Removal of elastic interface multiples from land and ocean bottom data using inverse scattering

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Summary

A method is presented which removes multiples associated with an elastic free-surface for land data or an acoustic layer in contact with an elastic boundary for ocean bottom data. This is the first multiple removal formulation for elastic measurements on the ocean bottom. The method is based on an elastic inverse scattering series and properly accounts for all wave phenomena e.g. ghosts, obliquity factors.

The method requires multi-component data and knowledge of medium properties at and above the sources and receivers. However, it requires no information about the earth below the sources and receivers. Tests indicate the method is robust with respect to missing data components and errors in estimating near surface properties. The source wavelet and near offsets are needed for effective multiple removal. This work sets the stage for the development of an inverse scattering internal demultiple method using an elastic reference medium.

Introduction

Traditional methods of multiple suppression rely on characteristics such as differential moveout or periodicity to distinguish and separate multiples from primaries. These methods are very effective when their underlying assumptions are valid. In situations where these assumptions are violated e.g. dipping beds, conventional methods become less effective and we must seek another path. Inverse scattering is one approach which provides a solution to this problem.

Using inverse scattering formulation, Carvalho et al. (1992) have identified a subseries which performs free surface multiple removal for marine seismic data. Others (Verschuur and Berkhout (1992), Fokkema and Van den Berg (1990)) have presented solutions to the marine free surface multiple problem using a surface elimination approach. Araujo et al. (1994) have developed an inverse scattering series to suppress internal multiples from marine seismic data. Verschuur et al. (1988) have also adapted the surface elimination approach, based on Huygen's Principle, to free surface elastic multiples.

The method of Carvalho et al. (1992) is applicable to marine seismic data where the sources and receivers are located in an acoustic medium, i.e., within the water column. When seismic data are recorded on land or at the ocean bottom, receivers are located on or in an elastic media. Using an elastic inverse scattering subseries, we derive a method that removes both reflected and converted multiples associated with an elastic free surface for land data, or an acoustic layer over an elastic boundary for ocean bottom data.

Ocean bottom data is of particular interest because of the potential for improved recovery through better reservoir characterization. By affixing receivers on the ocean bottom over a known oil or gas field and acquiring data at different times, we can seismically monitor the reservoir as it is being depleted thus providing information to aid in production strategy. Given the high degree of confidence required in development and production projects, multiple free seismic data is especially desirable.

Method

Elastic multiple removal

We employ a forward scattering description of seismic data which can be written as an infinite series of terms in f-k space

$$G = \mathbf{G_0} + \mathbf{G_0 V G_0} + \mathbf{G_0 V G_0 V G_0} + \dots .$$

In this equation G is the Green's function in an inhomogeneous medium, $\mathbf{G_0}$ is the Green's function in a reference or background medium and V is a perturbation operator that represents the difference in mechanical earth properties between the background and the actual medium. We define the data to be only the scattered portion of the wavefield $\mathbf{D} = \mathbf{G} - \mathbf{G_0}$. Each of the above quantities is a 2 by 2 matrix which has been transformed into P-S coordinates from x-z coordinates. Hence the data is

$$\mathbf{D} = \begin{bmatrix} D_{PP} & D_{PS} \\ D_{SP} & D_{SS} \end{bmatrix}$$

where the rows represent P or S wave measurements and the columns represents P or S wave sources. Next we obtain an inverse series which provides the framework for multiple suppression.

We postulate the existence of an inverse series

$$\mathbf{V} = \mathbf{V_1} + \mathbf{V_2} + \mathbf{V_3} + \dots$$

where $\mathbf{V_n}$ is n^{th} order in the measured data. Substituting this inverse series into the forward series and matching terms of equal order in the data gives a series of equations to solve for V.

$$\begin{aligned} \mathbf{D} &= \mathbf{G_0 V_1 G_0} \\ 0 &= \mathbf{G_0 V_2 G_0 + G_0 V_1 G_0 V_1 G_0} \end{aligned}$$

This series can be thought of as a step by step process to obtain the earth model V from the measured surface data D. Unfortunately, it has limited utility in providing inverse solutions. It is possible, however, to separate out the task of multiple removal by selecting a subseries from the full inverse series. This subseries is stable and removes all free surface or ocean bottom multiples order by order.

