Seabed variability and uncertainty characterization

ONR Uncertainty DRI
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Research Objectives

1. Assess and characterize seabed variability
   {NJ STRATAFORM, Malta Plateau, North Tuscany Shelf}
   - How do critical seabed properties vary in space?
   - How does variability impact sonar performance (reflection/scattering)?

2. Characterize uncertainty associated with the critical seabed parameters
   - What is the best way to characterize and transfer uncertainty from acoustic observation $\Rightarrow$ geoacoustic properties $\Rightarrow$ prediction?
   - How is geoacoustic uncertainty best captured?

OUTLINE

Char. variability

1. Inter- and intra- regional geoacoustic variability study
2. Sedflux geoacoustic prediction test (w/ Goff, Kraft, Overeem, Pratson, Syvitski)

Char/transfer uncertainty

3. Measurement Uncertainty of Seabed Reflection
4. Geoacoustic Uncertainty (w/ Dosso)
5. Signal-to-Reverb Uncertainty (w/ Harrison)
6. New technique for measuring sediment velocity dispersion

Intra- and Inter-Regional Variability

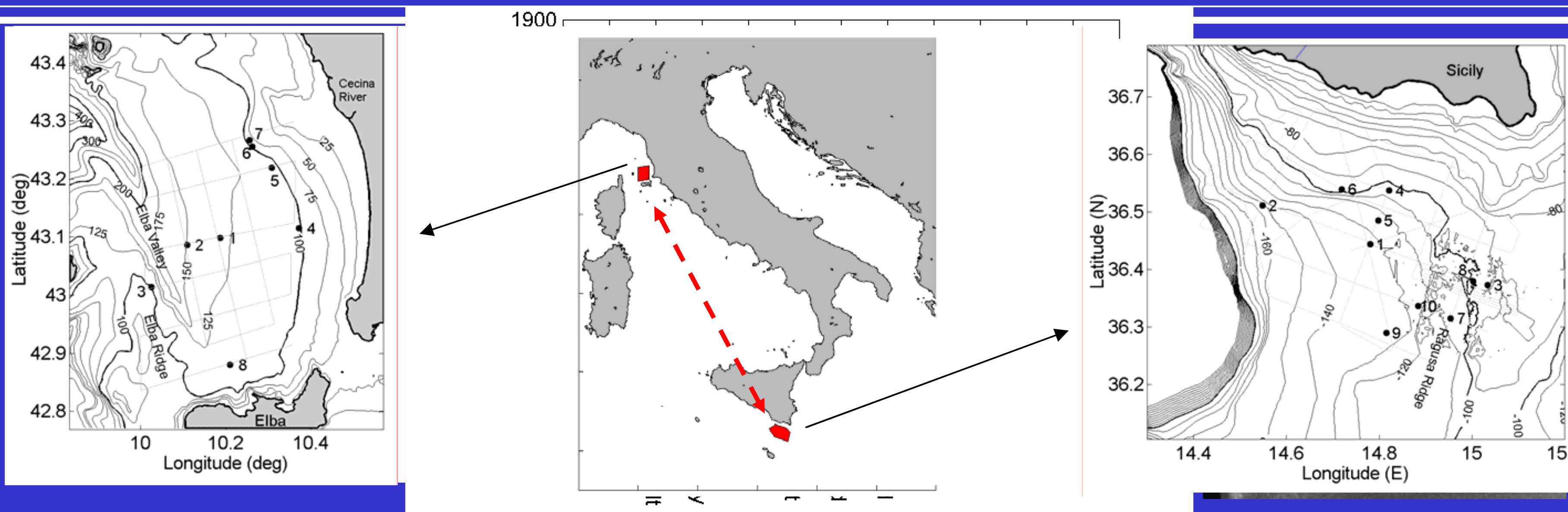
Background:

- Most geoacoustic observations are at points (1D) or lines (2D).
- Geoacoustic data is sparse.

Basic Research Issues:

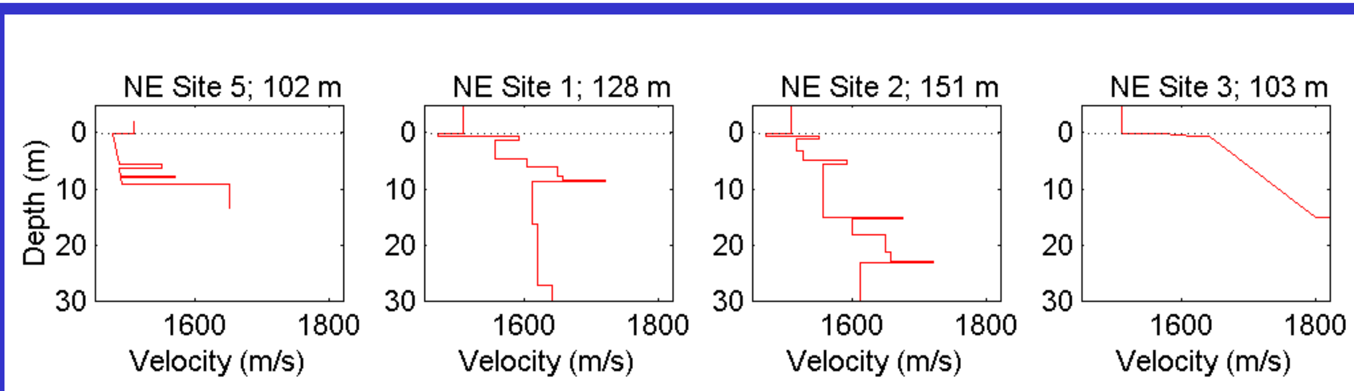
- How do geoacoustic properties vary meters - km from the measurement point? (intra-regional variability)
- Can geoacoustic properties be extrapolated O(100-1000 km) from measurement point? (inter-regional variability)

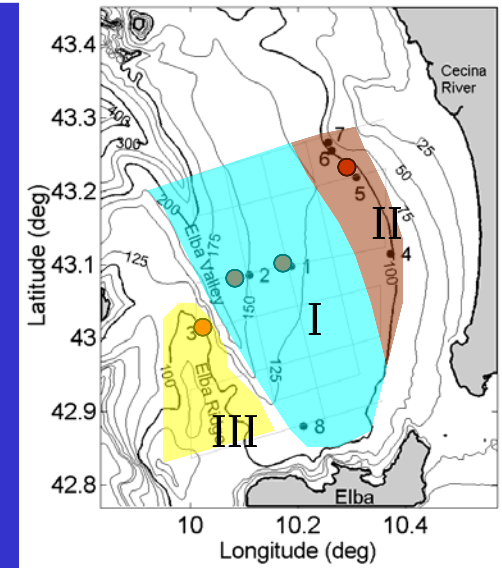
Approach



1. Analyze acoustic/G&G data in 2 distinct littoral regions
   - Reflection,scattering, TL, Reverb experiments (400 – 8000 Hz)
   - Core, seismic reflection, multibeam bathymetry, oceanographic, seabed photo.
2. Analyze variability within each region (define discrete scales)
   - Geoacoustic regimes O(1-10)km; same physical mechanisms,continuous variability
   - Sedimentary classes - distinct sedimentary units, layer geoacoustic properties
   - Seabed features – O(1-100)m discrete geologic entities that may produce clutter
3. Compare variability from region-to-region

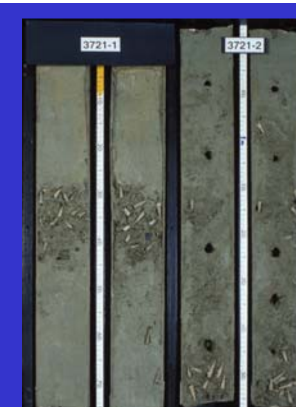
NE Geoacoustic Regimes





Regime I. Fine-scale layering

- Silty-clay host, random, thin shelly sand intercalating layers
- Variability is “continuous”; and produces modest acoustic variability
- Western boundary defined by Elba Ridge; eastern boundary not abrupt



