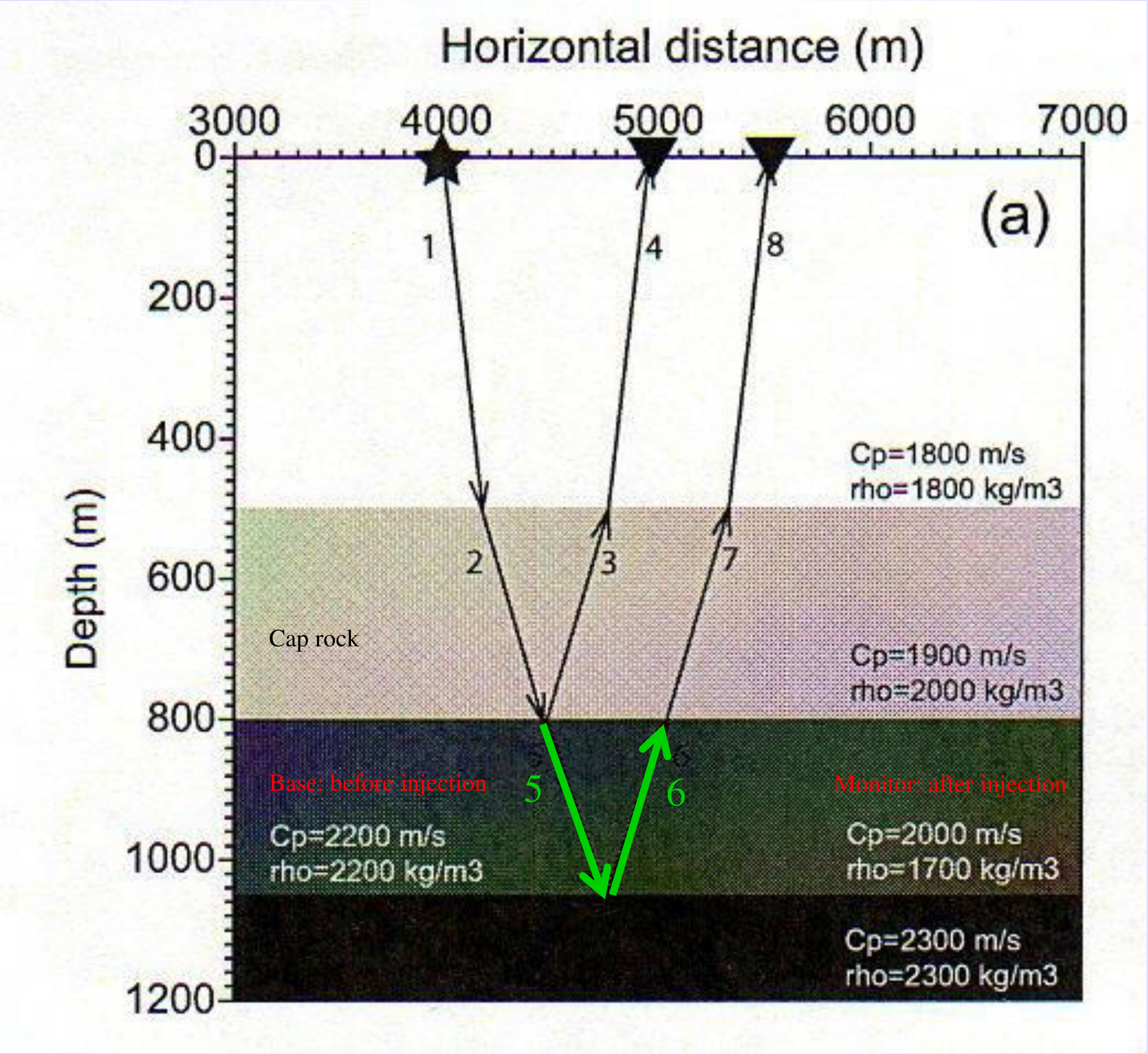


However, in case of a lossy medium and/or one sided illumination, spurious events will appear → nonphysical or “ghost” events !

