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

O. Eisen, U. Nixdorf, F. Wilhelms

AWI Bremerhaven

▷ Ice Penetrating Radar (IPR):

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

▷ Applications:

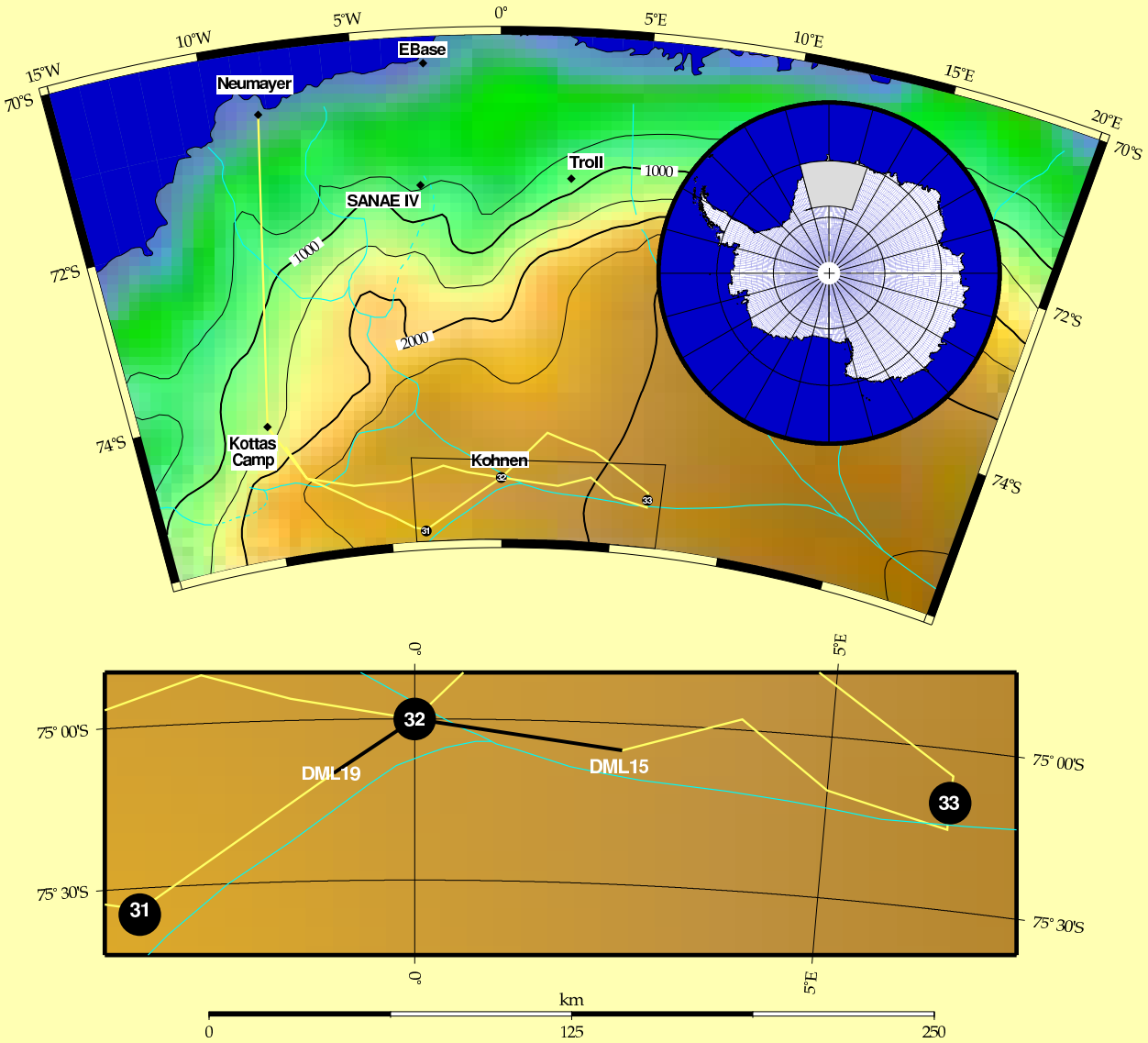
- distribution of accumulation rate (space & time)