Regime II. Thick silty clay over coarse sediment/rock

- 110-75 m contour, NE sector
- Acoustic response dominated by basement

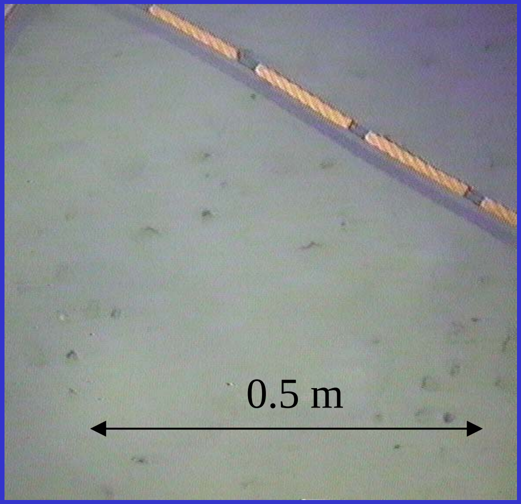
Regime III. Sand with rock outcrops

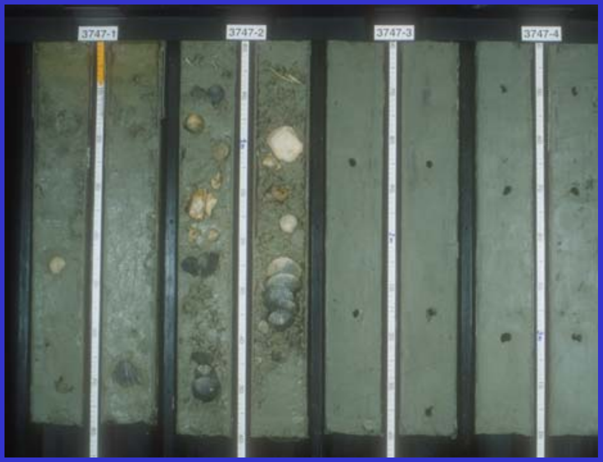
- Acoustic response is governed by sand properties and at higher freqs thin silty-sand layer
- Little is known about variability in this regime

NE Sedimentary Classes

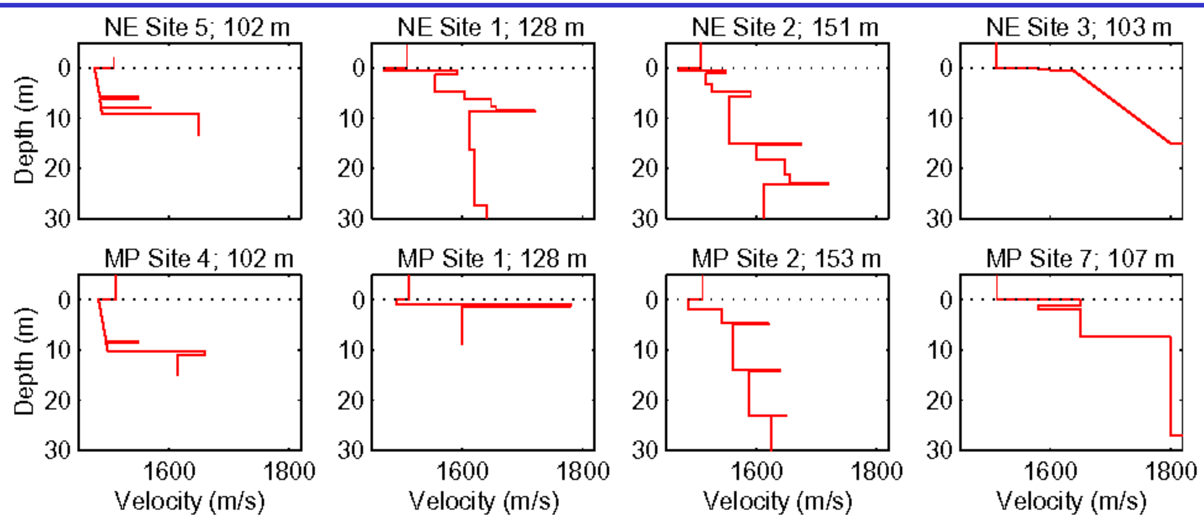
	Velocity (m/s)	Vel grad (s^{-1})	Density (g/cm^3)	Den grad ($g/cm^3/m$)	Attenuation (dB/m/kHz)
Silty-clay	1475± 3	1.5 +	1.32±0.04	0.1	0.01
Mud	1500± 15	5, β=-0.9	1.5	via vel.	0.015
Sand	1640	10	1.8	--	0.3
Shelly sand	1650±100	--	1.9±0.2	--	0.1
sandstone	v_s:1600±20	--	--	--	--

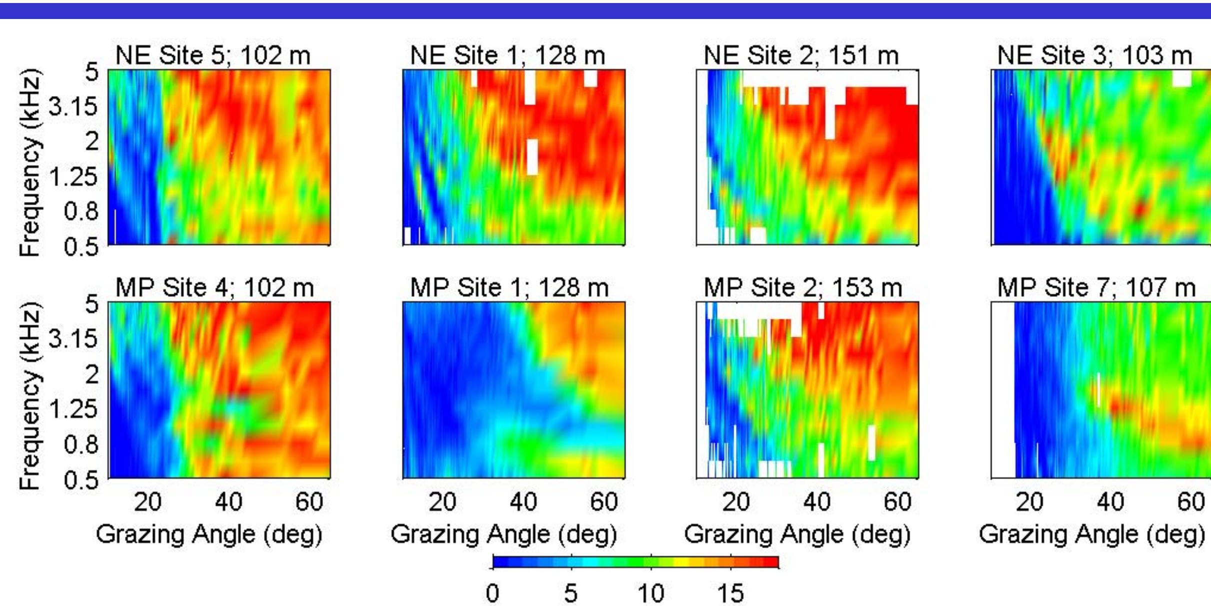
Velocity Variability is 80% of worldwide estimate (Hamilton)
Density variability is 90% of worldwide estimate (Hamilton)
Attenuation variability is 30% of worldwide estimate (Hamilton)



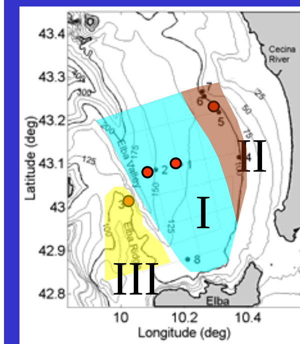


Inter-regional Comparison

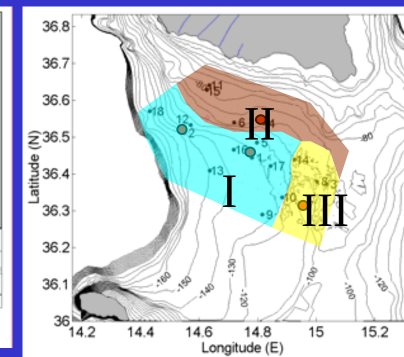




NE



MP



Strong inter-regional similarities

- Regime I, II, III
- Spatial extent,acoustic response

Inter-regional Differences

- Site 1 (prob feature)
- Site 7 weak Vp gradient

Regional Variability Summary

Holland, C.W., Intra and inter-regional geoacoustic variability in the littoral, in Impact of Littoral Environmental Variability on Acoustic Predictions and Sonar Performance, Lerici, Italy ed. by N. Pace and F. Jensen, 2002