CCS monitoring: use of "ghost" arrivals in seismic interferometry

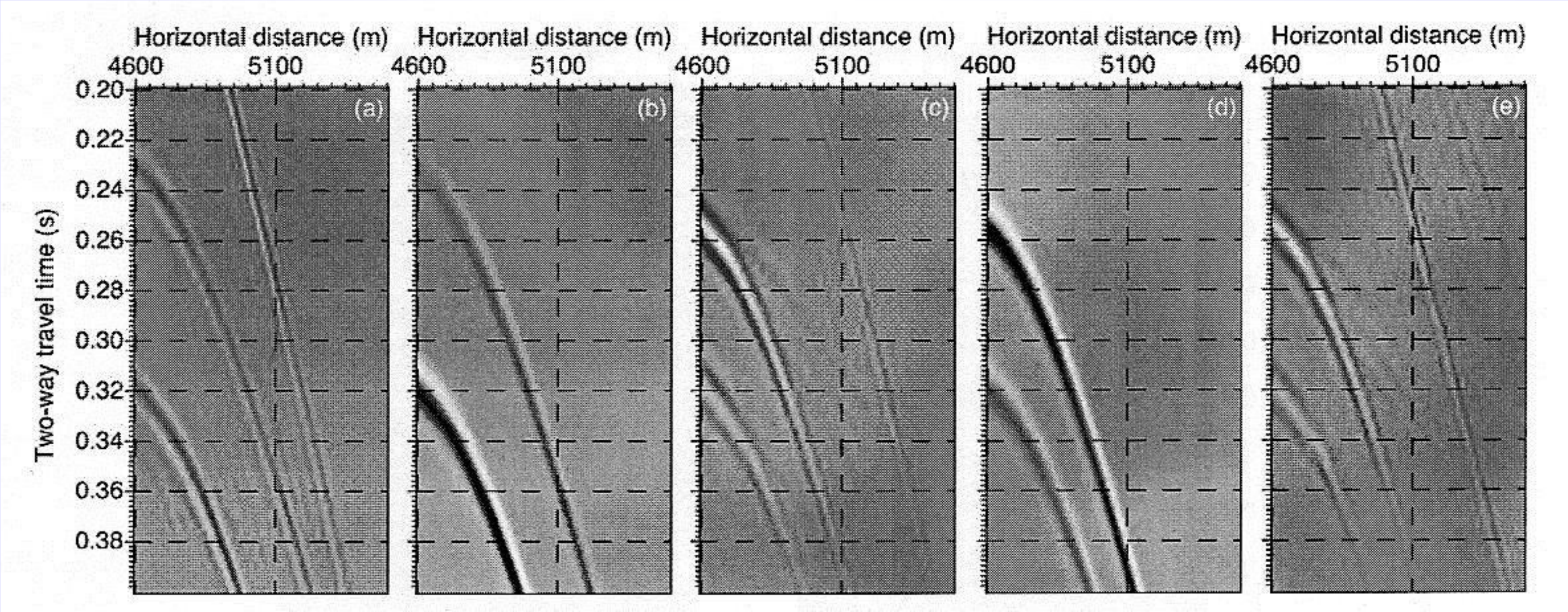
Model of Sleipner CCS Field, North Sea



CCS monitoring: use of "ghost" arrivals in seismic interferometry

Synthetic Model of Sleipner CCS Field, North Sea

SI Retrieval | Direct Modelling | SI Retrieval | Direct Modelling | SI Retrieval with Max 15 m Source Error



Base Survey

Monitor Survey

CCS monitoring: use of “ghost” arrivals in seismic interferometry

Synthetic Model of Sleipner CCS Field, North Sea

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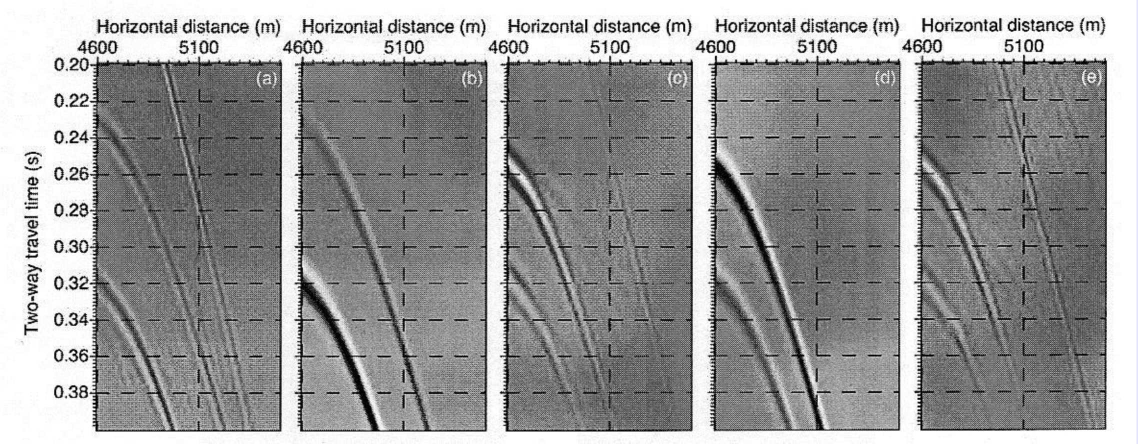