⇒ ground-truthing for satellite missions

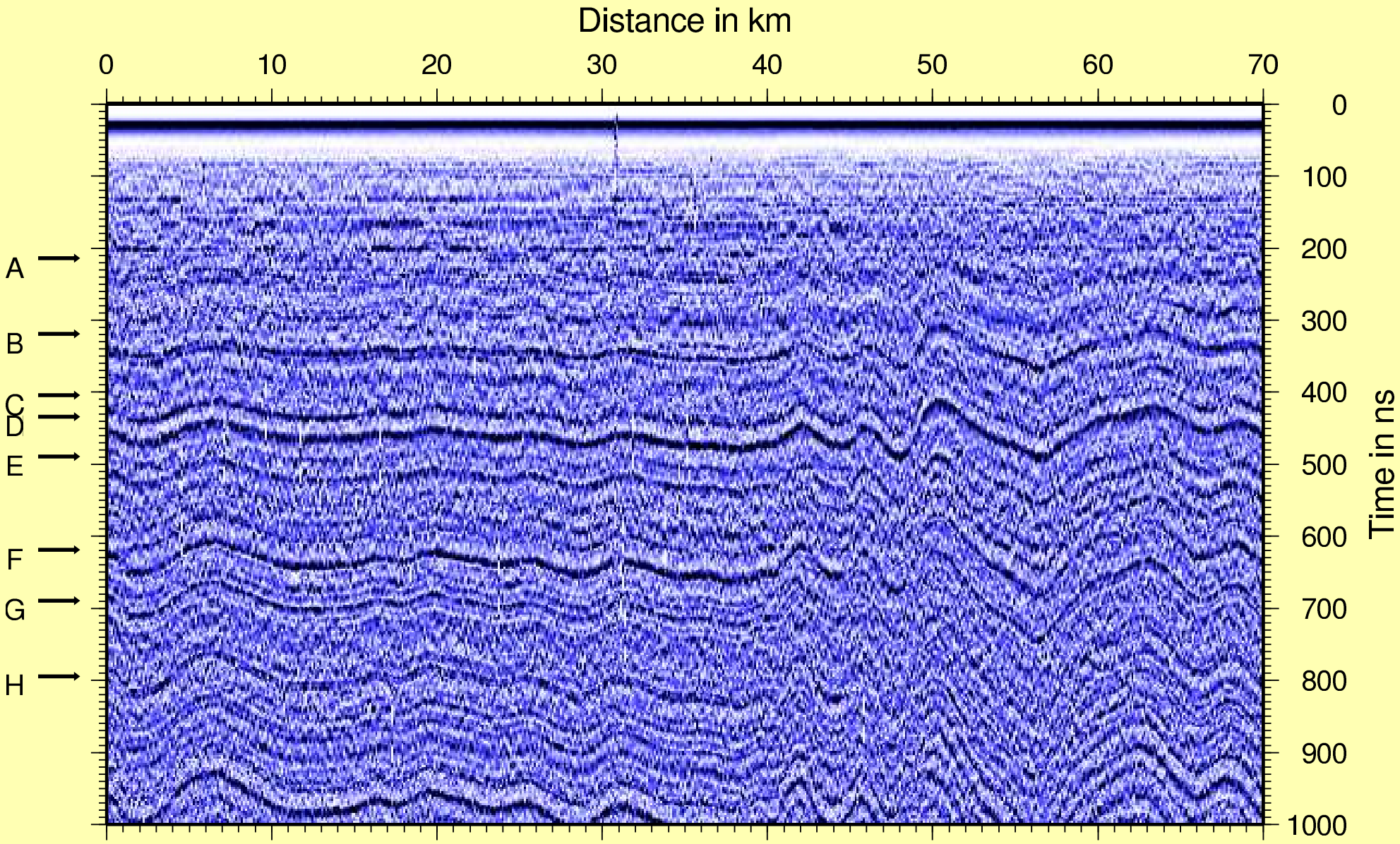
- validation of forward modelling

⇒ transfer approach to other scales

Map of Study Area



Internal Structure: IPR Profile



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

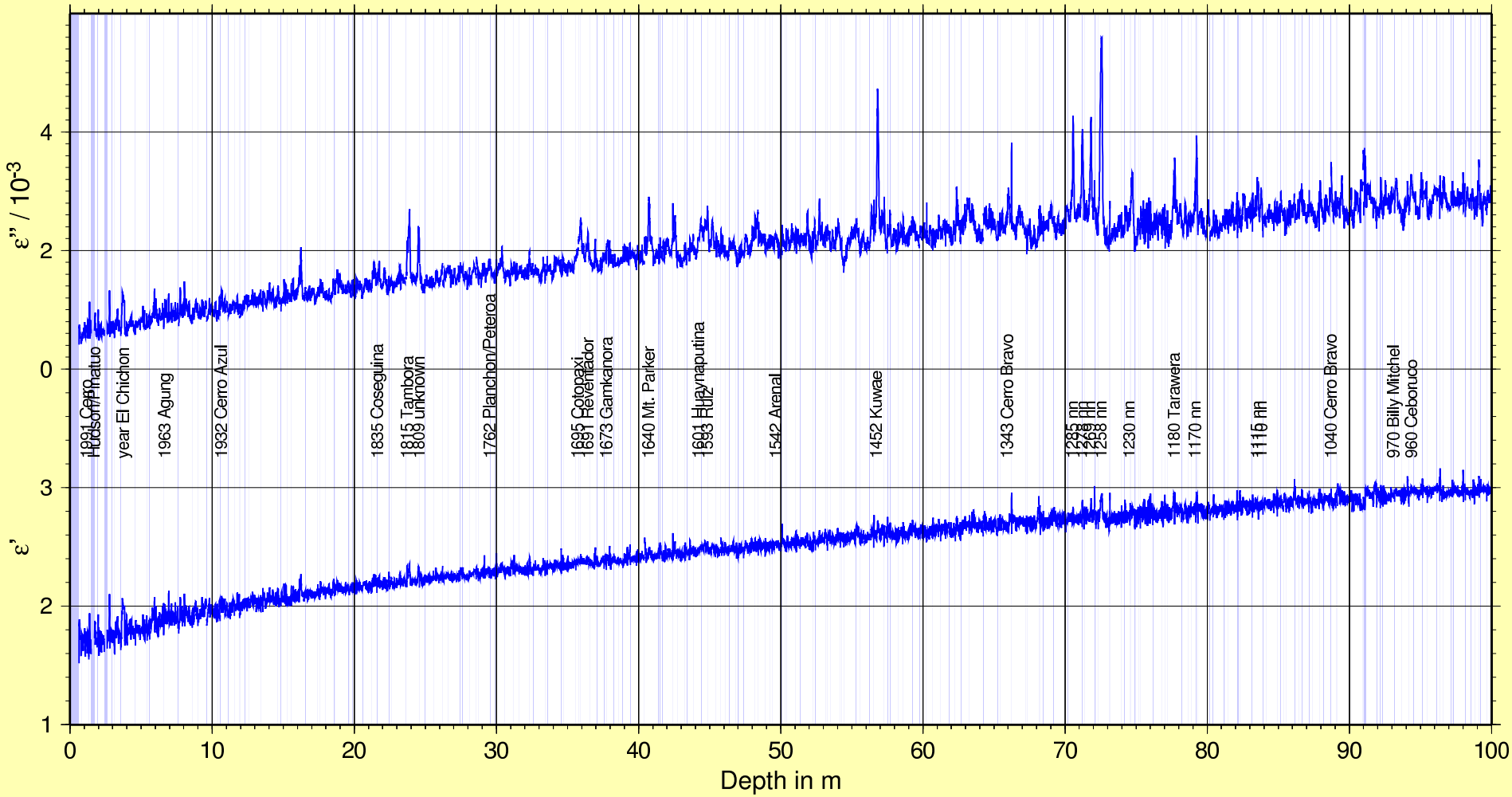
$$\varepsilon = \varepsilon' - i\varepsilon'' = \varepsilon' - i\frac{\sigma}{\varepsilon_0 \omega} = |\varepsilon| e^{-i\delta}$$

