

Remote Estimates of Physical and Acoustic Sediment Properties in the South China Sea Using Chirp Sonar Data and the Biot Model

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Abstract—A chirp sonar acquires sea-bed reflection data in the South China Sea, generates imagery of the sediment layering, and estimates sediment properties along the acoustic propagation paths selected for the Asian Sea International Acoustics Experiment (ASIAEX). Normal incidence reflection data, collected by the chirp sonar, are processed with an inversion technique based on the Biot model. The inputs for the inversion are reflection coefficient and attenuation rolloff measurements extracted from chirp sonar reflection data. The inversion provides the acoustic and physical properties of the sediments for the top layer of the sea bed. Porosity, predicted by the inversion, agrees with directly measured porosity. Estimates of porosity, mean grain size, permeability, fast wave velocity, and attenuation (in decibels/meter) are given for the uppermost sediment layer along each of the acoustic propagation lines.

Index Terms—Attenuation, Biot model, chirp sonar, sediment classification.

I. INTRODUCTION

DURING the Asian Sea International Acoustics Experiment (ASIAEX) in May 2001, moored acoustic transmitters and receivers measured sound propagation across the continental shelf in the South China Sea. The chart in Fig. 1 shows the locations of vertical and horizontal line arrays (VLAs/HLAs) and 400-Hz sources used during the sound propagation experiments. The two paths of acoustic propagation were oriented along the edge of the shelf in approximately 120 m of water (path A) and across the shelf break from 120 to 350 m of water depth (path B). In addition, 300- and 500-Hz sources were moored at the eastern 400-Hz site and a 224-Hz source was moored at the southern 400-Hz site [1].

In May 2001, a chirp sonar generated imagery of the sediment structure and acquired normal incidence reflection data over the band of 1.5–4.5 kHz along the acoustic propagation paths. The track lines of the chirp sonar survey are shown in Fig. 1. The reflection data were processed after the survey to generate estimates of porosity, permeability, mean grain size, fast wave velocity, and attenuation at 224, 300, 400, and 500 Hz, the frequencies of the propagation experiments. Porosity estimates agree with porosities extracted from cores C2 and C3 using the gamma ray attenuation logging technique. The images

of the sediment layering and sediment property estimates are intended to be used in acoustic propagation models being tested as part of ASIAEX and for comparison with sediment properties generated by inversions of acoustic propagation data.

Background on chirp sonar signal processing and the procedure for extracting sediment properties from chirp sonar data is given in Section II. Section III describes the calibration and inversion procedures used to extract sediment properties from ASIAEX chirp sonar data sets. The results in Section IV include tabulated estimates of sediment properties along the acoustic propagation paths and a comparison between porosities measured using cores C2 and C3 and porosities estimated from chirp sonar data collected near those sites.

II. BACKGROUND

A. Review of the Procedure for Estimating Sediment Properties From Chirp Sonar Data

The inversion estimates the properties of the top sediment layer from normal incidence reflection data using the procedure shown in Fig. 2. Reference [2] contains the background on the development of the inversion procedure, the expressions for the calculations described in Fig. 2, and examples of figures listed in Fig. 2. The first step of the procedure is to measure the reflection coefficient of the sediment–water interface. The reflection coefficient is measured at the low end of the operating band to minimize the effects of bottom roughness and porosity gradients at the sediment–water interface. The porosity of the surficial sediments is estimated from the reflection coefficient measurement using the Biot model, as described in [2]. The porosity of the upper layer is assumed to be equal to the surficial porosity. The next step of the inversion is measuring the attenuation rolloff, which is equal to the slope of the sediment transfer function, in units of decibels, divided by the two-way path length of sound traveling through the upper sediment layer. The transfer function is the spectral ratio of the echoes from the sediment–water and sediment–sediment interfaces that are time gated from the chirp sonar reflection data. The two-way acoustic path length is the product of the time difference between the interface echoes and the sediment velocity derived from the reflection coefficient-based porosity estimate. The attenuation rolloff measurements and a plot of attenuation rolloff against permeability, generated using the estimated porosity and the Biot model, are used to look up the permeability of the layer. The inversion is recursive using the last estimated permeability

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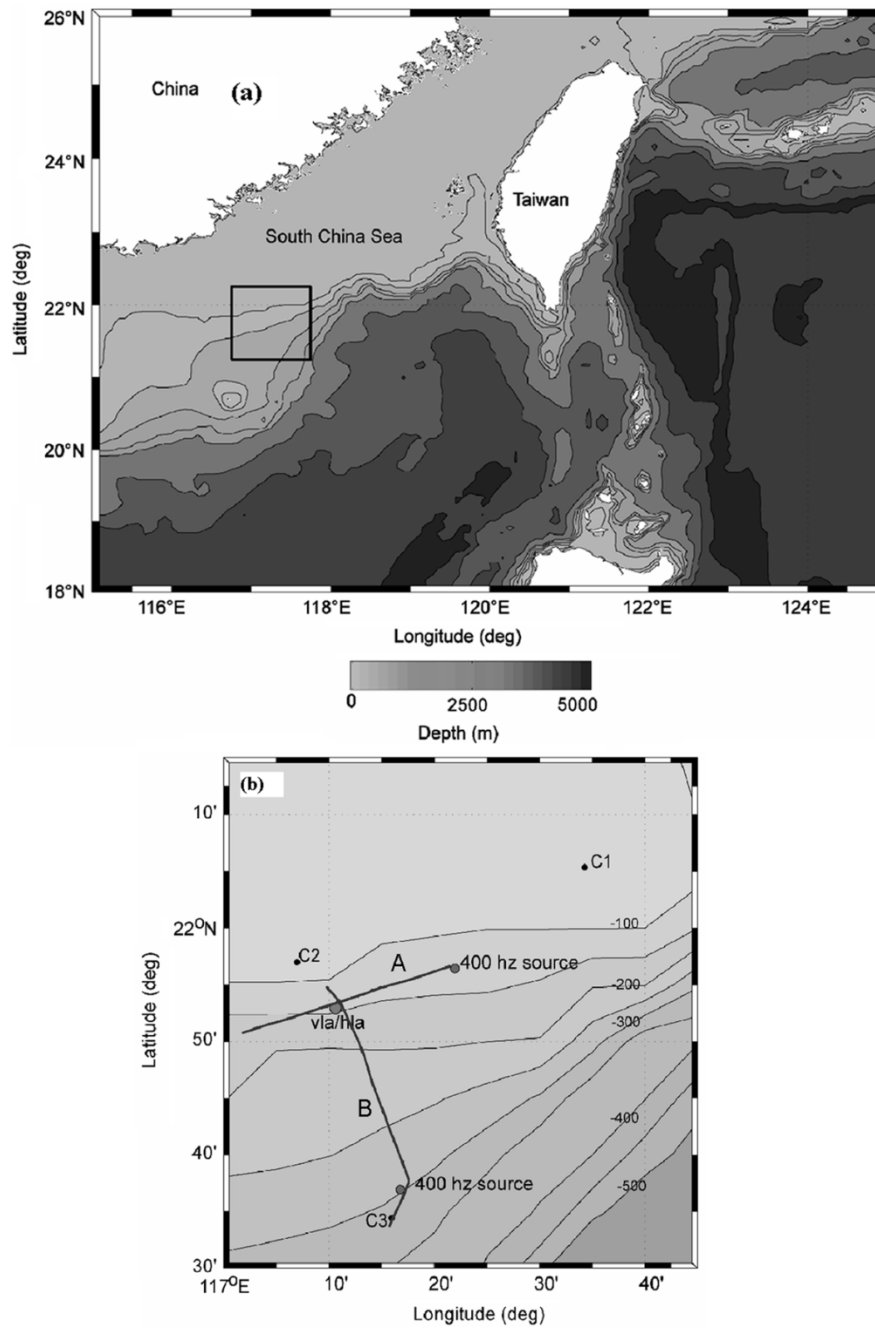


Fig. 1. (a) Chart of the South China Sea indicating the location of the ASIAEX experiment with a box. (b) Expanded view of the box in (a), showing locations of chirp sonar track lines A and B, acoustic sources and receivers used during the propagation experiments, and the locations of cores C1, C2, and C3. Water depths are in meters [1].

and the reflection coefficient to calculate an updated porosity and the last estimate of porosity and the attenuation rolloff to calculate a new permeability until the porosity and permeability values reach the desired accuracy. After two passes, the porosity and permeability updates are usually with 1% and 10% of the previous update for porosity and permeability, respectively. The porosity and permeability estimates are inserted into the modified Kozeny–Carman equation to obtain grain size and are entered into the Biot model to yield the compressional wave velocity and attenuation [2].