1. Significant geoacoustic variability exists within a region

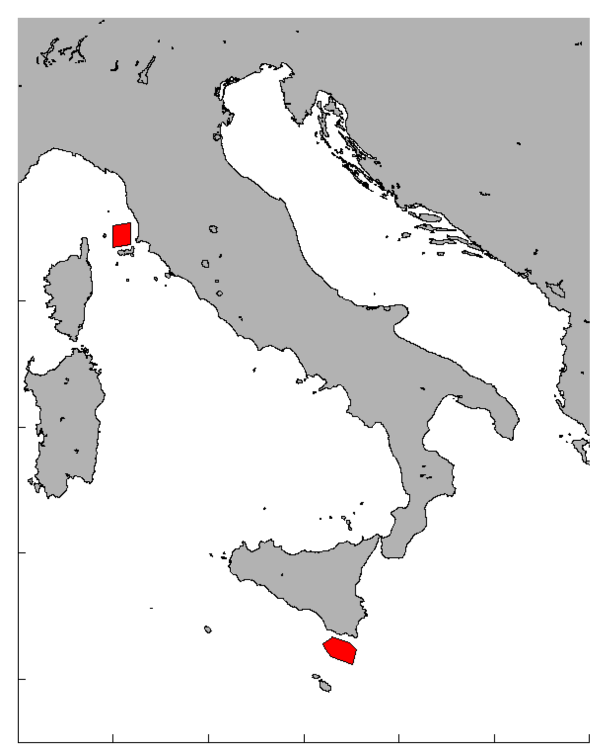
   Velocity variability of NE / MP 80% / 85%

   Density variability of NE / MP 90% / 90% of worldwide variability

2. Geoacoustic variability can have
   - modest impact on seabed reflection/scattering (e.g., Regime I)
   - significant impact on seabed reflection/scattering (e.g., Regimes II,III)

3. Remarkably strong similarities exist between two regions 800 km apart
   - geoacoustic regimes (same 3 represented AND at similar water depths)
   - sediment classes (very similar classes and geoacoustic properties)
   - range of geoacoustic variability

Burning Questions



Why are the two regions so similar?

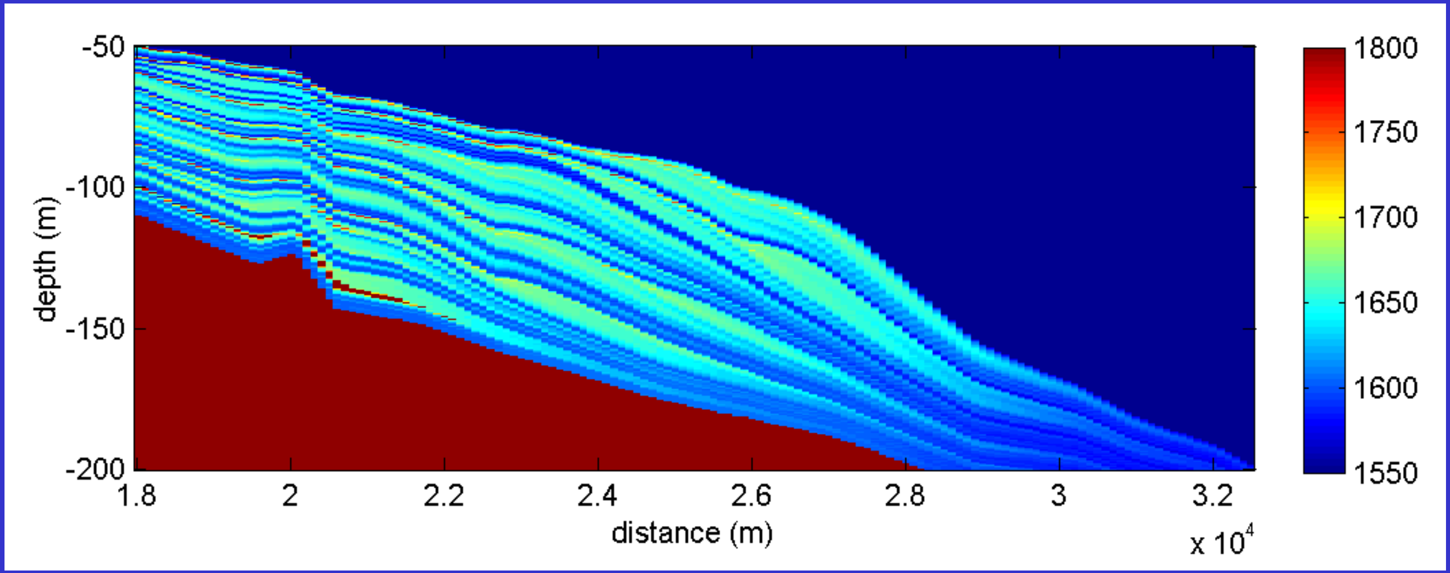
Are the similarities predictable?

- If so at what level? Regimes, classes…
- If not what theory/inputs are lacking?

Are such similarities expected in other regions of Italian littoral?

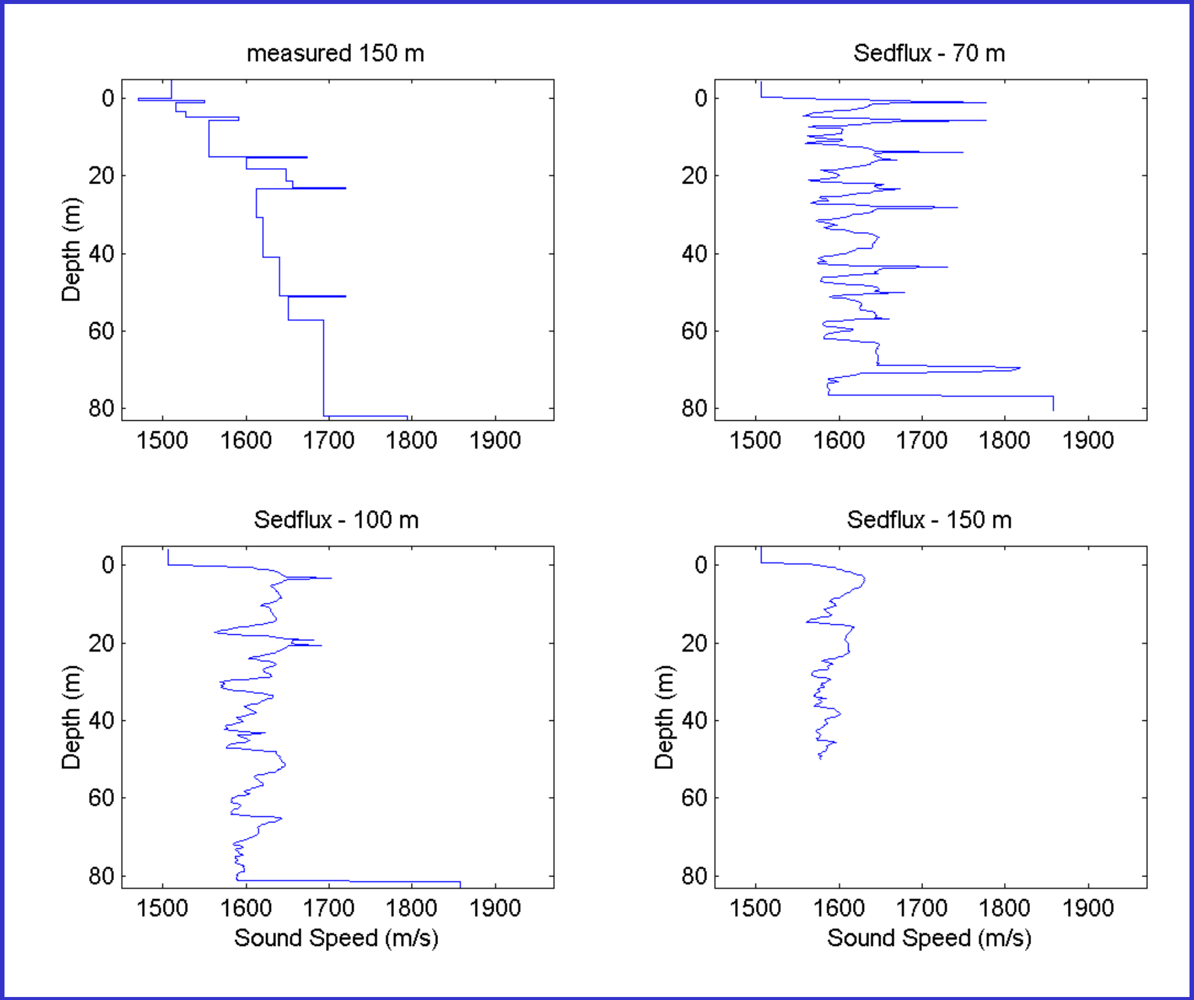
Geologic models (e.g., Sedflux) coupled with the geoacoustic observations provide the framework for addressing these crucial extrapolation issues

Sedflux Modeling on MP



Sedflux helps identify processes that control geoacoustics; geologic/geoacoustic observations constrain model inputs and may indicate missing processes

Observed vs Predicted layering



- Sedflux results help confirm that the intercalating layers are due to eustatic fluctuations
- Eustatic fluctuations could explain similarities between widely separated North Tuscany Shelf and the Malta Plateau
- Further work on model inputs will help refine the scales and depth dependence of the layering

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Reflection Measurement Uncertainty

Holland, C.W., Seabed reflection measurement uncertainty, J. Acoust. Soc. Am., 114, 1861-1873, 2003.

