Inferring marine sediment type using chirp sonar data: Atlantis field, Gulf of Mexico

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SUMMARY

Sediment-type profiling is important for geohazards and marine geology studies. Usually this data can only be acquired by coring, which is not only expensive and time consuming, but also sparsely distributed. This paper estimates the marine sediment type with a two-step procedure: First, we perform an envelop-inversion on chirp sonar data to build the acoustic impedance profile of the sub-bottom. Unlike the seismic envelop-inversion, which is used mostly for building the background model from later waveform inversion, chirp sonar envelop-inversion is able to invert the impedance profile with the same resolution as chirp data itself. This is due to the nature of chirp sonar data compressing in the chirp processor. The field data test of the envelop-inversion agrees with the coring measurement well. Then, we use empirical equations to retrieve the marine sediment characters from inverted impedance profile. The mean grain size profile, sand percentage profile is matched with sediment type. The field data test shows the resulting pseudo-coring agrees with real coring measurement nicely. Performing this process trace by trace will give us the whole sediment type profile. All the field data in this paper is from Atlantis field, Guld of Mexico (Custody of BP Exploration).

INTRODUCTION

Sub-bottom sediment structure is important for geohazard studies, reconstructing sedimentary history, and marine seismic investigation. Therefore, estimating high-resolution sub-bottom properties is valuable study since direct measurement is costly and sparse. Chirp sonar emits broad band high frequency sweep into the sub-bottom and produces sediment profiles in real time. The processor of the chirp sonar performs waveform correlation, attenuation estimation, and amplitude-compensation in real time (Schock et al., 1989). With these advantages, chirp sonar allows us produce detailed images the of sub-bottom.

Bull et al. (1998) estimate the reflection coefficient of the water bottom with chirp sonar. LeBlanc et al. (1992) converts the reflection coefficient estimation to impedance estimation and matches the resulting impedance with sediment type. These methods only reveal the parameters of the water bottom or the first sub-bottom layer. To reveal the deeper structure of the sub-bottom, performing waveform -inversion of the whole sonar trace is necessary. This was developed into two steps scheme: first, build a simplified layered model with few thick layers. Then, perform inversion with the fixed layered model (Wood and Lindwall, 1996; Seong and Park, 2001; Park et al., 2003). However, the sub-bottom structure usually is more complex than a few layers. For the purpose of sedimentary history and geohazard study, reconstructing the detailed sub-bottom parameters may be critical.

In this paper, we estimate the detailed sediment parameters along the whole chirp sonar. Different from seismic data, most of the chirp data is recorded and compressed as a magnitude instead of wiggle form. To estimate the sediment properties from chirp data, we perform an envelope-based objective function waveform-inversion (Wu et al., 2014; Chi et al., 2014). In addition, using an empirical relationship between sediment type and acoustic impedance developed by (Wentworth, 1992; Richardson and Briggs, 2002), we build the sediment type profile from chirp sonar data. Field data is tested with this method. Comparison between the result of waveform-inversion and coring measurement demonstrates the promise of this approach.

INVERSION SCHEME

Waveform-inversion retrieves the parameters of the subsurface by minimizing the difference between recorded waveforms and forward modeling waveforms with estimated model. It can be described as solving the nonlinear least-squares problem. The objective function is written as:

$$\sigma(\mathbf{d}) = \frac{1}{2}\sum_{s.r}\int_0^T |d_{model} - d_{obs}|^2 dt, \qquad (1)$$

where d_{obs} is the recoreded data, d_{model} is the forward modeling data, T is total recording time.

The chirp data before compression is an analytic signal:

$$d_a(t) = d(t) + iH(d(t)), \qquad (2)$$

where H(d(t)) is the Hilbert transform of the real part of the data, $d_a(t)$ is the analytic form of the data.