B. Chirp Sonar Description and Signal Processing

The chirp sonar is a broadband FM sonar that generates normal incidence reflection profiles of the sea bed. A drawing of the towed sonar vehicle used in the ASIAEX survey is shown in Fig. 3. The sonar vehicle is powered with 300 VDC over an armored single coaxial tow cable. The vehicle is designed to be neutrally buoyant so that it will trail about 10 m behind a depressor weight used for decoupling the heave of the survey vessel from the sonar vehicle. A pressure transducer provides the depth of the sonar vehicle. The sum of the vehicle depth

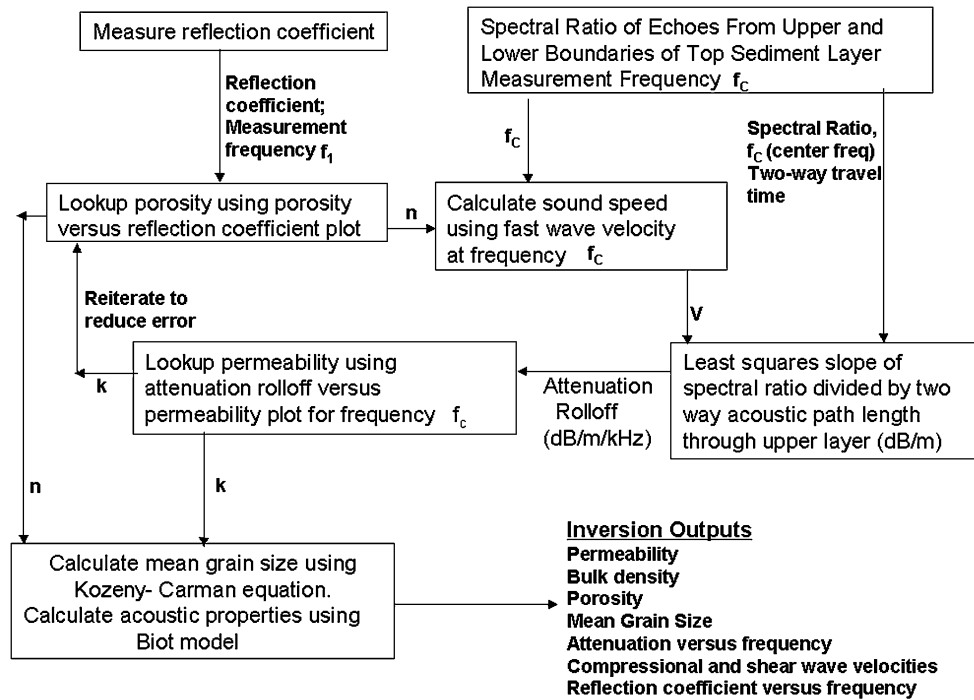


Fig. 2. Procedure for estimating the physical and acoustic properties of the sea bed from reflection coefficient and attenuation rolloff measurements.

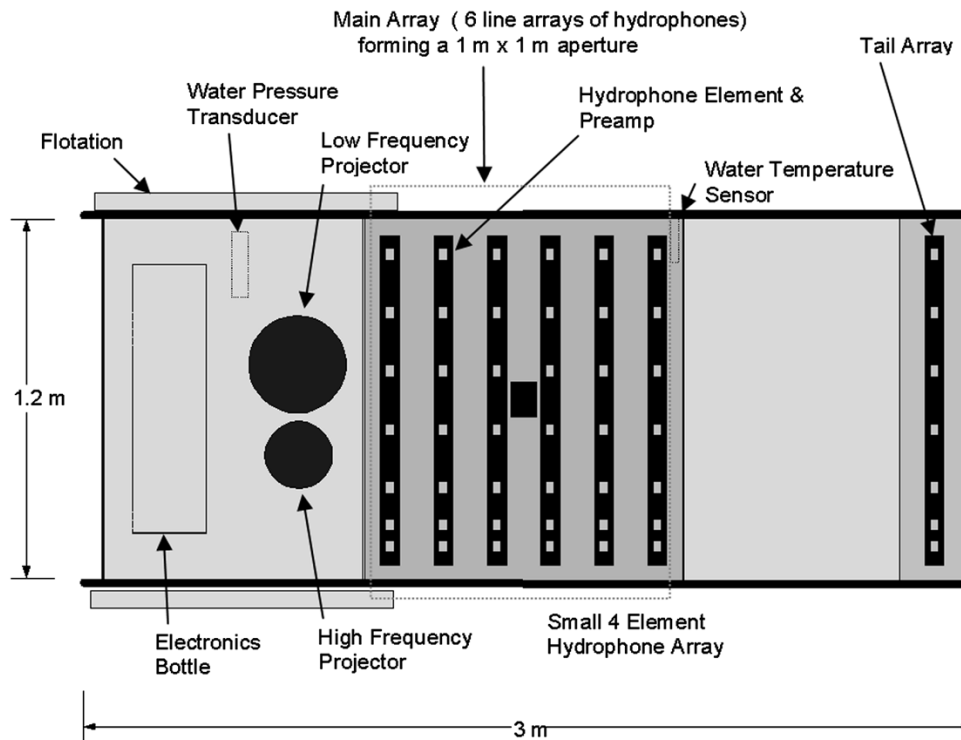


Fig. 3. Bottom view of the chirp sonar vehicle deployed during ASIAEX.

and the vehicle height derived from the two-way travel time of sound reflected off the sea floor provides the water depth.

The sonar vehicle has two Tonpilz-type piston sources with operating bands of 1.5–5 kHz and 4–16 kHz, respectively. The sonar processor, contained in the electronics bottle, uses dig-

ital-to-analog converters to generate pilot signals for two power amplifiers that simultaneously drive each projector with linear FM pulses, which have the form

$$x(t) = a(t) \cos \phi(t) \quad (1)$$

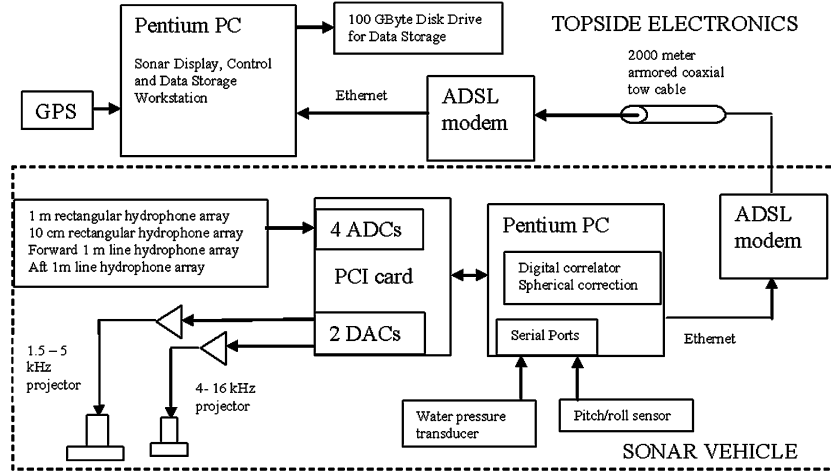


Fig. 4. Signal flow diagram for chirp sonar used during the ASIAEX survey.

where $a(t)$ is the amplitude weighting and the instantaneous phase is given by

$$\phi(t) = 2\pi f_c t + \pi b t^2. \quad (2)$$

The instantaneous frequency is

$$f_i = \frac{1}{2\pi} \frac{d\phi(t)}{dt} = f_c + b t \quad (3)$$

where b is the sweep rate in units of hertz per second [3]. Each pilot signal is a FM pulse given by

$$x(t) = \begin{cases} A \cos \phi(t) & -T/2 \leq t \leq T/2 \\ 0 & |t| > T/2 \end{cases}. \quad (4)$$

In practice, the ends of the FM sweep are tapered to reduce correlation sidelobe levels.