Generally the reference medium is selected to be the medium at and above the source and receivers. For land data, we choose the reference medium to be an elastic half space bounded by a free surface. For P and S sources and measurements at or below the free surface, the reference Green's function can be written as the sum of two parts $\mathbf{G_0 = G_0^D + G_0^{FS}}$. The first part represents propagation directly from the source to receiver. The second portion represents reflections from the free surface; it is responsible for constructing and eliminating events that arise due to the presence of the free surface.

For ocean bottom data, we choose the reference medium as the water layer overlying elastic ocean bottom material which extends to infinity (see figure (1)). For a P and S source at depth and a P and S measurement at the ocean bottom we can write $\mathbf{G_0} = \mathbf{G_0^D} + \mathbf{G_0^{WL}}$ where $\mathbf{G_0^{WL}}$ contains primary and multiple reflections from both the top and bottom of the water layer. This second term is used to select a subseries which removes all multiples associated with both the water top and water bottom.

Both the land and marine multiple elimination scheme can be written as a data series in the f-k domain

$$\begin{aligned} \mathbf{D'} &= \mathbf{D^{(1)} + D^{(2)} + D^{(3)}} + \ldots \\ &= \mathbf{D^{(1)} + D^{(1)} H D^{(1)}} \\ &\quad \mathbf{+ D^{(1)} H D^{(1)} H D^{(1)}} + \ldots \end{aligned}$$

where the n^{th} term is responsible for the removal of all of the $(n - 1)^{th}$ order free surface or water bottom multiples. In this equation, $\mathbf{D^{(1)}}$ is the input data Fourier transformed over shot, receiver and time domains, H depends on the free surface or acoustic-elastic reflection coefficients and D' is the data without multiples.

Inverse scattering multiple removal has some distinct advantages over more conventional methods. Most importantly, the method does not require a knowledge of the wave velocity below the sources or receivers in order to effectively remove multiples. In addition, primaries are preserved. The tradeoff for relaxation in velocity information is a requirement for source wavelet knowledge and near offset traces. A useful approach to this problem is to estimate the wavelet by minimizing the energy of the traces after multiple removal with respect to the wavelet parameters (Verschuur and Berkhout, 1992). Various realizations of this concept have been demonstrated for marine seismic data (Carvalho and Weglein, 1994 and Ikelle et al., 1995) and are also applicable to the land and ocean bottom cases.

Similar to the marine case, this method assumes a known elastic medium at and above the sources and receivers. This condition is more difficult to satisfy for elastic data because of the variability of the near surface and ocean bottom. We present synthetic examples which demonstrate that the multiple removal method is robust with respect to errors in estimating near surface parameters.

Two dimensional theory requires the use of 4 component (2 source and 2 receiver) data to remove all P and S multiples. We show that useful results can be produced using data with less than 4 components. This method also places high demands on a complete data set. Missing near offset traces must be either recorded or interpolated for optimum multiple suppression.

P-S decomposition

Before multiples can be removed from elastic data, the acquired data must be transformed from x-z coordinates to P-S coordinates. On land, we assume that the data have 4 components consisting of vertical and horizontal displacement (or velocity) surface measurements due to vertical and horizontal line sources. The source and receiver decomposition can be written as a multiplication by two matrices in f-k domain (Wapenaar et al., 1990) $\mathbf{D = N\mathcal{D}M}$ where $\mathcal{D}$ is data in x-z, D is data in P-S. This transforms the data into downgoing P and S waves at the source and upgoing P and S waves at the receiver. The receiver decomposition matrix, N, is given by

$$\mathbf{N} = \left(\frac{\beta}{\omega}\right)^2 \begin{bmatrix} -ik_g & \frac{i(\eta_g^2 - k_g^2)}{2\nu_g} \\ \frac{-i(\eta_g^2 - k_g^2)}{2\eta_g} & -ik_g \end{bmatrix}$$