After the chirp data is compressed, the data becomes a magnitude, or envelope, of the original analytic signal:

$$\begin{aligned} E(d_a(t)) &= \sqrt{Re[d_a(t)]^2 + Im[d_a(t)]^2} \\ &= \sqrt{d(t)^2 + H(d(t))^2}, \end{aligned} \qquad (3)$$

Therefore, the objective function of chirp inversion can be written as:

$$\sigma(\mathbf{d}) = \frac{1}{2}\sum_{s.r}\int_0^T |E(d_{model}) - E(d_{obs})|^2 dt, \qquad (4)$$

Because the sonar (ping) source and receiver are very close to each other compared to the water depth, the ray path can be approximated as normal incident. The converted wave (P-S wave) is ignored due to the low shear-wave velocity of the sediment (Ivakin and Jackson, 1998) and low conversion rate for normal incident (Brekhovskikh and Lysanov, 2003). Internal multiples are not considered due to the attenuation in marine sediment (Hamilton, 1972). Because the near-surface

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sediment structure can be approximated as layered, so 1-D inversion will be valid. For constructing a 2-D profile, one can perform 1-D inversion trace by trace.

The velocity and density of near-surface sediment in shallow water environment disturb very little (Hamilton, 1970; Hamilton and Bachman, 1982). As a result, the acoustic effect from each of these two properties,individually, is hard to distinguish. The chirp sonar is not sensitive to other parameters, i.e.,layer roughness and attenuation (Rakotonarivo et al., 2011). Given these facts, we will only invert for the impedance.

ENVELOPE-INVERSION OF CHIRP DATA

The chirp sonar data is from BP Exploration university donation data set. The survey area is Atlantis in Gulf of Mexico. To test the chirp sonar envelope-inversion, we choose sonar data with coring data available at the same location. The chirp sonar is high-frequency sweep from 2 to 10 kHz with record the length of 300 milliseconds. The synthetic modeling in Figure 1 shows chirp sonar data compressing flow: The received signal (raw data, Figure 1c) is autocorrelated with source sweep wavelet (Figure 1b) and then the resulting analytic signal (blue line in Figure 1c) is compressed as magnitude (red dash line in Figure 1d).

The sub-bottom profile is shown in Figure 2. The velocity used for time-depth conversion is 1500 m/s. One coring measurement available in this profile. The depth of coring measurement is 4 m. For the test purpose, envelop-inversion is perform on part of one trace which overlaps with the coring measurement. The coring measurement, real data, and the inversion results are shown in Figure 3.

From Figure 3, we can see that the envelope fits true data reasonable well. The acoustic impedance from the envelope-inversion agrees with the direct measurement trends. Even though the envelope of final result fits with true chirp sonar data, the inverse impedance is still more ambiguous because of the lack of phase information. Considering the range of jitter is minor comparing with the impedance difference of two sediment type, the variation on inverse impedance curve is acceptable and won't affect the sediment classification. The major events on the impedance curve resulted from inversion match with the chirp sonar trace, the resolution of inversion is at same order as chirp sonar itself. This is different from seismic waveform-inversion, which uses envelope-inversion as a tool for building a background model to compensate the low frequency content (Wu et al., 2014). Indeed, the chirp sonar waveform is already been transformed as an envelope, so as long as the envelope from inversion matches with the true data, the resolution should be preserved. To test how detailed envelope can be fitted in envelope-inversion, we test on an other trace with deeper penetration and more complex reflectors. The result is shown in 4. The water column is muted from the trace in order to avoid the noise effect from it. With complex layering, the envelop-inversion still be able to fit with data in detailed and reveal the major impedance disturbances. This means envelope-inversion with chirp sonar data can give rea-