A signal flow diagram for the chirp sonar is shown in Fig. 4. The electronics bottle in the sonar vehicle contains a PC with four analog-to-digital converters that digitize the outputs of the following acoustic channels:

- summed output of the forward six hydrophone line arrays that form a 1-m $\times$ 1-m planar receiver aperture;
- output of small rectangular 10-cm $\times$ 10-cm hydrophone array;
- output of the forward 1-m line array;
- output of the aft 1-m line array.

All sediment property estimates, described in this paper, are the result of processing the output of the 1-m² rectangular array. That array provides better spatial filtering (scattering noise rejection) than the other arrays.

The sonar processor performs real-time cross-correlation to compress the reflected FM signals in time to zero phase wavelets. For plane wave propagation in lossless seawater, the frequency spectrum of an acoustic return, measured at the receiver, is given by

$$Y(f) = X(f)H_X(f)H(f)H_R(f) + N(f) \quad (5)$$

where $X(f)$ is the Fourier transform of the pilot signal

$$X(f) = \int_{-\infty}^{\infty} x(t)e^{j2\pi ft} dt \quad (6)$$

and $H_X(f)$, $H_R(f)$, and $H(f)$ are the frequency responses of the acoustic projector, the hydrophone array, and the sea bed, respectively. The noise spectrum $N(f)$ consists of ambient noise, electronic noise, vehicle self noise, etc. The output of the correlation filter is

$$s(t) = \int_{-\infty}^{\infty} y(\tau)f(t+\tau) d\tau \quad (7)$$

where the $f(t)$ is the correlation replica and $y(t)$ is the acoustic return.

The correlation filter is called a matched filter when $y(t)$ is a known signal in white noise and $f(t)$ is the corresponding noise-free signal. A matched filter provides the optimal signal to in-band noise improvement for a known signal in white noise. The signal-to-noise improvement for matched filter processing is given by

$$\text{SNR}_{\text{out}} - \text{SNR}_{\text{in}} = 10 \log TW \quad (8)$$

where T is the pulse length and W is the pulse bandwidth. Note that increasing pulse length, or pulse bandwidth, improves the signal-to-in-band noise ratio at the output of a matched filter [4].

The matched-filter design requires that the frequency response of the filter matches the frequency spectrum of an acoustic echo. The design is based on the assumption that the echo originates from a white reflector so that the echo is identical to the pilot signal convolved with the system response. The impulse response of the correlation filter, the correlation replica, is

$$f(t) = \int_{-\infty}^{\infty} H_X(f)H_R(f)X(f)e^{-j2\pi ft} df \quad (9)$$

which matches the waveform of an acoustic echo from a white reflector. In practice, the system frequency response is measured, with the sonar vehicle inverted, using echoes from a smooth air–water interface.

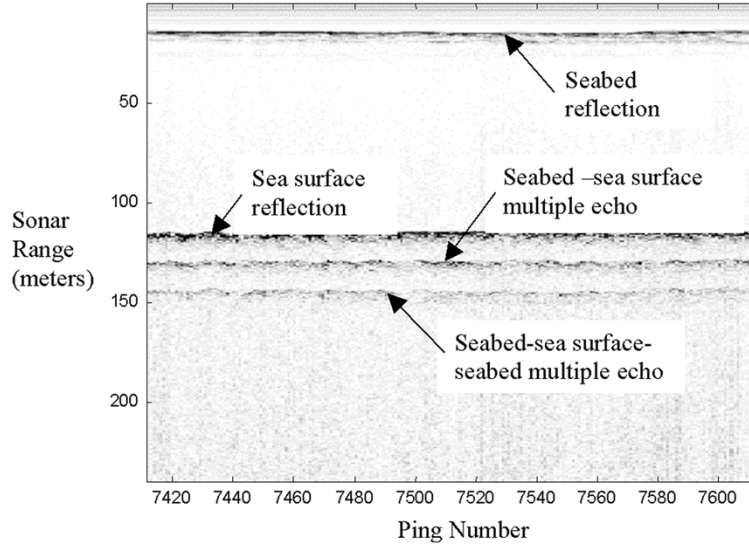


Fig. 5. Reflection profile of a sandy sea bed in the South China Sea showing water multiples and the sea bed-sea surface-sea bed multiple echo used to calibrate the chirp sonar.

The correlation processing is implemented in the frequency domain using Fourier transforms. The output of the correlator, an analytic signal, is given

$$S_a(t) = \int_{-\infty}^{\infty} Y(f)F^*(f)e^{-j2\pi ft} df. \quad (10)$$

After applying spherical spreading corrections, the sonar processor, a Pentium PC, merges the analytic signal with auxiliary sensor data, such as water pressure, in a modified SEG-Y data format and transmits the data to the surface ship via Ethernet using an ADSL modem pair located at both ends of a 2000-m towed, armored, coaxial cable. As shown in Fig. 4, the topside computer, which is connected to an ADSL (asymmetric digital subscriber line) modem via an Ethernet connection, integrates and stores the sonar data and global positioning system (GPS) position data. The image of the sediments is constructed by mapping the envelope, the magnitude of the analytic signal, to shades of gray, where each vertical line of pixels in the image represents the envelope of one acoustic return.

III. APPROACH

A. Procedure for Calibrating the Chirp Sonar Using South China Sea Data

There was no opportunity to calibrate the sonar with the sonar vehicle inverted in the presence of a ripple-free sea surface during ASIAEX, so bottom multiples were used to calibrate the chirp sonar. The reflection intensity coefficient of the sea bed is approximately equal to the ratio of the energies of the bottom echo and the upward traveling multiple of the bottom echo caused by a sea surface reflection. This calibration method is not exact due to errors associated with scattering noise caused by sea surface and bottom roughness requiring

careful selection of the frequency band and sea-bed and sea surface conditions when conducting the calibration.

The multiple calibration technique provides an estimate of the system transfer function

$$H_S(f) = H_X(f)H_R(f) \quad (11)$$

and the reflection coefficient of the sea bed. With the correlation replica set equal to the pilot signal, the spectrum of the correlated seabed echo after correcting for spherical spreading is

$$B_1(f) = \frac{1}{2r_1}X(f)H_S(f)X^*(f)R(f) \quad (12)$$

where the r_1 is the height of the sonar vehicle above the sea bed and the reflection coefficient of the sediment-water interface is defined by

$$R(f) = \frac{P_r}{P_i} \quad (13)$$

where P_r and P_i are the frequency spectra of the reflected and incident waves measured just above the sediment-water interface.

The spectrum of the bottom-surface-bottom multiple echo, shown in Fig. 5, is given by

$$B_2(f) = \frac{-1}{2r_2}X(f)H_S(f)X^*(f)R^2(f) \quad (14)$$

where r_2 is equal to the water depth plus the vehicle altitude above the sea bed. The reflection coefficient of the air-water interface is assumed to be equal to -1 .

Divide (14) by (12) to obtain the reflection coefficient in terms of the ratio of bottom echo spectra

$$R(f) = -\frac{r_2 B_2(f)}{r_1 B_1(f)}. \quad (15)$$

The system transfer function $H_S(f)$ is obtained by substituting (12) into (15) and solving for $H_S(f)$ to yield

$$H_S(f) = \frac{-2r_1^2 B_1^2(f)}{r_2 X(f)X^*(f)B_2(f)}. \quad (16)$$

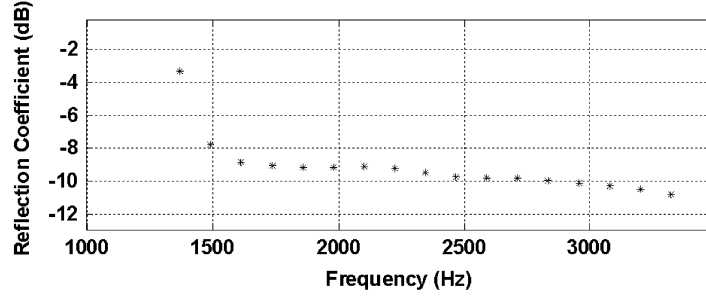


Fig. 6. Reflection coefficient of a sandy sea bed calculated using the water multiple method (18). The reflection coefficient is reported at 2 kHz where signal-to-noise ratio (SNR) is high and the wavelength is long with respect to sea surface and sea-bed roughness.