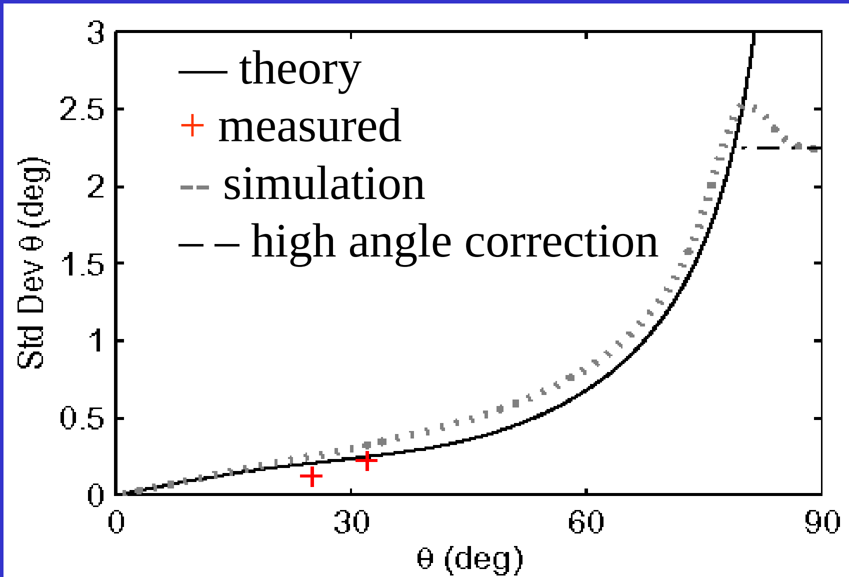
Amplitude and angular uncertainty equations were derived based on fundamental geometry and environmental uncertainties.

This predictive model give a good estimate of reflection uncertainties based on measurement repeatability experiments

Typical uncertainties are

- ±0.5-1.5 dB; which can be reduced by angle averaging
- ± 0.1-0.3° from 0-45° grazing angle

Knowledge of measurement uncertainties are crucial for predicting derived uncertainties, i.e., geoacoustic properties



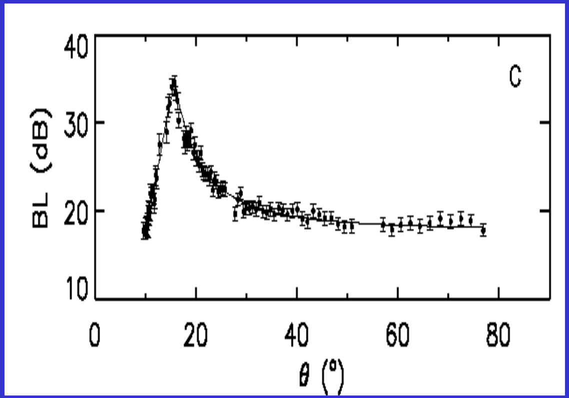
Transferring uncertainty in *R* to geoacoustic uncertainty

Dosso, S. E. and Holland, C.W., Geoacoustic uncertainties from inversion of seabed reflection data, J. Acoust. Soc. of Am. (in review).

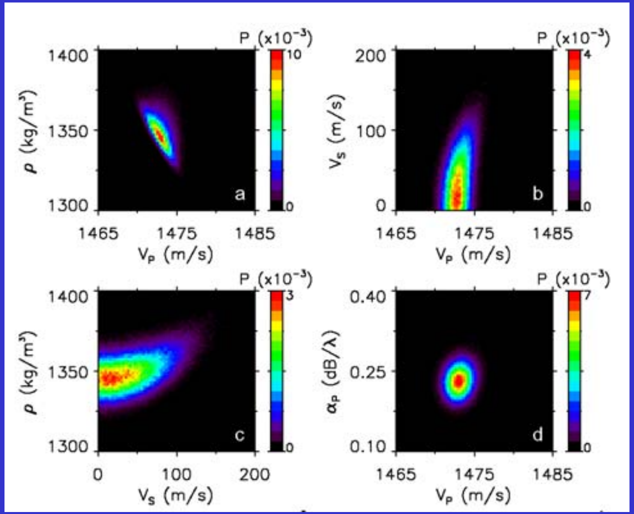
Bayes theorem provides a fully non-linear approach to geoacoustic parameter and uncertainty estimation

The uncertainties associated with the inverse problem are characterized by its posterior probability density

Measured Data and Fits



Joint Marginal Prob Distributions



Maximum a posteriori statistics

c_p = 1474 ± 3 m/s

α_p = 0.28 ± 0.03 dB/λ

ρ = 1.36 ± 0.02 g/cm^3

c_s = 5 ± 100 m/s

α_s = 1.9 ± 3 dB/λ

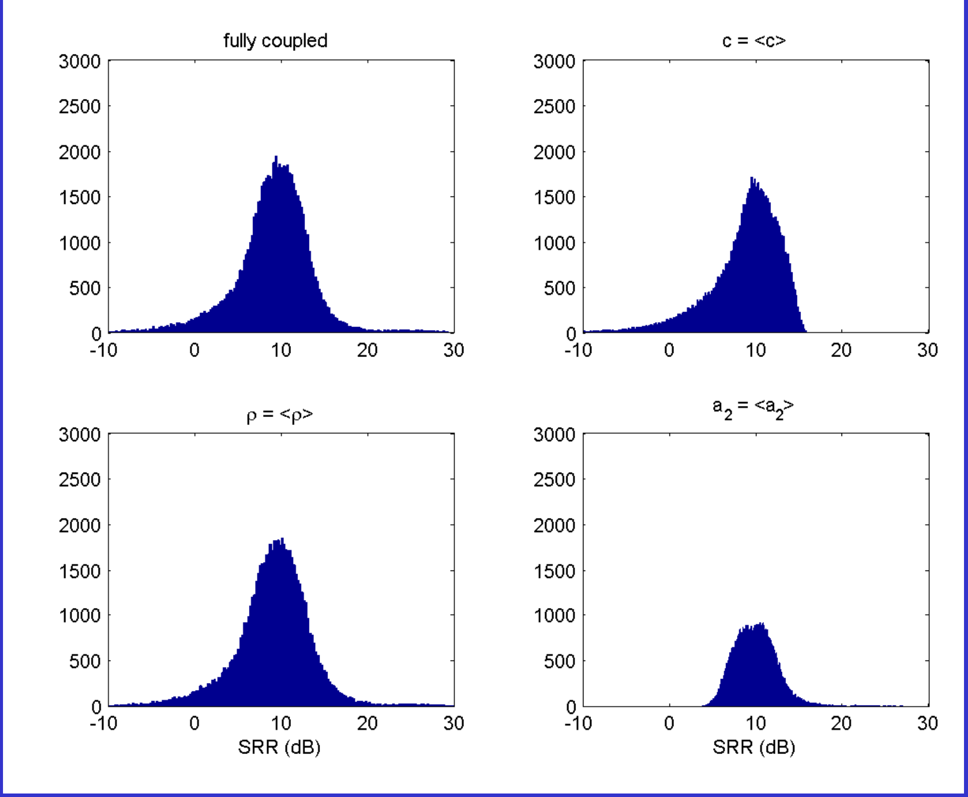
1. Uncertainty dominated by measurement uncertainty not theory error
2. Fine-grained sediments have smaller uncertainties (~2x) than coarse grained

Geoacoustic Uncertainty to Signal to Reverberation Ratio (SRR)

For Pekeris waveguide, r>3 km; Lambert

$$\mathrm{SRR} \cong 4 \frac{S_T \pi \alpha}{H \mu \Phi c t_p}$$

Weston/ Harrison



$10 \log(S_T) = 5$ dB (target strength)

$10 \log(\mu) = -27$ dB (Lambert coeff)

H= 100m (water depth)

$\Phi = 2°$ (beam width)

$t_p = 50$ ms (pulse length)

$$\alpha = \frac{\rho_2}{\rho_1} \frac{\beta^2}{\arccos^3(\beta)} \frac{a_2}{20\pi \log_{10}(e)}; \quad \beta = \frac{c_1}{c_2}$$

$\rho_2\, c_2\, a_2$ from PPD

Attenuation (a_2) uncertainty dominates SRR uncertainty for this PPD

Velocity Dispersion

Background:

The velocity in marine sediments is often considered to be independent of frequency

- geoacoustic databases
- frequency extrapolation from core or in-situ probe measurements

Uncertainty in acoustic predictions occurs if intrinsic sediment velocity dispersion is present.