where k_g is wavenumber over geophone domain and ν_g and η_g are vertical wavenumbers given by

$$\nu_g = \frac{\omega}{\alpha}\sqrt{1 - \left(\frac{\alpha k_g}{\omega}\right)^2}, \ \eta_g = \frac{\omega}{\beta}\sqrt{1 - \left(\frac{\beta k_g}{\omega}\right)^2}$$

with α and β being the P and S wave velocities of the reference medium and ω is the angular temporal frequency. Similarly, the source decomposition matrix is

$$\mathbf{M} = \left(\frac{\beta}{\omega}\right)^2 \begin{bmatrix} ik_s & \frac{-i(\eta_s^2 - k_s^2)}{2\eta_s} \\ \frac{i(\eta_s^2 - k_s^2)}{2\nu_s} & ik_s \end{bmatrix}$$

where k_s is wavenumber over shot domain.

For ocean bottom data, we assume vertical and horizontal measurements and a pressure source in the water column. A decomposition transforms the data into upgoing P and S waves at the receivers and is written as D = $\mathbf{Q}\mathcal{D}$ where Q is

$$\left(\frac{\beta_2}{\omega}\right)^2 \begin{bmatrix} -ik_g & \left(\frac{i(\eta_{2g}^2-k_g^2)}{2\nu_{2g}} + \frac{(1-Z^2)}{(1+Z^2)}\frac{i\rho_1\omega^2}{2\nu_{1g}\rho_2\beta_2^2}\right) \\ \frac{-i(\eta_{2g}^2-k_g^2)}{2\eta_{2g}} & \left(-ik_g - \frac{(1-Z^2)}{(1+Z^2)}\frac{ik_g\rho_1\omega^2}{2\nu_{1g}\eta_{2g}\rho_2\beta_2^2}\right) \end{bmatrix}.$$

Here $Z = e^{2i\nu_1 z_{wb}}$ with z_{wb} being the water depth. Subscripts indicate whether the quantities refer to the water (medium 1) or solid (medium 2). Since an airgun will not provide an effective shear wave source in the water, a source P-S decomposition is not possible. Alternatively, we perform an operation to deghost and partially dereverberate the source. We deal with the lack of shear source components in the data by setting them to zero in the multiple removal algorithm.

Synthetic example

We present two simple synthetic examples to demonstrate the principle of elastic multiple removal. The first is a land example which consists of an elastic layer over a half space as in figure (1). Two orthogonal sources are shot into 128 multicomponent receivers spaced at 10 m. Panels a) and b) in figure 3 show the vertical component of the vertical shot and the P-P component of the decomposed data respectively. The data after removal of the first two orders of free surface multiples are shown in panel c).

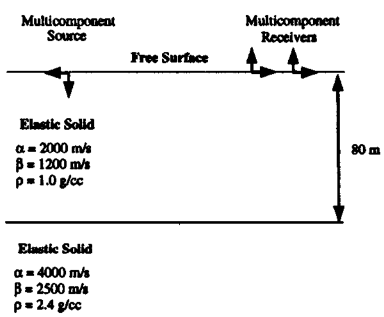

Figure 1: Land acquisition model.

The ocean bottom model is illustrated in figure(2). A single pressure source at 6 meters depth is shot into 128 multi-component receivers spaced at 10 m and placed on the ocean bottom at 80 m depth. Figure 4 shows the vertical and P decomposed components in panels a) and b) respectively. After 2 passes of multiple suppression, we obtain the data in panel c).

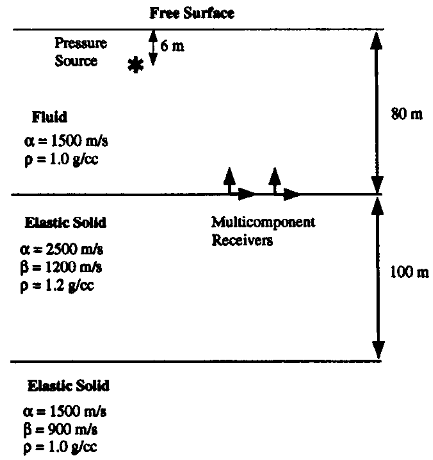

Figure 2: Water bottom acquisition model.