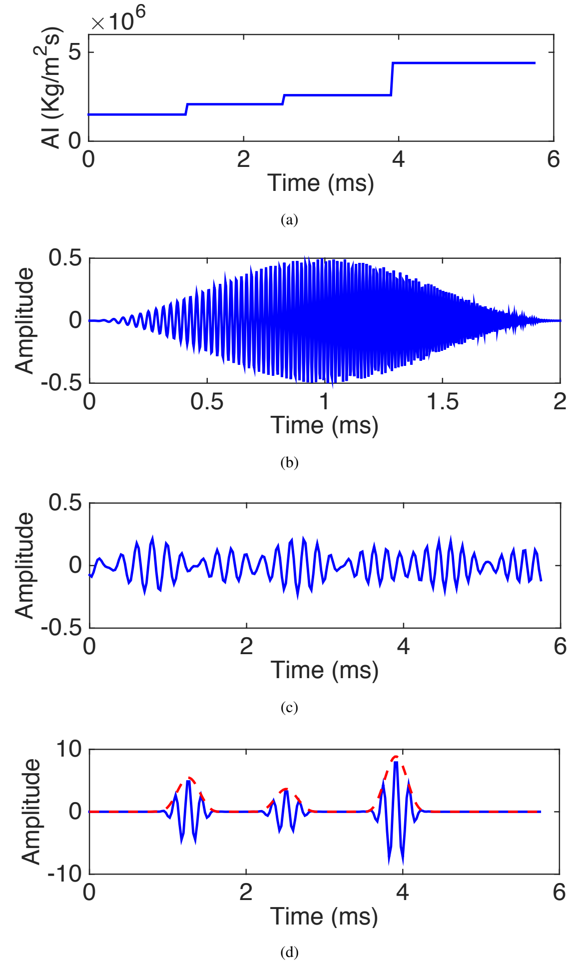

Figure 1: Synthetic test data. (a) Acoustic impedance model. (b) Source sweep, the frequency is from 2 to 10 kHz. (c) Raw data. (d) Blue: Analytic signal after cross-correlating source sweep (b) with raw data (c). Red: Compressed chirp data, with is the envelope of the analytic signal.

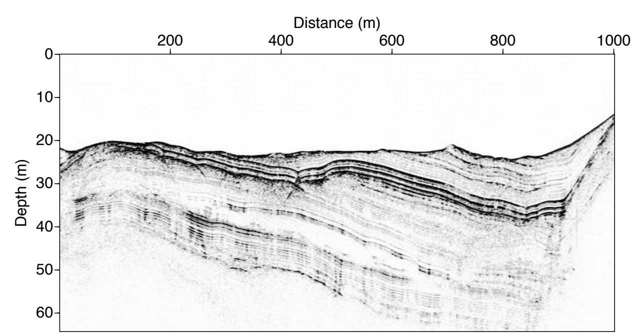

Figure 2: Chirp sonar profile from Atlantis in Gulf of Mexico. The data is donated by BP Exploration. The velocity used for Time-Depth conversion is 1500 m/s.

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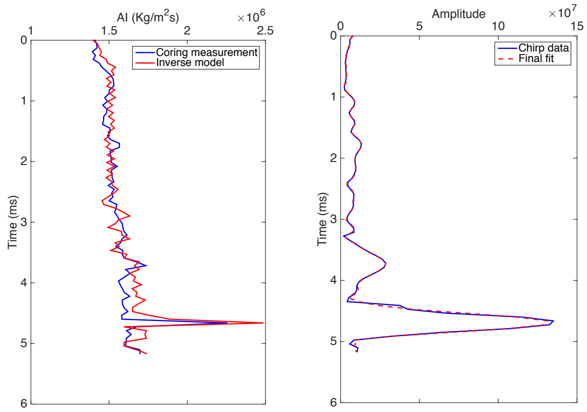
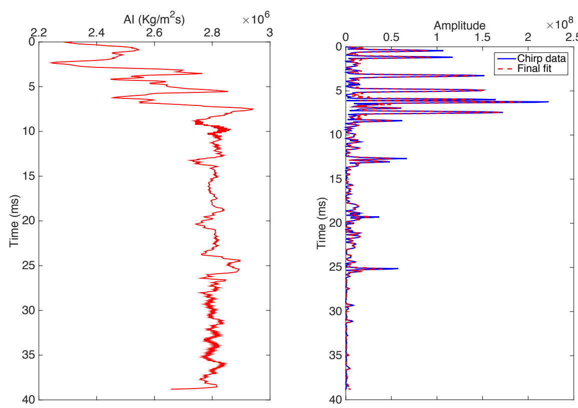
sonable results with resolution preserved.