Basic Research Issue:

Is velocity dispersion important in unconsolidated marine sediments; if so under what conditions ?

validate theoretical model
validate primitive parameters

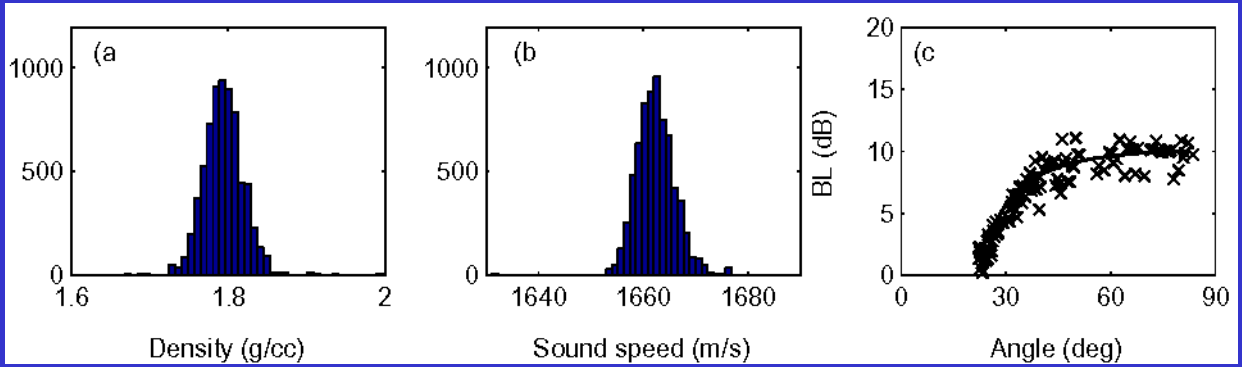
Direct Observation

Dispersion Results

Holland, C.W. Dosso, S.E., and Dettmer, J., A technique for measuring in-situ compressional wave velocity dispersion in marine sediments, IEEE J. Oceanic Eng., in review

1. Conducted analyses at two sandy locations
   - NJ STRATAFORM site AMCOR 6010
   - Strait of Sicily – Ragusa Ridge

2. Velocity uncertainties were typically ± 5 m/s at 1 standard deviation. Expected velocity dispersion (Biot theory) was O(100) m/s.



3. No significant velocity dispersion was observed at either site from 100 – 10,000 Hz

Summary

1. Assessed and characterized seabed variability
   - Quantified (enormous) geoacoustic variability within 3 regions
   - Discovered surprising similarities between widely separated regions
   - Early geologic modeling results indicate at least 1 process that explains similarities

Remaining Question: What role can/will geologic process models play in geoacoustic characterization

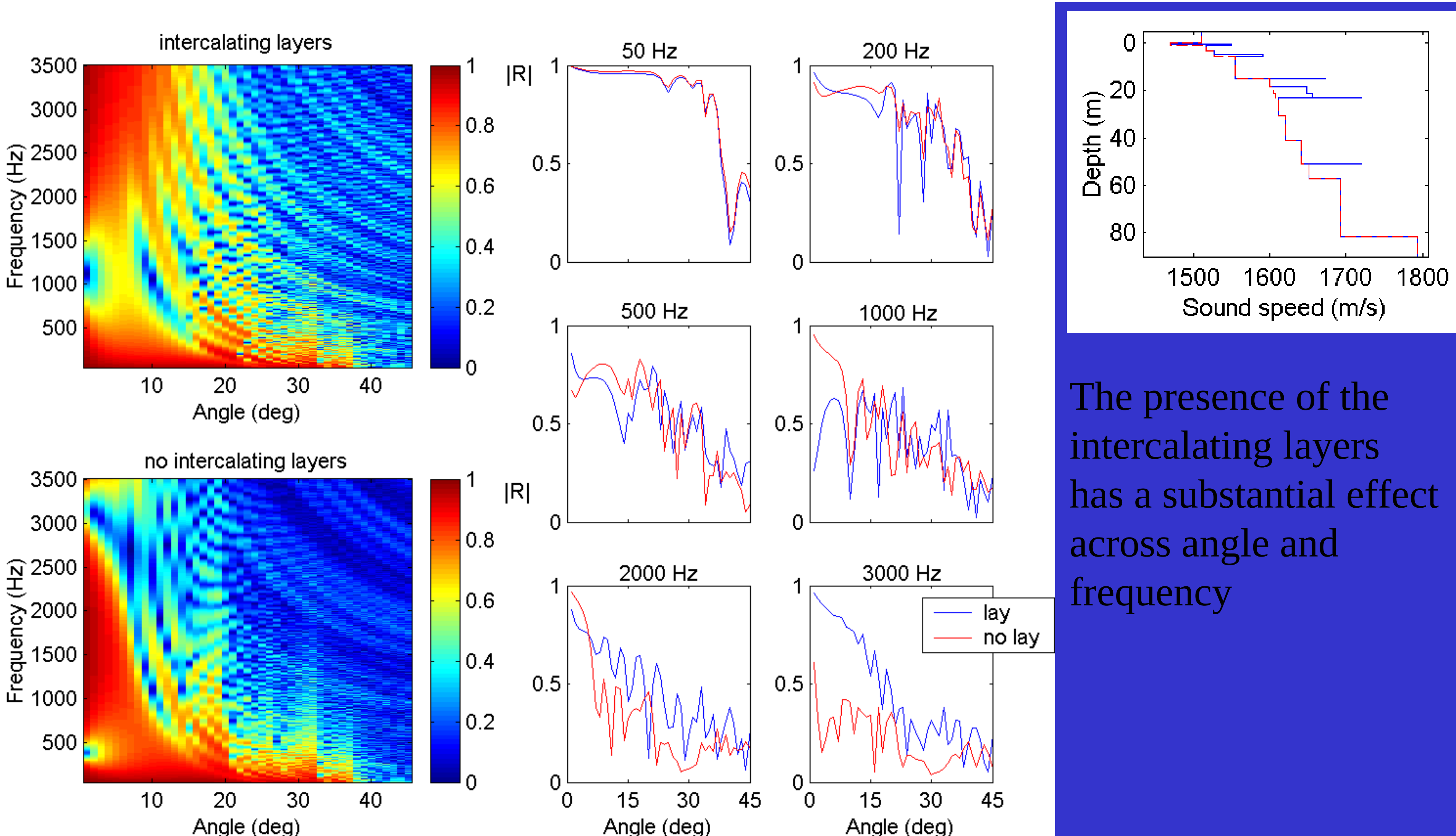
2. Characterized and transferred seabed uncertainty
   - Transferred measurement uncertainty to geoacoustic uncertainty using Bayesian approach. Geoacoustic uncertainty char. as fully-coupled PDF.
   - Demonstrated how geoacoustic uncertainty affects signal-to-reverb ratio
   - Developed method for quantifying effects of sediment velocity dispersion

Remaining Questions:

Char/transfer of uncertainty for arbitrary layered seabed

How do dispersion results vary spatially? e.g., within 10^{3-5} m

Effect of Layering



The presence of the intercalating layers has a substantial effect across angle and frequency

