Attenuation inversions using broadband acoustic sources

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[Work sponsored by ONR, code 321OA]

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Outline

- Attenuation from modal amplitude ratios (inversion approach similar to Lin Wan/Zhou)
- Field Experiments
  - » New England Bight (Primer)
  - » East China Sea
  - » SW 06 (New Jersey Shelf)
- Results –
  - » Mode sensitivity with depth
  - » Spatial/ Depth variations of frequency dependent attenuation

Attenuation Estimation- Issues

- Frequency dependence (discussed in detail in the morning session)
- At our frequencies of inversion, depth of acoustic penetration high.
- At low frequencies, energy losses due to
  - » Transmission through multiple layers
  - » Intra-bed multiple reflections
  - » Scattering, volume inhomogeneities etc.
  - » Shear wave conversion (Pierce/Carey)
- *In situ* measurement of attenuation difficult.
  - » Estimation from sediment cores done at higher frequencies.
  - » Deep cores sampling sub-surface layers unavailable most of the time.

Attenuation Inversion

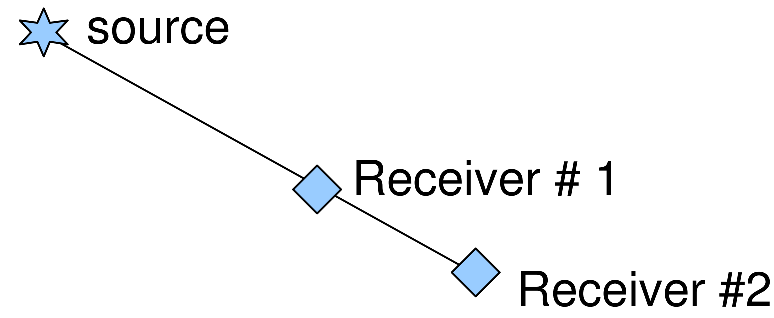
- Long ranges, low frequencies (<200 Hz), low modes (modes 1 to 6)

- Based on Ratios Modal Amplitudes at two ranges

- Individual mode amplitudes by wavelet analysis

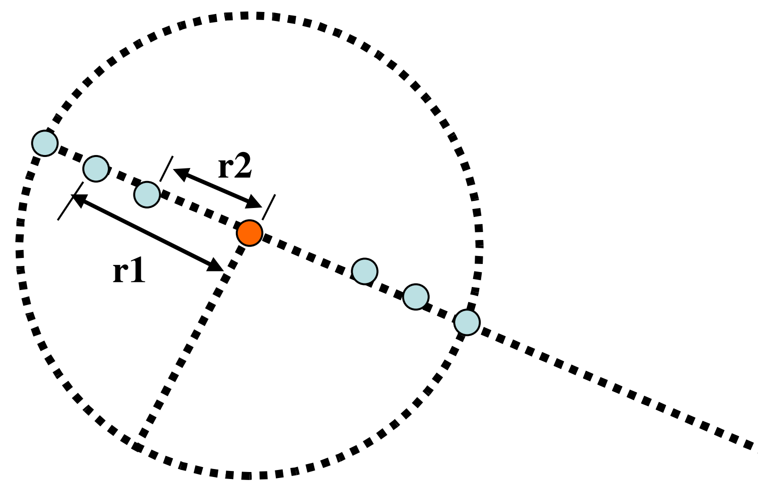
- Attenuation (compressional wave) modeled using $\alpha(z) = k\, f^n$; k and n unknowns

Attenuation Inversion



$$\kappa_m \beta_m = \int_0^\infty \alpha(z) k(z) \left|\psi_m(z)\right|^2 dz \quad \textbf{(1)}$$

$$P_m(r,z) = \frac{i e^{-i\pi/4}}{\rho\sqrt{8\pi}\sqrt{r}} \psi(z_s)\psi(z) \frac{e^{i\kappa_m r}}{\sqrt{\kappa_m}} e^{-\beta_m r} \quad \textbf{(2)}$$



$$\frac{P_m(r1,z)}{P_m(r2,z)} = \sqrt{\frac{r1}{r2}} \frac{\psi_{m1}(z_{s1})}{\psi_{m2}(z_{s2})} \frac{e^{i\kappa_{m1} r1}}{e^{i\kappa_{m2} r2}} \frac{\sqrt{\kappa_{m1}}}{\sqrt{\kappa_{m2}}} \frac{e^{-\beta_m r1}}{e^{-\beta_m r2}} \quad \textbf{(3)}$$

ρ	density	β	modal attenuation coefficient
r	source-receiver range	ψ	mode shape for mode m
z_{s1} , z_{s2}	source depths	$\alpha(z)$	attenuation profile
z	receiver depth	$k(z)$	ω / $c(z)$
κ	horizontal propagation constant	ω	angular frequency

C(z) from CTD and Sediment inversions

k and n unknown parameters

$\alpha = k f^n$

$$\kappa_{rm}\beta_m = \int_0^\infty \alpha(z)k(z)\left|\psi_m(z)\right|^2 dz$$

β – for different modes

Modal amplitude ratios (same mode and receiver depth, Different range)

$$\frac{P_m(r1,z)}{P_m(r2,z)} = \sqrt{\frac{r1}{r2}}\,\frac{\psi_{m1}(z_{s1})}{\psi_{m2}(z_{s2})}\,\frac{e^{i\kappa_{m1}r1}}{e^{i\kappa_{m2}r2}}\,\frac{\sqrt{\kappa_{m1}}}{\sqrt{\kappa_{m2}}}\,\frac{e^{-\beta_m r1}}{e^{-\beta_m r2}}$$

Mode amplitude ratios from Time-frequency diagrams

Minimize the difference between data and prediction

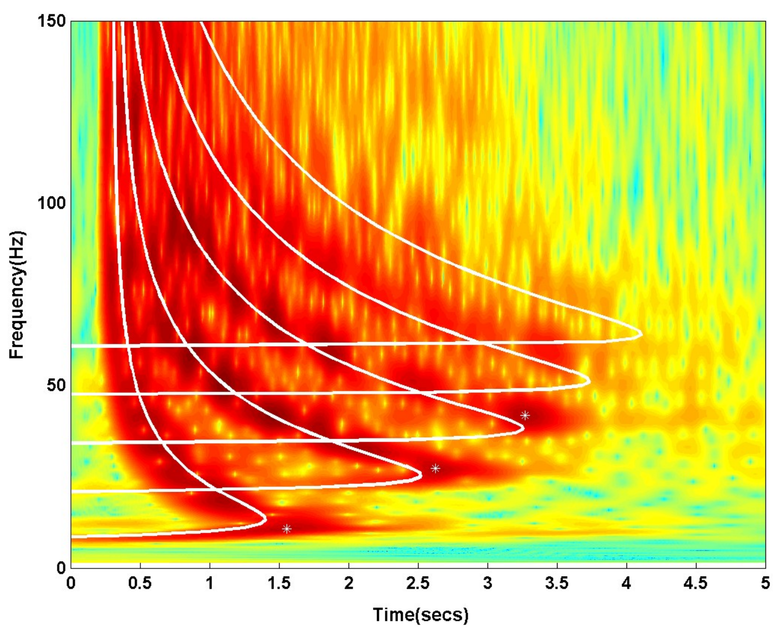
Best estimate k and n

Field Experiments: PRIMER (New England Bight)

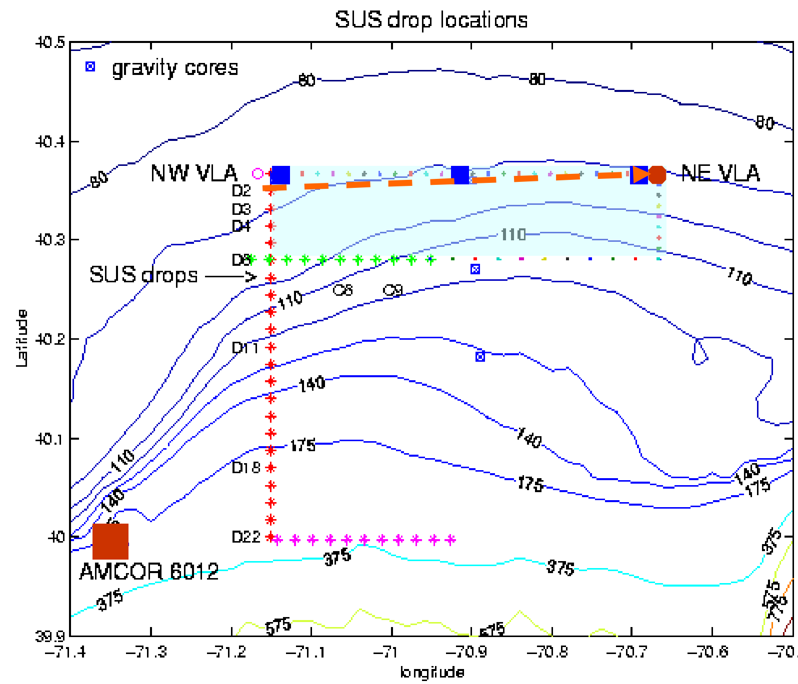
Range: 40 km
Water depth ≅ 100 m
Charge Weight: 0.8 kg
Source depth: 18 m

Arrival spread 4 s and 10- 150 Hz.

PRIMER



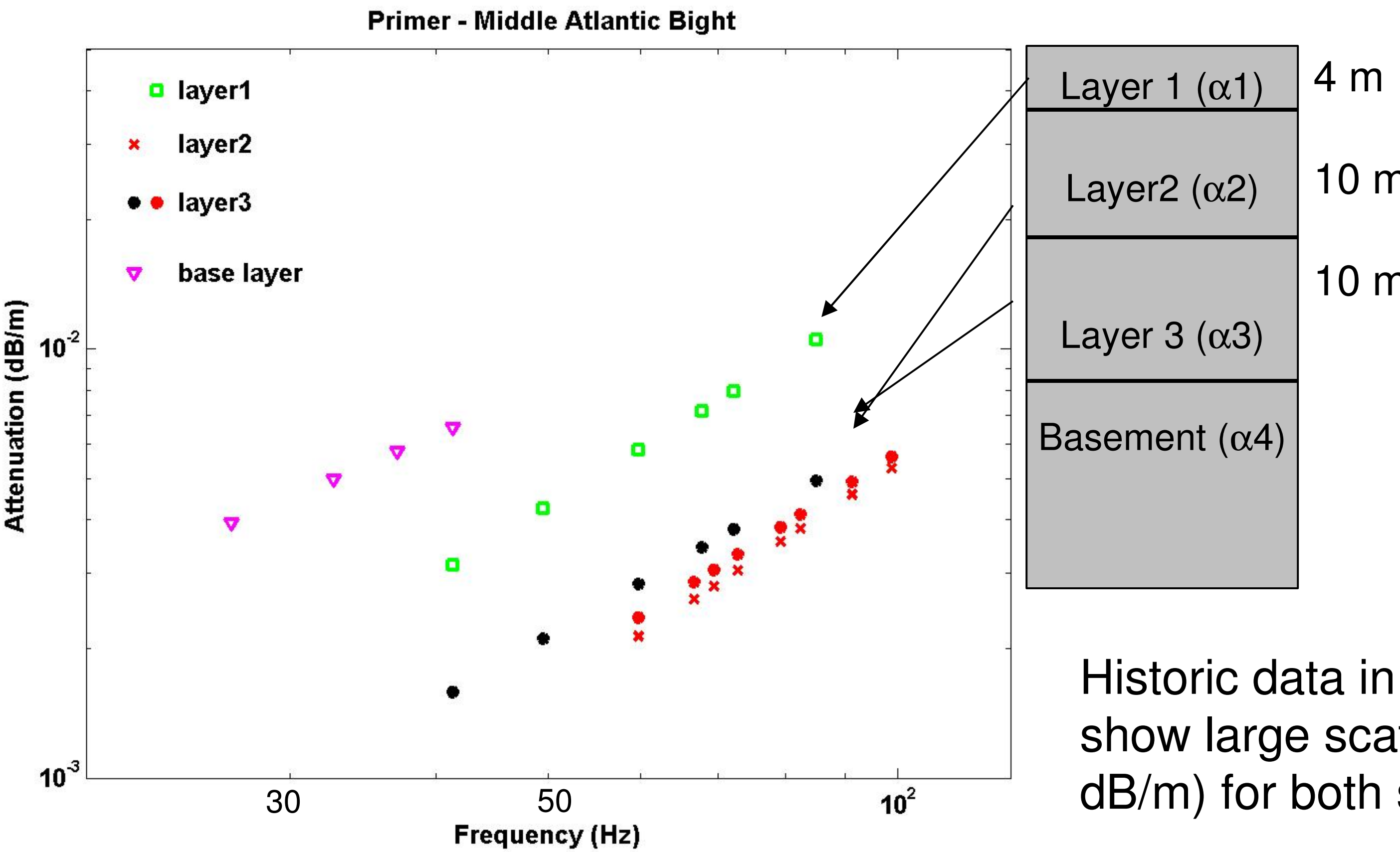
Loud source, Excellent SNR, large range (~ 40 km) – large arrival time spread, well separated mode arrivals



PRIMER (New England Bight)

Primer Attenuations

Depth averaged inversions compare well with other published data (Zhou)



Historic data in this frequency band show large scatter (10^{-3} to 10^{-2} dB/m) for both silt/clay and sands.