▷ Firn is multiphase system:

- dielectric decomposition of mixture (Wilhelms, 2000):

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

In-Situ Data: Dielectrical Profiling of Ice Cores



Interpretation: Forward Modeling of Radargrams

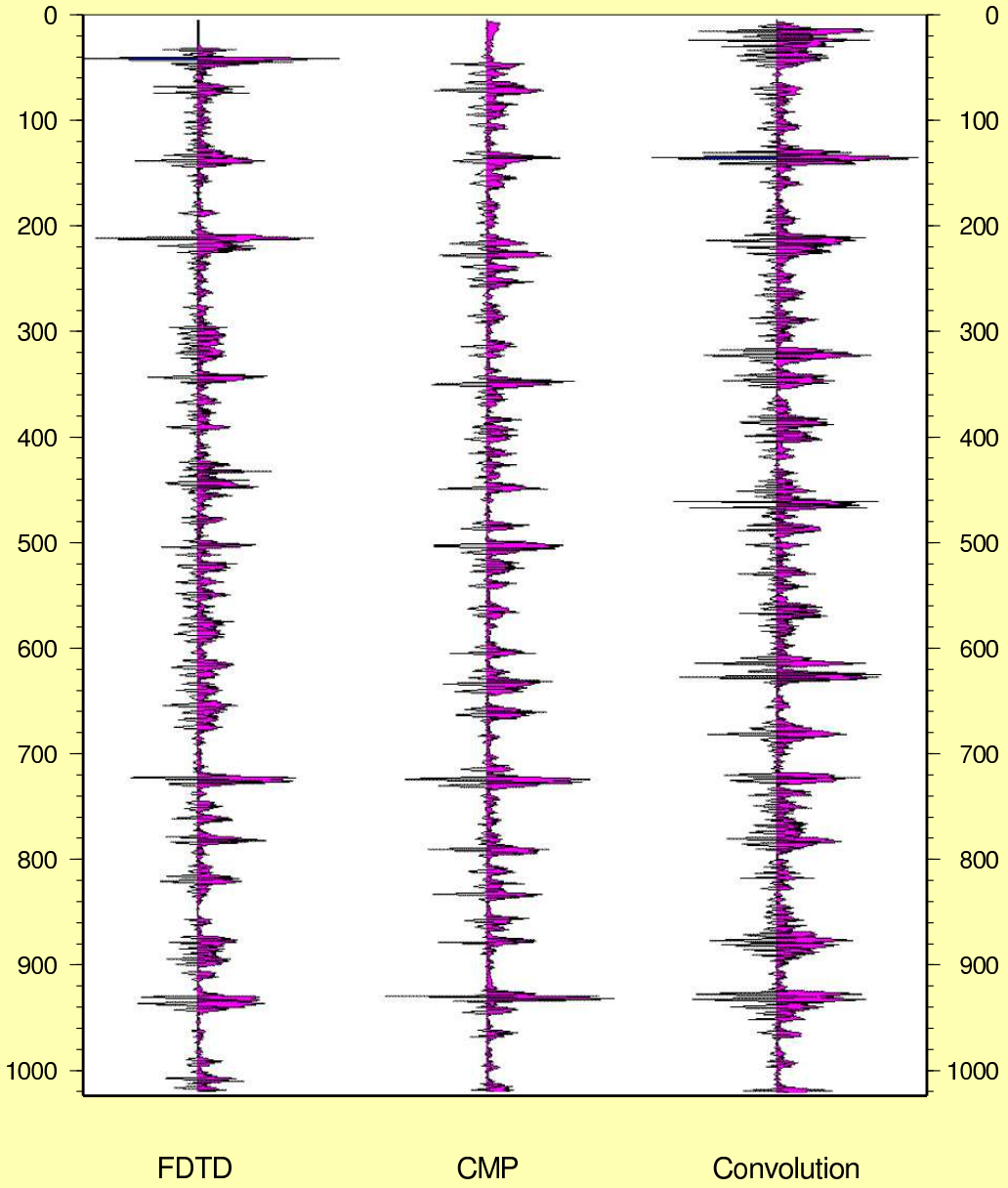
▷ Main Principle:
- assume IPR reference trace as local truth
- establish successful modeling of synthetic trace S

→ 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 $S_{FD} : (\vec{H}, \vec{E})_{t+1} = f(\vec{H}, \vec{E}, \varepsilon)_t$
+ implicit consideration of physics
+ tracking of reflections in space–time slices
– parallel supercomputing required

