Pre-stack inversion of a Gulf of Thailand OBC data set
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Summary
Pre-stack seismic waveform inversion is a highly challenging task. Non-linearity and non-uniqueness together with compute intensive forward modeling make the problem close to intractable. We report on the results obtained with a new approach to pre-stack inversion based on a gradient descent scheme that makes use of innovative gradient calculation, adaptive regularization, and an efficient conjugate gradient algorithm. Our inversion approach exploits sparsity of the gradient matrix in designing an algorithm that is computationally very efficient. Results are highly encouraging in that we are able to invert large data set with nearly 600 model parameters fairly rapidly. Because of the use of adaptive regularization, we are able to track smooth as well as sharp variations in the impedance, Vp and Vs profiles when realistic initial solutions are used to start the inversion. We have applied the technique successfully to the inversion of a hydrophone data set recorded on ocean bottom cables in the Pattani basin of the Gulf of Thailand. This basin is one of the major gas producing regions in the world. Several AVO anomalies and bright spots characterize the data set. We were able to obtain detailed maps of compressional wave velocity, shear wave velocity and density. These were then mapped into profiles of Lame’ parameters, Poisson’s ratio and compressional and shear impedances. Several gas zones were identified based on the anomalies resolved by these attribute sections.

Introduction
Full waveform pre-stack seismic inversion as an aid for reservoir characterization is still a challenging task in the seismic industry. A seismic waveform is characterized by its travel time, amplitude and phase. These three intrinsic parameters contain information on the variation of elastic properties of a medium in which seismic wave propagates. For example, analysis of travel time data yields information about the low frequency or smooth component of the velocity field whereas amplitude and phase are sensitive to the high frequency component of the velocity field (e.g., Sen and Stoffa, 1995; Xia et al., 1998). A detailed knowledge of the velocity field with both high and low frequency component is essential in delineating elastic properties of the medium and helps in the direct detection of hydrocarbon, lithology discrimination, estimation of fluid contents (e.g., Castagna and Backus 1993), etc. Travel time inversion or even migration of seismic wave field in pre-stack domain provides an estimate of the low frequency velocity field. However, to obtain an estimate of high frequency velocity field either amplitude variation versus offset (AVO) type inversion or a pre-stack inversion is required. Conventionally, AVO analysis determines fractional change in P-impedance and Poisson’s ratio from a linear fit of NMO corrected P- reflection amplitude to the square of the sine of angle of incidence. Thus, conventional AVO analysis deals with ‘primaries only’ model; mode-converted waves and internal multiples are not included. Inverting a full waveform seismic data in pre-stack domain is vital for the precise mapping of the subsurface variation in elastic properties. However, practical implementation of such an inversion scheme on a routine basis becomes difficult as (1) the inverse problem is highly nonlinear, (2) the error function, a measure of data misfit possesses multimodality, (3) the forward problem is extremely compute-intensive and (4) careful data processing is necessary to preserve true amplitudes. Here, we use a constrained gradient-descent scheme to invert plane wave (t-p) transformed seismic data that can be used as a tool for reservoir characterization.

Forward Problem and Optimization
In our inversion we make use of data transformed into the plane wave domain and generate plane wave synthetics using reflectivity method. We modified the reflectivity calculations such that partial responses are stored and a gradient matrix can be computed as a by-product of the forward modeling. Our new gradient calculation scheme requires only one extra forward modeling evaluation. We also have an option to pre-compute the reflectivity response of the overburden layers and only invert for the properties of the target zone.

If \( \mathbf{d} \) is the vector of observed data, \( g(\mathbf{m}) \) is the vector of computed data for some model \( \mathbf{m} \) then we may define the data misfit error \( E_d \) or error functional as

\[
E_d = (\mathbf{d} - g(\mathbf{m}))^T \mathbf{C}_d^{-1} (\mathbf{d} - g(\mathbf{m})) \quad (1)
\]

For better performance, we minimize a smooth variant of the error functional whose smoothness is controlled adaptively. We thus define a smooth functional as

\[
S(\mathbf{m}; \alpha) = E_d + \alpha(\mathbf{m} - \mathbf{m}_{pr})^T \mathbf{C}_m^{-1} (\mathbf{m} - \mathbf{m}_{pr}) \quad (2)
\]
where, $m_{ap}$ is the a-priori model, $C_m^{-1}$ is the model covariance matrix and $\alpha$ is the regularizing weight which plays a central role in the algorithm. We minimize $S(m, \alpha)$ via non-linear conjugate gradient technique to obtain model update vector $\Delta m^\alpha$ corresponding to each $\alpha$ value wherein the regularization weight is obtained via a modified discrepancy principle (Roy, 2002).