The reflection coefficient for the ASIAEX data set is calculated after filtering the analytic signal data using a bandpass filter with a center frequency of 2000 Hz and a -3 -dB bandwidth of 500 Hz. The low end of the operating band is used for the calibration and reflection coefficient measurements to minimize the effects of sea surface and sea-bed roughness. The output of the filter is

$$s_{2000}(t) = \int_{-\infty}^{\infty} Y(f)X^*(f)H_B(f)e^{-j2\pi ft} df \quad (17)$$

where $H_B(f)$ is the frequency response of the filter and $Y(f)$ is the Fourier transform of an acoustic return.

The magnitude of the reflection coefficient (15) at 2000 Hz is calculated using

$$R_{2000} = \frac{\left\langle \frac{r_2^2}{r_1^2} \int_{t_2-T/2}^{t_2+T/2} s_{2000}(t)s_{2000}^*(t) dt \right\rangle}{\left\langle \frac{r_2^2}{r_1^2} \int_{t_1-T/2}^{t_1+T/2} s_{2000}(t)s_{2000}^*(t) dt \right\rangle} \quad (18)$$

where t_1 and t_2 are the arrival times of the bottom echo and the multiple of the bottom echo and T is the width of the gating window, which is approximately equal to twice the inverse of the bandwidth of the bandpass filter. The brackets $\langle \rangle$ indicate averaging over several transmissions.

The expression for calculating the magnitude of the system transfer function (16) at 2000 Hz is given by

$$H_{2000} = \frac{2 \left\langle \frac{r_1^2}{r_2^2} \int_{t_1-T/2}^{t_1+T/2} s_{2000}(t)s_{2000}^*(t) dt \right\rangle}{X_{2000}X_{2000}^* \sqrt{\left\langle \frac{r_2^2}{r_1^2} \int_{t_2-T/2}^{t_2+T/2} s_{2000}(t)s_{2000}^*(t) dt \right\rangle}} \quad (19)$$

The system transfer function (19) is used to calibrate the entire ASIAEX data set. The transfer function is estimated from echoes generated by 200 transmissions over a sandy bottom just to the west of the horizontal line array/vertical line array (HLA/VLA) site shown in Fig. 1. Ten groups of 200 acoustic transmissions provide ten independent estimates of the system transfer function. The average of these estimates is used to calibrate the ASIAEX data set. The 70% confidence limits of the system amplitude response are ± 0.25 dB at 2 kHz. In Section IV, those confidence limits are used to determine the error of the porosity estimates.

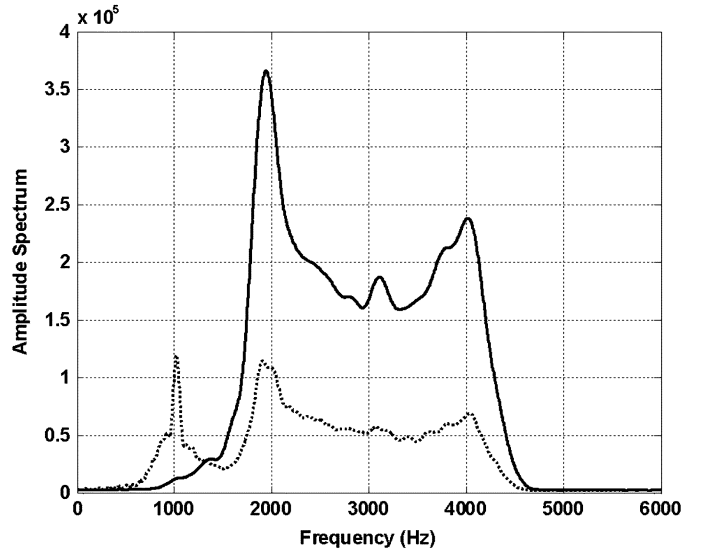


Fig. 7. Amplitude spectrum of sediment–water interface reflection (solid line) and amplitude spectrum of bottom multiple (dashed line). The spectra are corrected for spherical spreading. The low-frequency portion of the bottom multiple spectrum has relatively low SNR due to a noise source near 1 kHz. The noise source is probably radiated noise from FR-1. The sonar reflection data is calibrated at 2 kHz.

The reflection coefficient, estimated using the multiple calibration procedure (18), is plotted in Fig. 6 for several frequencies across the operating band. This figure shows that the reflection coefficient of the sandy sea bed at 2000 Hz is about -9 dB. The rapid increase in the measured reflection coefficient below 1800 Hz is due to a 1000-Hz noise source shown in the frequency spectrum of the bottom multiple plotted in Fig. 7. This 1000-Hz source may be radiated noise from vessel FR-1.

B. Procedure for Calculating the Reflection Coefficient of the Sea Bed in the South China Sea

Solving (12) for $R(f)$ provides the expression for the calibrated reflection coefficient for any sediment–water interface echo in the ASIAEX data set.

$$R(f) = \frac{2r_1B_1(f)}{X(f)H_S(f)X^*(f)} \quad (20)$$

where the system transfer function, given by (16), is calculated using a portion of the reflection data set with low bottom and sea surface roughness.

Equation (20) is implemented by averaging the energy of the sea-bed echo after correlation processing using the pilot signal as the correlation replica, passing the analytic signal through a

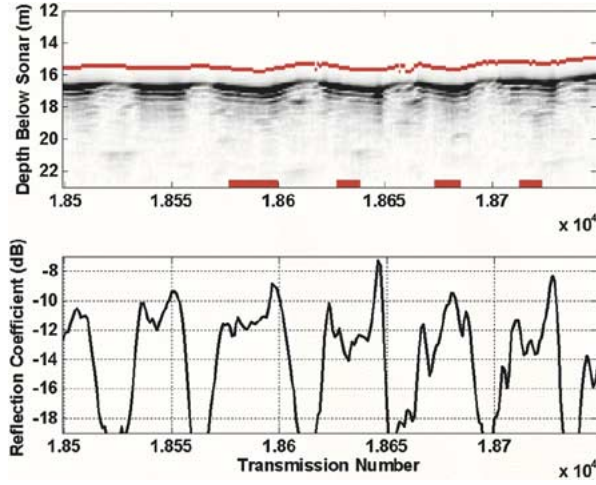


Fig. 8. Section of reflection profile collected along track line A showing dropouts in reflection coefficient caused by irregularities in the sediment–water interface. A red mark is placed under echoes meeting the 12-dB down repeatability criterion for a valid reflection coefficient measurement. The red line just above the sediment–water interface is the indicator for the automatic bottom tracker.

bandpass filter centered at 2000 Hz, and correcting the data for the sonar transfer function H_{2000} given by (19). The resulting expression for the reflection coefficient measurement is given by

$$R_{2000} = \frac{\left\langle \frac{4r_1^2}{X_{2000}H_{2000}X_{2000}^*} \int_{t_1-T/2}^{t_1+T/2} s_{2000}(t)s_{2000}^*(t) dt \right\rangle}{X_{2000}H_{2000}X_{2000}^*}. \quad (21)$$

The average value of the reflection coefficient (21) is calculated using a 20-ping moving average. The reflection coefficient measurement is discarded if the standard deviation of 20 successive reflection coefficients is greater than 25% of the mean value of the 20 measurements. As shown in Fig. 8, the 20-ping average corresponds to a spatial length that is just shorter than distance between sea-bed anomalies causing loss in echo strength. This procedure reduces reflection coefficient measurement errors introduced by irregularities in the sediment–water interface caused by bottom roughness, layering at the sediment–water interface within the resolution of the bandpass filter, and other sources of horizontal variability, such as fluidization of sediment due to bottom currents. Fig. 8 is a section of the reflection profile for the track A, showing large drops in the single-ping reflection coefficient caused by horizontal variability in the sediment–water interface. The red marks in the figure denote groups of pings with low ping-to-ping variability of the measured reflection coefficient. The denoted reflection measurements are saved for subsequent averaging.