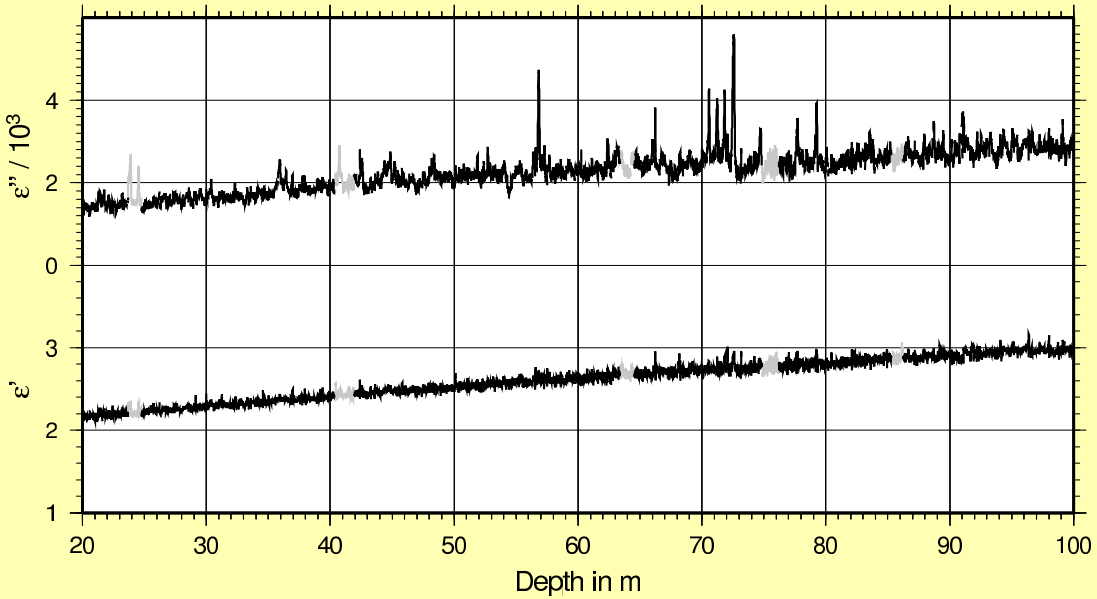
Model Validation

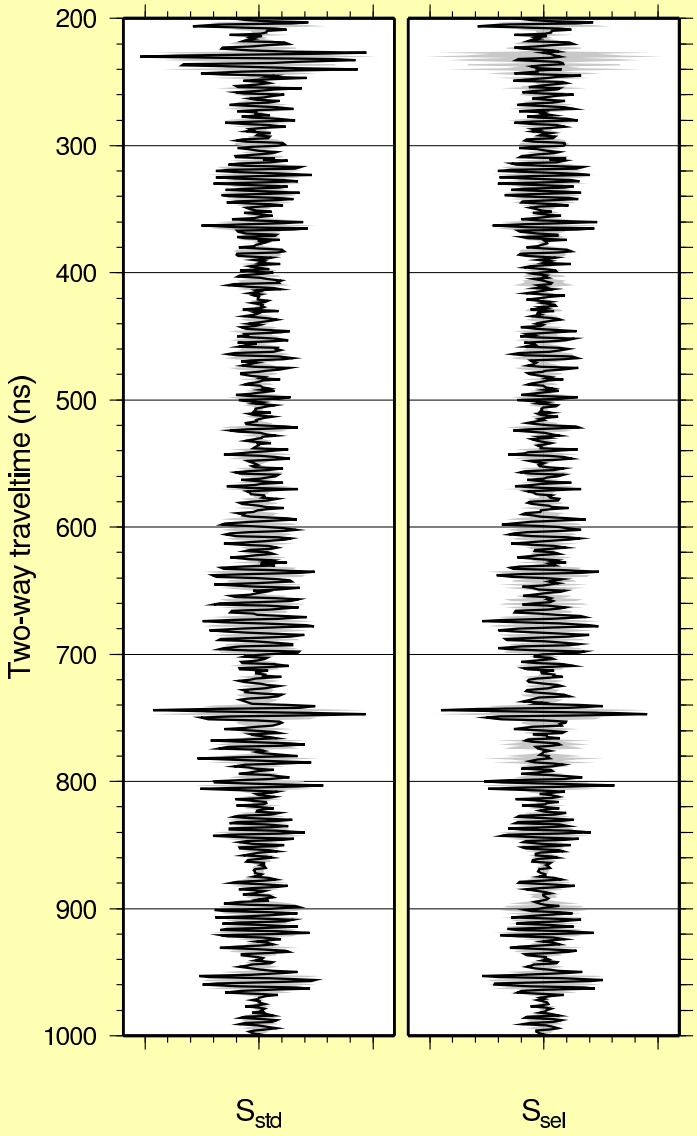


Nature of Reflections

- ▷ Sensitivity studies:
  - remove dominant ε',σ–peaks

  $\longrightarrow$ depth range of origin





Reflection Origin and Properties

- ▷ Cause of reflections (> 100 m):
  - permittivity peaks important
  - conductivity negligible
  - strong correlation of ε', σ for several reflections:

  $\longrightarrow$ some ε'-peaks related to chemical events (how?)

  $\longrightarrow$ corresponding reflections are isochrones

Reflection Origin and Properties

- Cause of reflections (> 100 m):
  - permittivity peaks important
  - conductivity negligible
  - strong correlation of ε', σ for several reflections

  $\longrightarrow$ some ε'-peaks related to chemical events (how?)

