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# Numerical investigations of electromagnetic reflections in ice and derivation of accumulation rates

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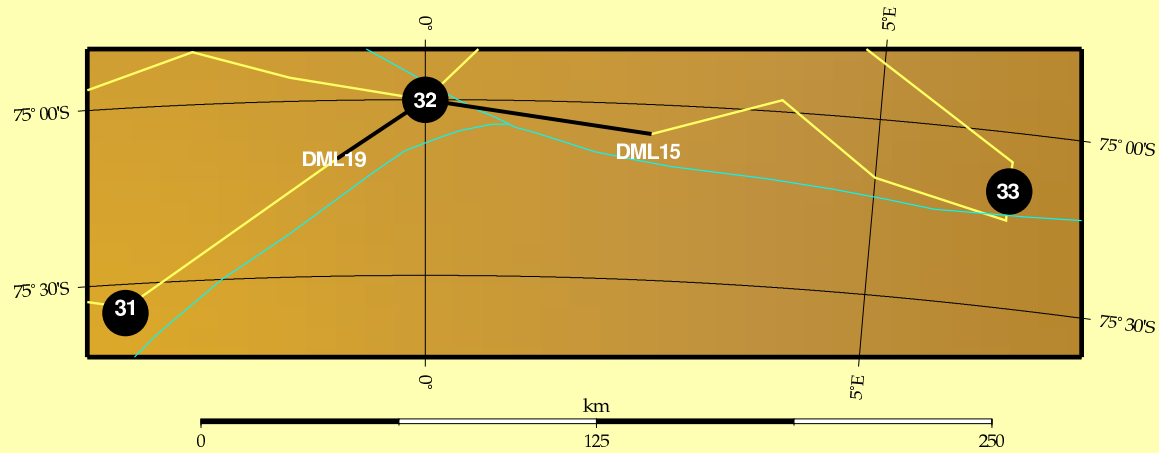
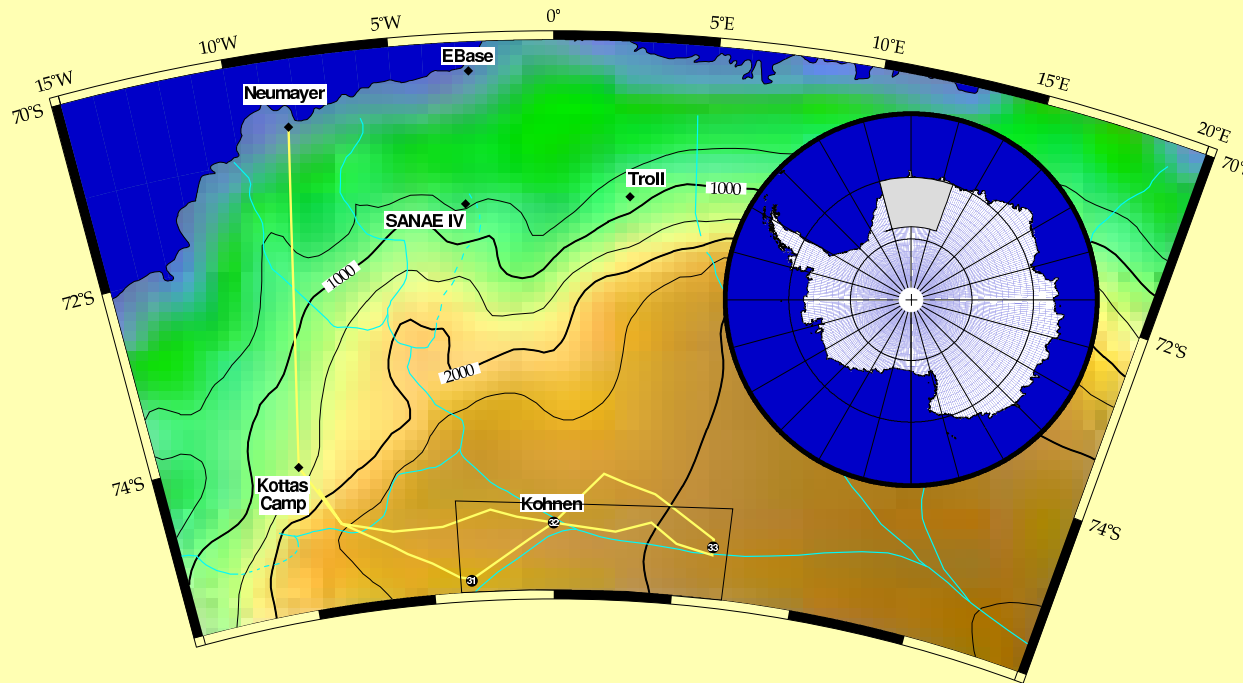
## ▷ Ice Penetrating Radar (IPR):

- **internal structure** on regional scale
- qualitative interpretation: **in-situ data**
- physical/chemical insights: **synthetic radargrams**