Summary

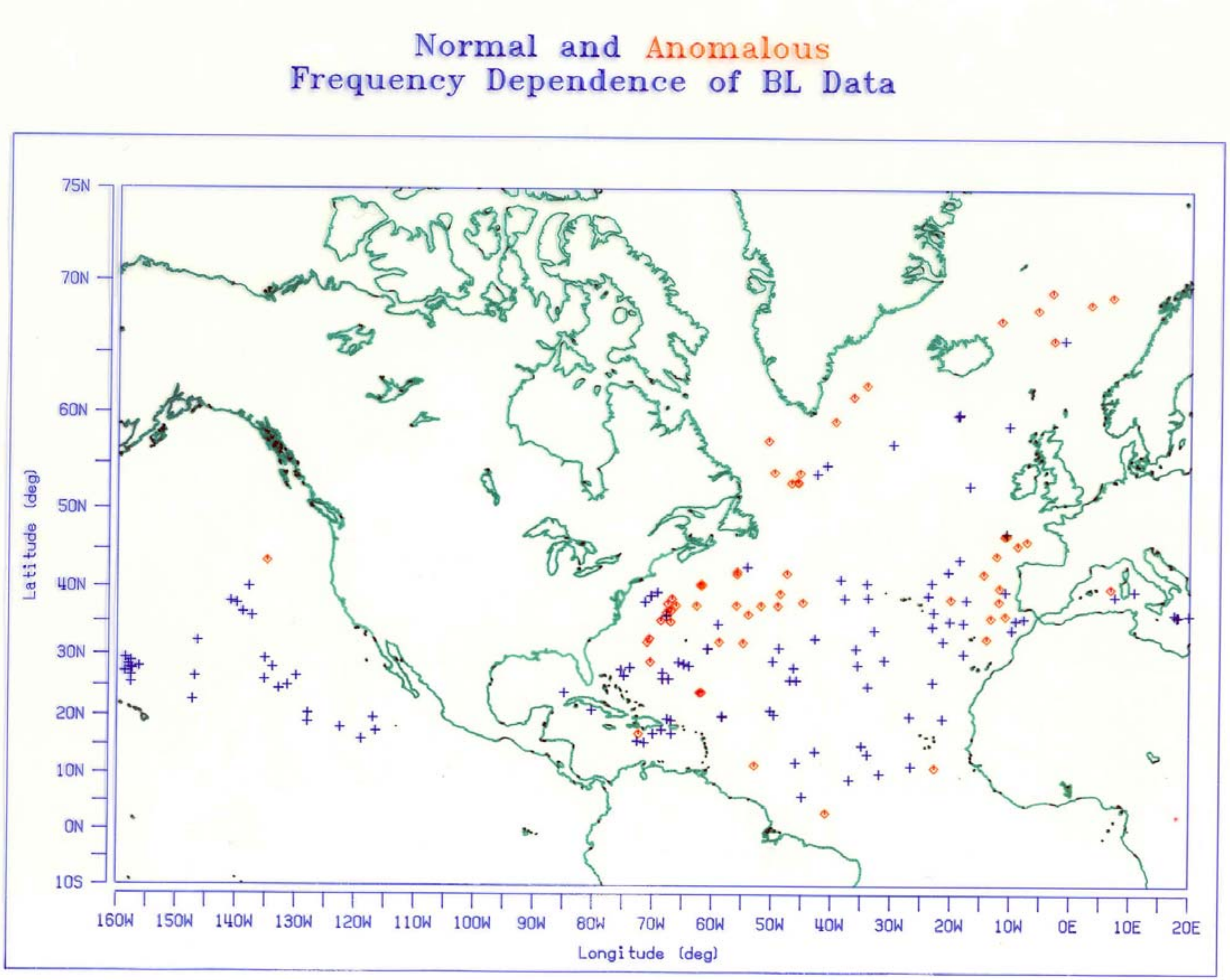
Accomplishments:

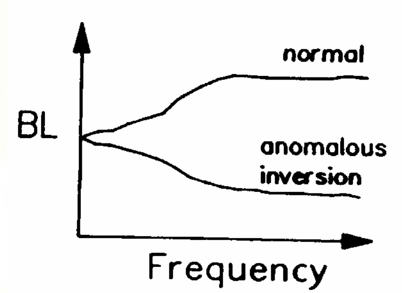
- Quasi-periodic layering observed in two diverse shallow water areas in the Italian littoral (Strait of Sicily and north Tuscany shelf)
- Intercalating layers are relatively thin, often $O(10^{-1})$m but have an important effect on seabed reflection
- Sedflux confirmed eustatic fluctuations cause quasi-periodic layering on Malta Plateau

Open questions:

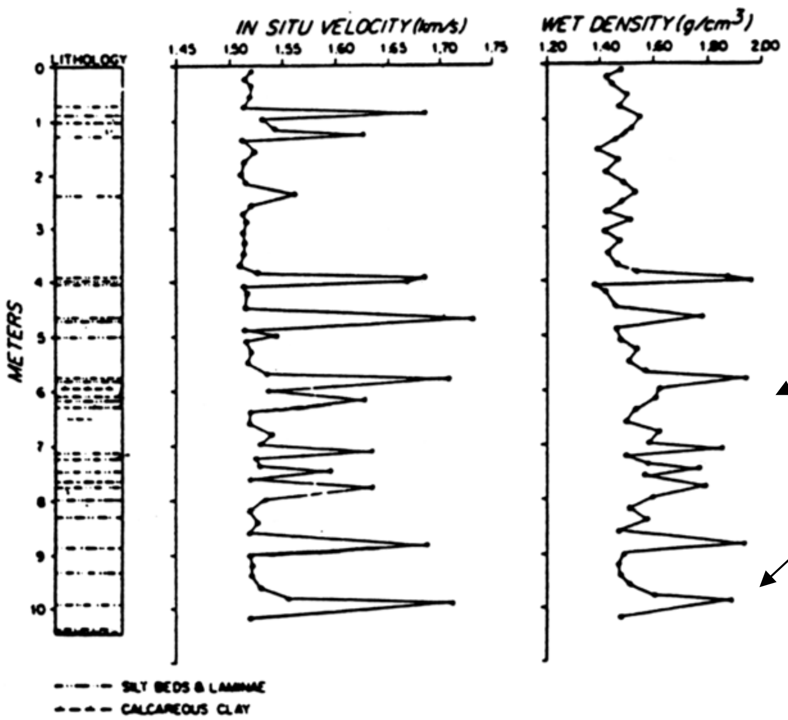
- can Sedflux predict the observed depth dependent layering?
- can Sedflux explain the high regional variability in sediment classes and the apparent similarity between distant (10^{6})m regions
- What kind of statistical approach should be used for predicting the effect of the "random" layering on seabed reflection/scattering?