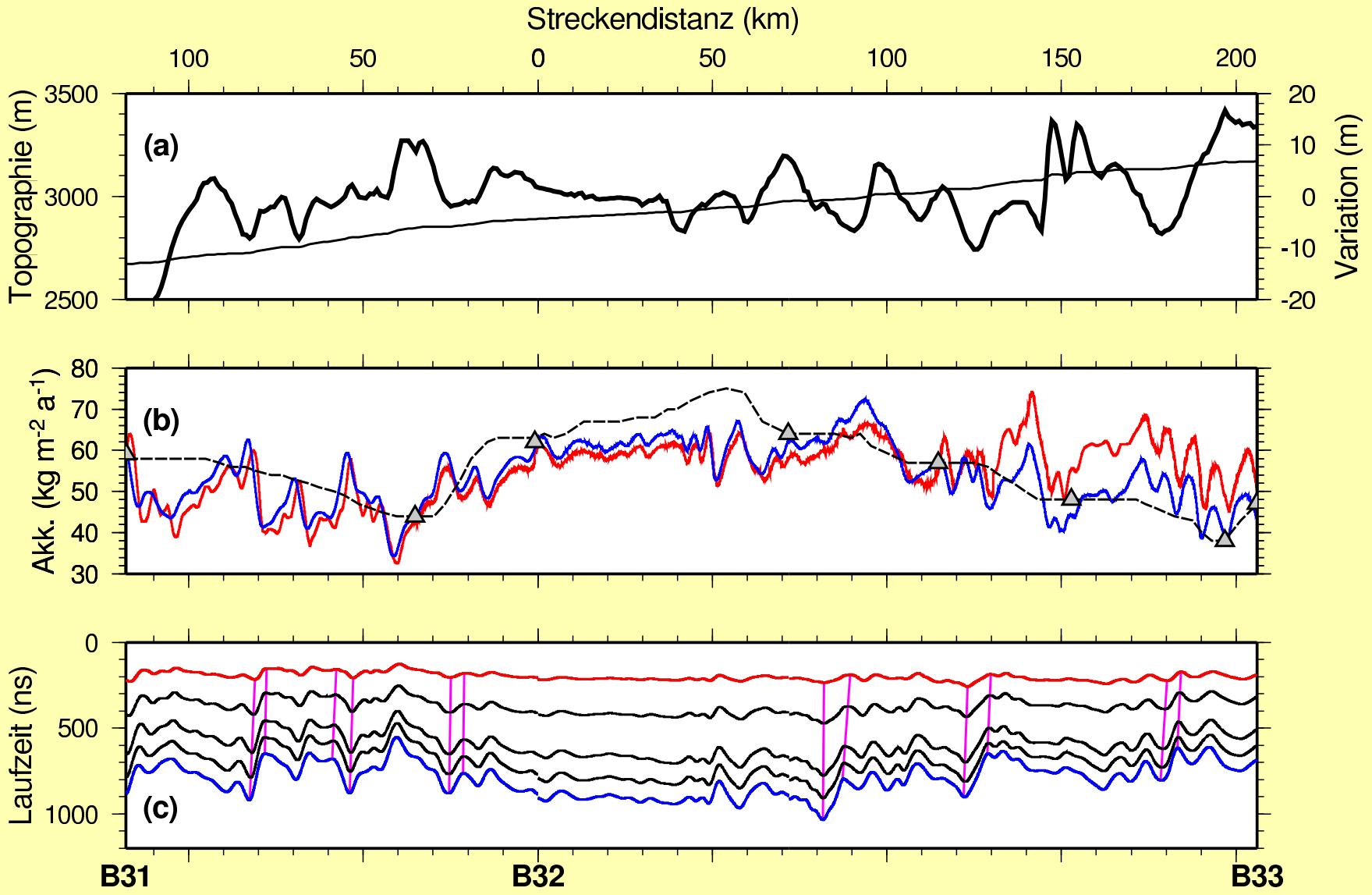
  $\longrightarrow$ corresponding reflections are isochrones

- Application:
  - transfer ice core datings to reflections

  $\longrightarrow$ regional age–depth distribution
  - comparison with several ice core records

  $\longrightarrow$ error estimate of horizon ages

Variation of Accumulation Rate



AWI

Dating of Reflection Horizons

ice core	210 ns	415 ns	650 ns	780 ns	890 ns
			Conventional Dating		
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
			FD Sensitivity Studies		
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.

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

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

▷ Outlook:

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

Reference Trace: Common Midpoint Survey

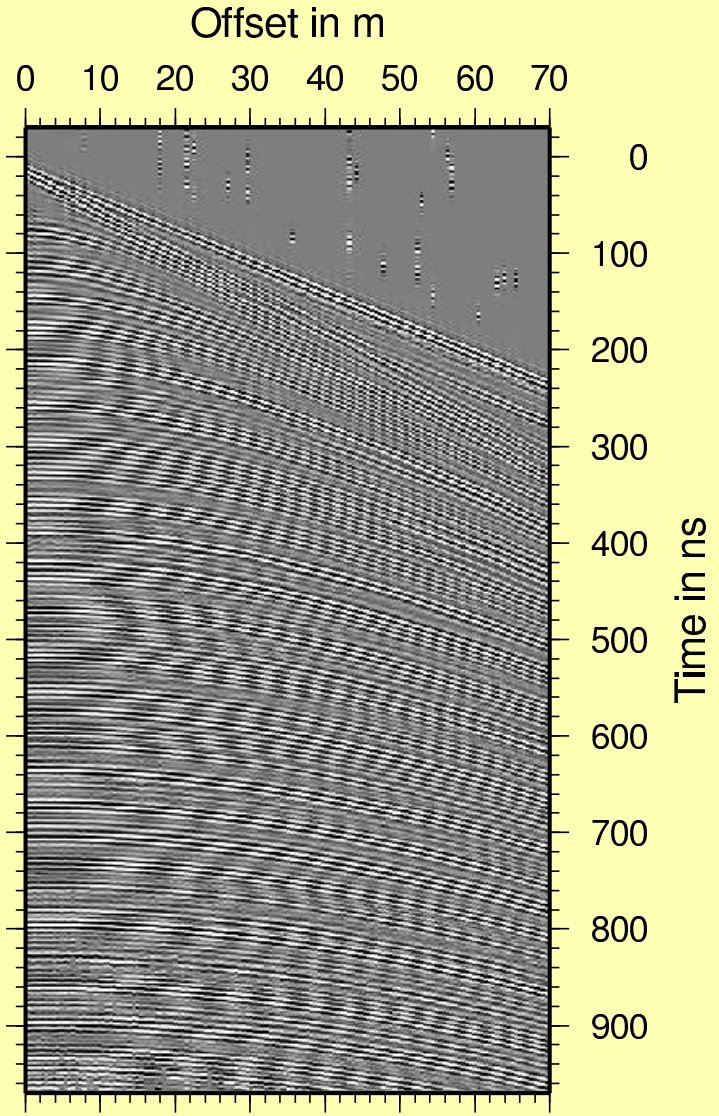
- ▷ Problems for IPR reference trace:
  - lateral inhomogeneities of physical properties

- ▷ CO IPR profiles:
  - TX–RX configuration constant
  - limited stacking (decoherence)

  → low quality SNR

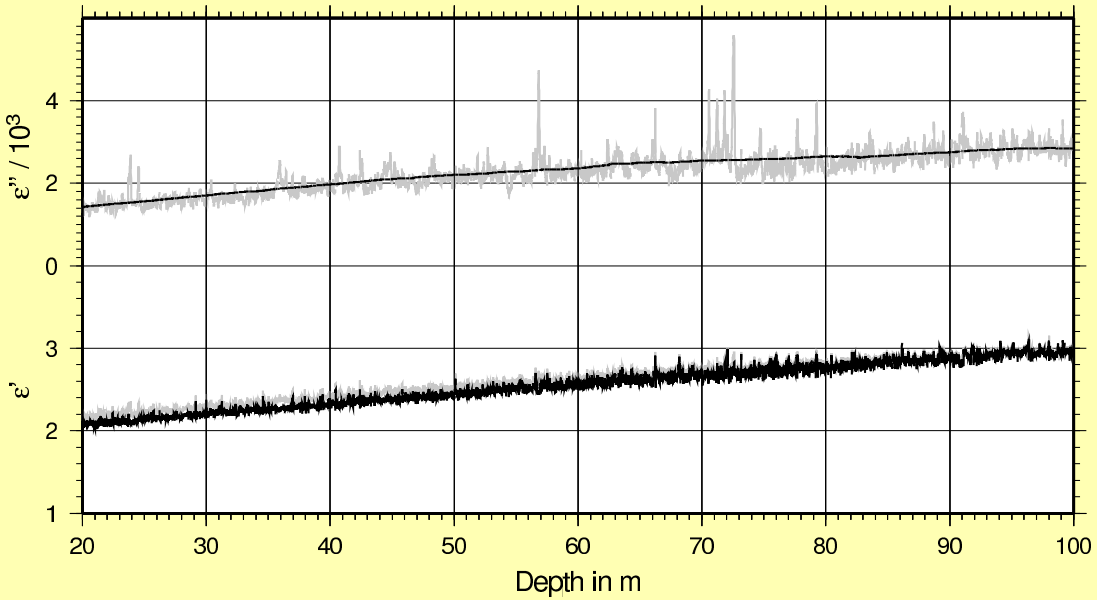
- ▷ Advantages of CMP:
  - spatial averaging (wide angles) (NMO correction & stacking)
  - independent velocity information