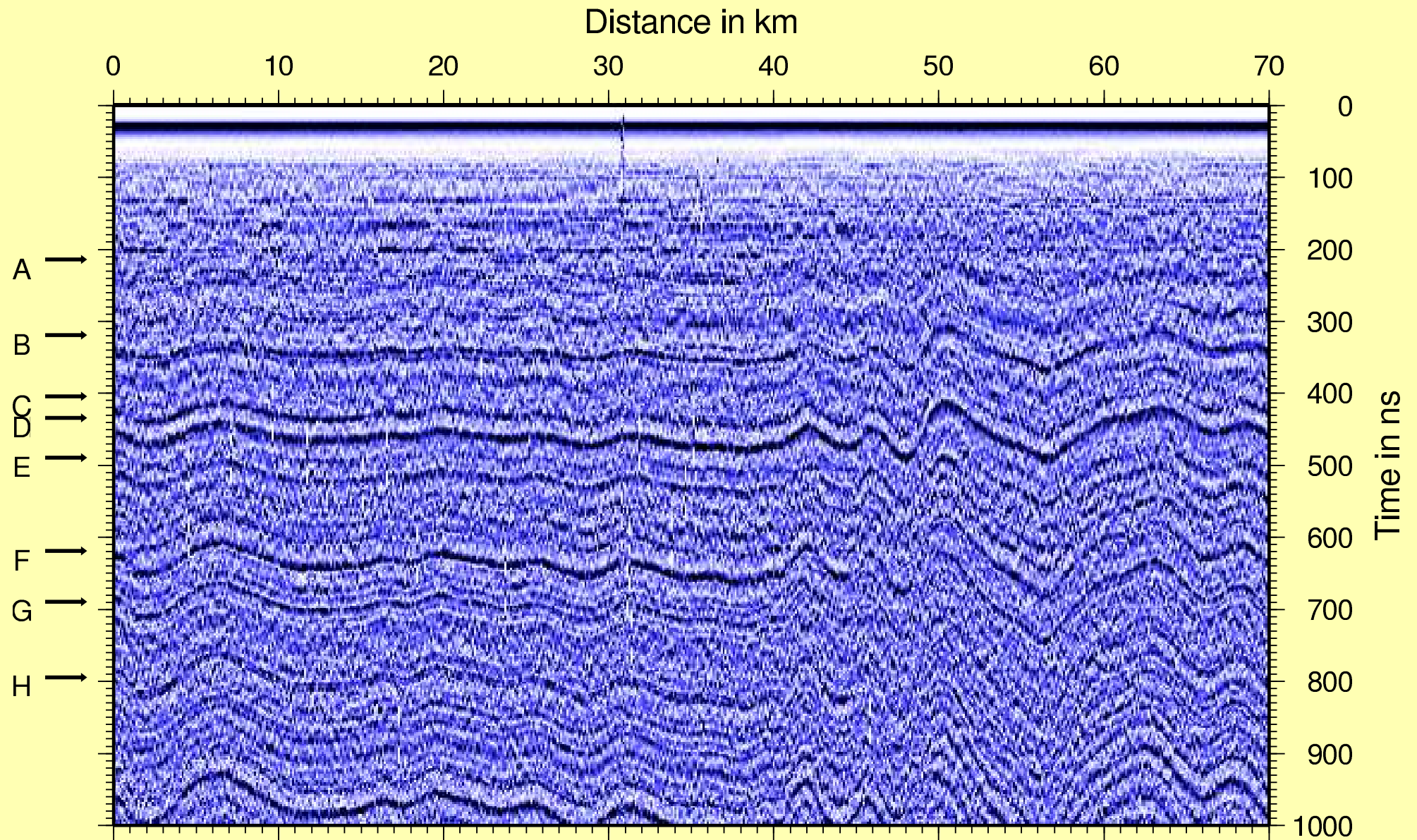
## ▷ Applications:

- distribution of accumulation rate (space & time)
- ⇒ **ground-truthing** for satellite missions
- validation of forward modelling
- ⇒ **transfer approach** to other scales

# Map of Study Area



# Internal Structure: IPR Profile



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# Forward Modeling: Physical Background

▷ Reflection of electromagnetic waves:

- dielectric impedance contrast → reflection coefficient:

$$R_k = R'_k + iR''_k$$

$$R_k = \frac{\sqrt{\varepsilon_{k-1}} - \sqrt{\varepsilon_k}}{\sqrt{\varepsilon_{k-1}} + \sqrt{\varepsilon_k}}$$

- complex dielectrical constant

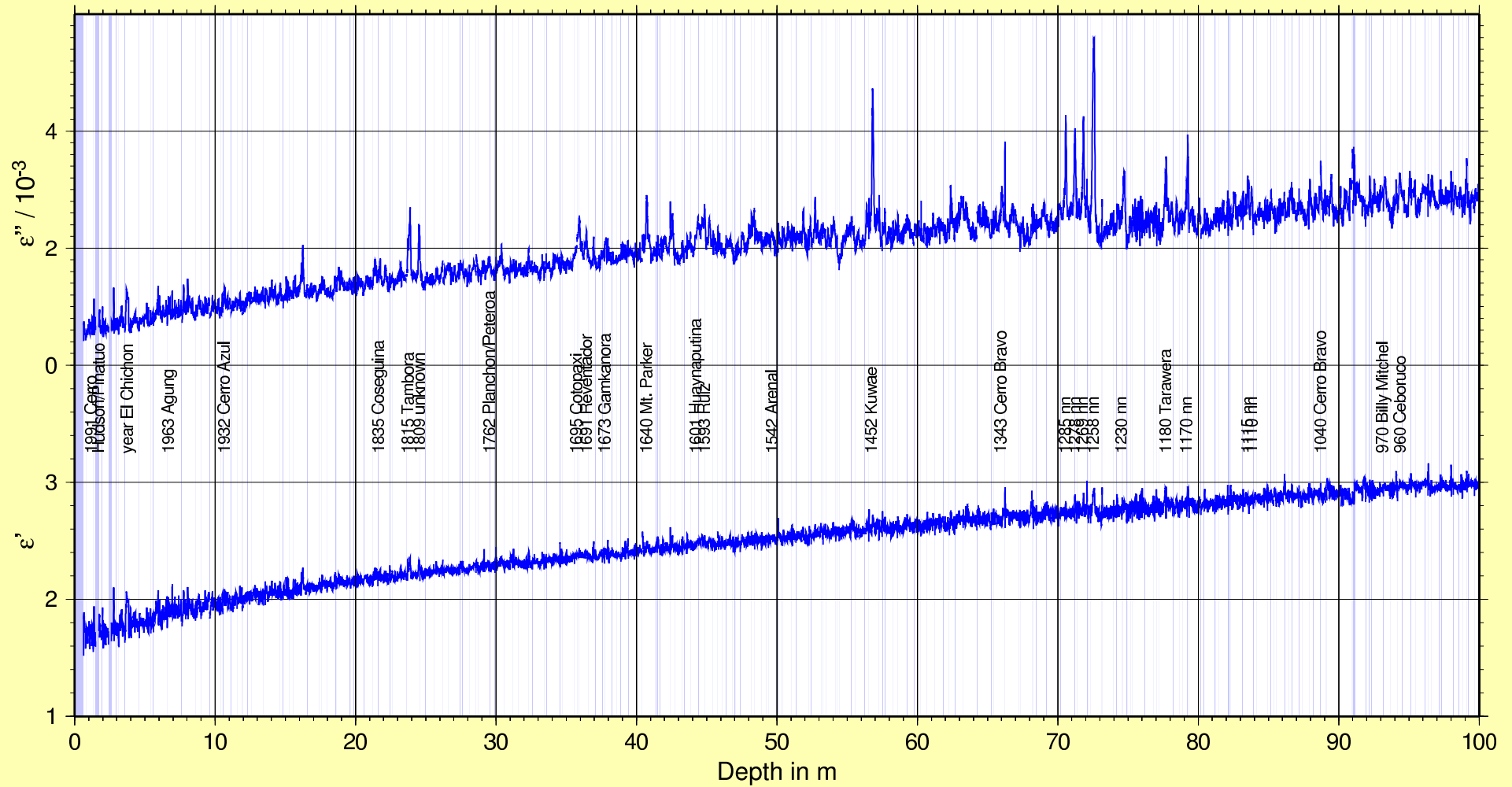
$$\varepsilon = \varepsilon' - i\varepsilon'' = \varepsilon' - i\frac{\sigma}{\varepsilon_0\omega} = |\varepsilon|e^{-i\delta}$$