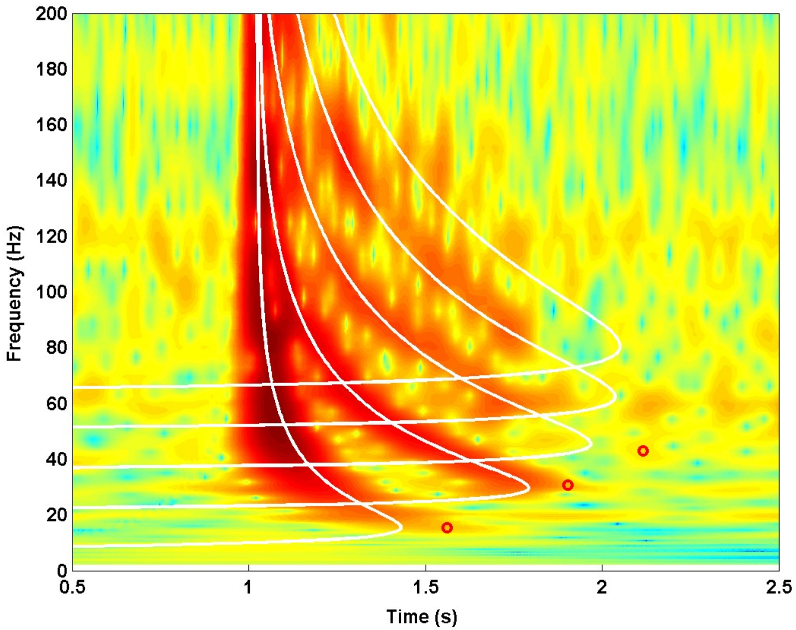
Layer 1 values different (higher) from bottom layers

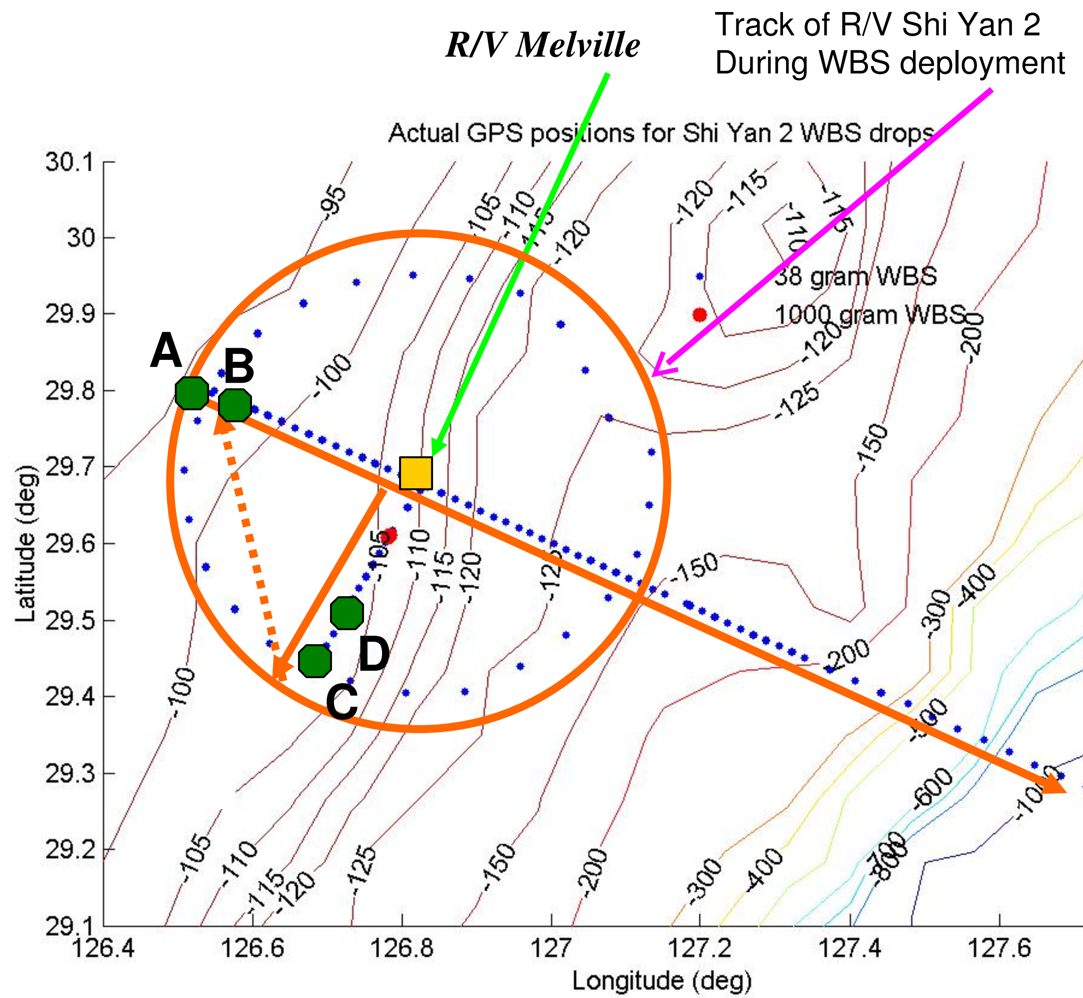
Sub-surface layers: depth, layering effects in addition to possible difference in sediment type

ASIAEX- East China Sea Data

Range: 30km
Water depth ≅ 100 m
Charge Weight: 38 g;
Source depth: 50 m
Range – 30 km
Arrival spread 1 s and 10- 200 Hz.

ECS Shot 60



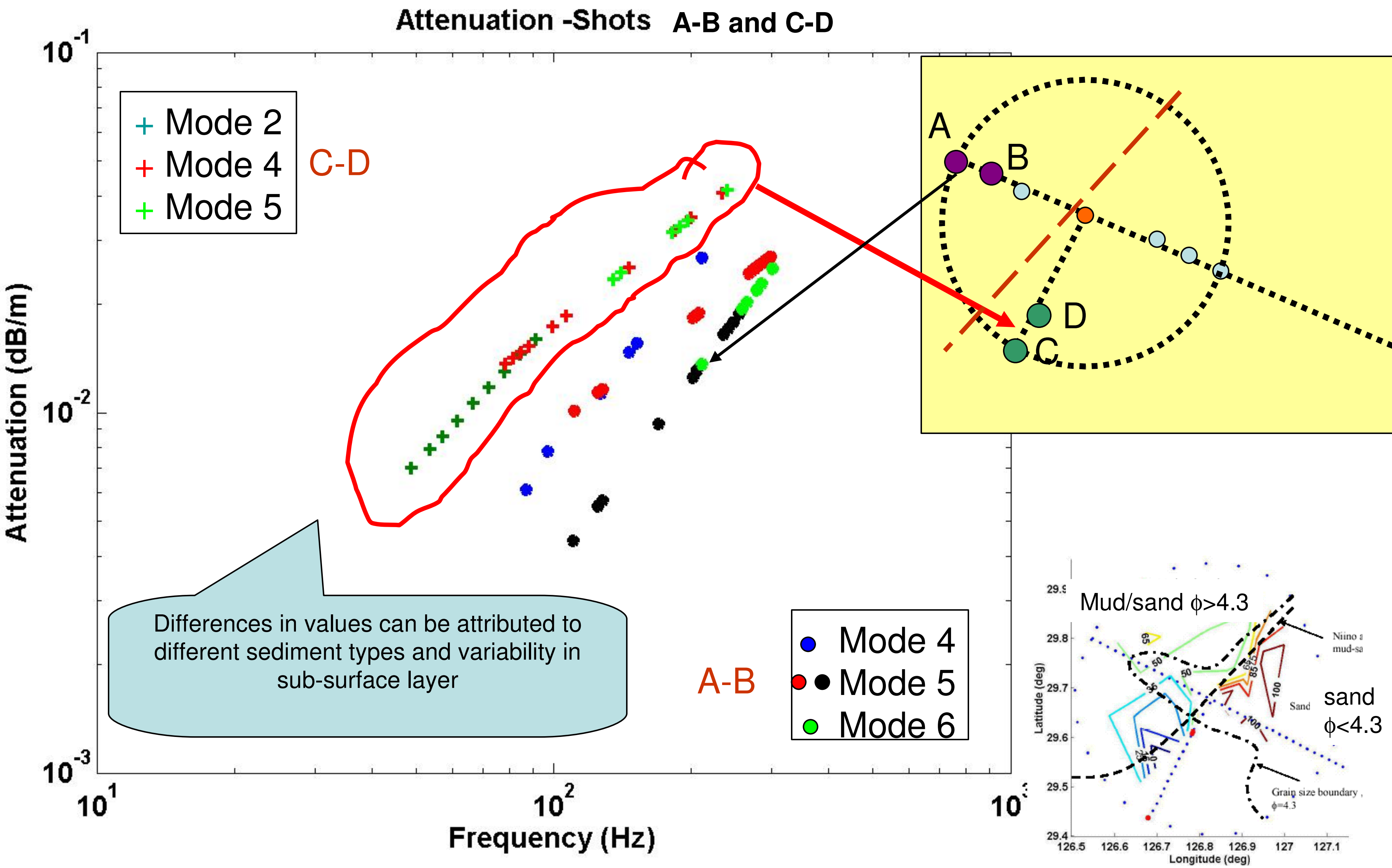


Dahl et al. ., “Overview of results from the Asian Seas International Acoustic Experiment in the East China Sea,” IEEE J. of Oceanic. Eng., 29(4), 920-928, 2004

Miller et al., " Sediments in the East China Sea," IEEE J. Oceanic. Eng., 29(4), 940-951, 2004.

ECS Attenuation - 80 to 350 Hz

No depth variation in attenuation; using separate inversion using individual modes

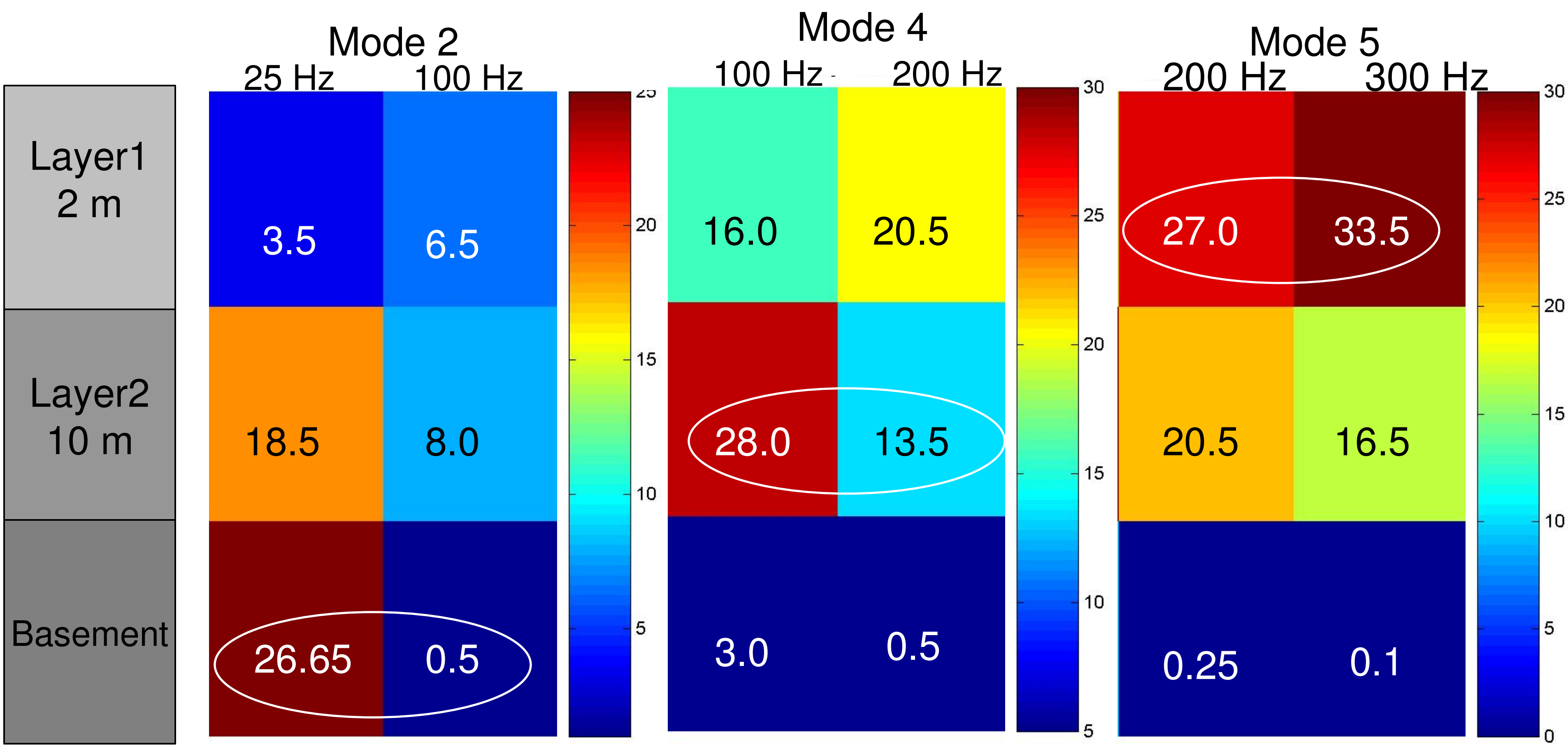


Sensitivity of Modal Amplitude Ratios to Changes in Attenuation Coefficient in Sediment Layers and Basement

•Sensitivity shown represents percentage change in Mode Amplitude Ratios (for two ranges) for a given change in α in a particular layer from a reference environment.