(a) (b)

Figure 3: (a) Direct measurement from coring (blue) and the impedance from envelope-inversion (red).(b) True chirp sonar data (blue) and the final best fit envelope (red).



(a) (b)

Figure 4: (a) Impedance from envelope-inversion.(b) Original trace (blue) and the final best fit envelope (dash red).

SEDIMENT TYPE ESTIMATION

A main property of marine sediment is its sediment type, which is dominantly characterized by mean grain size and sand percentage (Kim et al., 2004). Richardson and Briggs (2002) developed the empirical relationship between acoustic impedance and sediment properties such as mean grains size (θ) and sand percentage:

$$\theta = 17.9 - 6.0(IOI) = 17.9 - 6.0(AI/Vp), \quad (5)$$

$$R = -113.4 + 89.1(IOI) = -113.4 + 89.1(AI/Vp), \quad (6)$$

where IOI is the Index of Impedance, which is the product of the sediment bulk density and sound velocity ratio between in the sediment and in the water. AI is the acoustic impedance. Vp is the sound velocity in the water. R is the sand and gravel percentage in the sediment.

Table 1: Wentworth (1922) grain size classification. Only θ from 0.0 to 14.0 is listed.

Mean grain size (θ)	Sediment type
0.0 – 1.0	Coarse sand
1.0 – 2.0	Medium sand
2.0 – 3.0	Fine sand
3.0 – 4.0	Very fine sand
4.0 – 5.0	Coarse silt
5.0 – 6.0	Medium silt
6.0 – 7.0	Fine silt
7.0 – 8.0	Very fine silt
8.0 – 14.0	Clay

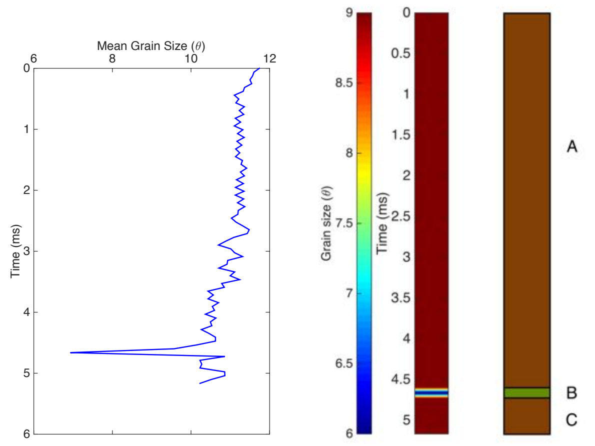
Hence, we can retrieve the mean grains size (θ) and sand percentage from chirp sonar data by inputting envelope-inversion result into Equation 5 and Equation 6. Wentworth (1992) links the mean grain size directly with the sediment type. Table 1 shows parts of Wentworth (1992)'s table that describes many ocean bottom cases (soft bottom).

To reconstruct the sediment information of the sub-bottom with chirp sonar data, we can input the envelope-inversion result into Equation 5 and Equation 6. The result will be like a pseudo-coring. Then match this pseudo-coring with Table 1 and give them the meaning of sediment type. In Figure 3 (a), we reconstruct the pseudo-coring from the envelop-inversion result. Figure 5 (b) shows the comparison between reconstructed pseudo-coring measurement and actual coring measurement. The pseudo-coring agrees with actual coring measurement nicely.

Applying the same procedure to the trace with deeper penetration in Figure 4. The results are shown in Figure 6. As we can see, in the shallow part, the sediment is mainly muddy sediment with small sand and gravel percentage. As moving deeper, the particle size of sediment becomes bigger and more sandy. Notice even inside same type of sediment layer, there are still impedance variations causing reflections. Comparing to the impedance variation between different sediment type, these variations are relatively small. So, the definition of layers from the acoustic reflection point of view dose not necessary agree with sediment type.