▷ Firn is multiphase system:

- dielectric decomposition of mixture (Wilhelms, 2000):

$$\varepsilon_{mix}^{*1/3} = \frac{\rho_{mix}}{\rho_{ice}} \left( [\varepsilon_{ice} - i\frac{\sigma_{ice}}{\omega\varepsilon_0}]^{1/3} - 1 \right) + 1$$

# In-Situ Data: Dielectrical Profiling of Ice Cores



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# Interpretation: Forward Modeling of Radargrams

▷ Main Principle:

- assume **IPR reference trace** as local truth
  - establish successful modeling of **synthetic trace**  $S$
- **sensitivity studies** to reveal nature of reflections

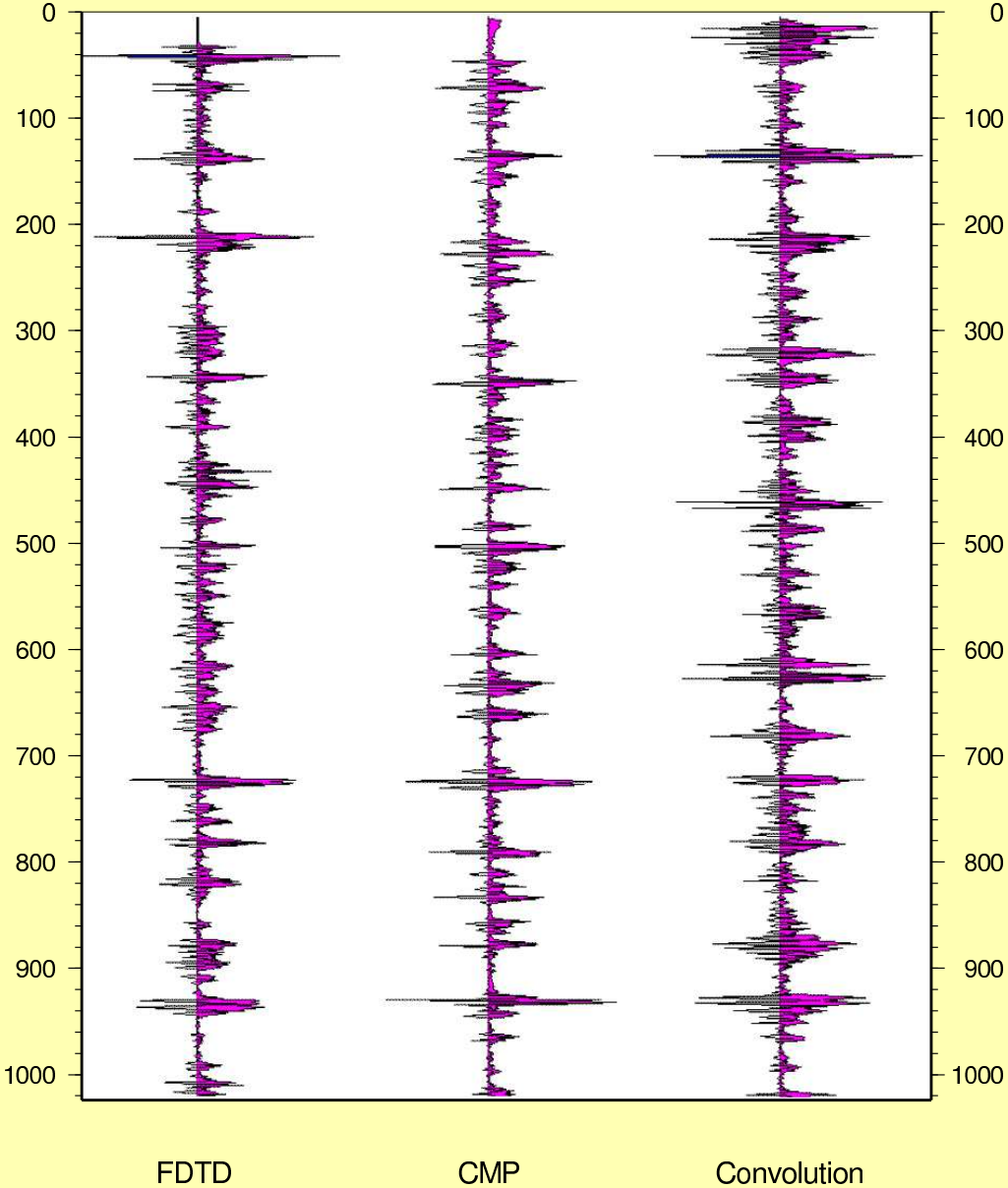
▷ Convolution technique:  $S_C = W * R$

- + low computation time (minutes)
- indirect localisation of reflection cause
- no implicit inclusion of wave phenomena