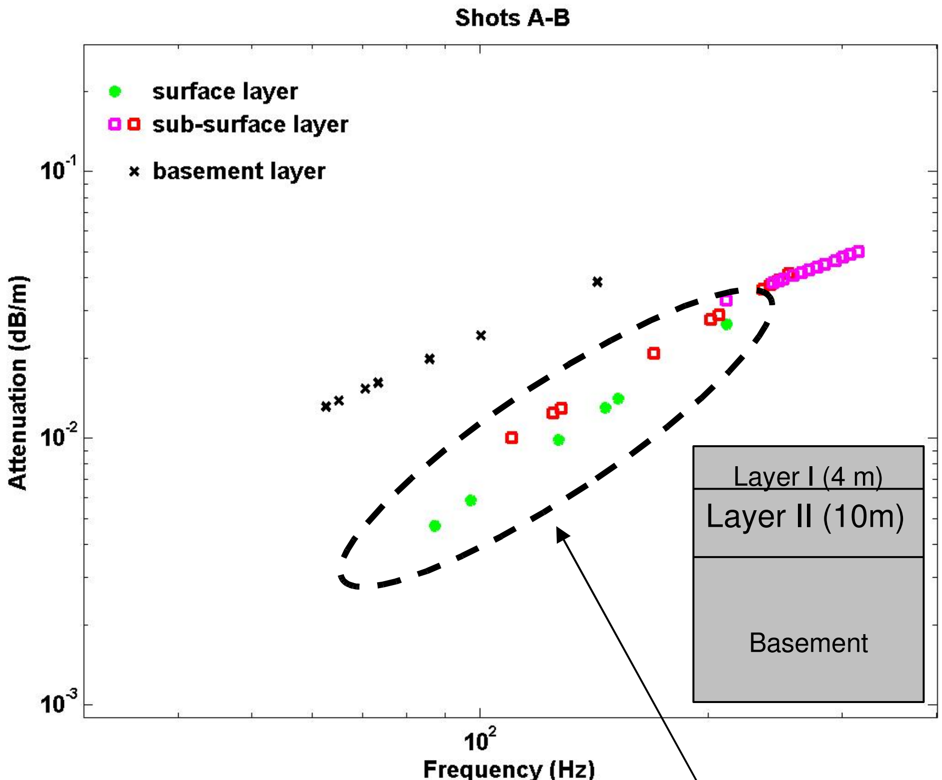
•The reference environment and geometry resembles East China Sea.

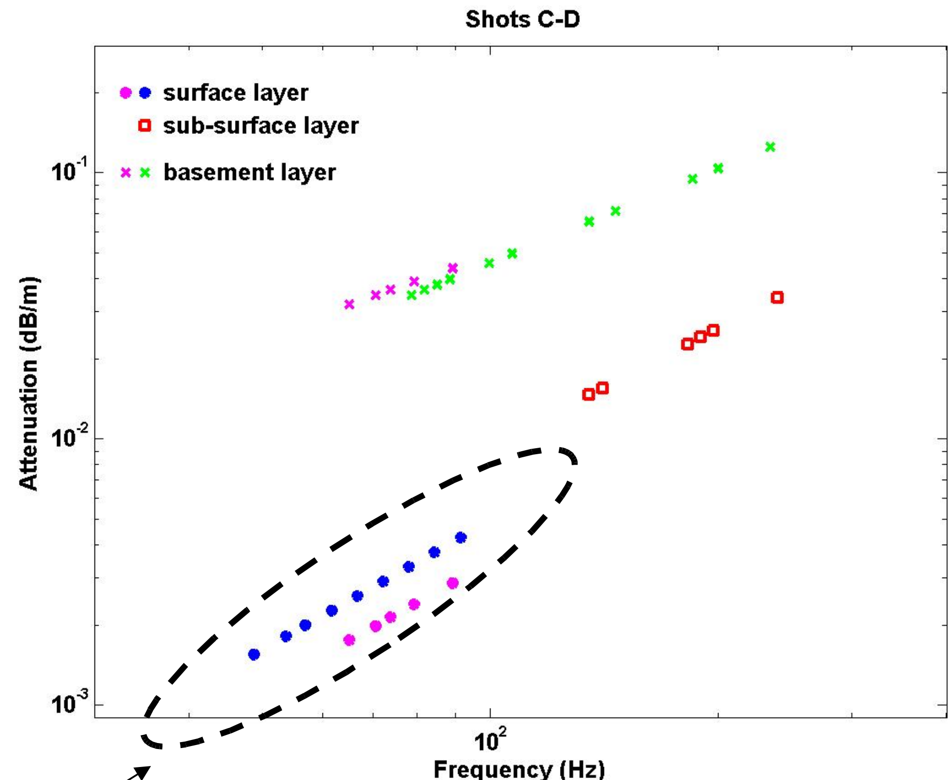
•Different mode – frequency band combinations can be used to ‘probe’ different depths (layers) of sediment leading to efficient use of time-frequency mode decomposition capability.

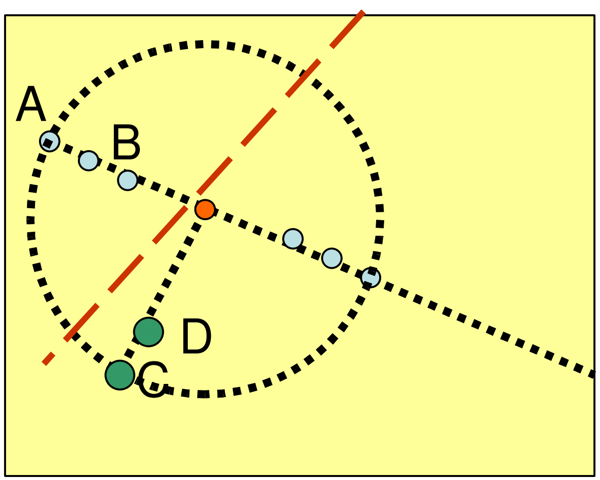


[Color scale and Numbers indicate Sensitivity in Percentage]

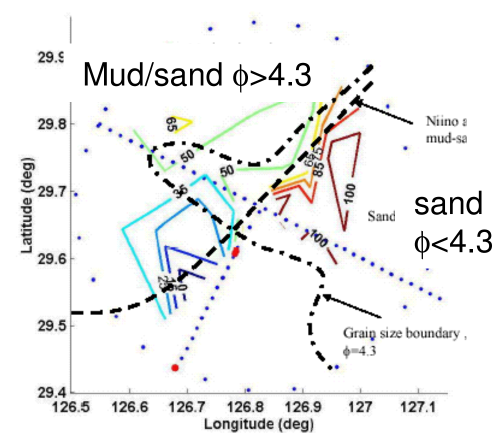
Attenuation – East China Sea south-west and north-west sides







Significant variations in the surface layer attenuations



Field Experiments – SW 06

SW06 (2006) – New Jersey Shelf; Combustive Sound Sources (CSS) (Preston Wilson, David Knobles (ARL-Univ.Texas)

- **CSS is not intended to be a direct replacement for explosives**

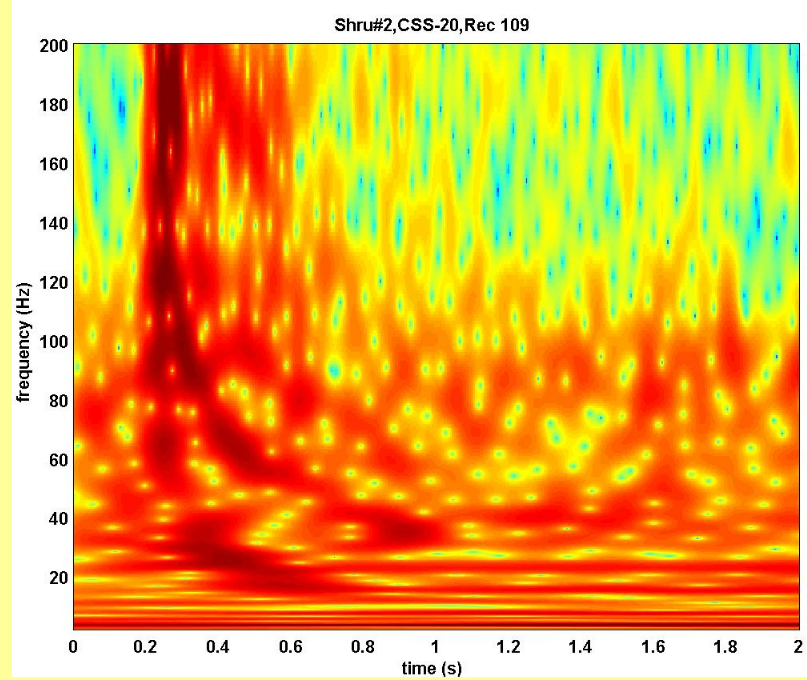
- **It is intended to offer a sharp impulse, and have good low-frequency energy, but still more environmentally friendly.**

SW06 CSS System

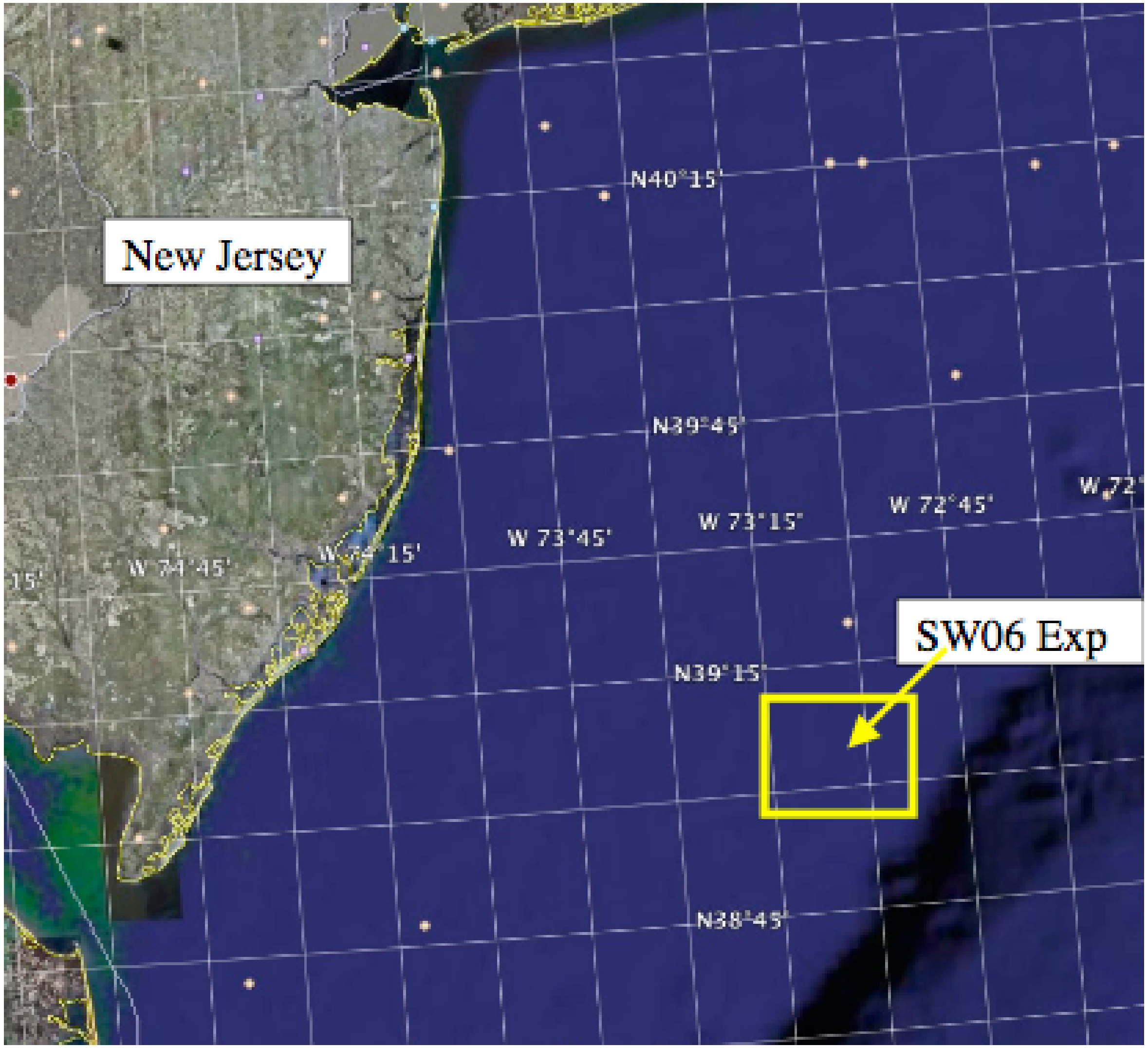
Range: 21.24 km
Water depth ≅ 90 m
Source depth: 26 m

Arrival spread 1 s and 10- 200 Hz.