Another Example of Layering





Geologic Correlation



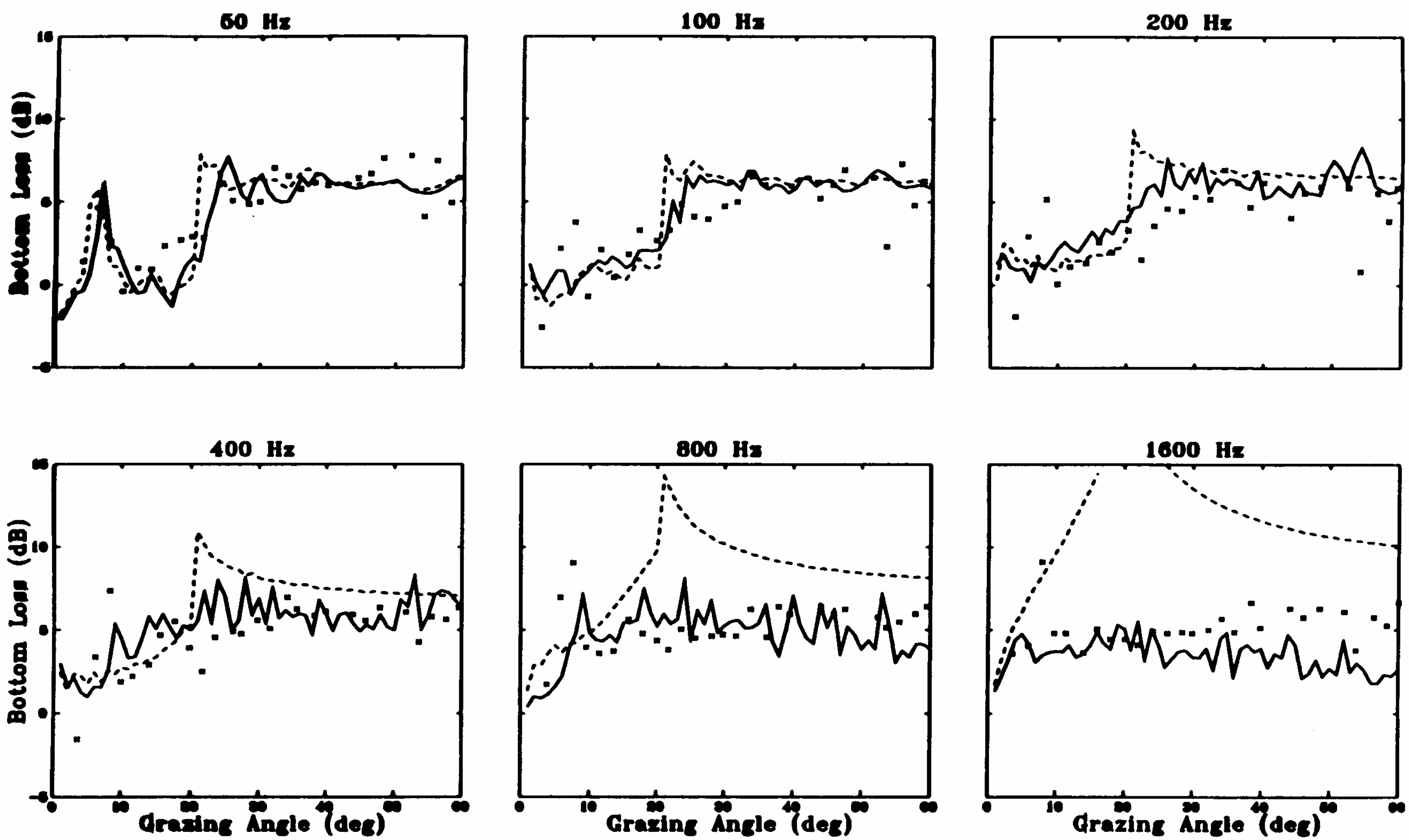
Core data showing intercalating silt layers (Tucholke (1980))

Intercalating layers

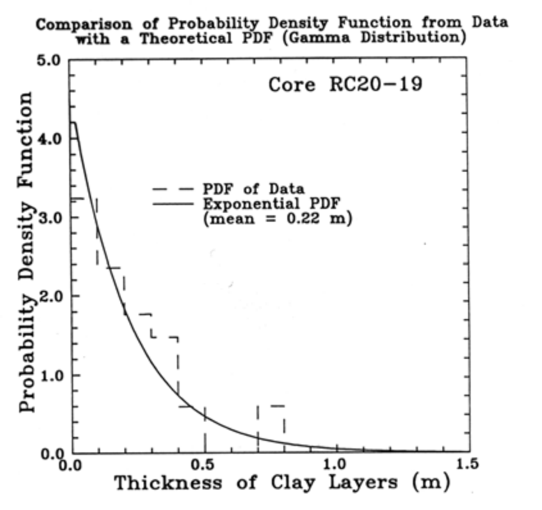
The anomalous frequency dependence turned out to be correlated with abyssal plains where the sediment column is composed of intercalating caly-sand (or silt) layers (turbidities) often O(10^{-1})m layering