▷ FDTD modeling  $S_{FD} : (\vec{H}, \vec{E})_{t+1} = f(\vec{H}, \vec{E}, \epsilon)_t$

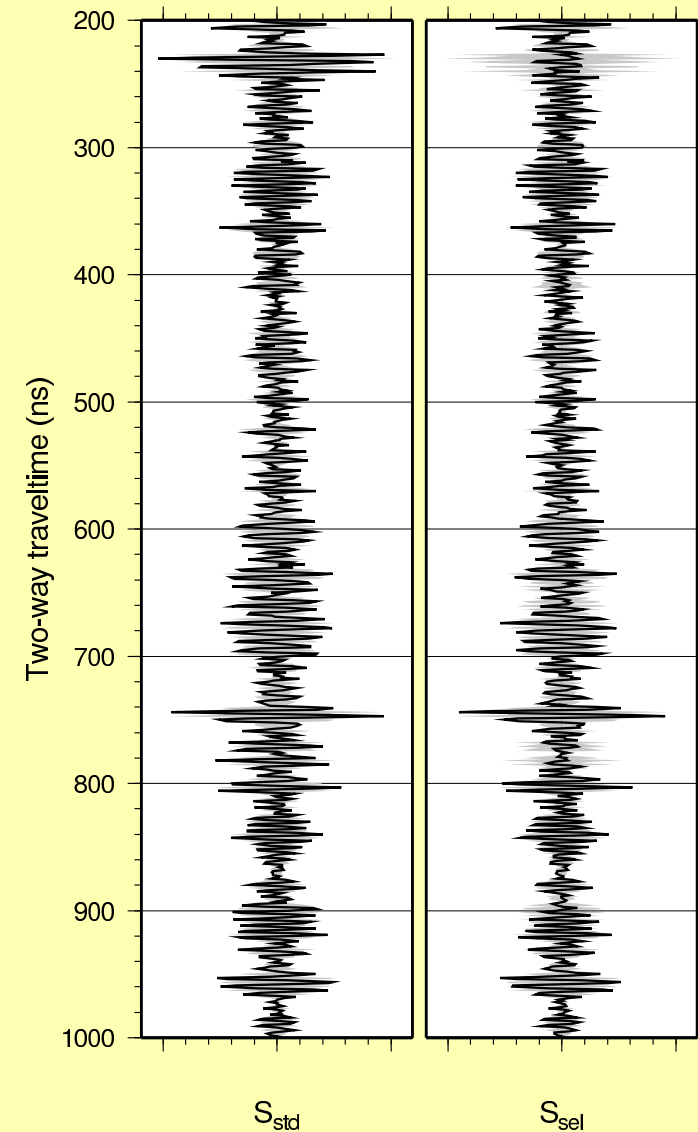
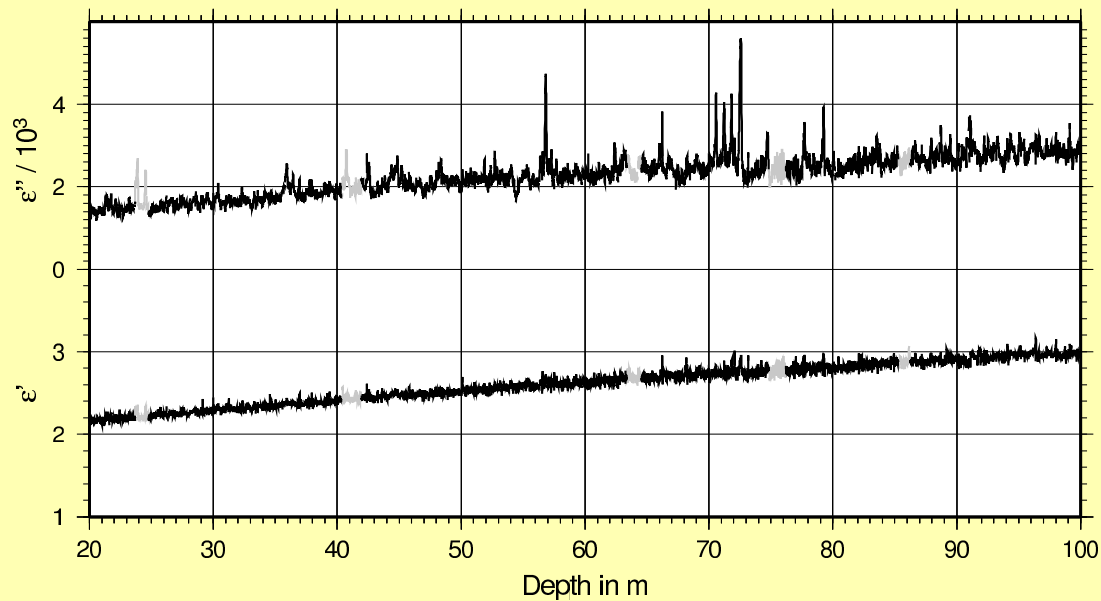
- + implicit consideration of physics
- + tracking of reflections in space–time slices
- parallel supercomputing required

# Model Validation



# Nature of Reflections

- ▷ Sensitivity studies:
  - remove dominant  $\epsilon'$ ,  $\sigma$ -peaks
  - depth range of origin



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# Reflection Origin and Properties