CSS- SW06

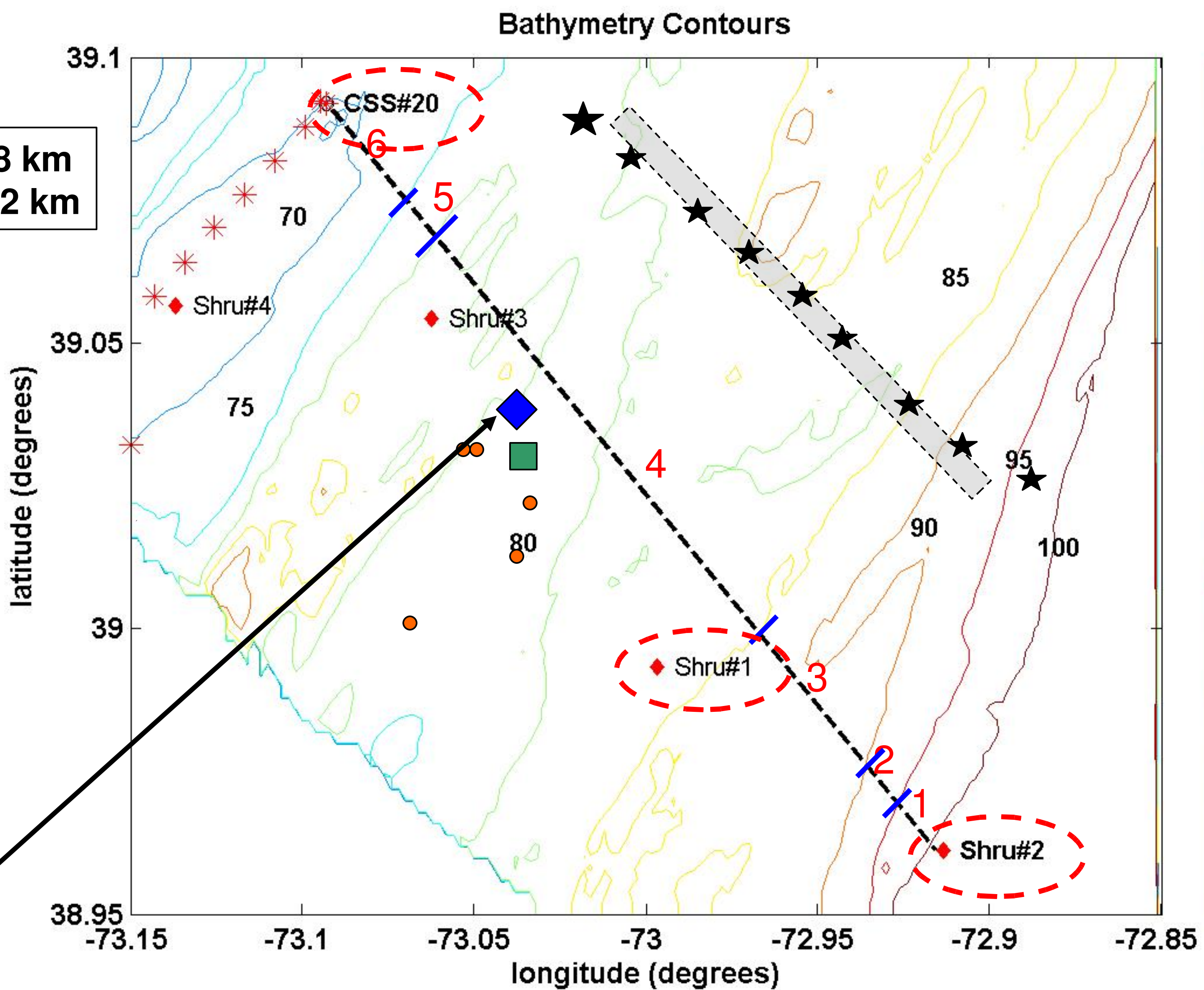


SW 06 – Experimental Area



Source – Receiver Locations

CSS 20 to SHRU 1 - 13.8 km
CSS 20 to SHRU 2 – 21.2 km



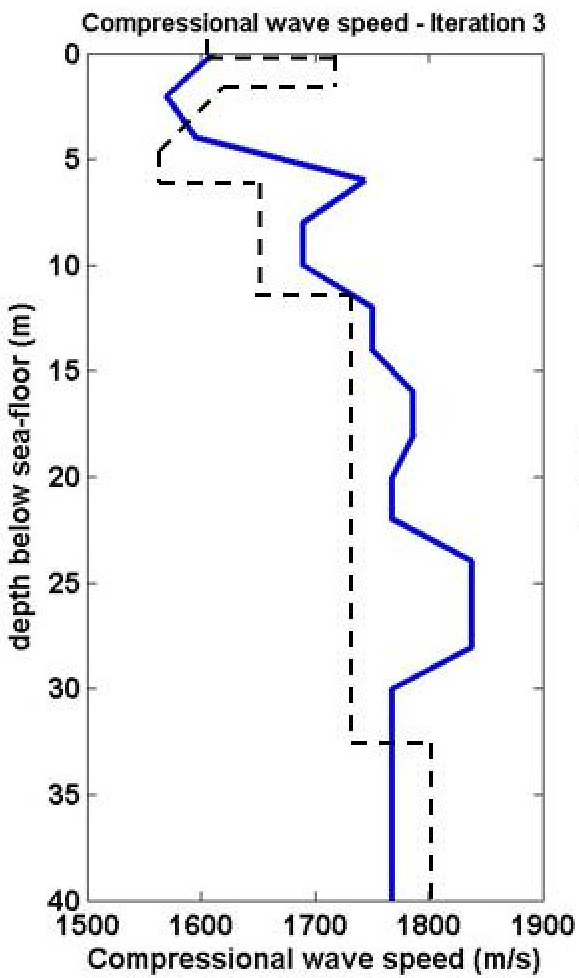
Grab samples ★

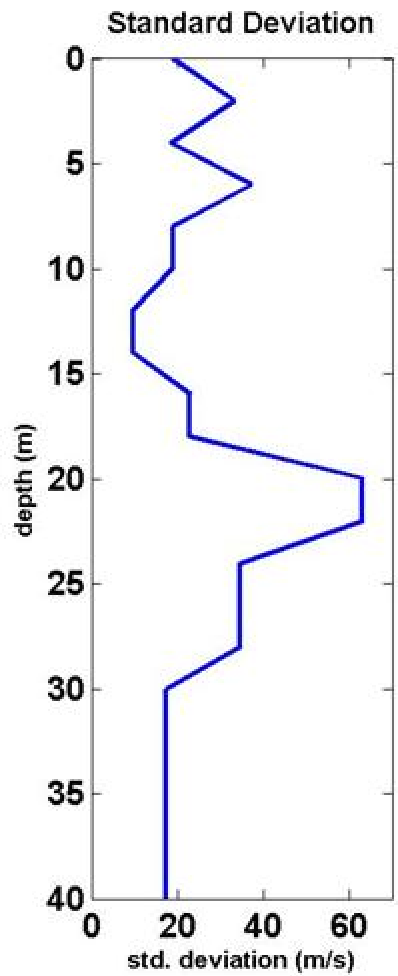
In situ probes

Short core- station 77

AHC – 800 Core

Inversion Results- Compressional Wave Speed



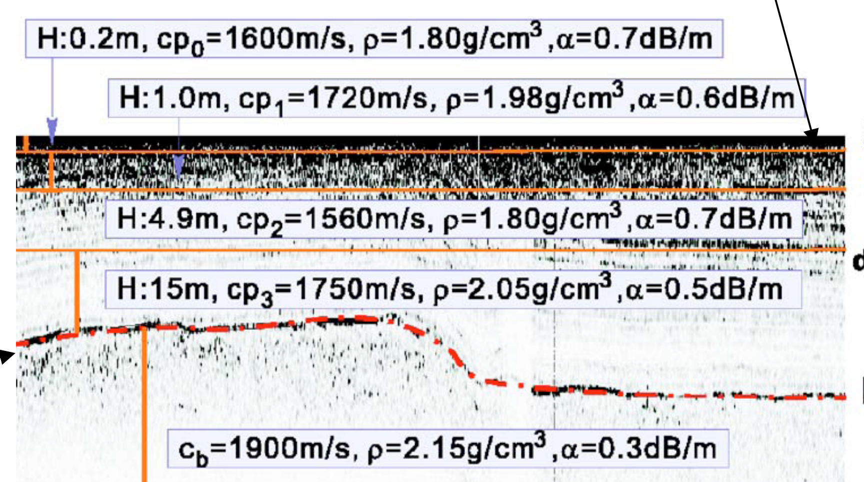


Compressional wave speed (top 40 m) compared with Jiang et al. model (JASA-2007)

Standard deviation ~ 20 m/sec.

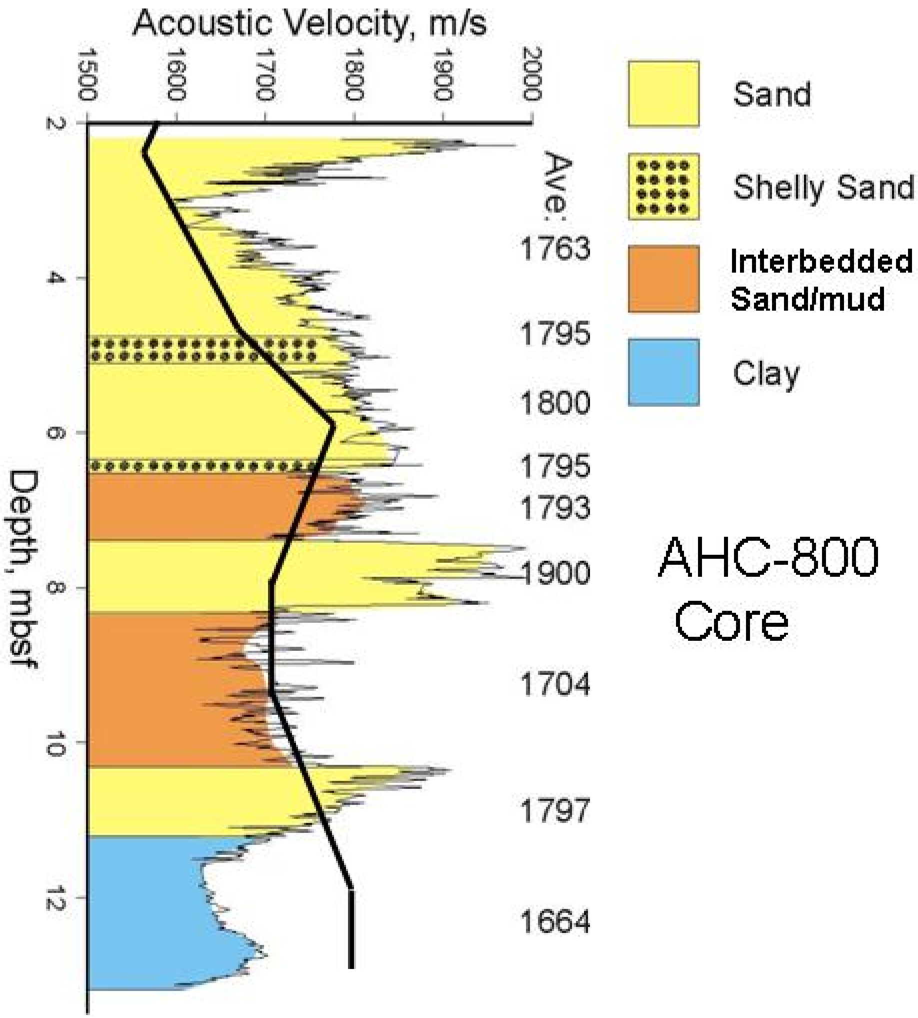
The R- reflector is approx. around 20 m

Sea floor



R - Reflector

Inversion Results- Compressional Wave Speed



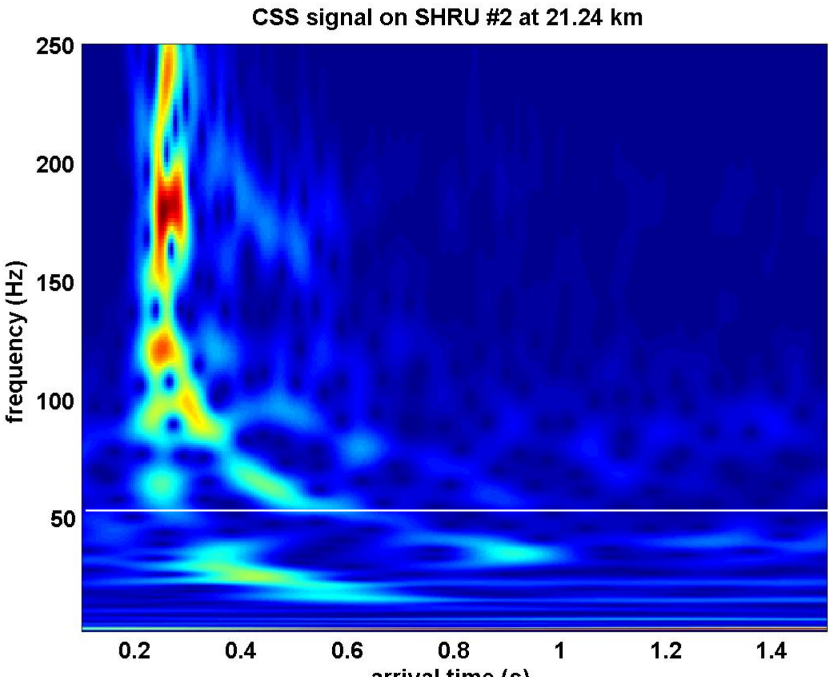
Sediments in top 15 m generally sandy interbedded with mud and shells.

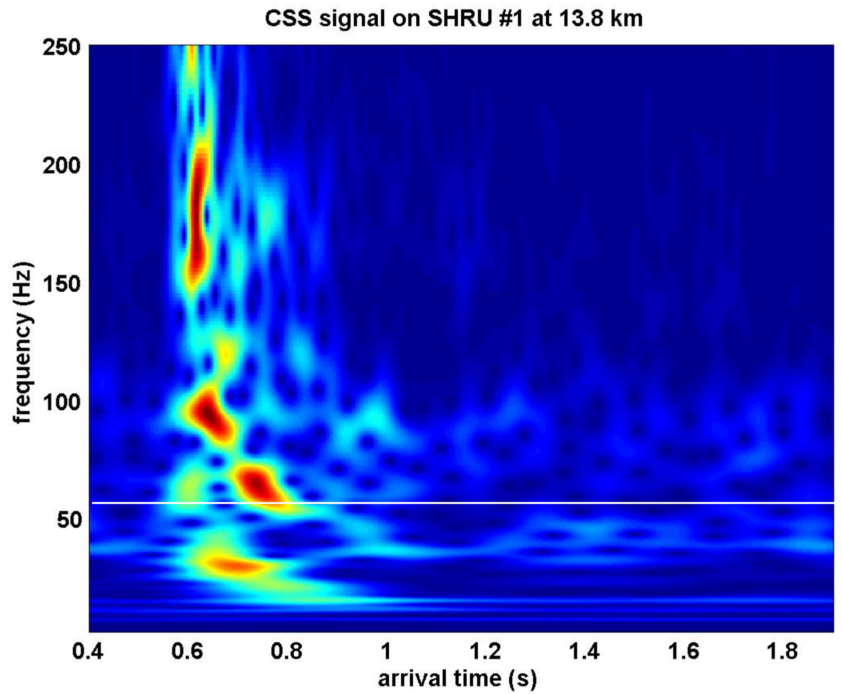
Inversion captures the trend in core data; but lower in magnitude

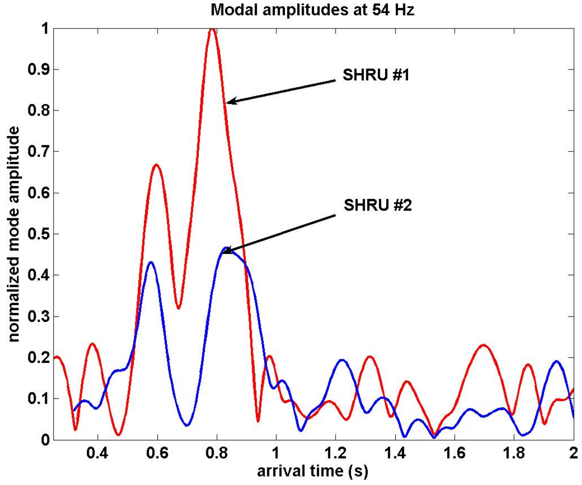
Resolution not sufficient to capture high-speed layers at 8 m and at 11 m.