Base Survey — Monitor Survey

Brine-to-CO2 saturation ratio:
(using Gassmann’s equation)

Base: 0.98	**Monitor: 0.80 →**	**Input Model**
Base: 0.97	**Monitor: 0.77 →**	**From SI Ghosts**

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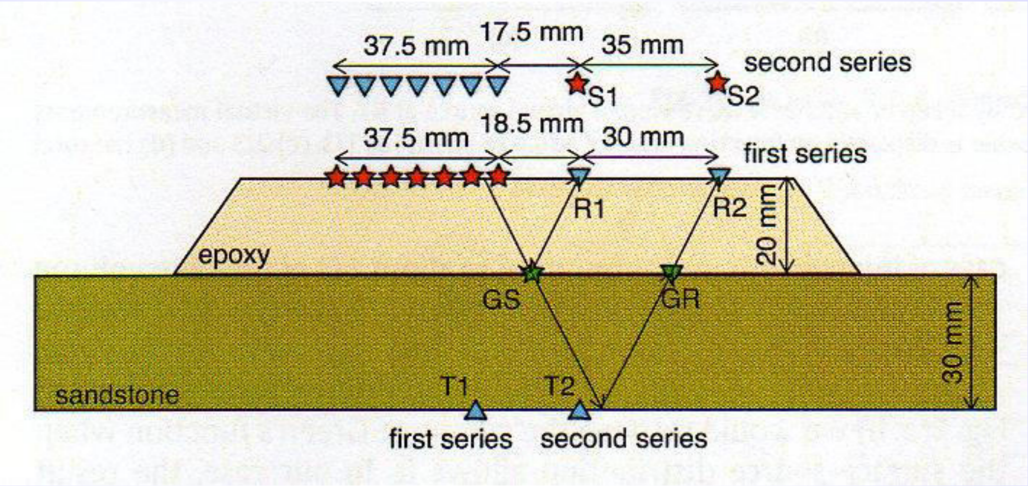