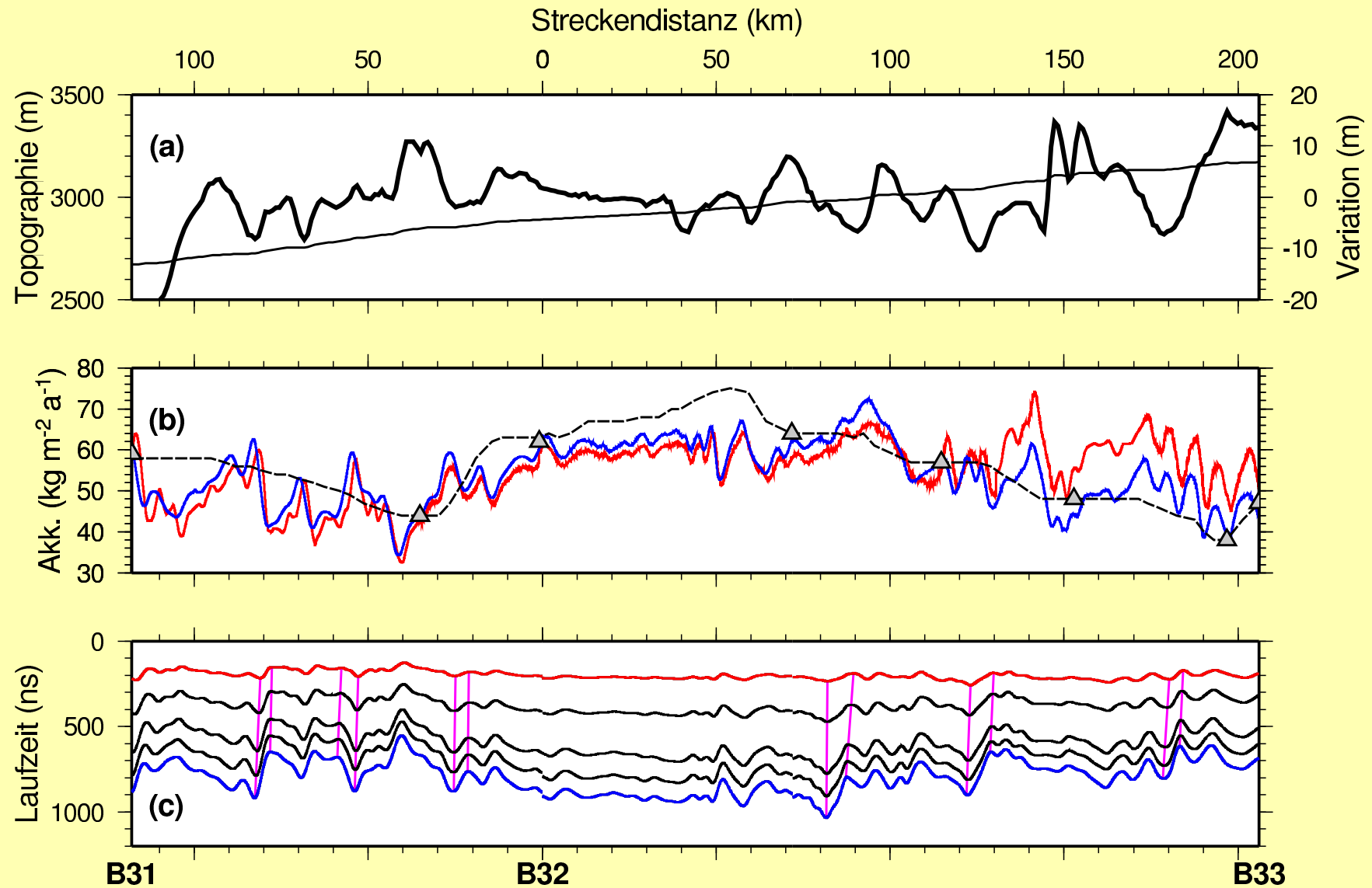
- ▷ Cause of reflections ( $> 100$  m):
  - permittivity peaks important
  - conductivity negligible
  - strong correlation of  $\varepsilon'$ ,  $\sigma$  for several reflections:
    - some  $\varepsilon'$ -peaks related to chemical events (how?)
    - corresponding reflections are isochrones

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- ▷ Application:
  - transfer ice core datings to reflections
  - regional age–depth distribution
  - comparison with several ice core records
  - error estimate of horizon ages

# Variation of Accumulation Rate



# Dating of Reflection Horizons

ice core	210 ns	415 ns	650 ns	780 ns	890 ns
<i>Conventional Dating</i>					
B31	1815	1624	1376	1212	1085
B32	1822	1619	1362	1208	1075
B33	1813	1615	1371	1194	1071
mean	1817	1619	1370	1205	1077
std.dev.	±5	±5	±7	±10	±7
<i>FD Sensitivity Studies</i>					
B31	1819 – 1809	1645 – 1632	1394 – 1382	1233 – 1215	1097 – 1081
B32	1819 – 1807	1645 – 1627	1374 – 1360	1229 – 1210	1092 – 1078
B33	1820 – 1808	1647 – 1633	1395 – 1364	1213 – 1185	1093 – 1067
mean	1819 – 1808	1646 – 1631	1388 – 1369	1225 – 1204	1094 – 1075
std.dev.	±1 ±1	±1 ±3	±12 ±12	±11 ±16	±3 ±7

dates in a A.D., std.dev. in a.