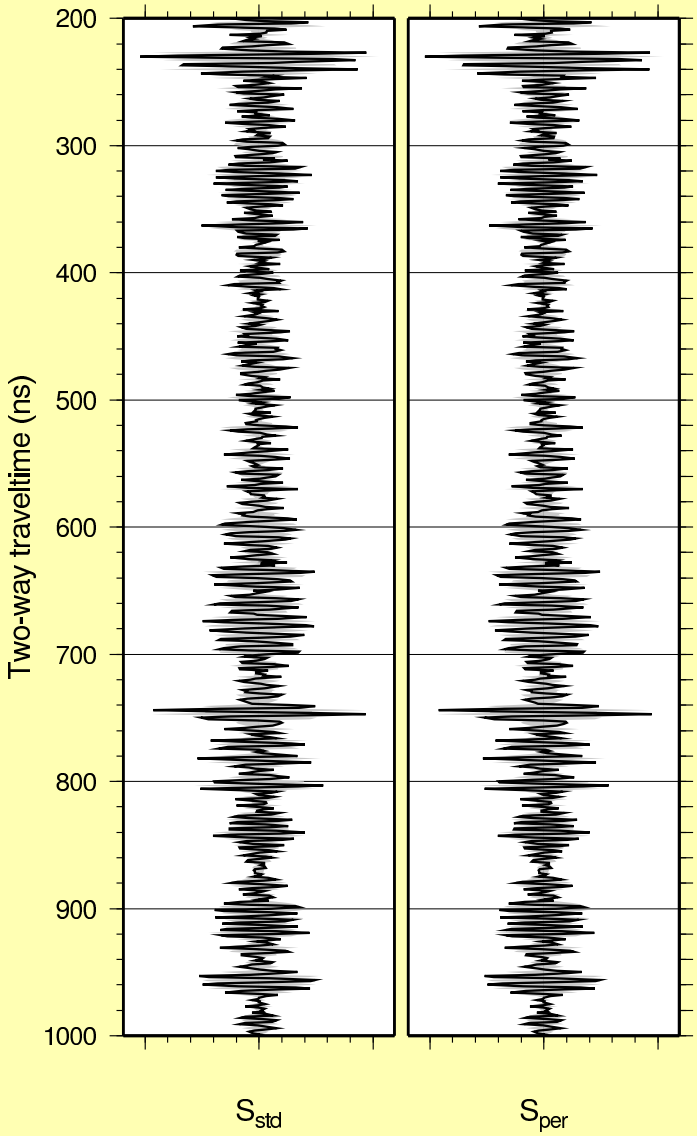
  → single trace with high SNR



Nature of Reflections

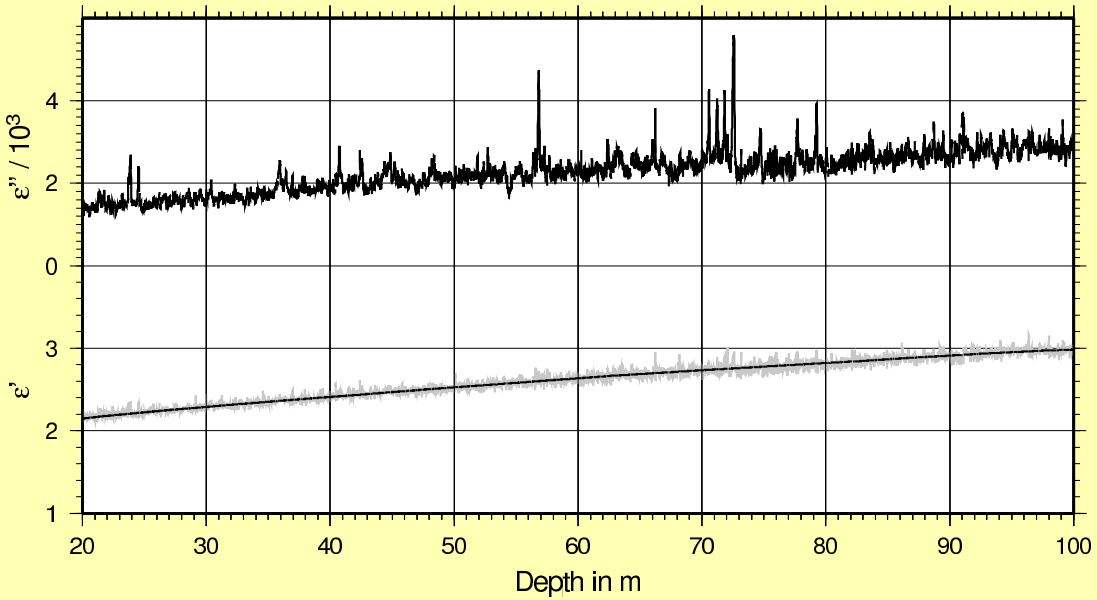
- ▷ Sensitivity studies:
  - smoothed conductivity σ