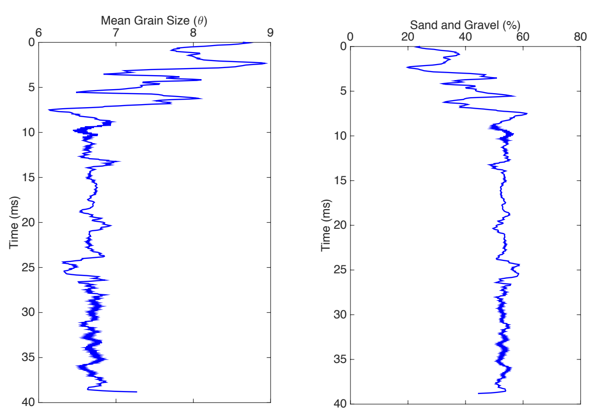
To reveal the sedimentary structure of the whole chirp sonar profile, one can repeat the above envelope-inversion following by sediment classification procedure trace by trace. One could also just perform the same procedure only at the critical traces and extrapolate the result to the rest part of the profile. Figure 7 shows the sediment classification of the whole chirp sonar profile in Figure 2.

The sediment classification profile reveals the sediment type and sand and gravel percentage up to 40 m depth below the seafloor, which are usually expensive to acquire or not available from coring survey. In the shallow part of the profile, the



(a) (b)

Figure 5: (a) The mean grain size (θ) profile retrieved from chirp envelop-inversion in Figure 3 (a). (b) Left: The estimated coring measurement from (a). Right: The actual coring measurement, where A is very soft clay, B is very firm silt, C is soft clay.



(a) (b)

Figure 6: (a) The mean grain size (θ) profile retrieved from chirp envelope-inversion.(b) The sand and gravel percentage profile retrieved from chirp envelope-inversion.

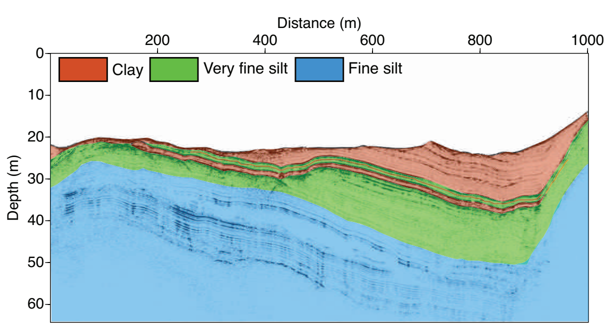


Figure 7: Sediment type profile of the whole chirp sonar session in Figure 2. The three colors signify three types of sediments: Clay (brown), very fine silt (green), and fine silt (blue).

sediment type changes frequently, which may due to the effect of marine current flow. In the deeper part (blue area in Figure 7), even though there are several significant reflection events, they still belong to same sediment type. Revisiting amplitude (Figure 4 (b)) and impedance profile from inversion (Figure 4 (a)), the impedance contrast and amplitude is not as high as sedimentary boundary.

CONCLUSIONS

In this paper, we propose a two-step procedure to estimate the sediment type with chirp sonar data. First, we perform the envelope-inversion on chirp-sonar data to invert the impedance profile. Then, using the inverted impedance profile and empirical equations, we reconstruct pseudo-coring along each trace. From there, we can rebuild the sediment type profile. Envelope-inversion of chirp sonar data can reveal the detailed impedance structure of the sub-bottom. Unlike seismic envelope-inversion, which is used mostly for building background model for consequent waveform-inversion, chirp sonar data is already compressed as envelope data, so performing envelope-inversion on chirp-sonar data will generate the same resolution profile as chirp data. Due to the normal incident nature of chirp sonar configuration, the envelope-inversion is perform in 1-D scheme, which is very efficient. The field data test shows the inversion result agrees with the coring measurement well. The sedimentary characters, such as mean grain size, sand and gravel percentage, and sediment type, are important to geohazard and marine geology study. Usually this type of information is either only can be acquired by coring or unavailable. Combing the envelop-inversion result with empirical relationship between impedance and these sediment characters, we can reconstruct the sediment characters profile of the sub-bottom.