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# Conclusions

▷ Ice core & FDTD:

- successful modeling of radargrams:
  - physical cause of reflections
  - age range of horizons

▷ Ice cores & IPR:

- spatial & temporal variability of accumulation
  - reliable dating uncertainty from multi-core data
    - statistical characteristics
    - improved error estimates
- ⇒ **complementary information** to point samples

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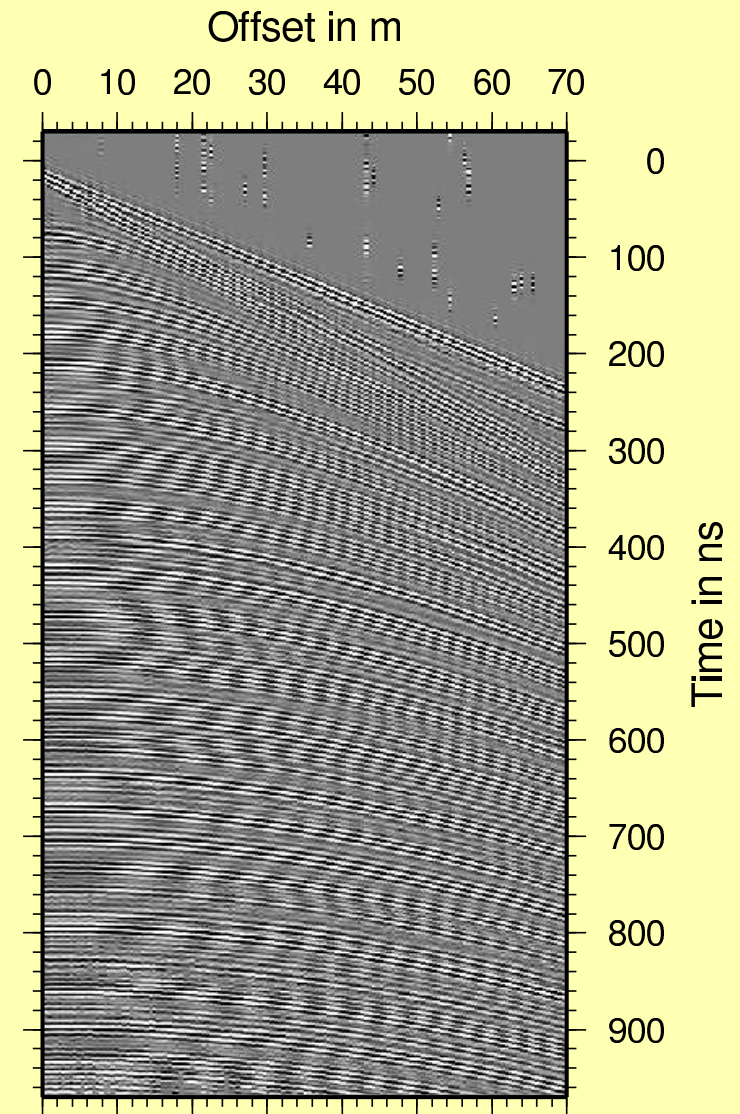
## ▷ Outlook:

- physical extension of FDTD model
- frequency dependence / waveforms
- interaction structure–impurities–radar



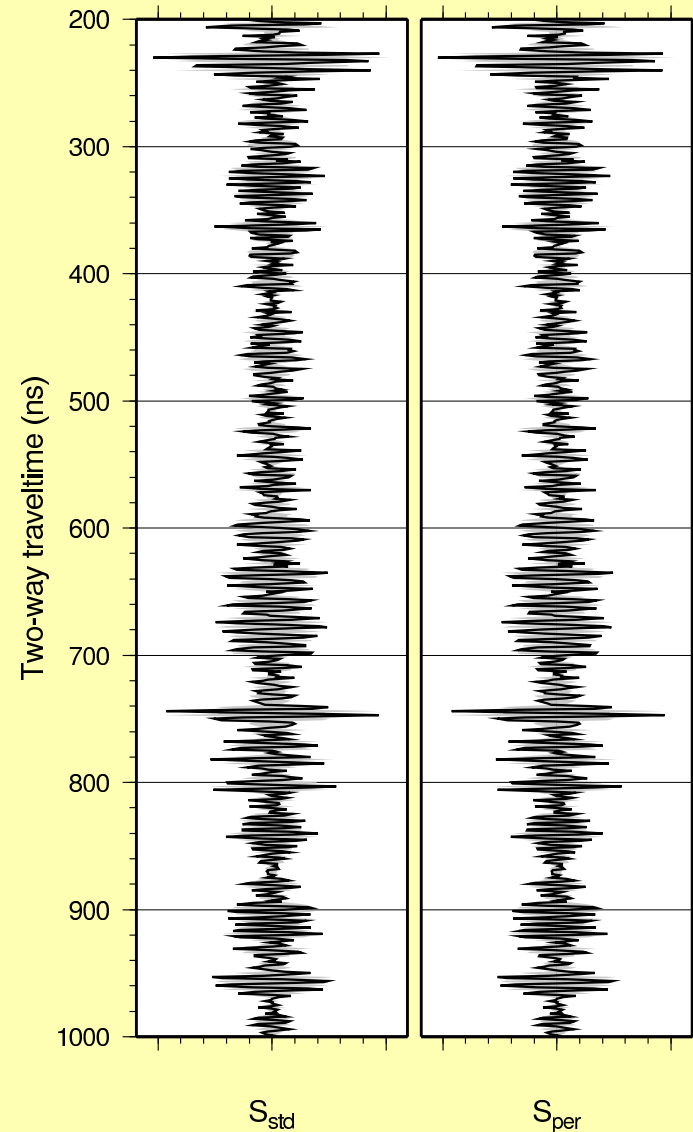
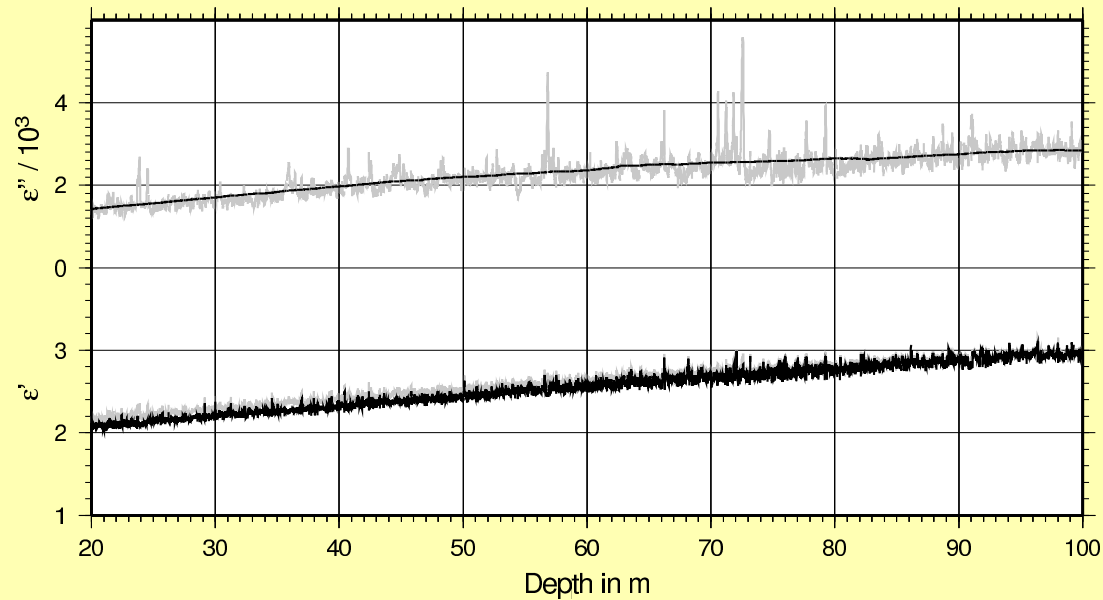
# Reference Trace: Common Midpoint Survey