The retained reflection coefficient values are averaged and reported every 1000 transmissions. The 70% confidence limits of the reported reflection coefficients are about ± 0.1 dB. This error is less than that of measuring the system constant using the bottom multiple method. Consequently, the reflection coefficient values given in Section IV are reported with the system transfer function measurement error of ± 0.25 dB.

C. Procedure for Calculating Attenuation Rolloff for the Top Sediment Layer in the South China Sea

The attenuation rolloff is the slope of the relative attenuation function, the spectral ratio of the echoes from the lower and upper interfaces of the top sediment layer divided by the two-way path length for sound traveling through the layer. For thick sediment layers, the change in the relative attenuation with frequency is dominated by the attenuation mechanism and not by the frequency dependence of interface reflection coefficients [2].

The expression for calculating the spectral ratio at frequency f_c is given by

$$T(f_c) = \sqrt{\frac{\left\langle \int_{t_S-T/2}^{t_S+T/2} r_2^2 s(f_c, t) s^*(f_c, t) dt \right\rangle}{\left\langle \int_{t_1-T/2}^{t_1+T/2} r_1^2 s(f_c, t) s^*(f_c, t) dt \right\rangle}} \quad (22)$$

where t_1 and t_S are the arrival times of the bottom echo and the echo from the lower interface of the top sediment layer and T is the width of the window for calculating the energy of the echoes, which is set approximately equal to twice the inverse of the bandwidth of the bandpass filter. The brackets indicate spatial averaging using echoes from 20 to 100 transmissions, depending on the length of the subsurface reflector between discontinuities in the reflector. The function $s(f_c, t)$, the analytic signal after filtering with a bandpass filter with center frequency f_c , is given by

$$s(f_c, t) = \int_0^\infty Y(f)X^*(f)H_B(f_c, f)e^{-j2\pi ft} df \quad (23)$$

where $H_B(f_c, f)$ is the frequency response of a bandpass filter with center frequency f_c .

The attenuation rolloff is the slope of a line fitted through a plot of $10 \log T(f_c)/2z$ versus f_c , where z is the sediment thickness. The two-way travel path $2z$ is equal to the difference in arrival times of the echoes from the layer interfaces multiplied by the sound-speed estimated from the reflection coefficient measurement using the Biot model.

IV. RESULTS

A. Description of the Chirp Sonar Deployment in the South China Sea

Track lines A and B were surveyed with the chirp sonar on May 19th and 22nd, 2001, respectively, using the Taiwanese research vessel *FR-1*. The track of the research vessel derived from GPS fixes is shown in Fig. 1. During the survey, the sonar transmitted 40-ms-long LFM pulses over the band of 1.5–4.5 kHz. The amplitude spectrum of the transmitted pulse, estimated from a sea-bed echo, is plotted in Fig. 7. The sonar vehicle was towed approximately 10–20 m above the sea bed in order to minimize the distance between the sonar and the sea bed, thereby reducing scattering noise and shipborne noise and improving horizontal spatial resolution of the reflection profiles. The topside chirp sonar control and display computer merged the data from a dedicated GPS antenna with the sonar

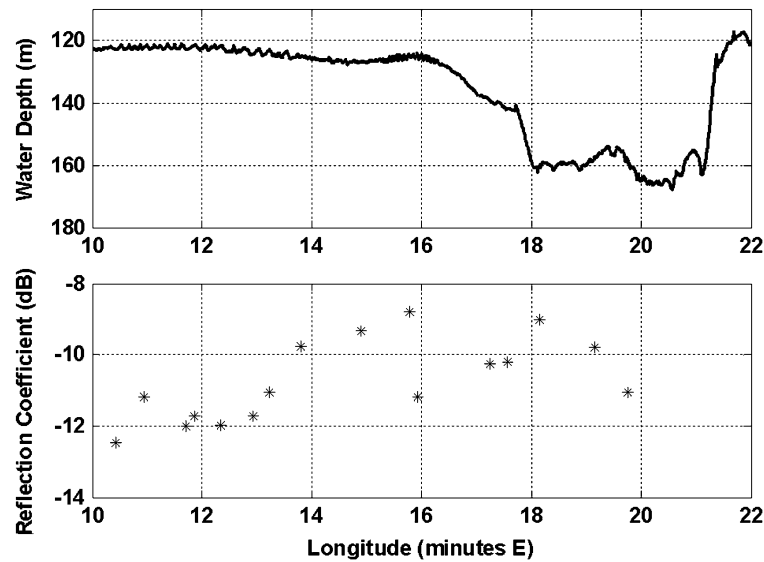


Fig. 9. Bathymetry and reflection coefficient measurements along track A. The water depth is the sum of the vehicle depth measured with a pressure sensor and the vehicle altitude calculated using the arrival time of the bottom echo. The reflection coefficient is measured after passing the bottom echo through a bandpass filter with a center frequency of 2000 kHz and a -3 dB bandwidth of 500 Hz. No reflection data are reported west of 117° , 20 min East due to the sonar being retrieved after hitting the sea bed.

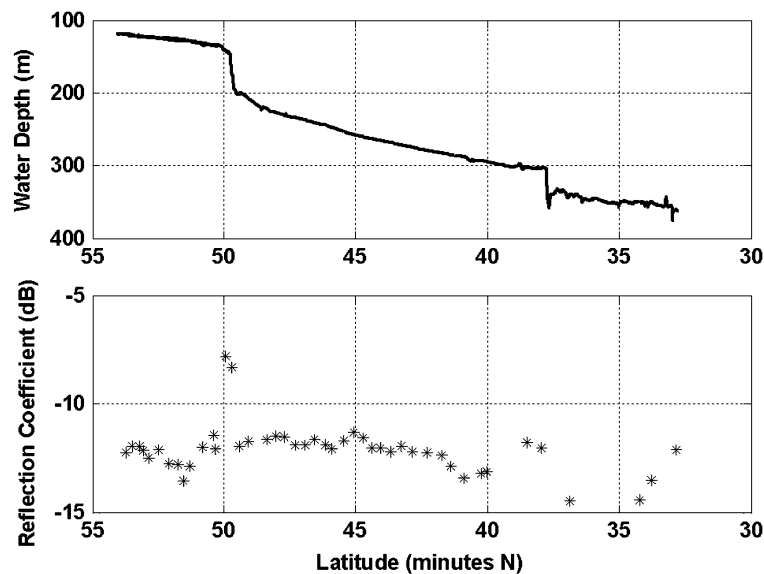


Fig. 10. Bathymetry and reflection coefficient measurements along track B. The water depth is the sum of the vehicle depth measured with a pressure sensor and the vehicle altitude calculated using the arrival time of the bottom echo. The reflection coefficient is measured after passing the bottom echo through a bandpass filter with a center frequency of 2000 kHz and a -3 dB bandwidth of 500 Hz.

data. The GPS position measurements of *FR-1* are based the WGS-84 datum. The relative position of the chirp sonar with respect to the ship was not measured, so the locations of imagery and sediment property measurements have an offset from the reported positions. This error is expected to be less than three times the water depth, since the towing configuration used a depressor weight that helped minimize towing cable scope.

B. Reflection Coefficient Measurements

The reflection coefficient is estimated using (21) with a 20-ping moving average. As described in Section III, measurements with a high standard deviation are discarded and the reflection coefficient is reported every 1000 transmissions. Figs. 9 and 10 contain the reflection coefficient measurements

and bathymetry for track lines A and B. The water depth is the sum of vehicle depth, estimated from the pressure sensor in the sonar vehicle, and vehicle altitude based on the two-way travel time of the bottom echo. The reflection coefficient measurements have 70% confidence limits of ± 0.25 dB, an error caused by the bottom multiple calibration procedure.