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EDITED REFERENCES

Note: This reference list is a copyedited version of the reference list submitted by the author. Reference lists for the 2015 SEG Technical Program Expanded Abstracts have been copyedited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

REFERENCES

Brekhovskikh, L. M., and I. P. Lysanov, 2003, Fundamentals of ocean acoustics: Springer Science & Business Media.

Bull, J. M., R. Quinn, and J. K. Dix, 1998, Reflection coefficient calculation from marine high resolution seismic reflection (chirp) data and application to an archaeological case study: Marine Geophysical Researches, **20**, no. 1, 1–11. http://dx.doi.org/10.1023/A:1004373106696.

Chi, B., L. Dong, and Y. Liu, 2014, Full waveform inversion method using envelope objective function without low frequency data: Journal of Applied Geophysics, **109**, 36–46. http://dx.doi.org/10.1016/j.jappgeo.2014.07.010.

Hamilton, E. L., 1970, Reflection coefficients and bottom losses at normal incidence computed from pacific sediment properties: Geophysics, **35**, 995–1004. http://dx.doi.org/10.1190/1.1440149.

Hamilton, E. L., 1972, Compressional-wave attenuation in marine sediments: Geophysics, **37**, 620–646. http://dx.doi.org/10.1190/1.1440287.

Hamilton, E. L., and R. T. Bachman, 1982, Sound velocity and related properties of marine sediments: The Journal of the Acoustical Society of America, **72**, no. 6, 1891–1904. http://dx.doi.org/10.1121/1.388539.

Ivakin, A. N., and D. R. Jackson, 1998, Effects of shear elasticity on sea bed scattering: Numerical examples: The Journal of the Acoustical Society of America, **103**, no. 1, 346–354. http://dx.doi.org/10.1121/1.421094.

Kim, G. Y., M. D. Richardson, D. L. Bibee, D. C. Kim, R. H. Wilkens, S. R. Shin, and S. T. Song, 2004, Sediment types determination using acoustic techniques in the northeastern Gulf of Mexico: Geosciences Journal, **8**, no. 1, 95–103. http://dx.doi.org/10.1007/BF02910282.

LeBlanc, L. R., L. Mayer, M. Rufino, S. G. Schock, and J. King, 1992, Marine sediment classification using the chirp sonar: The Journal of the Acoustical Society of America, **91**, no. 1, 107–115. http://dx.doi.org/10.1121/1.402758.

Park, C., W. Seong, P. Gerstoft, and M. Siderius, 2003, Time- domain geoacoustic inversion of high-frequency chirp signal from a simple towed system: IEEE Journal of Oceanic Engineering, **28**, 468–478.

Rakotonarivo, S., M. Legris, R. Desmare, J.-P. Sessarégo, and J.-F. Bourillet, 2011, Forward modeling for marine sediment characterization using chirp sonars: Geophysics, **76**, no. 4, T91–T99. http://dx.doi.org/10.1190/1.3590717.

Richardson, M. D., and K. B. Briggs, 2002, Empirical predictions of seafloor properties based on remotely measured sediment impedance: Technical report: DTIC Document.

Schock, S. G., L. R. LeBlanc, and L. A. Mayer, 1989, Chirp subbottom profiler for quantitative sediment analysis: Geophysics, **54**, 445–450. http://dx.doi.org/10.1190/1.1442670.

Seong, W., and C. Park, 2001, The fine scale geo-acoustic inversion of the shallow water sub-bottom using chirp signals: OCEANS, 2001. MTS/IEEE Conference and Exhibition, IEEE, 723–730.

Wentworth, C. K., 1992, A scale of grade and class terms for clastic sediments: The Journal of Geology, 30, 377–392.

DOI http://dx.doi.org/10.1190/segam2015-5918190.1

Wood, W. T., and D. Lindwall, 1996, Full waveform inversion of field sonar returns for a visco-acoustic earth; a comparison of linearized and fully nonlinear methods: IEEE Journal of Oceanic Engineering, 21, 423–431.

Wu, R.-S., J. Luo, and B. Wu, 2014, Seismic envelope inversion and modulation signal model: Geophysics, **79**, no. 3, WA13–WA24. http://dx.doi.org/10.1190/geo2013-0294.1.