**Gulf of Thailand OBC data**

We present a case study of pre-stack inversion of a Gulf of Thailand ocean bottom cable (OBC) data set. Our study area is Pattani basin, the largest gas field (~300 Km long and 50-80 Km wide) and most prolific hydrocarbon basin in Gulf of Thailand. Pattani basin primarily contains alluvial lacustrine deposits of tertiary age and its basin fills is composed of both non-marine or marginal marine siliciclastic sediments. Sediments contain carbonaceous shale, dirty sand and coal deposits. The gas source rocks are the early Miocene fluvial-deltaic coals and the carbonaceous shale. Reservoir rocks are considerably thin (average pay thickness of sands are 4.6 m) and do not exhibit a strong lateral continuity. However, high porosity (10 to 25%) and high permeability values (~2000 md) make the basin a significant commercial source for natural gas. The zone of exploration (marked with red rectangle in Figure 1) is located within both the fluvial flood plain and the lower delta plain of middle Miocene age. Geco-Prakla under contract from Unocal Corporation acquired 2D 4-components 120 channels of OBC seismic data in the study area. During data processing P and vertical velocity components were summed to attenuate multiples. True amplitudes were restored and the gathers were time migrated (Figure 1).

For our inversion run we chose pre-processed (P and Z components) time migrated CMP gathers. We identified the zone of interest at around 1.5 to 2.0 s. First we transform the CMP gathers to $\tau$-$p$ (plane wave) domain and scale the data appropriately using well log information and estimated a source wavelet from a post-stack seismic section before any inversion was run. Figure 2 is a plot of the without and with NMO CMP-2215 gather and $\tau$-$p$ transformed CMP-2215 gather respectively. Since our zone of interest lies between 1.5 s to 2 s we present results between 1.5 to 2 s for clarity. Here, we can identify several events where there is strong evidence of AVO effect. Those are at 1.61, 1.66, 1.70, 1.77, 1.81, 1.86, 1.90, 1.93, 1.95 s respectively. For clarity we designate these events as Ev-1, Ev-2, Ev-3, Ev-4, Ev-5, Ev-6, Ev-7, Ev-8 and Ev-9 respectively. From a general inspection it is obvious that events Ev-1, Ev-2, Ev-6 Ev-8 and Ev-9 exhibit an initial increase of amplitude with offset, and then the amplitude diminishes with larger offset. On the other hand events Ev-3, Ev-4, Ev-5 and Ev-7 show an increases in amplitude with offset and form bright spots. This suggests that Ev-1, Ev-2, Ev-6, Ev-8 and Ev-9 correspond to class I type gas sands whereas, Ev-3, EV-4, EV-5 and Ev-7 correspond to class III type gas sands. In Figure 3 we present results after inverting a CMP gather (CMP-2215). Note that the sharp fall in $V_p$, $V_s$ and $\rho$ correspond to the strongest bright spot at 1.77s (Ev-4). There is a considerable fall in $\lambda$ value at event Ev-4 which indicates the presence of gas bearing zone. Additional zones (possibly gas bearing) are also identified at 1.61s, 1.90s and 1.95s. We then inverted a suite of CMP gathers within the zone marked with a red box in Figure 1. The results are presented as color contour maps in Figure 4. Several different anomalous zones are clearly observed in our inverted results.

**Conclusions**

In order to achieve our goal to derive elastic parameter profiles for reservoir characterization, we have developed and implemented a fast pre-stack inversion algorithm. Application of the algorithm to the inversion Gulf of Thailand data set provided detailed maps of elastic properties including Lame parameters and Poisson’s ratio. The latter map can be derived efficiently and can be used effectively in resource evaluation.

**References**


**Acknowledgements**

The work reported here has been supported by a grant from the US department of Energy DE-FC26-00BC15305. We would like to express our gratitude to UNOCAL Corporation for release of the field data set described in this extended abstract.
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**Figure 1.** Time migrated stack section of P+Z data. The area inscribed inside the red rectangle is the zone of interest.

**Figure 2.** CMP-2215 processed gather — before NMO (left panel), after NMO (middle panel) and after τ-p transformation (right panel).
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**Figure 3:** Results from pre-stack inversion of CMP-2215: NMO corrected CMP gather and the derived profiles of Vp, Vs, density, Lame parameters and Poisson's ratio. The characters in the inverted profiles can be correlated with horizons.

**Figure 4:** Contour sections derived from pre-stack inversion. Prominent lows in Vp, \(\lambda\), \(\mu\) and \(\sigma\) around 1.70s can easily be observed in the cross sections.