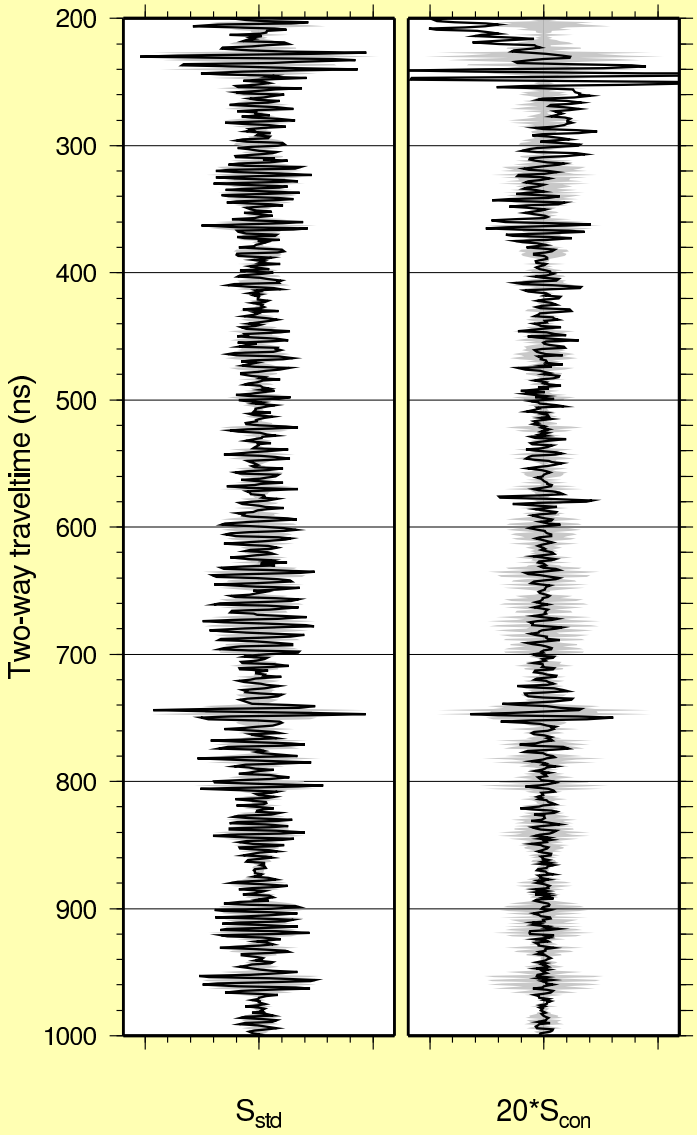




Nature of Reflections

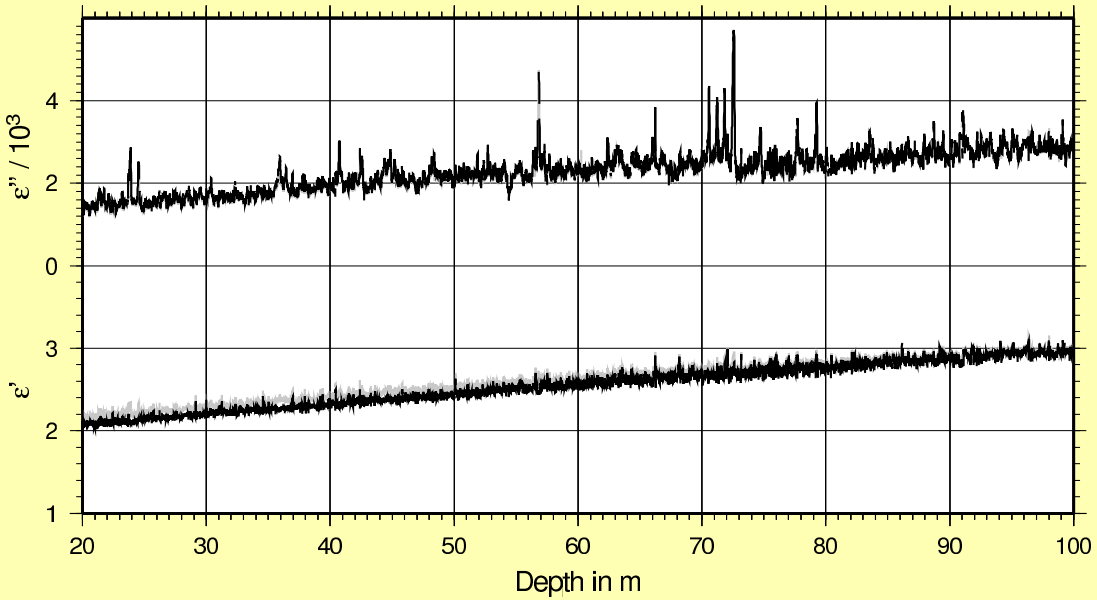
- ▷ Sensitivity studies:
  - smoothed conductivity σ
  - smoothed permittivity ε'

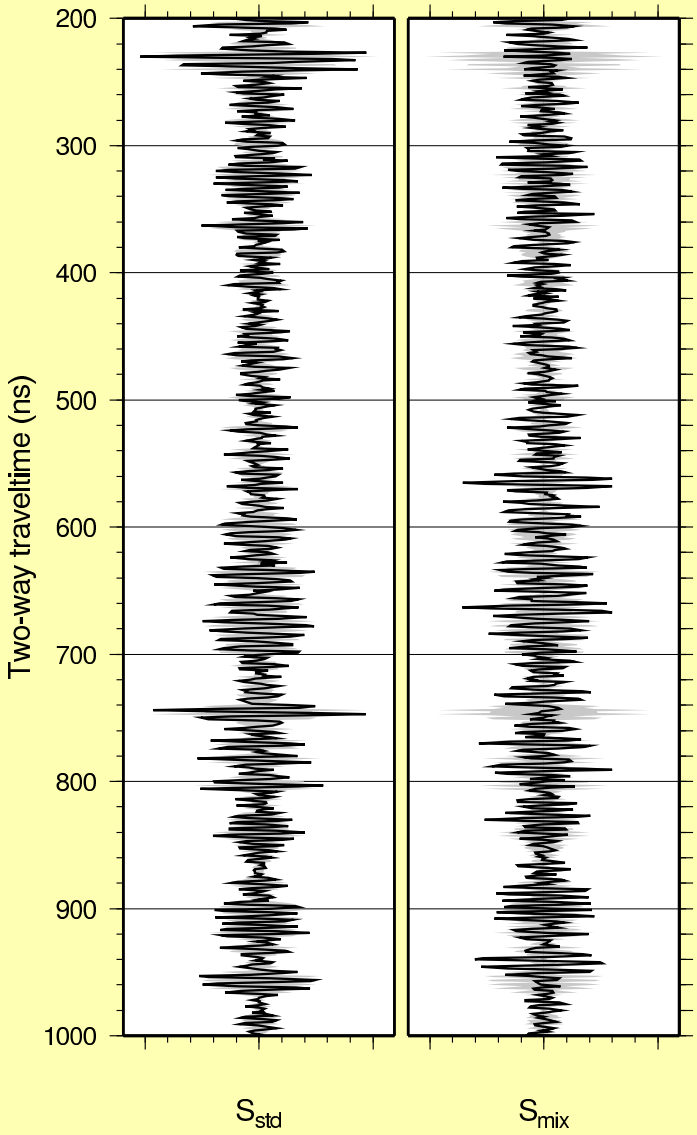




Nature of Reflections

- ▷ Sensitivity studies:
  - smoothed conductivity σ
  - smoothed permittivity ε'
  - remove dominant ε',σ–peaks
  - application of dielectric mixing





Nature of Reflections

- ▷ Sensitivity studies:
  - smoothed conductivity σ
  - smoothed permittivity ε'
  - remove dominant ε',σ–peaks
  - application of dielectric mixing