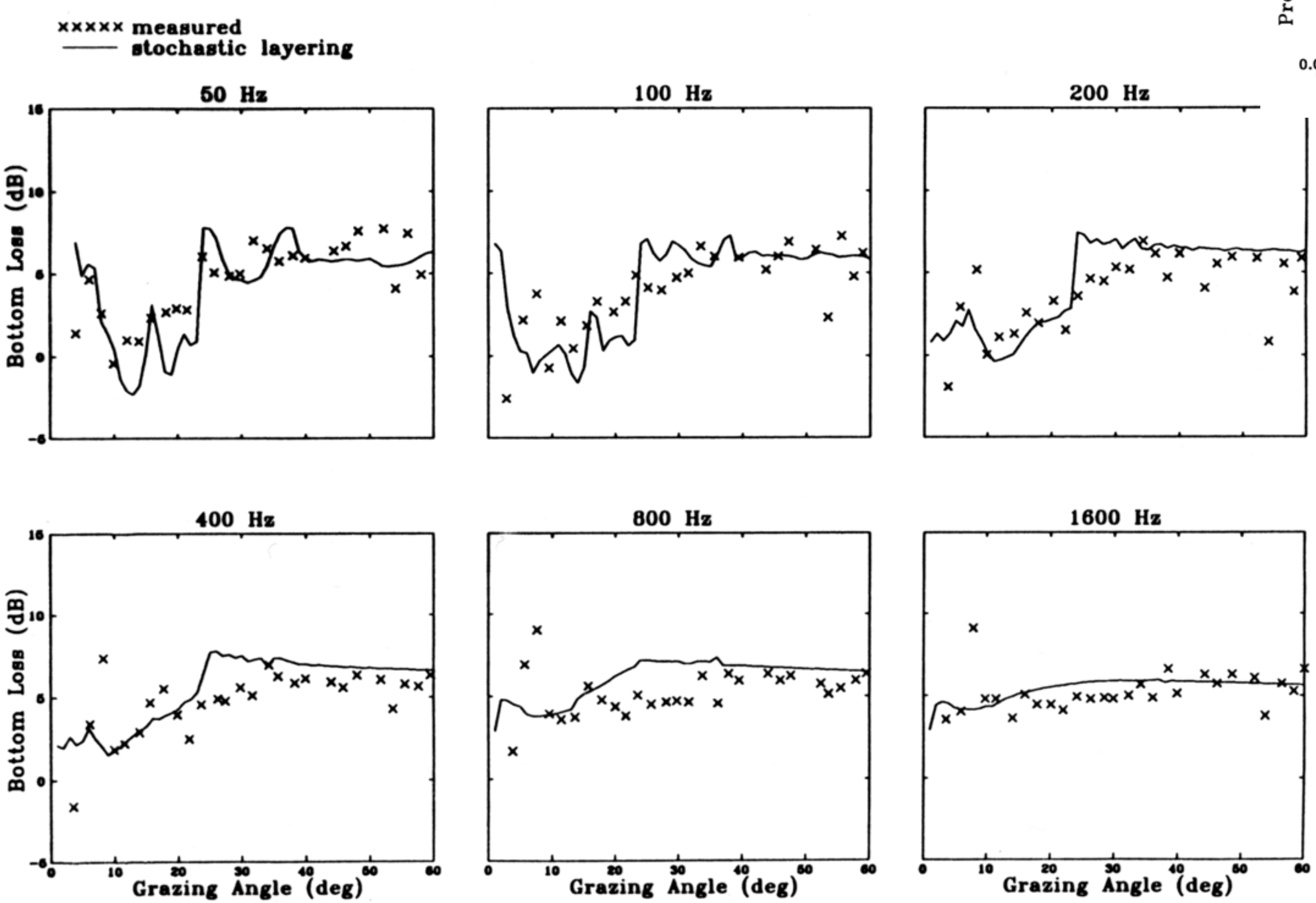
Acoustic Confirmation

× × × × × measured
- - - - - no layering
——— layering

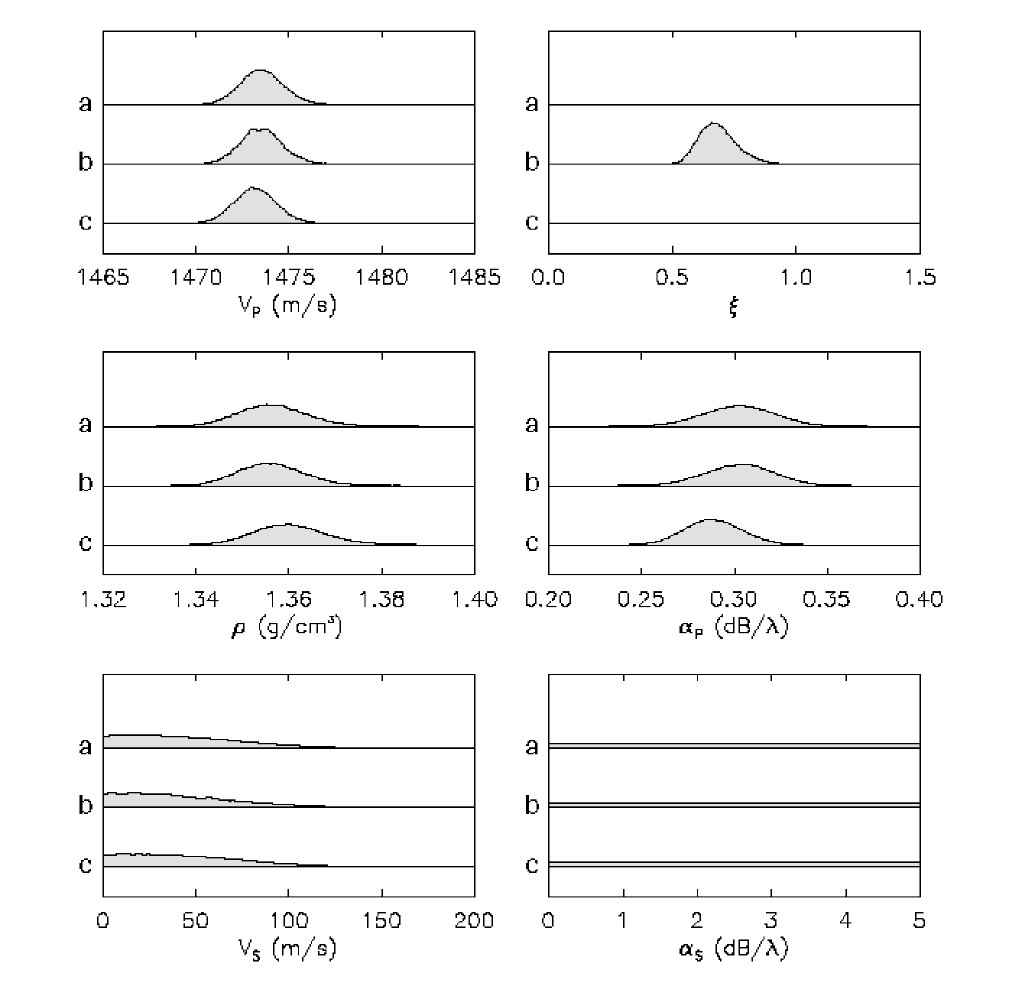


Stochastic Model





Marginal Probability Dist.



Maximum a posteriori (MAP)

c_p = 1474 ± 2 m/s

α_p = 0.28 ± 0.03 dB/λ

ρ = 1.36 ± 0.02 g/cm^3

c_s = 5 ± 100 m/s

α_s = 1.9 ± 3 dB/λ

95% HPD credibility intervals

c_p = [1472 1477] m/s

α_p = [0.25 0.31] dB/λ

ρ = [1.34 1.38] g/cm^3

c_s = [0 90] m/s

α_s = [0.2 5] dB/λ

Inter-Reg. Sedimentary Classes

North Tuscany Shelf

	Velocity (m/s)	Vel grad (s^{-1})	Density (g/cm^3)	Den grad ($g/cm^3/m$)	Attenuation (dB/m/kHz)
Silty-clay	1475±10	1.5 +	1.32±0.04	0.1	0.01
Mud	1500	5, β=-0.9	1.5	via vel.	0.015
Sand	1640	10	1.8	--	0.3
Shelly sand	1650±100	--	1.9±0.2	--	0.1
sandstone	v_s:1600±20	--	--	--	--

Malta Plateau

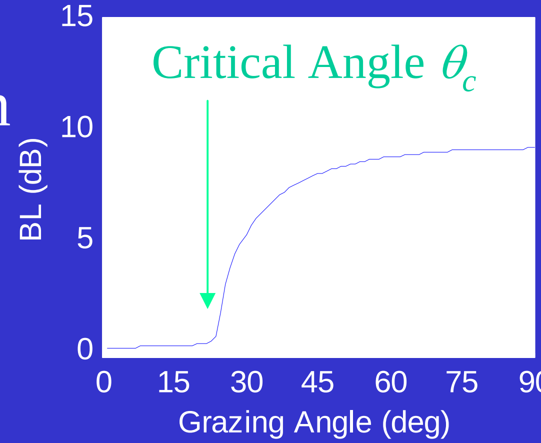
	Velocity (m/s)	Vel grad (s^{-1})	Density (g/cm^3)	Den grad ($g/cm^3/m$)	Attenuation (dB/m/kHz)
Silty-clay	1480±10	1.5 +	1.32 ±0.04	0.1	0.01
Mud	1500	15, -0.99	1.5	via vel.	0.015
Sand	1650	--	1.8	--	--
Shelly sand	1650±100	--	1.9±.2	--	0.1
Cobble	1780	--	1.85	--	0.2

Velocity variability of NE / MP 80% / 85%
Density variability of NE / MP 90% / 90%
Attenuation variability NE / MP 30% / 30%

} of worldwide variability

Velocity Dispersion Approach

Measure broadband (0.1-10 kHz) seabed reflection coefficient



Determine velocity dispersion via frequency dependence of critical angle

Advantages of approach

- Continuous observation of phenomenon (vs. low freq/ high freq extremes approach)
- Identification of critical angle is robust (easily observable)
- Remote measurement; i.e., no sediment disturbance
- Measurements are rapid, can be done in survey mode

Disadvantage of approach

- other mechanisms besides velocity dispersion can produce $\theta_c(f)$

Dispersion Study Summary

Kramers-Kronig relation can be used to estimate dependence of attenuation on frequency from frequency dependence of velocity

Technique appears to a useful method for measurement of undisturbed in-situ velocity dispersion.

Remaining Question

How do these results vary spatially? e.g., within 10^{3-5} m (could be answered with AUV/towed array method)

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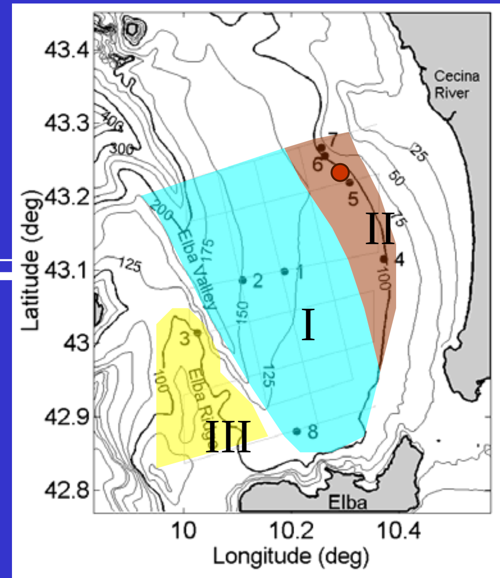
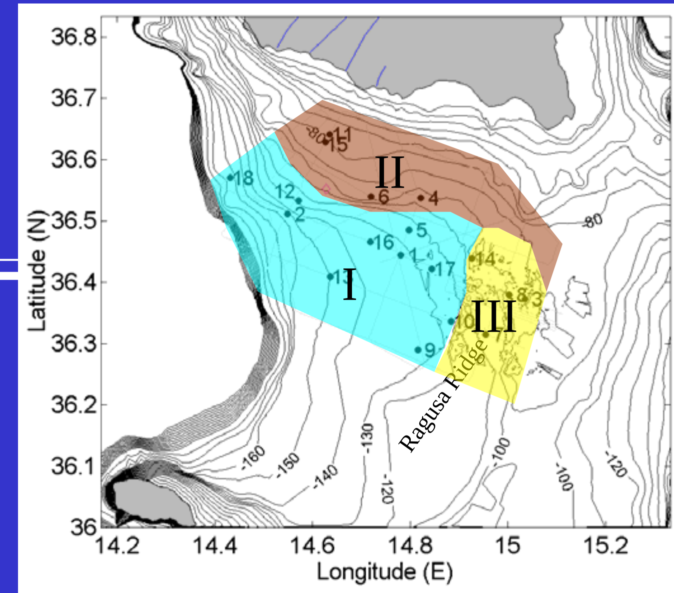
Geoacoustic Regimes





Regime I. Fine-scale layering

- Silty-clay host, random, thin shelly sand intercalating layers
- Variability is “continuous”; modest acoustic variability
- One boundary defined by ridge; one boundary poorly defined

Regime II. Thick silty clay over coarse sediment/basement

- 110-75 m contour, NE sector; basement may be unconsolidated or consolidated
- Acoustic response dominated by basement which may have strong relief

Regime III. Ponded sand with rock outcrops

- Acoustic response is governed by sand properties, intermittent rock outcrops, and at higher freqs thin silty-sand layer