Conclusions

Inverse scattering series is used to formulate a method to remove multiples associated with a free surface for land data and multiples associated with the top and bottom of the water column for ocean bottom data. This method is wave theoretic and complete; all wave phenomena such as obliquity factors, ghosts, and diffractions, are properly accounted for. It is also the first demultiple formulation for elastic measurements on the ocean bottom.

The method involves first a P-S decomposition, then generation of a data series which removes the unwanted multiples. No subsurface information is required below the receivers to remove all orders of reflected and converted multiples.

Theory requires a known elastic medium at or above the sources and receivers and four component data for optimum multiple suppression. Tests indicate that the method is robust with respect to errors in estimating near surface parameters and missing components. Both the source wavelet and near offsets are required to effectively remove multiples.

This work sets the stage for the development of an inverse scattering internal demultiple method using an elastic background medium.

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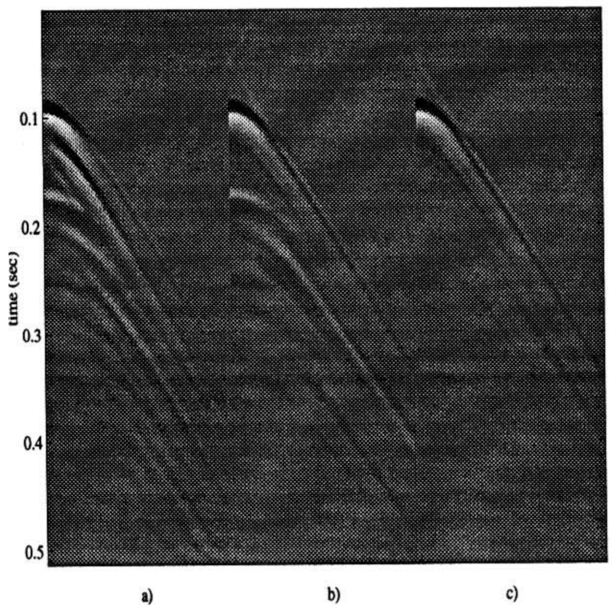

Figure 3: Land example: a) vertical sourcereceiver shot gather, b) P-P decomposed shot gather, c) P-P shot gather after two passes of elastic demultiple.

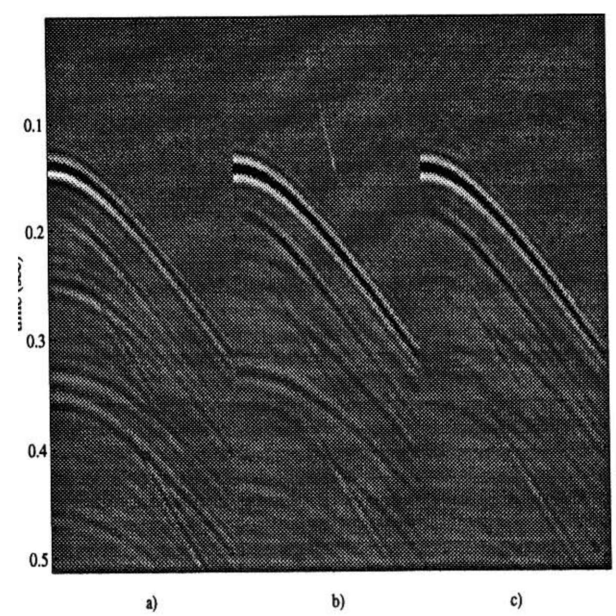

Figure 4: Ocean bottom example: a) vertical receiver shot gather, b) P decomposed shot gather, c) P shot gather after two passes elastic demultiple.