Potty, Miller, Wilson, Lynch and Newhall, “Geoacoustic inversion using combustive sound source signals,” J. Acoust. Soc. Am., 124(3), 2008.

Modal Amplitude Ratios



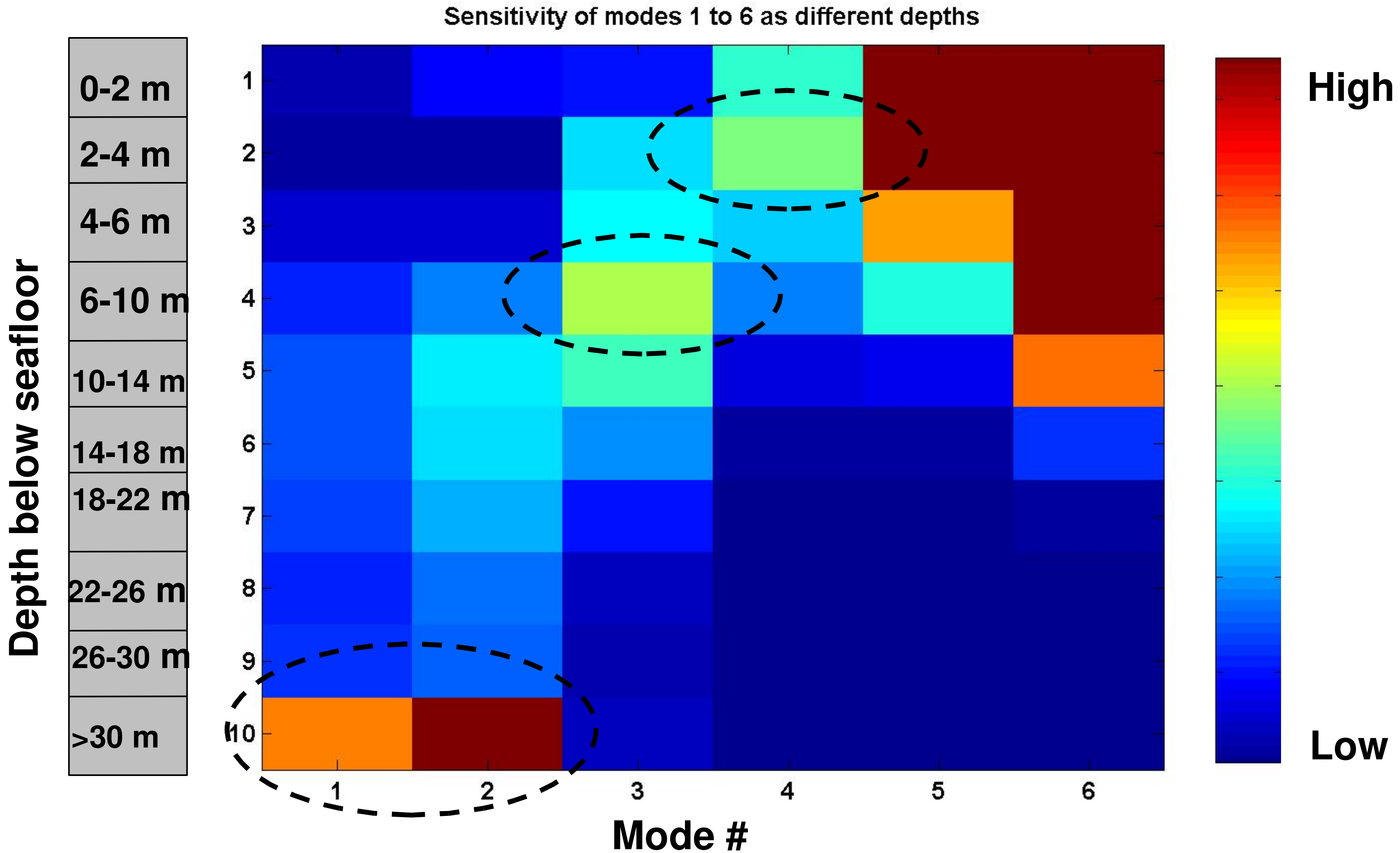




Mode 1 and 2 ratios in the frequency range 20 Hz to 80 Hz used for inversion

Inversion for attenuation using the dominant modes – modes 1 and 2

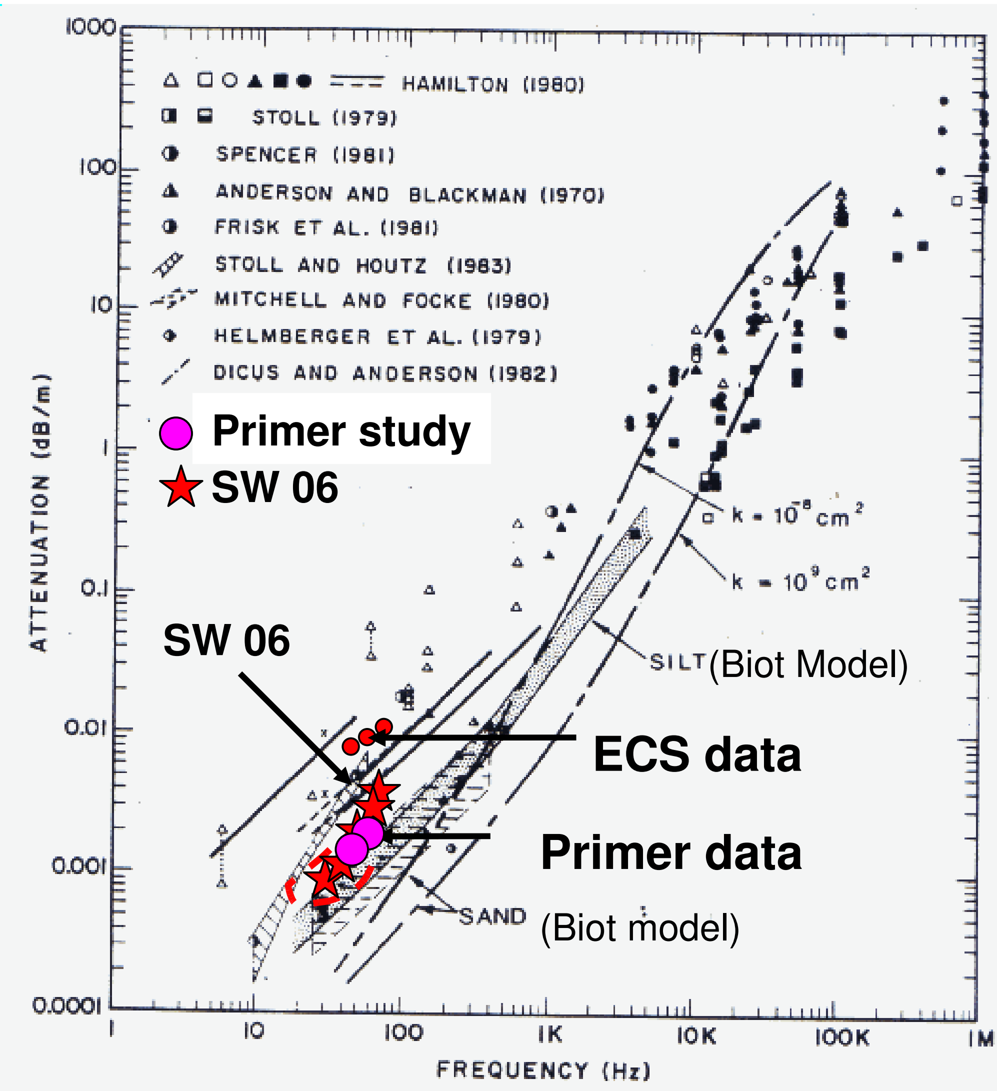
Relative Sensitivity of modes

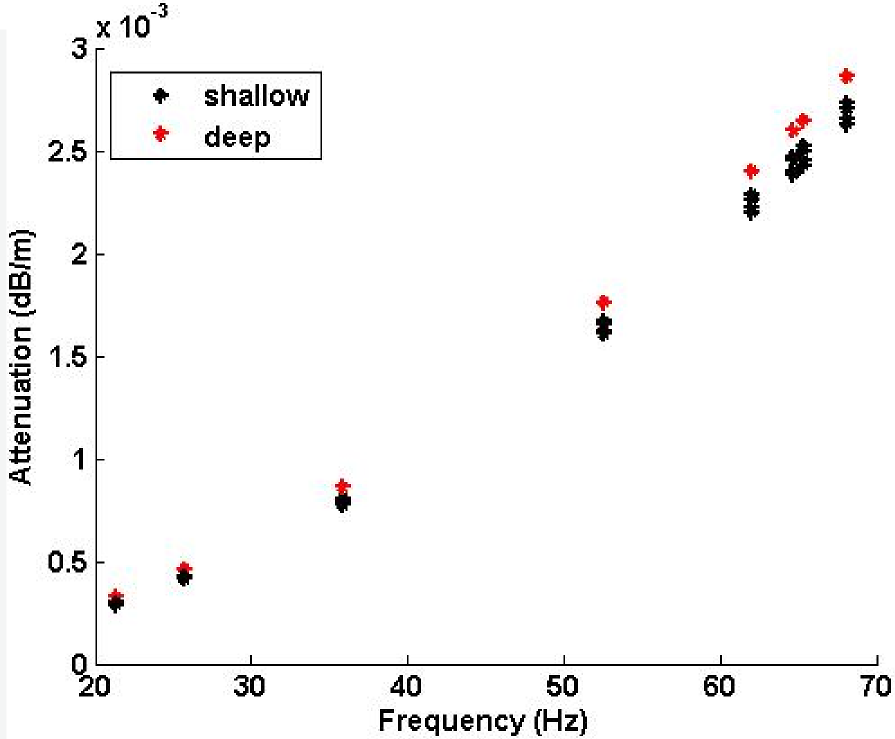


Attenuation Inversion Results
Mode 1 and 2

Freq. exponent ~ 1.86 (deep)
1.89 (shallow)

Published data – all types of sediments (Stoll- 85)



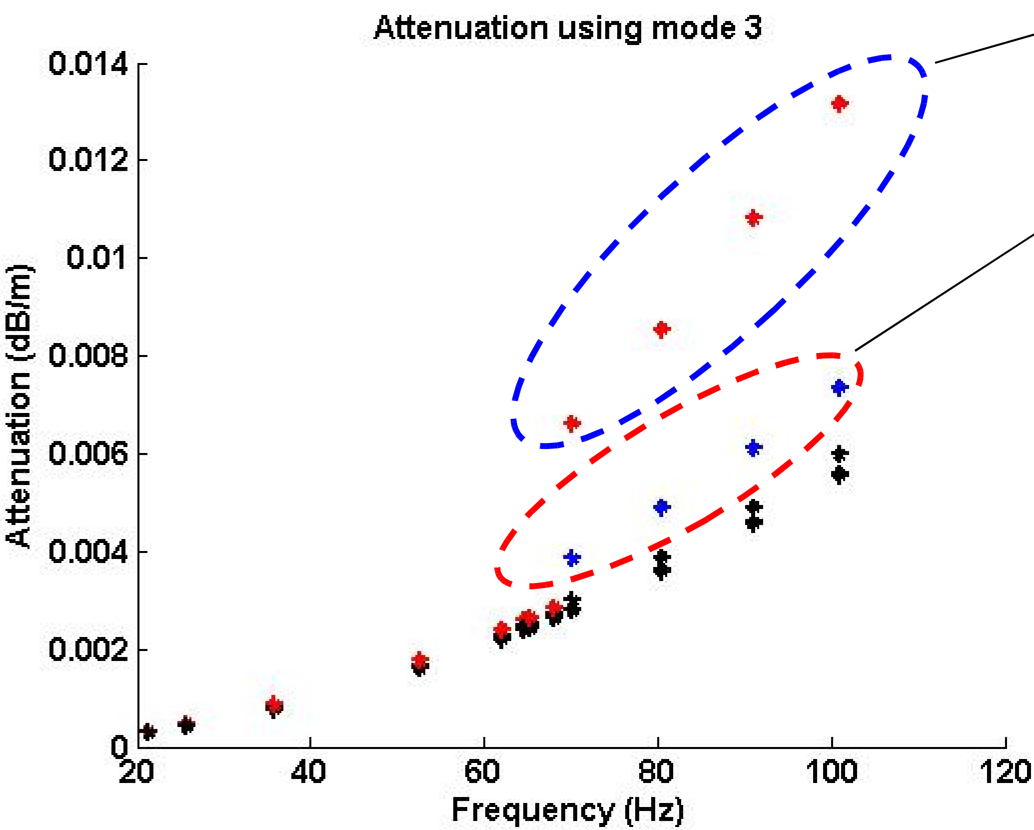


Inversions compare well with earlier (Primer) inversions

Frequency exponent agrees with Holmes et al. (JASA-EL;2007) value of 1.8 +/- 0.2

Attenuation Estimates – Mode 3

Different colors indicate attenuation at different depths
Mode 3 data at frequencies 70 to 100 Hz