- ▷ **Problems** for IPR reference trace:
  - **lateral inhomogeneities** of physical properties
  
- ▷ CO IPR profiles:
  - TX–RX configuration constant
  - limited stacking (decoherence)→ low quality SNR
  
- ▷ Advantages of CMP:
  - spatial averaging (wide angles) (NMO correction & stacking)
  - independent velocity information→ **single trace with high SNR**



# Nature of Reflections

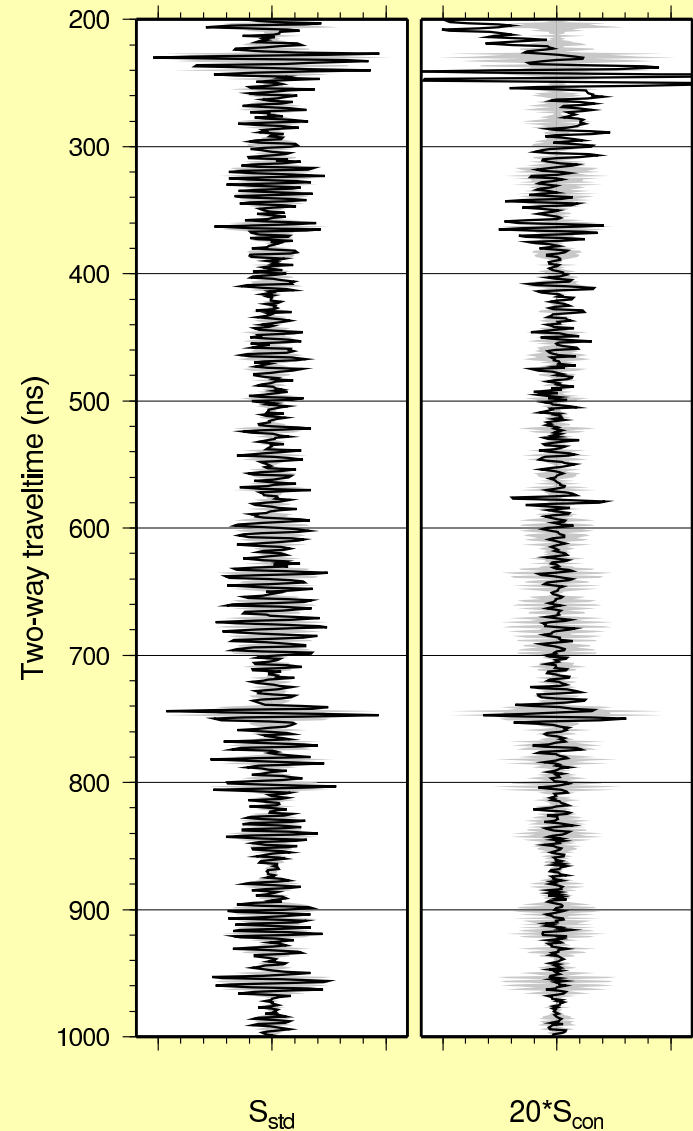
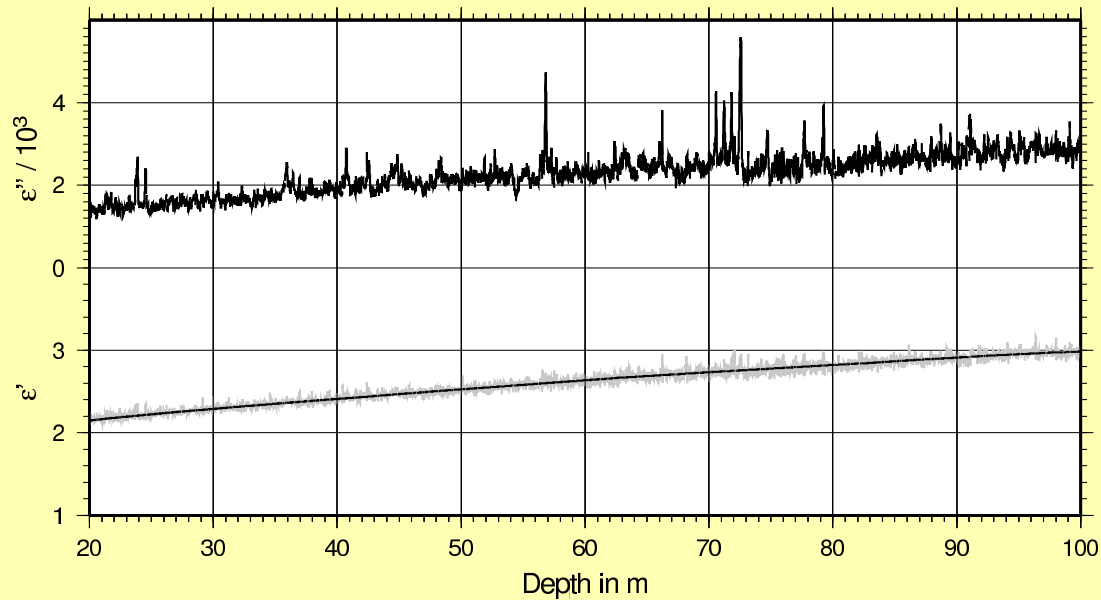
- ▷ Sensitivity studies:
  - smoothed conductivity  $\sigma$