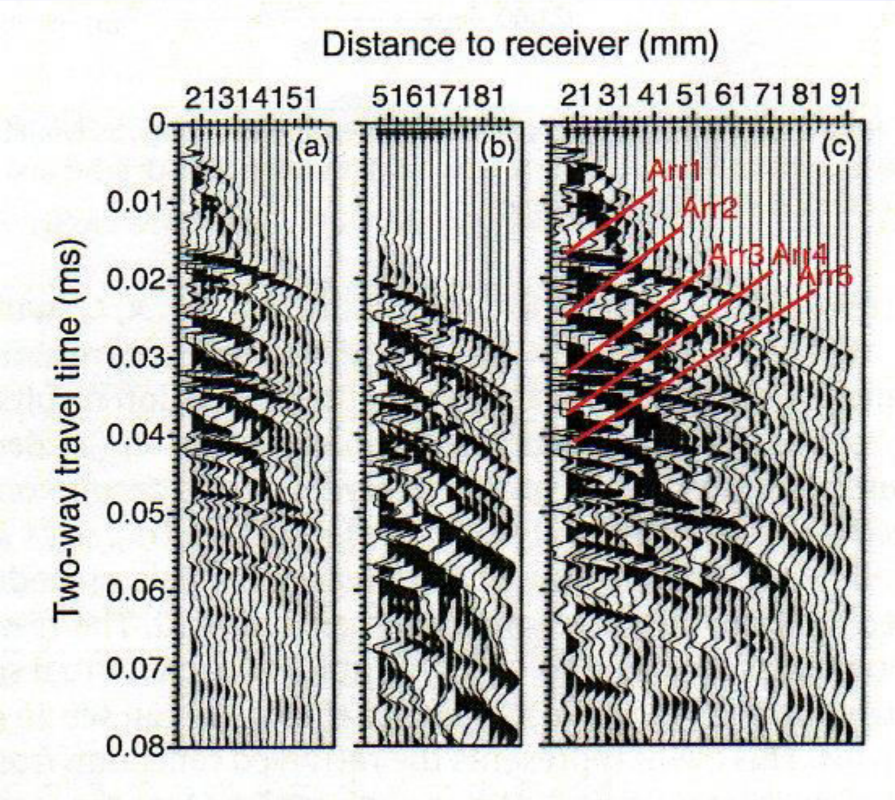

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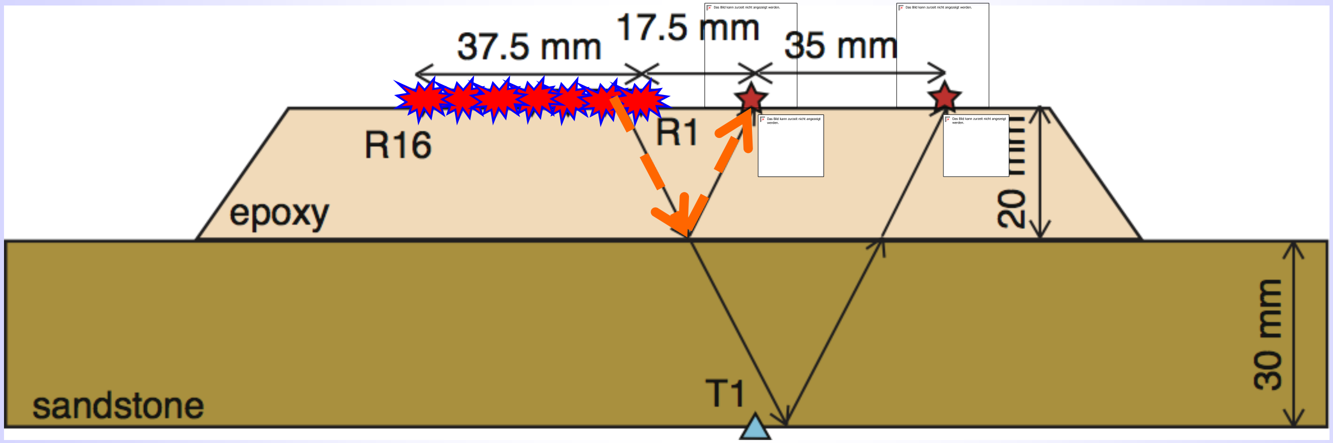

- Aim: to monitor velocity changes in a reservoir during displacement of brine by ethanol

- Using retrieved ghost reflections

- (In practice the events can be identified using a vertical well or the difference in expected arrival times of reflections from the cap rock and the reservoir)

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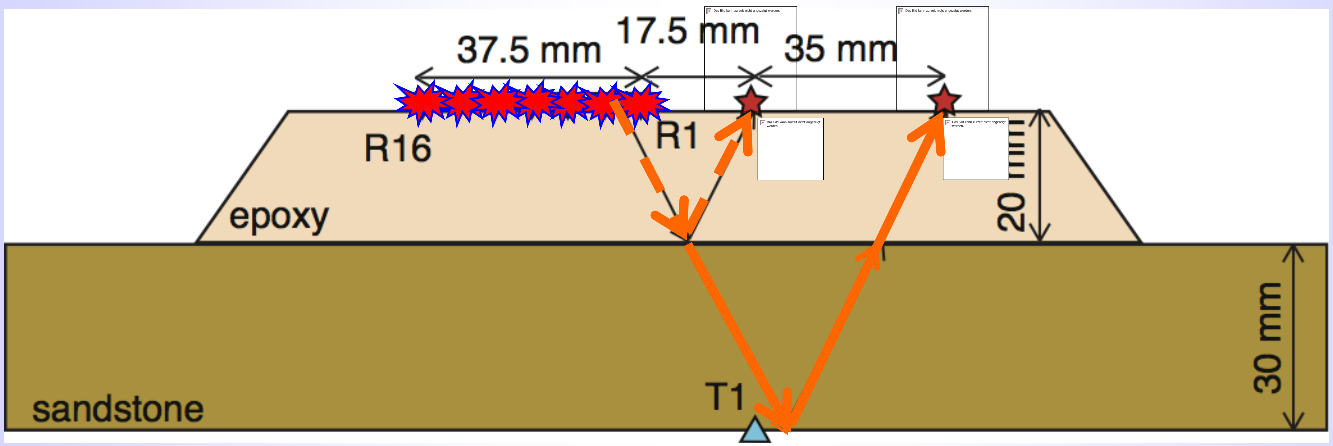