Mode 1 and 2 strong > 30 m

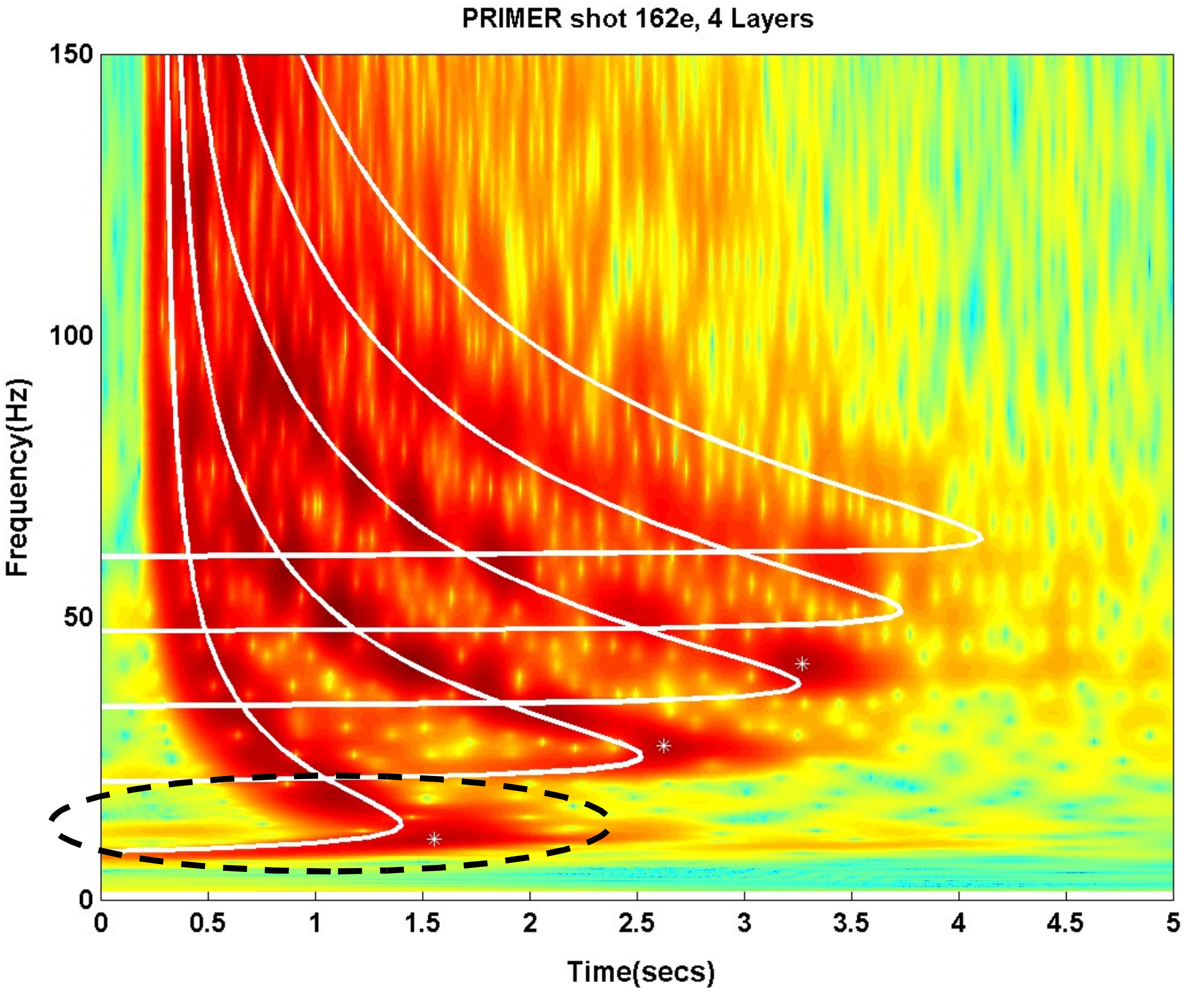
Mode 3 strong – 2 to 20 m

Deeper sediments (red) very different (depends on modes 1 and 2; mode 3 not very sensitive at this depth

Sediments at 2 to 20 m more reliable (mode 3 sensitive at this depth)

Future Work: Early arrivals

PRIMER



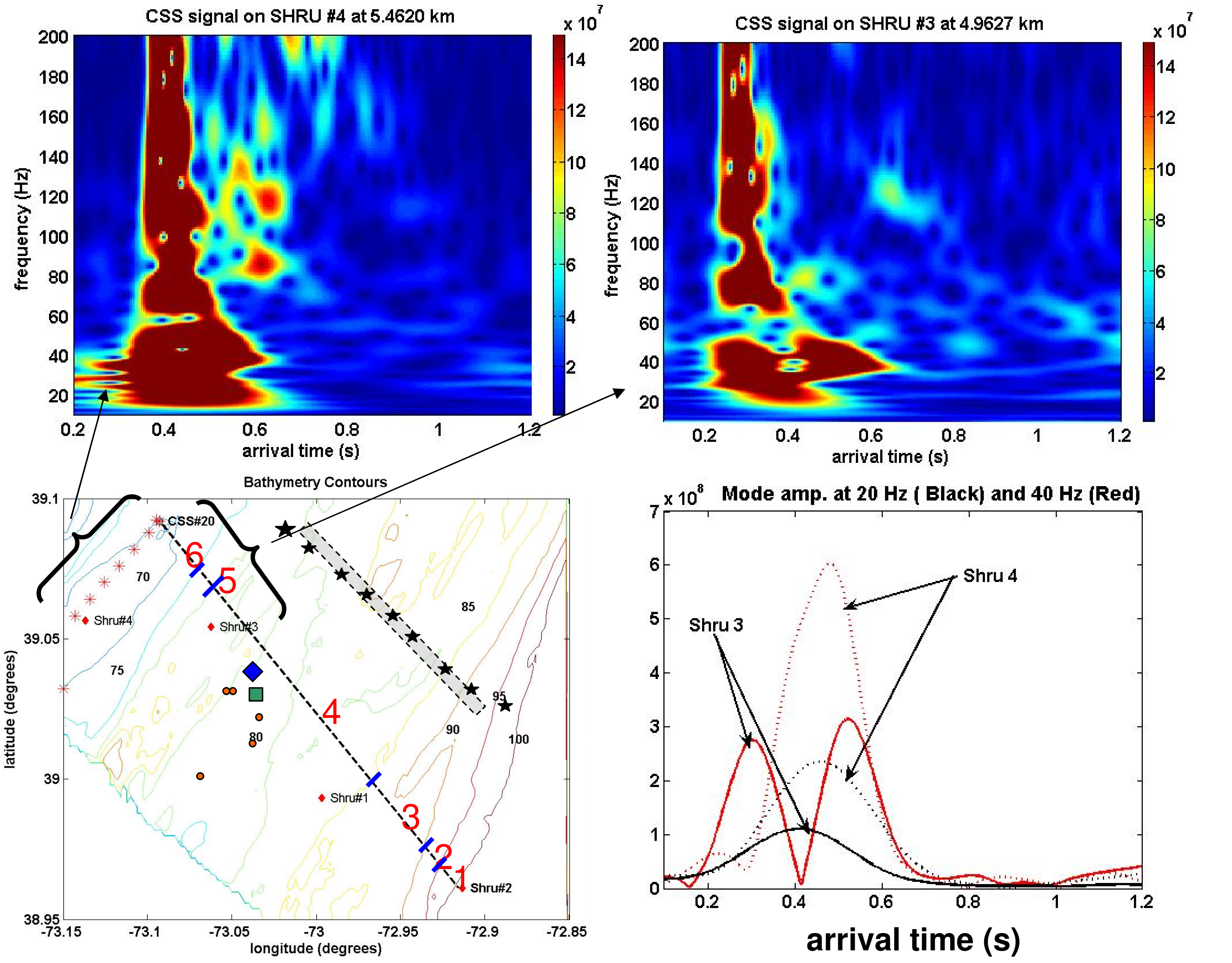
Multiple source-receiver combinations

Use early arrivals (Ground wave; Airy Phase) for the inversion of sediment geoacoustic properties (Shear ???)

Effect of shear wave conversion (Pierce/ Carey development)

Thanks !!!!!!!!!!!

Future Work : Multiple source-receiver combinations



$$f_L = \frac{c_2}{4H\sqrt{1-\frac{c_1^2}{c_2^2}}}$$

$c_1 = 1500\ \mathrm{m/s};\ \mathrm{c}_2 = 1700\ \mathrm{m/s}$

$\mathrm{H} = 100\ \mathrm{m}$

$f_L \approx 10\ \mathrm{Hz}$

Attenuation Inversion – Results
(Comparison with published data for Fine Grained sediments)

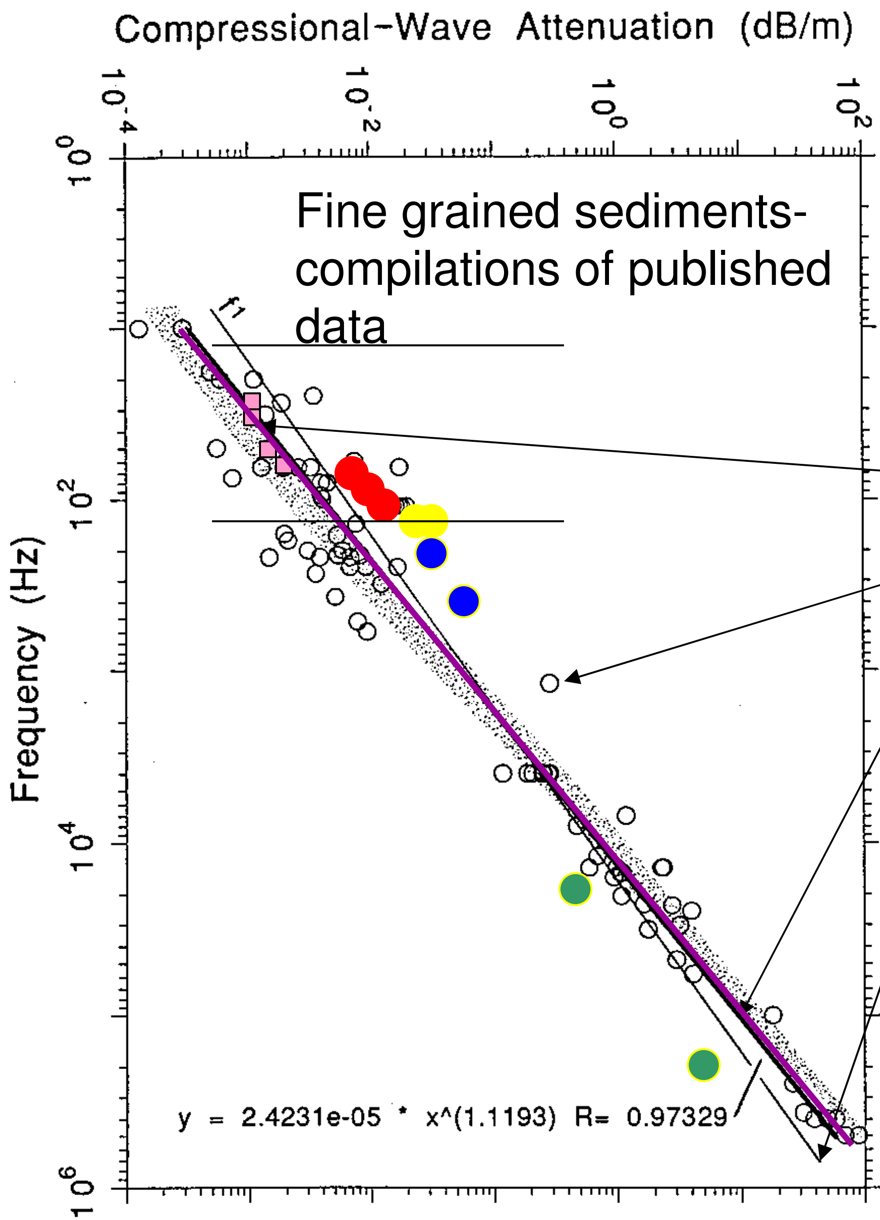


Figure in the background shows:

- **Primer data**
- **Published data for fine grained sediments– circles**
- **Heavy line- Power curve fit to the data [α (dB/m) =2.42 X 10^{-5} $f^{1.12}$]**
- **f^1 line –first power of frequency dependence**
- **Shaded area – range of attenuation values for silts and clays calculated from Biot- Stoll model**

From Bowles,"Observations on attenuations and shear wave velocity in fine grained marine sediments," JASA, 1997