Fast steam front:

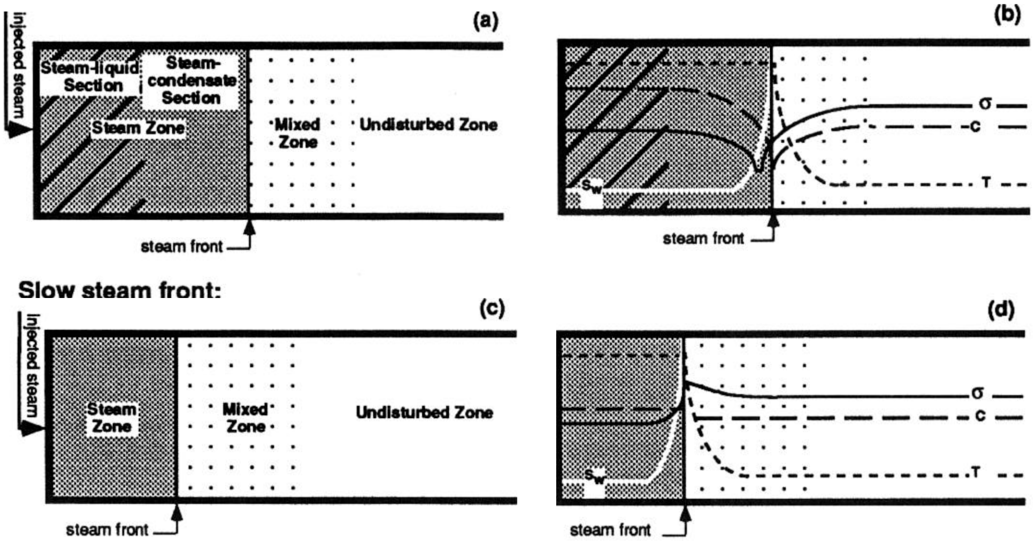

Fig. 1: Schematics of regions that develop in steam-flooded clay-free reservoirs (a,c), and associated profiles of water saturation S_w temperatue T, salinity c, and conductivity o(b, d).

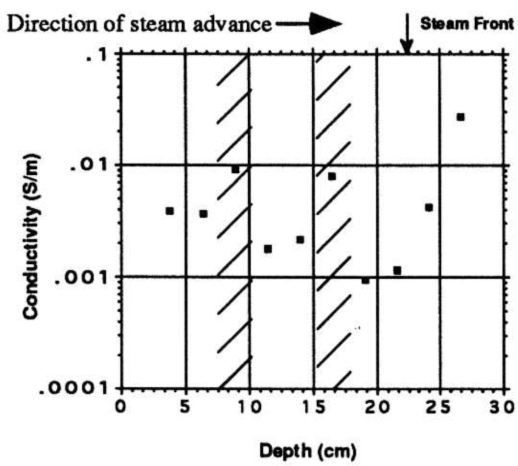

Fig. 2: Conductivity as a function of depth in the cell.

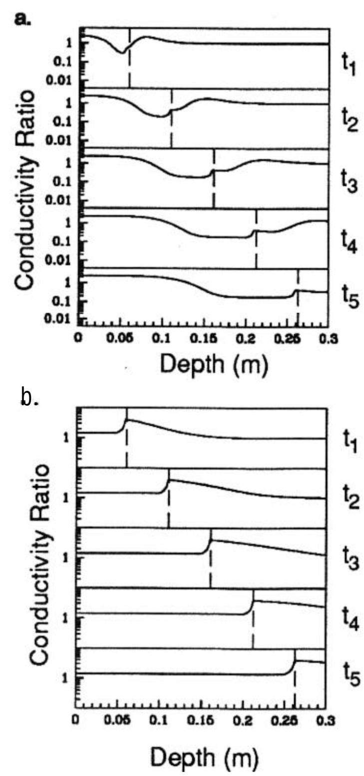

Fig. 3: Simulated conductivity profilcs for a clay-rich sand for (a) a fast steam front, and (b) a slow steam front.