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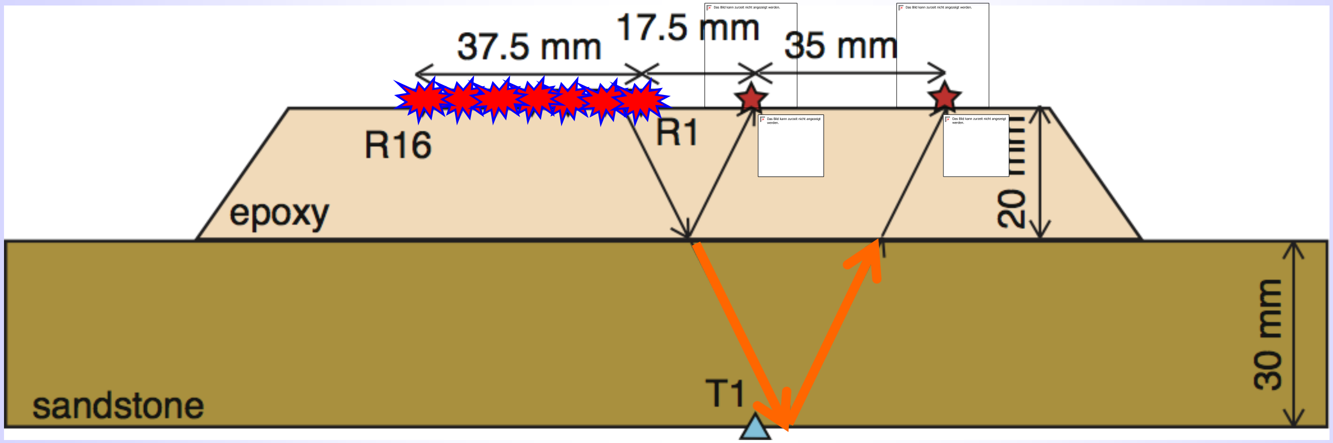