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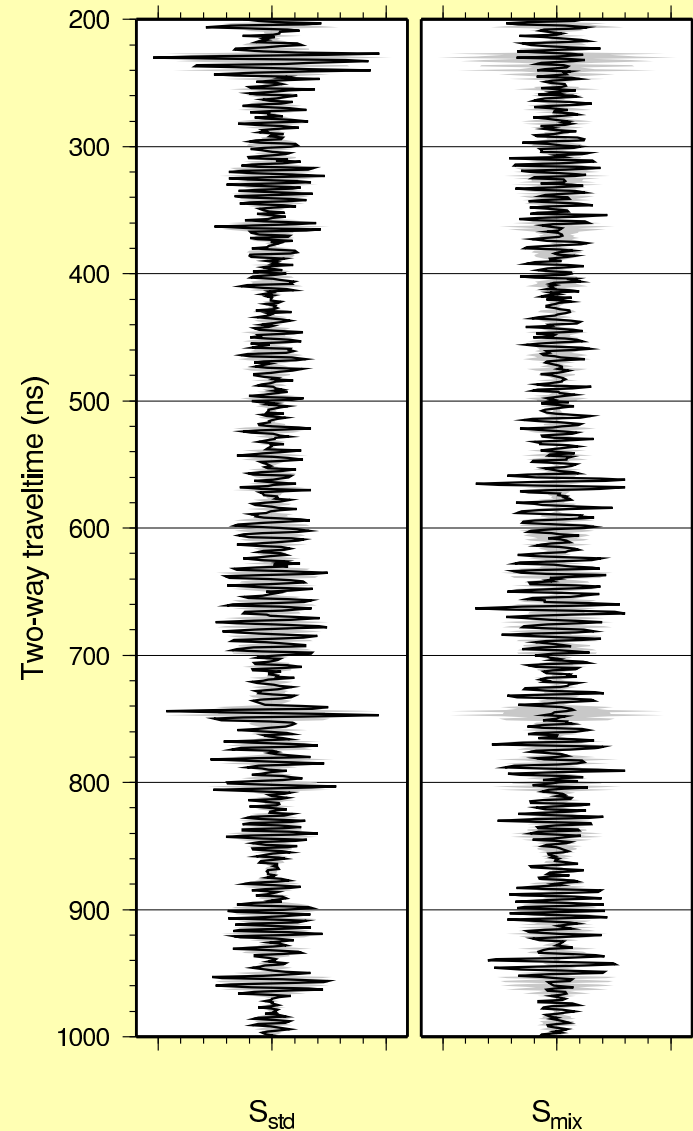
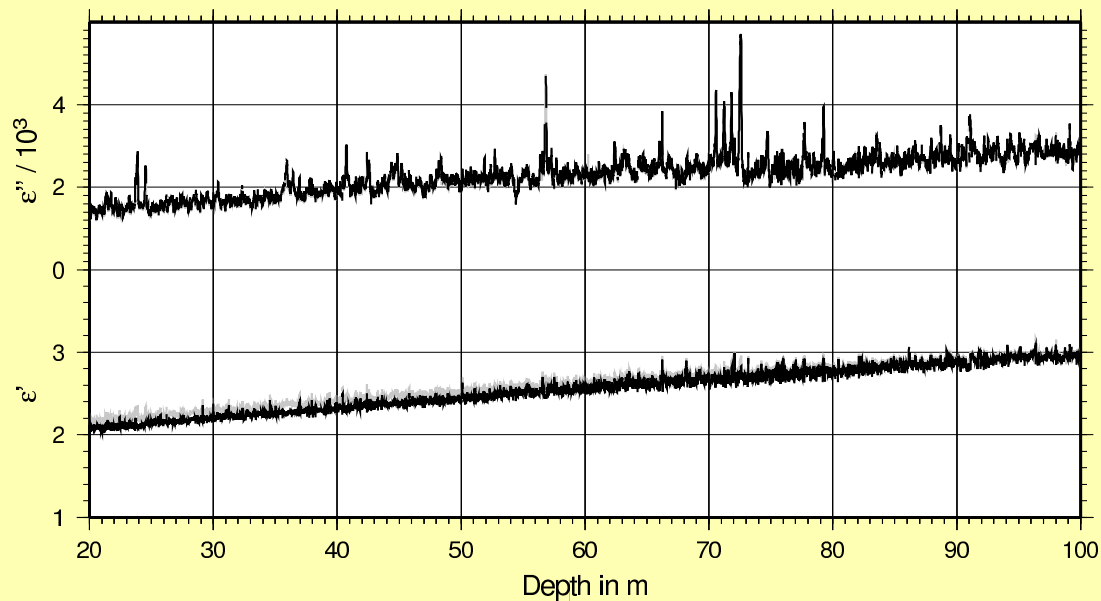
- smoothed conductivity  $\sigma$
- smoothed permittivity  $\epsilon'$



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