C. Attenuation Rolloff Measurements

The first step in the attenuation rolloff calculation is measuring the spectral ratio of echoes from the interface at the surface and bottom of the uppermost sediment layer. It can be measured only at locations where the lower interface is effectively a step change in impedance. If vertical impedance change is gradual with respect to the wavelength of the measurement, the

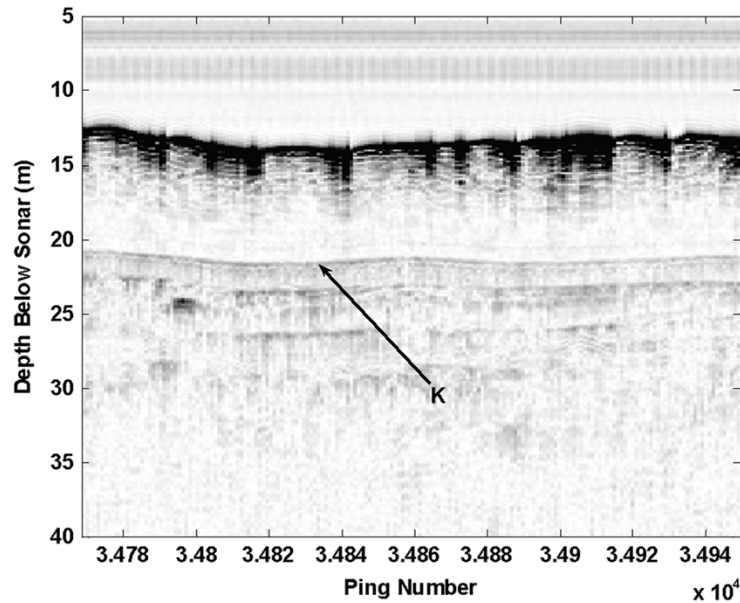


Fig. 11. Reflection profile of sandy sea bed showing reflector K that generated an echo used to estimate the attenuation rolloff of the upper 8 m of sediments. The vertical scale is based on the water sound speed of 1510 m/s.

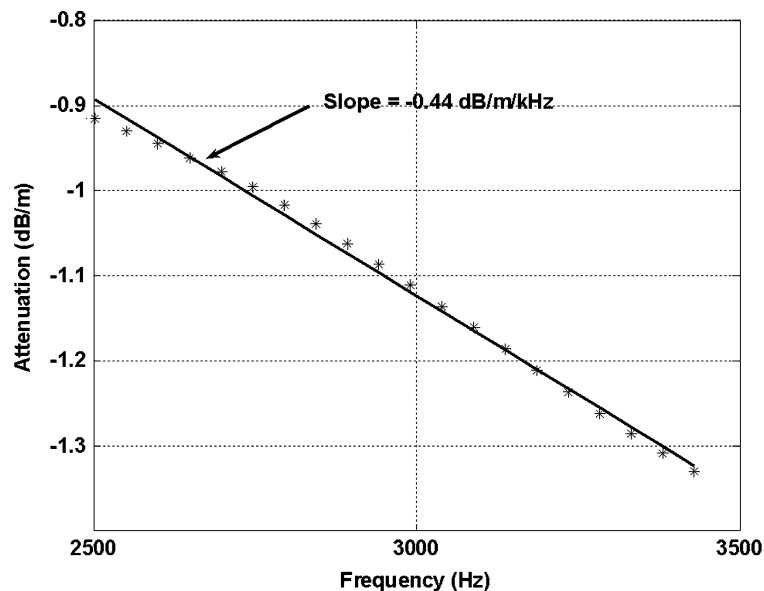


Fig. 12. Plot of relative attenuation, the layer spectral ratio divided by the two-way acoustic path through the layer above reflector K , shown in Fig. 11. The slope of the line fitted through the attenuation data is the attenuation rolloff, 0.44 dB/m/kHz.

scattered echo is smeared in time and causes an interference pattern in the spectral ratio. An example is provided in [2]. Spectral ratio measurements containing interference are discarded. The center frequency of the spectral ratio measurement is 3 kHz. The -3 -dB bandwidth of the bandpass filter used to calculate the spectral ratio (22) is 1 kHz. The filter bandwidth is determined by trading off frequency resolution with the SNR of the measurement, which degrades with decreasing bandwidth. A reduction in bandwidth causes a reduction in temporal resolution and an associated increase in scattering noise from sediments above and below the layer interface.

The attenuation rolloff is the slope of a line fitted through a plot of the relative attenuation plotted against frequency. The relative attenuation is the spectral ratio (22) divided by

the two-way path length. The path length is the product of time difference in the wavelet arrival times and the sediment sound speed. The sediment sound speed is estimated from the reflection coefficient measurements using the Biot model and the expected value of permeability for a given value of porosity, as described in [2].

Fluid density and bulk modulus, Biot model inputs, are based on an average bottom-water temperature at the ASIAEX site. The temperature profile measured at the 350-m mooring varied from about 18 – 12°C as subsurface depth increased from 120 to 350 m [1], the range of sonar vehicle towing depths. For an average water temperature of 15°C , an assumed salinity of 35 ppt, and a water depth of 200 m, the UNESCO (1981) equation of state [5] yields a bulk density of 1027 kg/m^3 . The sound speed

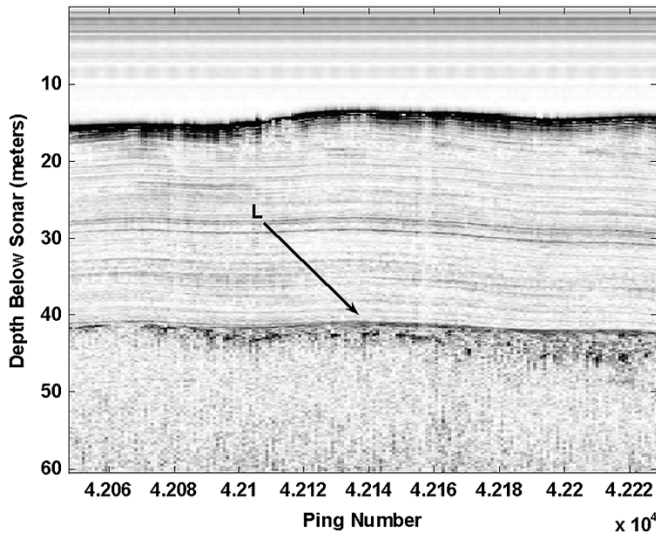


Fig. 13. Reflection profile of sandy sea bed showing reflector K that generated an echo used to estimate the attenuation rolloff of the upper 8 m of sediments. The vertical scale is based on the water sound speed of 1510 m/s.

is estimated to be equal to 1510 m/s based on an expression for sound speed provided by Clay and Medwin [6].

The bulk modulus of the seawater is calculated using

$$K_f = c_f^2 \rho_f \quad (24)$$

where c_f is the phase velocity of sound in seawater.

Grain density and bulk modulus values, also Biot model inputs, are based on the mineralogy of the sediments. Sawyer [7] reported that the sediments were a mixture of quartz grains and shell fragments. The values for the grain density and bulk modulus of quartz grains used in the SAX-99 study [2] are used in the ASIAEX calculations.

Two examples of images showing reflectors selected for attenuation rolloff measurements are shown in Figs. 11 and 13. The attenuation rolloff measurements corresponding to these images are shown in Figs. 12 and 14. The image of the sandy sea bed in Fig. 11 shows reflector K at a subsurface depth of about 8 m. This measurement site provides a good example of the application of the inversion method to a surficial sediment layer with a lower boundary that is effectively a step change in impedance. The sand layer is characterized by low volume scattering and a lack of structure, indicating that the layer is homogeneous, an assumption of the inversion procedure. The attenuation rolloff of the sand layer is 0.44 dB/m/kHz.