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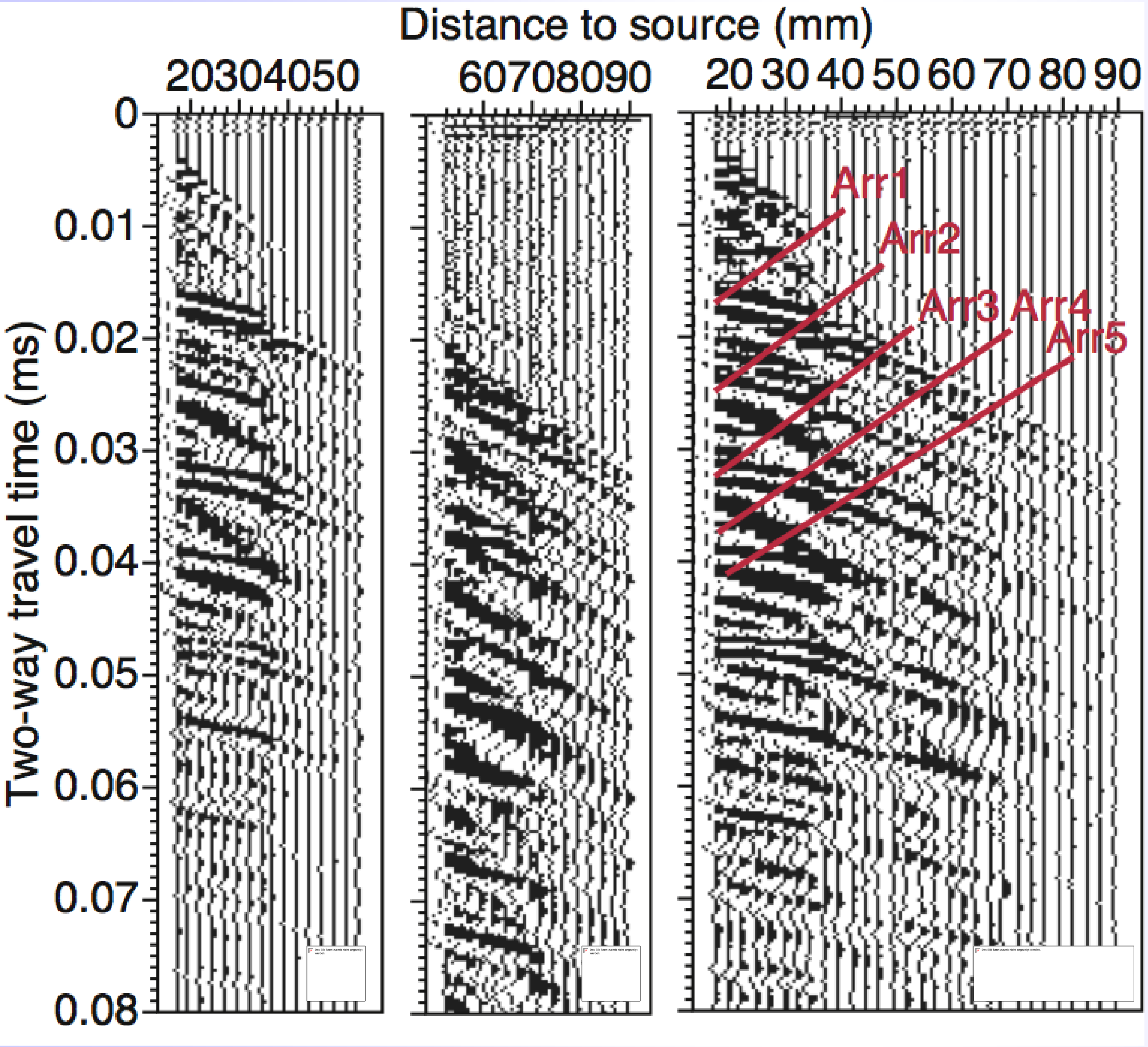
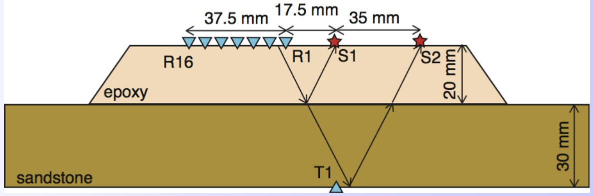
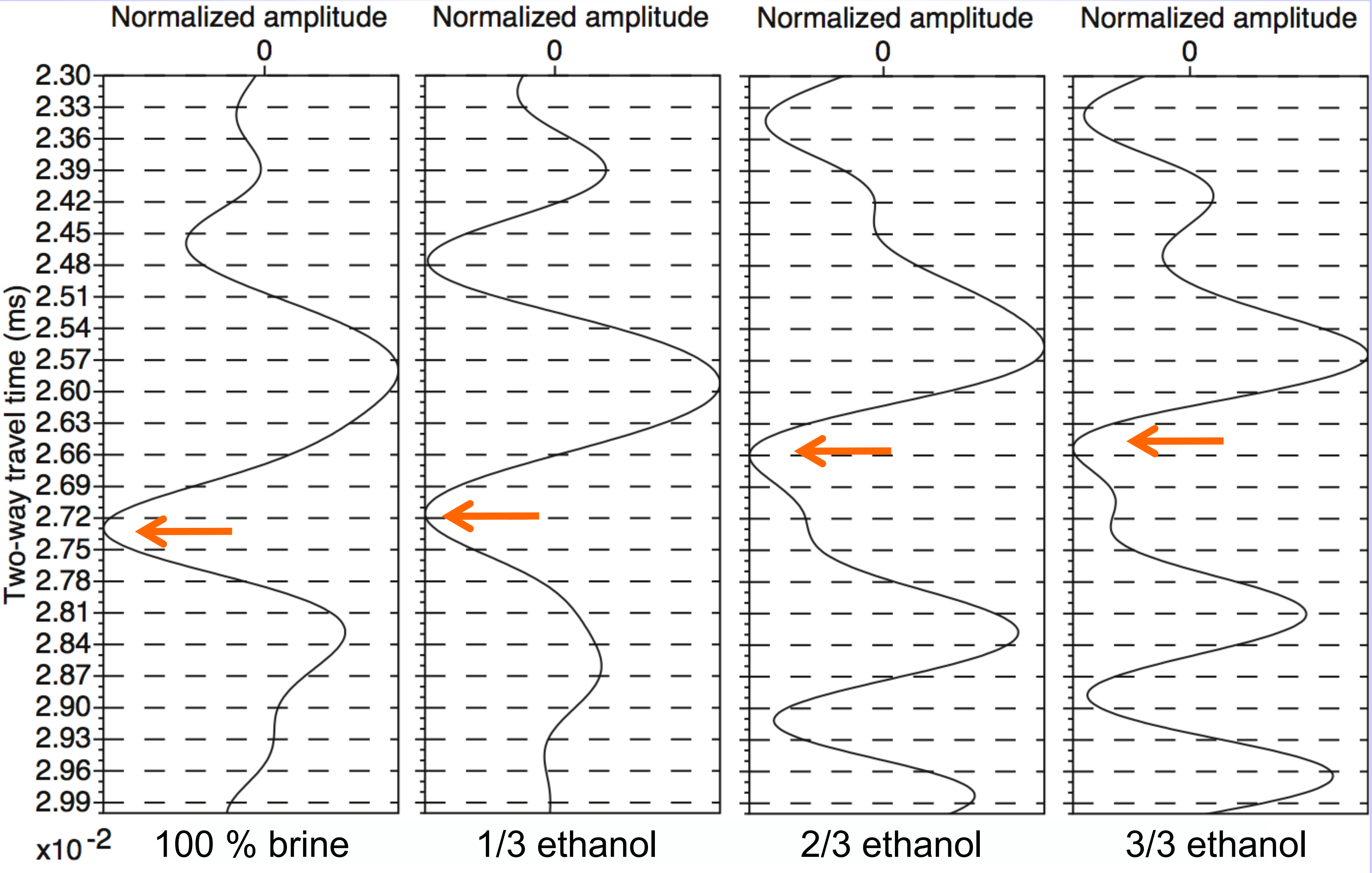