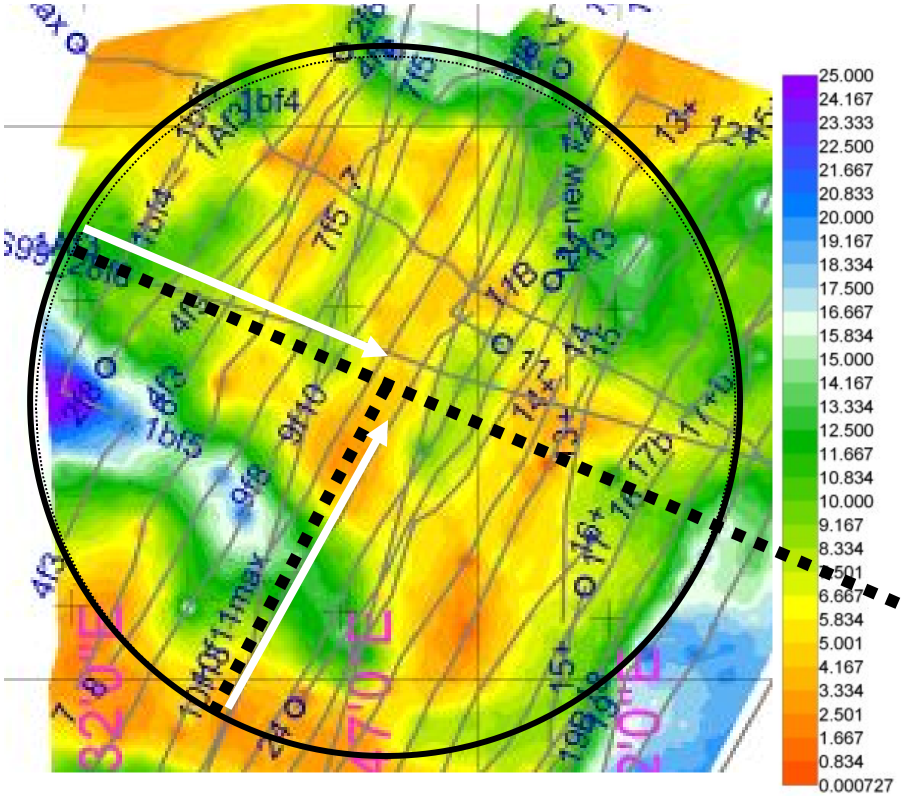
Modal Attenuation Coefficient

$$\beta_n = V_{ph,n} \frac{\int \frac{\alpha(\omega)}{\rho c} Z_n^2 dz}{\int \frac{Z_n^2}{\rho} dz}$$

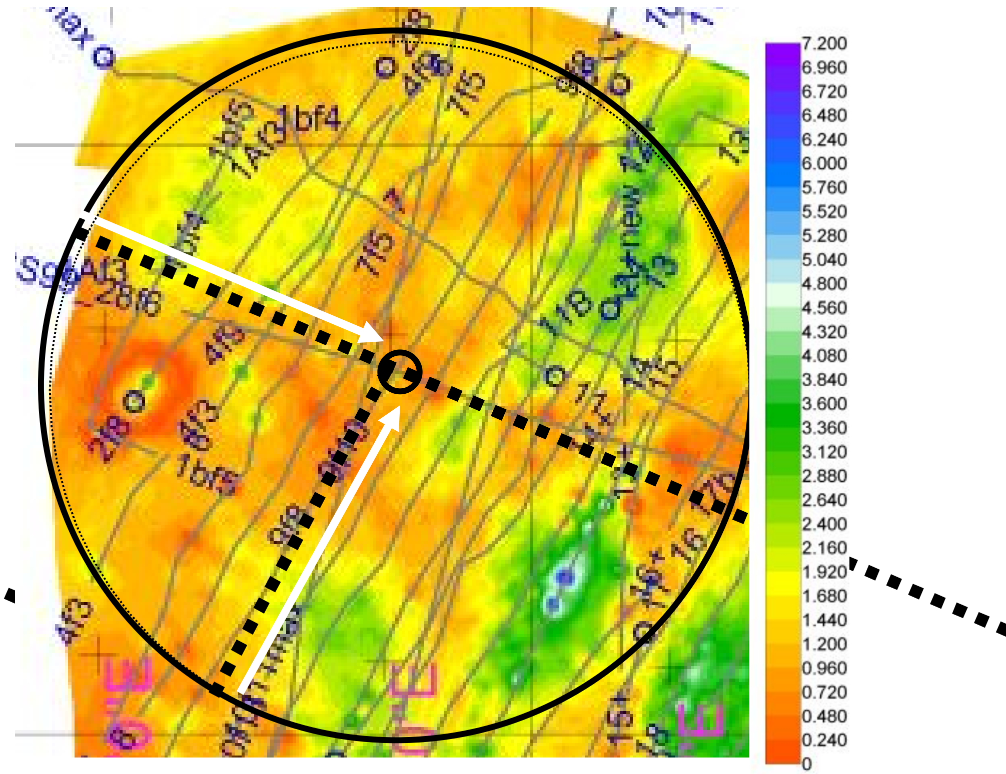
- For sandy sediments, with depth dependent sound speed, attenuation, density and porosity profiles, the measured attenuation will have a frequency dependence less than quadratic.

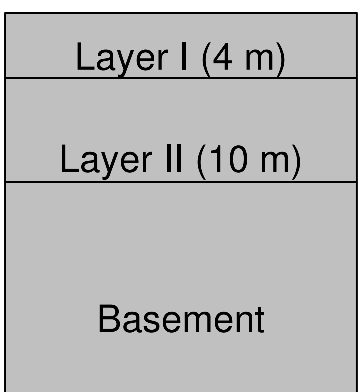
Sediment Variation in Depth – East China Sea