The next example of a site where the attenuation rolloff measurement is applied is shown in Fig. 12. This site contains finely layered sediments. There is no surficial layer of homogeneous sediments. The use of echoes from thin layers for the spectral ratio measurement causes an interference pattern in the relative attenuation spectrum, preventing measurement of the attenuation rolloff. Reflector L at a subsurface depth of about 30 m is the shallowest reflector that approximates a step change in impedance. Since the upper layer is not homogeneous, the inversion method may not provide an accurate estimate of sediment

properties. However, if the same depositional process is responsible for the formation of the upper 30 m of sediment and porosity and other physical properties are fluctuating about mean values, the attenuation rolloff measurement and inversion procedure may provide accurate estimates of the average sediment properties. Further modeling and field studies are needed to establish the error of making such an assumption. The attenuation rolloff estimated from the echo from reflector L is 0.107 dB/m/kHz, as shown in Fig. 14. The linearity of the relative attenuation data shows that the presence of the fine layering has not affected the linear relationship between attenuation and frequency, as seen at sites with homogeneous surficial sediment layers.

D. Data Summary for Track Lines A and B

The estimates of the acoustic and physical properties of the sea bed and subsurface imagery along track lines A and B are given in Figs. 15 and 16, respectively. The reflection profiles are constructed using the full operating band of 1.5–4.5 kHz. The table under each image contains the results of inversions for sites A–M, the locations of attenuation rolloff measurements. The table lists the reflection coefficient measurements extracted from Fig. 9 or 10, the average value of attenuation rolloff measurements at each site, the thickness of the uppermost layer used in the attenuation rolloff measurement, and the sediment property estimates. The results include the porosity, permeability, grain size, and sediment type for the top sediment layer. The predicted values of porosity and permeability are inserted into the Biot model to estimate fast wave attenuation and velocity at 224, 300, 400, and 500 Hz, the frequencies of the ASIAEX propagation experiments, and at 3000 Hz, the center frequency of the chirp pulse.

A sensitivity analysis using the Biot model provides the relationships between chirp sonar measurement errors and errors in the predicted sediment properties. The attenuation rolloff measurements have 70% confidence limits of about 20%. Varying the attenuation rolloff measurement by 20% causes a 30% error in permeability and a 30% error in attenuation (in decibels/meter). The 70% confidence limits of the reflection coefficient are based on the 0.25-dB error in estimating the system constant using the bottom multiple method. A 0.25-dB change in the reflection coefficient causes a 0.015 error in porosity estimate and a 0.5% error in estimating fast wave velocity. The large $\pm 0.9\phi$ error in estimating the grain size is primarily due to the error of the Kozeny–Carman relationship, which provides the interrelationship between grain size, permeability, and porosity. This error is due to the weak relationship between mean grain size and pore properties such as permeability and porosity [2].

E. Comparison of Porosities From Inversion of Chirp Sonar Data and From Sediment Cores

Gravity core C3 provides the only sediment core data near a chirp sonar track as of the submittal date of this paper. The location of C3, near the south end of the track line B, is shown in Fig. 1. The chirp sonar passed within 1 km of the core site. Porosity, estimated from gamma-ray attenuation measurements,

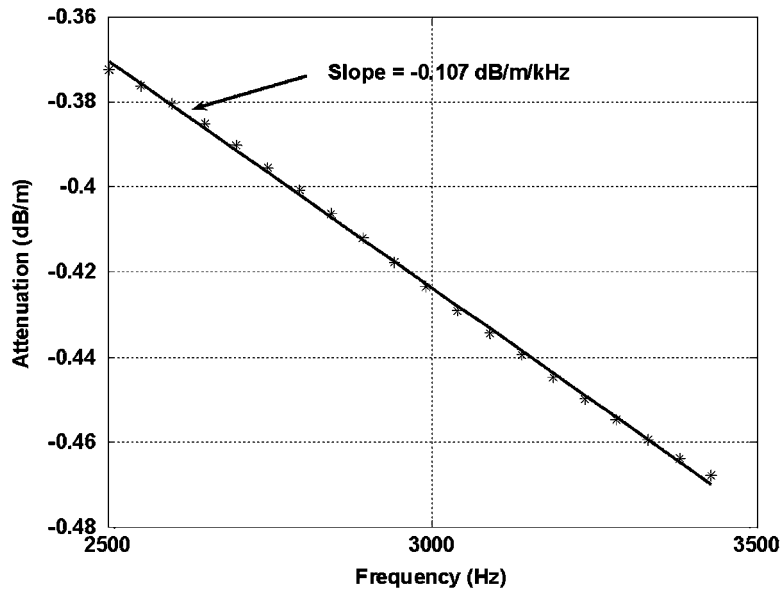


Fig. 14. Plot of relative attenuation, the layer spectral ratio divided by the two-way acoustic path through the layer above reflector *K*, shown in Fig. 12. The slope of the line fitted through the attenuation data is the attenuation rolloff, 0.11 dB/m/kHz.

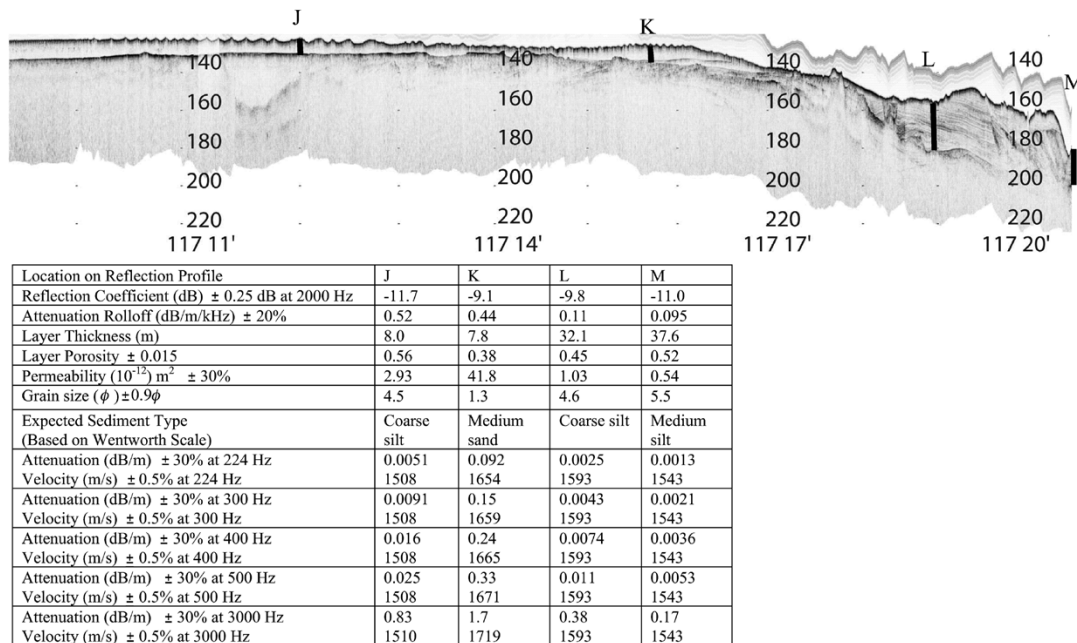


Fig. 15. Chirp sonar reflection profile collected along ASIAEX propagation line A showing longitude of research vessel *FR-I* during the survey. The table of predicted sediment properties is based on reflection coefficient and attenuation rolloff measurements of the upper sediment layer made by the chirp sonar. The vertical black bars on the reflection profile show the thicknesses of the upper sediment layer.

varies between 0.5–0.75 in the top meter of the core, as shown in Fig. 17. The core is described as muddy sand with clay content increasing with depth [7]. The sand fraction is a mixture of quartz grains and shell fragments. Due to the proximity of the chirp sonar line and core C3, and the consistency of imagery over several kilometers near the site, the uppermost layer of site H is expected to be the same layer that was sampled by core C3. The inversion of chirp sonar data at site H provides a porosity of 0.68 ± 0.015 and mean grain size of $5.1 \pm 0.9\phi$, cor-

responding to an expected sediment type of coarse or medium silt. The porosity profile in Fig. 17 and the core description, a muddy sand with increasing clay content with depth, appear to agree with the porosity and mean grain size predicted from chirp sonar data for the upper layer sediment layer, which is 13 m thick.