- Arr1 – P-wave reflection from bottom of epoxy
- Arr2 – converted-wave reflection
- Arr3 – free-surface multiple of Arr1
- Arr4 – S-wave reflection from bottom of epoxy
- Arr5 – P-wave reflection from bottom of sandstone

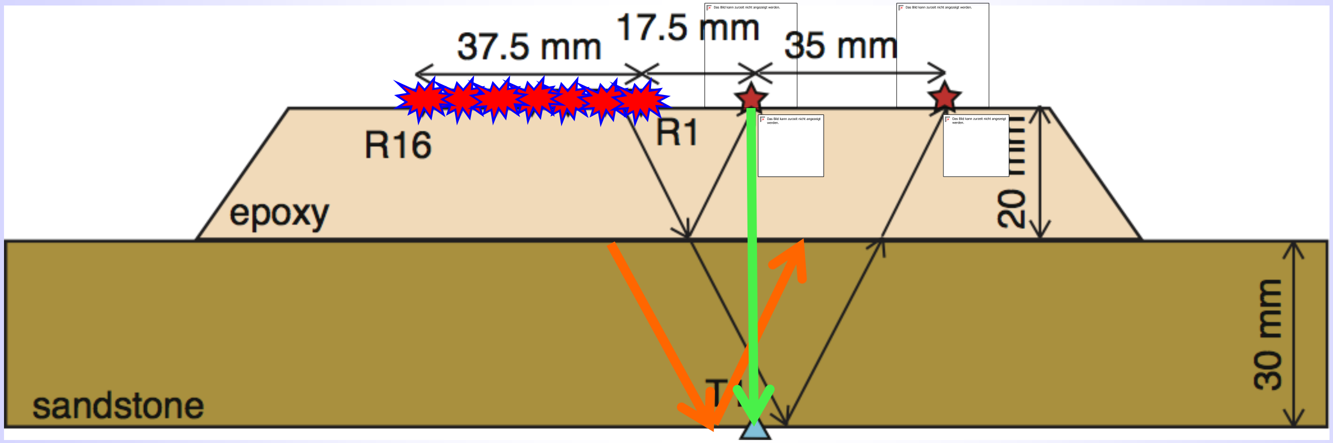
Recorded arrivals and their interpretation