Thickness (m) of Sub-bottom Layer



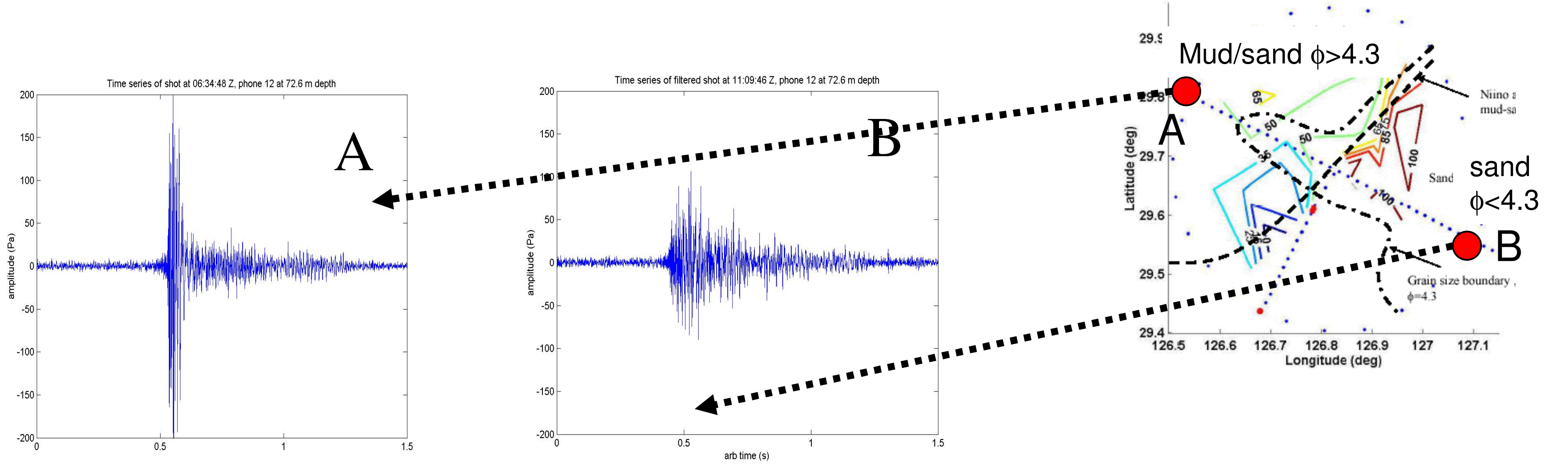
Thickness (m) of Surface Layer

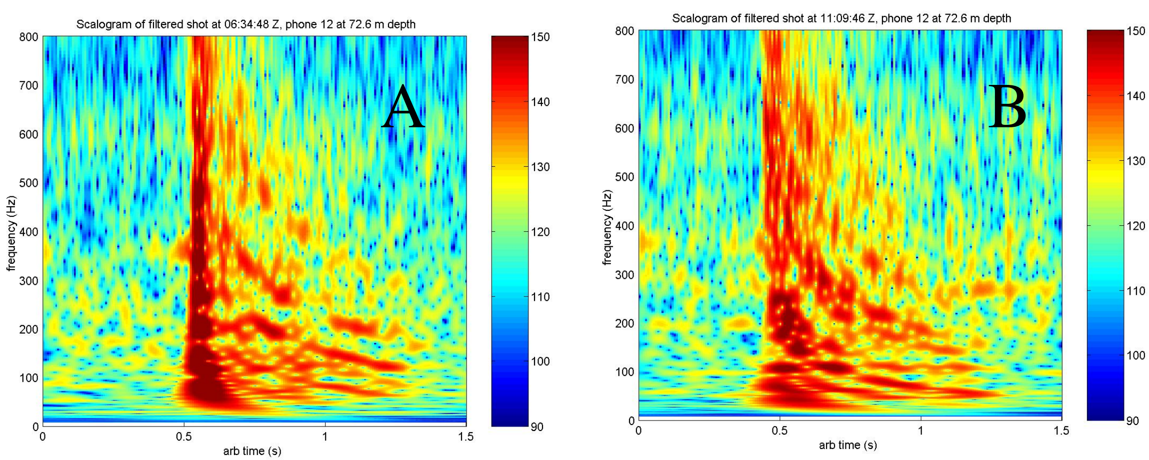




Attenuation in two layers (Layer I and II) and Basement are unknowns

Modal Dispersion - East China Sea





Receiver depth - 78.6 m

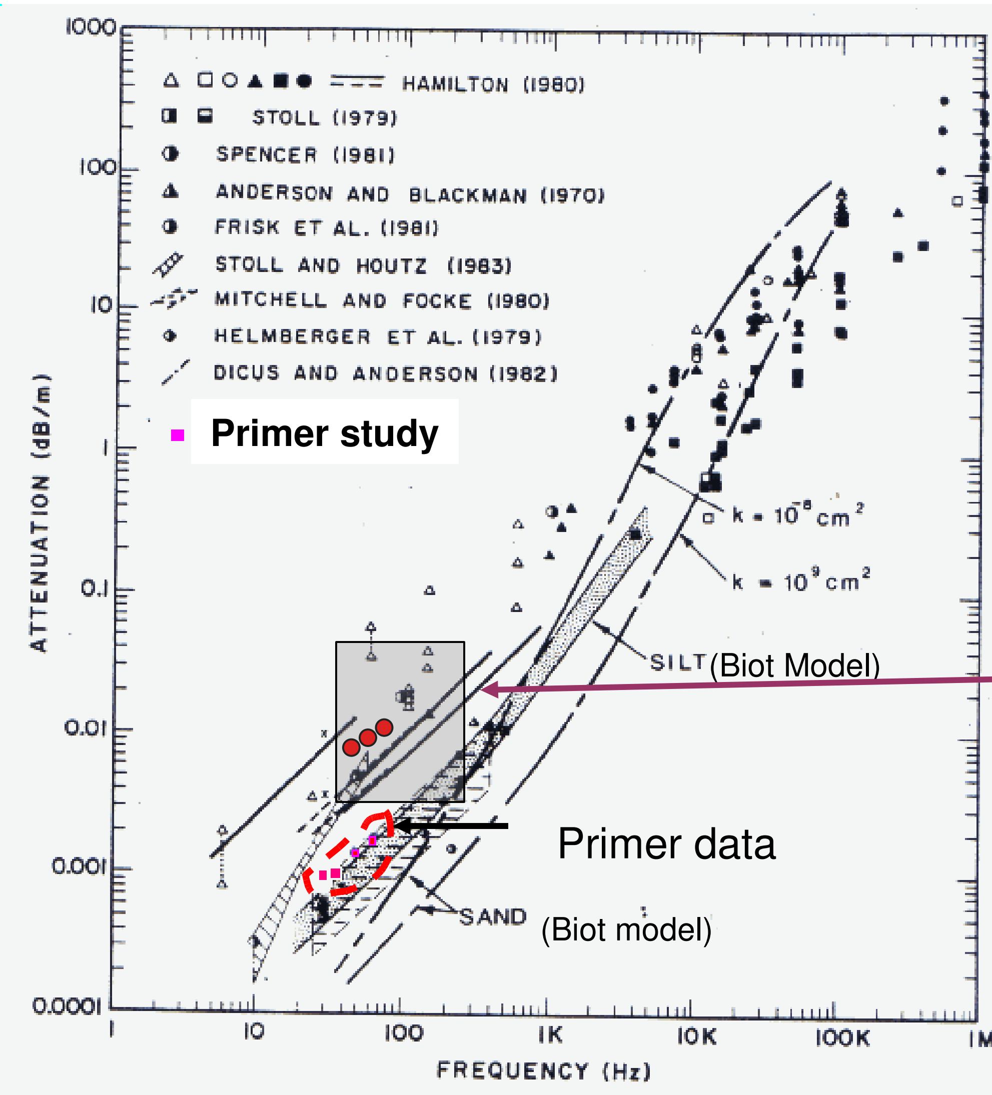
38 gm WBS charges at 50 m

Range- 30 km

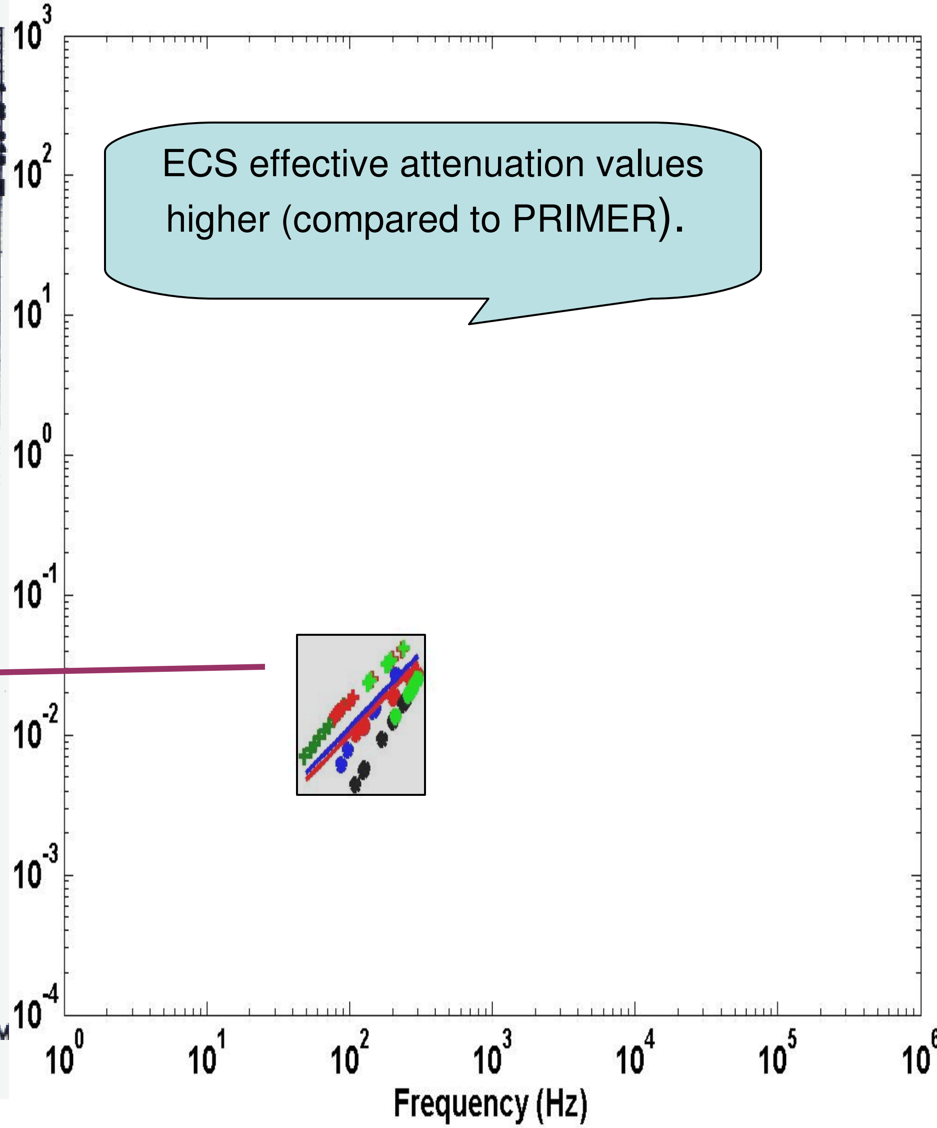
- **The initial arrival is stronger in Shot ‘A’ whereas the higher modes are more prominent in Shot ‘B’.**

Attenuation Inversion- Historic Data

Published data – all types of sediments (Stoll- 85)

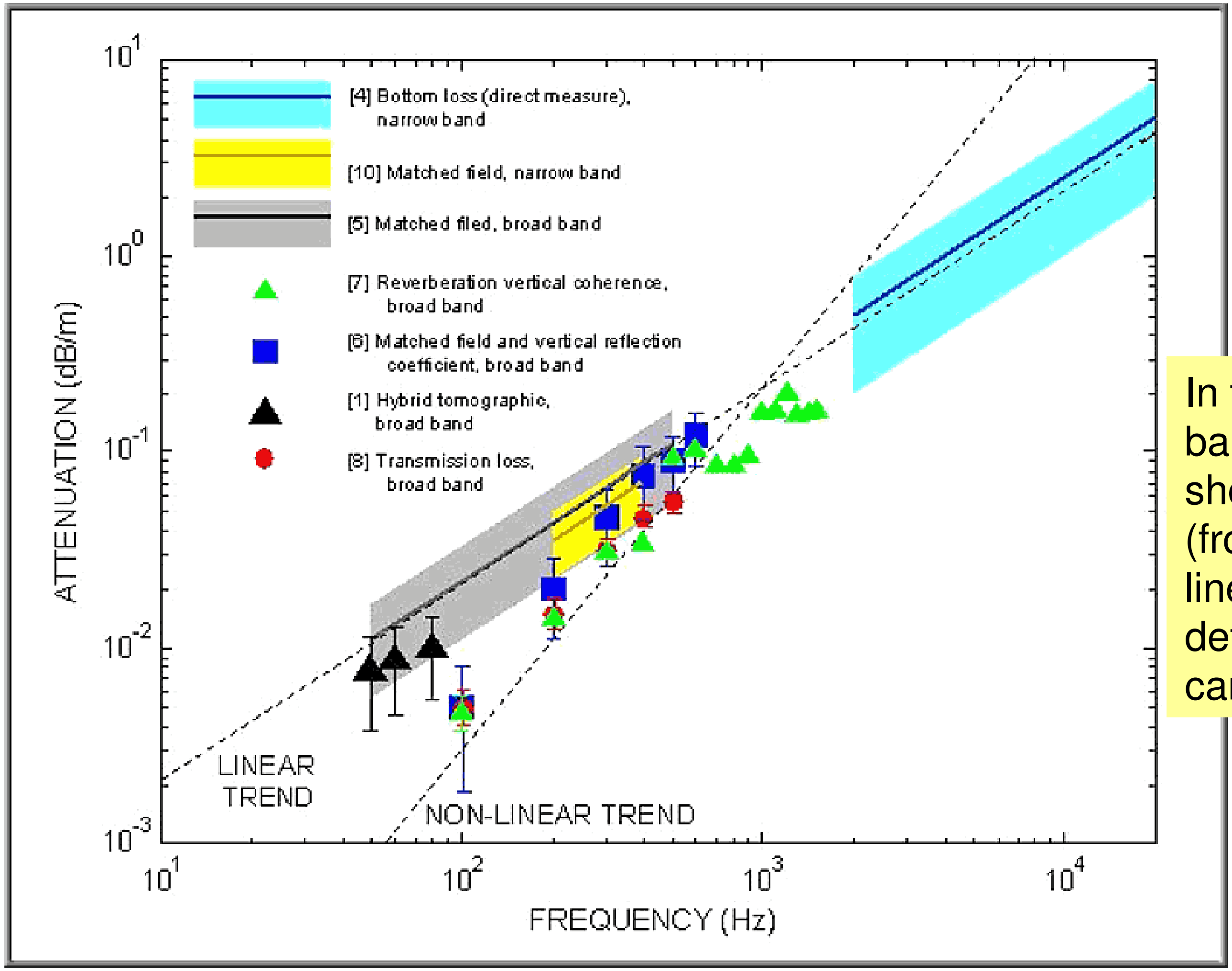


Inversion



[No depth variation in attenuation]

Attenuation Inversions at East China Sea

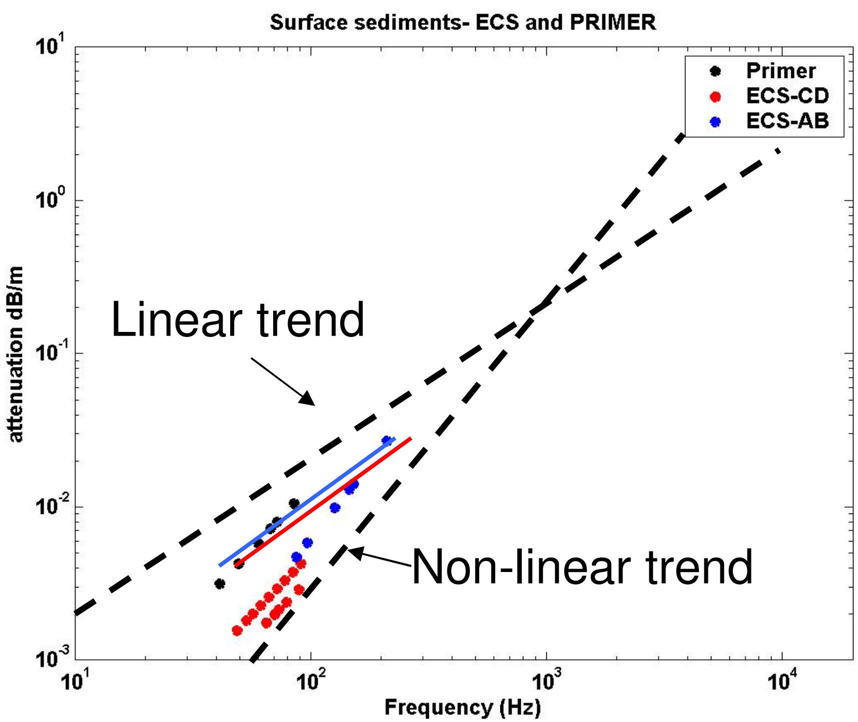


In the 40 – 200 Hz band inversions show wide scatter (from linear to non-linear trend). No definite conclusions can be drawn.

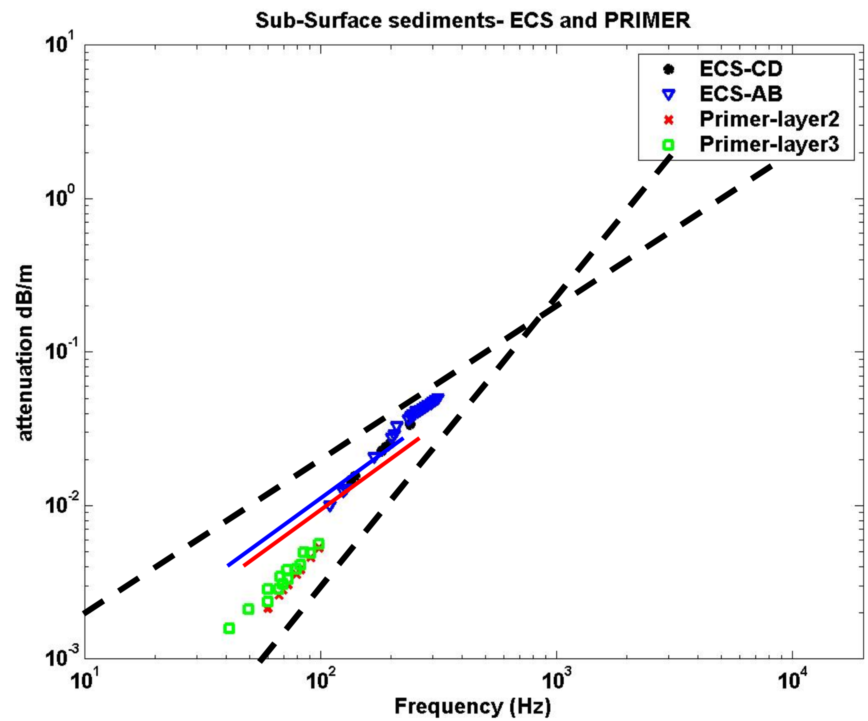
From: Dahl et al. ., "Overview of results from the Asian Seas International Acoustic Experiment in the East China Sea," IEEE J. of Oceanic. Eng., 29(4), 920-928, 2004

Surface and Sub-Surface Sediments – ECS and Primer

Buckingham Model for ECS AB (blue) and CD (red)



Surface sediments – ECS and PRIMER



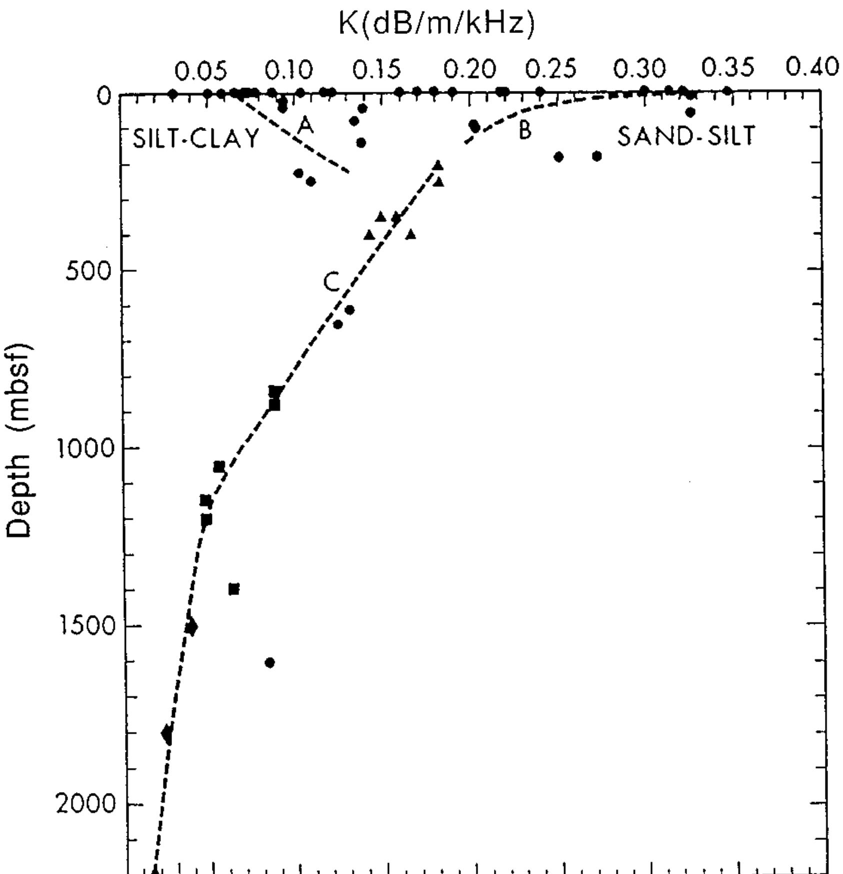
Sub-surface sediments – ECS and PRIMER

- East China Sea sediments in the Northwest side (ECS-AB) tend to resemble PRIMER surface sediments

- Sub-surface sediments: PRIMER tend towards non-linear trend whereas ECS tends towards linear (at different frequency bands)

Depth Variation of Attenuation

- There is a depth-pressure- effect on attenuation (important at lower frequencies).
- Attenuation *decreases* with pressure in sands and granular materials. This is attributed to decrease in inter-granular friction (Hamilton, JASA, 1976).
- Porosity reduction with depth dominates the variation of attenuation in clays with depth. Down to a certain depth the attenuation in clay *increases* with depth. Thereafter pressure effect becomes dominant and attenuation *decreases*.



Hamilton depth variation, as described above, has coarse grained bias (Bowles-JASA 1997).

Mitchell and Focke depth variation (JASA -1980) better choice for fine grained sediments