The location of core C2 is about 10 km from the closest chirp sonar track line, so it should not be used to check the accuracy of inversion. The northern end of track line B ended at a water

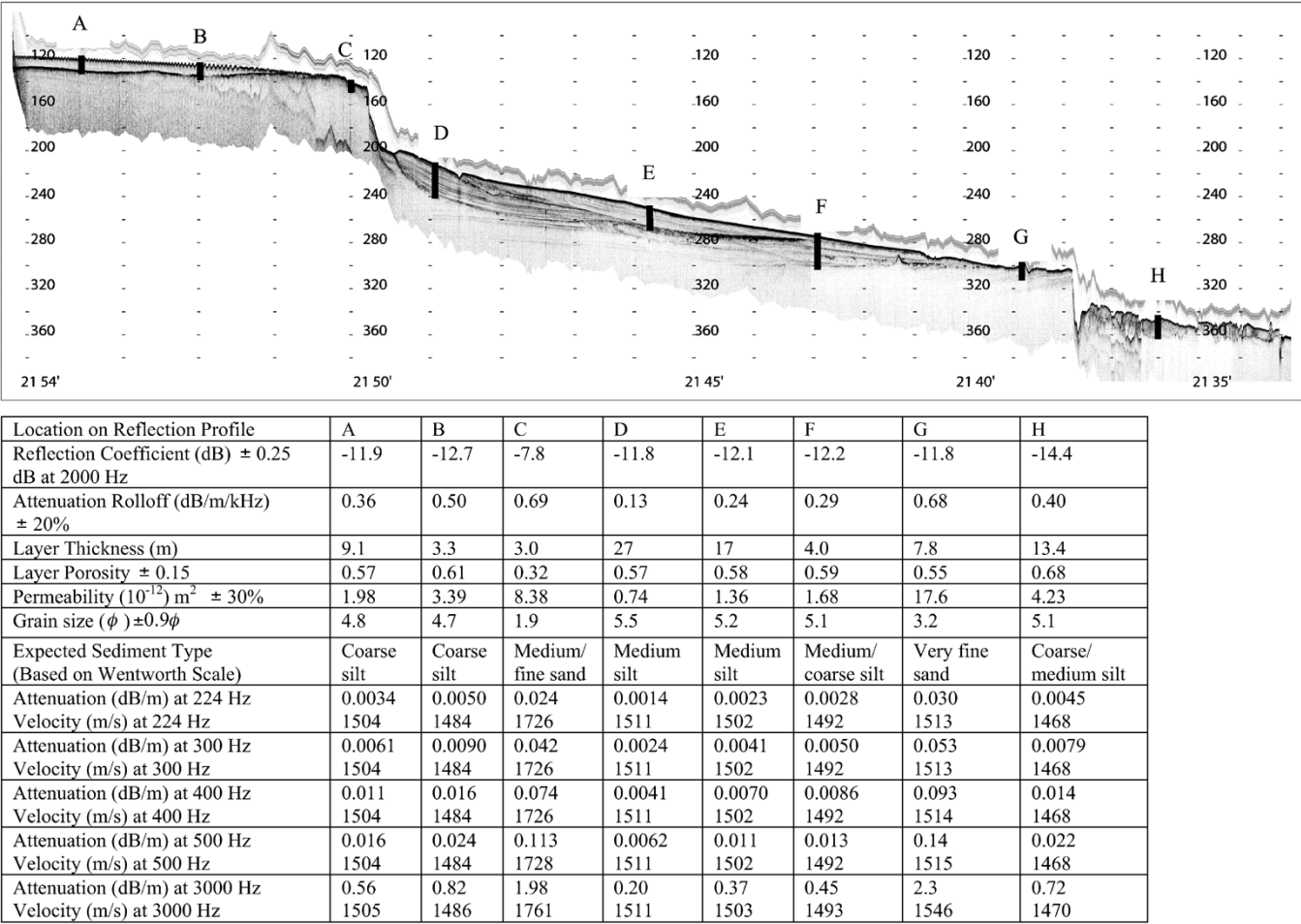


Fig. 16. Chirp sonar reflection profile collected along ASIAEX propagation line B showing latitude of research vessel *FR-1* during the survey. The table of predicted sediment properties is based on reflection coefficient and attenuation rolloff measurements of the upper sediment layer made by the chirp sonar. The vertical black bars on the reflection profile show the thicknesses of the upper sediment layer.

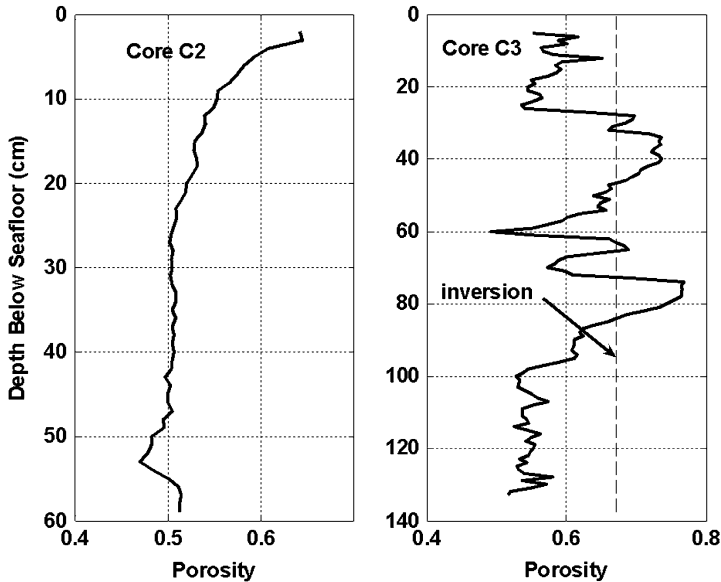


Fig. 17. Porosity profiles for cores C2 and C3 determined by the gamma ray attenuation method. The dashed line in the plot of C3 porosity represents the porosity predicted by inversion of chirp sonar data.

depth of 120 m. The C2 was collected on the continental shelf in less than 100 m of water, as shown in Fig. 1. The sediments in C2 are described as fine sand with some mud content. The sand fraction is a mixture of quartz grains and shell fragments. The porosity profile for C2 is given in Fig. 17 [7]. The porosity decreased from 0.65 near the sediment–water interface to 0.5 at 30 cm. The northernmost estimate of porosity using the inversion is at site A, where the estimated porosity is 0.57, which falls in the middle of the range of porosities for core C2. However, this agreement should not be given much weight due to the large horizontal variability of mean grain size and porosity on the continental shelf and the 10-km distance between inversion site A and core site C2.

According to Fig. 17, sediments at Core C2 have a porosity gradient, suggesting that the assumption of constant porosity may introduce a significant error into the inversion. This is one reason why the reflection coefficient measurements are made at 2 kHz near the low end of the operating band, where the acoustic wavelength is much longer than the width of the gradient, thereby reducing the effect of the gradient on the reflection coefficient measurement and the porosity estimate.

V. CONCLUSION

Sediment properties along the acoustic propagation paths of ASIAEX were estimated from chirp sonar reflection data. The relationships between the acoustic and physical properties of porous media, described by the Biot model, provided the basis for calculating the physical properties of the uppermost sediment layer. Estimates of permeability and porosity are used to calculate mean grain size using the Kozeny–Carman relation. The sediment types varied from medium silts to medium sands along the propagation lines. The distribution of sediments is shown in Figs. 15 and 16. The porosity and core descriptions reported for C3 and C2 were consistent with predictions based on chirp sonar data. However, the two core measurements do not provide sufficient data to verify the results of the chirp sonar data inversions along the ASIAEX propagation lines.

The physical properties estimates from the inversion were used to calculate the attenuation and velocity for fast waves

in the upper sediment layer along the two ASIAEX propagation paths. These acoustic properties were estimated using the Biot model at the frequencies of the propagation experiments. Acoustic propagation studies being conducted as part of ASIAEX are expected to provide estimates of sediment properties that can be compared with the results of this paper.

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