CCS monitoring: use of "ghost" arrivals in seismic interferometry



Results from SI by CC

CCS monitoring: use of “ghost” arrivals in seismic interferometry



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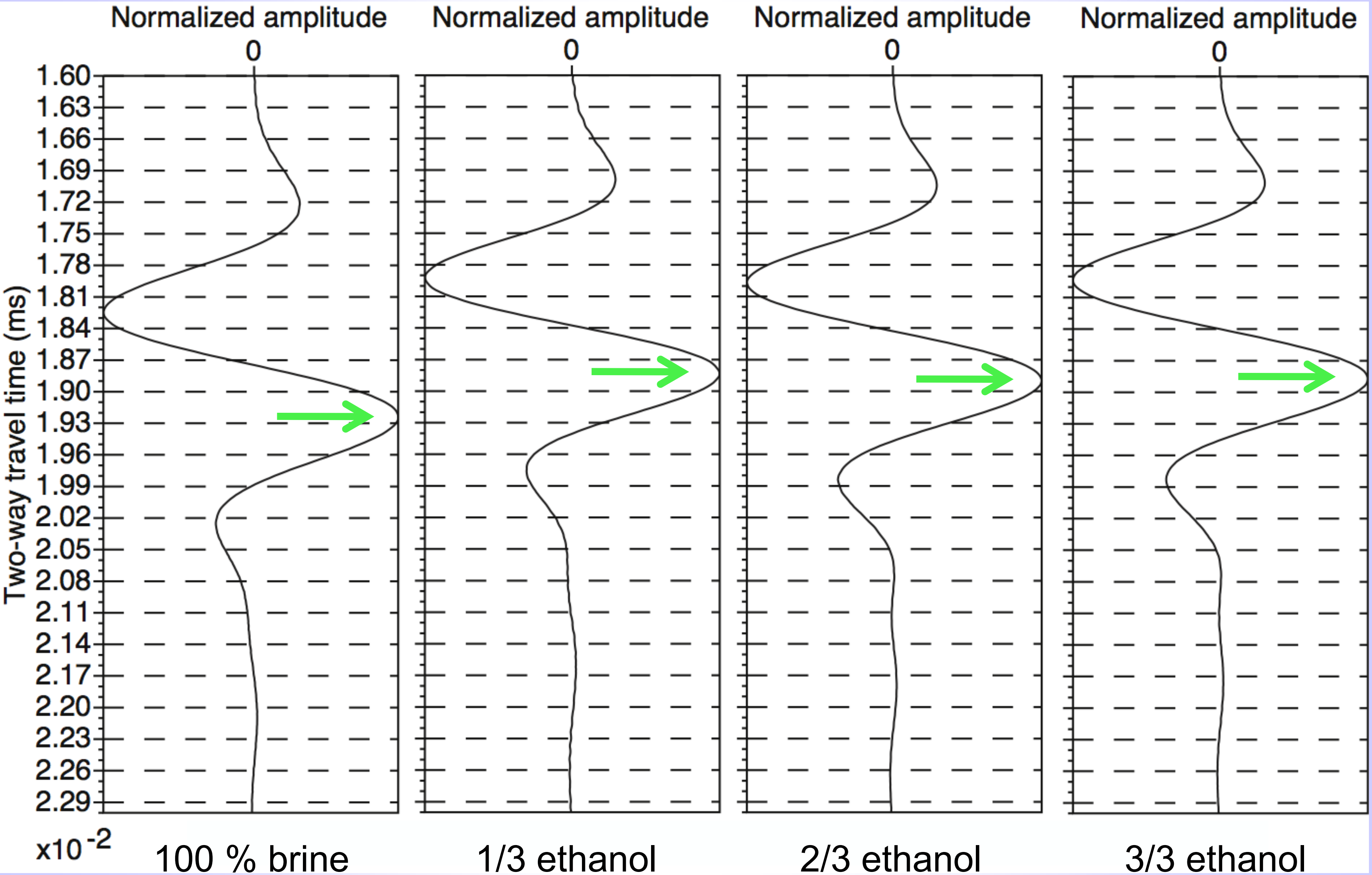

Results from transmission measurements

CCS monitoring: use of “ghost” arrivals in seismic interferometry

Method	100 % brine: velocity (m/s)	1/3 ethanol injected: velocity (m/s)	2/3 ethanol injected: velocity (m/s)	3/3 ethanol injected: velocity (m/s)
Ghost reflection	2544	2558	2611	2616
Transmission	2520	2607	2594	2596

Difference (%)	**0.95**	**1.88**	**0.66**	**0.77**

CCS monitoring using ghosts in SI

- Layer-specific changes in velocity monitored using ghost reflections retrieved from SI by cross-correlation of reflection measurements
- The effect of overburden and source positioning error minimized
- Good saturation estimates

Conclusions

CCS monitoring using complex electrical measurements

- Real part of complex permittivity is clearly sensitive to CO_2 phase changes
- Both the amplitude and phase of the phase of complex impedance shows significant sensitivity to CO_2/brine saturation → inversion
- Ongoing work: upscaling the results to field

CCS monitoring using ghosts in seismic interferometry

- Layer-specific changes in velocity can be monitored using ghost reflections retrieved from SI by CC between reflection measurements
- The effect of overburden and source positioning error can be minimized
- Saturation estimates are quite accurate

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