Characteristics of the Free Surface Multiple Attenuation Using Wave Field Extrapolation*

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Abstract

An important task in seismic data processing is the identification and subsequent suppression of multiple reflections so as to avoid false interpretations about the true subsurface characteristics. A strategy for the prediction and elimination/attenuation of ocean-bottom multiple energy on synthetic marine seismic data is exploited. The methodology proposed for the multiple attenuation is based on forward wave field extrapolation theoretical principles in which the one-way Rayleigh integral uses the input data as a prediction operator by extrapolating its reflections (primaries and multiples) forward in time. The predicted multiples have amplitudes compared with the input data in order to be adaptively filtered by the application of a program from the Seismic Unix package called Sushape. After the filtering process, the estimated multiples are then subtracted from the input data. Instead of using the Kirchhoff summation process, wave plane shots were employed for the prediction step in order to diminish computational costs. The highlight of wave field prediction and subtraction process over other methods is the ability in suppressing multiples that interfere with signals of primaries without coincidentally attenuating the primaries when the water bottom is either flat or irregular (dip). This work analyzes the reliability of forward acoustic wave field extrapolation in the multiple reflection prediction. The effectiveness and possible issues of this scheme in suppressing multiples are described and discussed for two different synthetic velocity models.

Introduction

Multiple reflections are frequently present in marine and land surveys. However, for the marine case this problem has shown to be more peculiar: when the ocean bottom velocity is higher than the water velocity, part of the energy transmitted could be trapped between the water surface and the ocean bottom. The contrast of velocity makes the free surface behave as a quite strong reflecting mirror, i.e., much of the energy will reverberate between the water surface and the interface of the seabed.

During the last years, the interest in developing techniques so as to suppress multiple reflections has been stimulated by the industry trend in the face of more complex explorations goals. These techniques are much more required in case of deep water exploration (due to the long period multiples that may accidentally coincide with the top of a reservoir), in complex seabed geometries (that can generate very complex multiple reflections) and imaging targets being subsalt areas (due to the high velocity contrast which can generate many multiple reflections).

The approach of the attenuation method presented in this paper is based on Verschuur's research (2006). This technique is part of a group of methods that are aimed at removing surface-related multiples (water layer reverberations and peg-legs, for example), which have been researched by Berkhout (1982), Verschuur et al., (1992), and Berkhout and Verschuur (1997).

Forward Wave Field Extrapolation

In 1883, Kirchhoff described, mathematically, the Huygens Principle by solving the scalar wave equation, based on Helmholtz's research (Bucci et al., 1994). In his research, Kirchhoff obtained the mathematical quantification for the prediction process, the so-called Kirchhoff-Helmholtz Integral. This integral is also known as the Acoustic Representation Theorem, which allows calculating the acoustic pressure at any point of a medium in terms of a volume integral and closed surface integral. This representation was achieved for a medium characterized as a volume D enclosed by a surface S. It can be described in the frequency domain by (Wapenaar and Berkhout, 1989):

$$P(\overrightarrow{r_A}, \omega) = \frac{-1}{4} \oint_S P \frac{\partial G}{\partial n} - G \frac{\partial P}{\partial n} \, dS, \qquad (1)$$

where $\vec{r}_A$ is the position of the point *A* inside the volume where the pressure field is desired *P* is the pressure field on the surface *S*; *G* is the Green's Function and $\vec{n}$ is an outward vector normal to *S* (Figure 1).

In this work, the Green's Function is interpreted as the impulse response of a medium to an impulsive source applied at certain position. In the synthetic seismic modeling, the Green's wave field is the impulsive response convolved with the source function (the second derivative of Gaussian's function), being a representative wave field.

Despite the Equation (1) calculating the pressure field at any point inside a closed volume, in the case of an open, flat, and extensive medium (Figure 2) the application of this expression would not be consistent. Moreover, the only information is the pressure wave field on the Earth's surface. Considering these facts, Rayleigh simplified the geometry configuration resulting in a new expression, because the terms of the Equation (1) become identical in modulus (Wapenaar and Berkhout, 1989):

$$P(\vec{r}_A, \omega) = \frac{1}{2\pi} \int_S P \frac{\partial G}{\partial z} dS \qquad (2)$$

The Equation (2) is known as the one-way Rayleigh Integral II, which can be interpreted as a tool that reconstructs the wave field at any point *A* by the sum of scaling (amplitude) and displacement (wave field) in time, throughout the surface *S* (Verschuur, 2006). This expression provides the exact extrapolation of the wave field whether all the properties are known or the medium is homogeneous (if so, the

media where the physical wave field and Green's field propagate are equivalent, although this situation does not occur in real seismic survey) (Martins, 2008).

Multiple Attenuation Process

This method has the major advantage of the characteristic of not interfering with the energy of primary reflections, plus the ability to be applied to models with complex seabed geometry. Using the one-way Rayleigh Integral II primary reflections of the original data are shifted in time generating a new data that contain only multiple reflections.

The Equation (2) of the previous section will not be implemented here, but rather, represented as wave fields in the time domain, in order to predict free-surface multiple reflections for two synthetic models (flat and dip).

The prediction process and the surface-related multiples attenuation can be described according to the following steps:

1. The seismogram that contains primaries and multiples (plane wave shot recorded on the surface; i.e., the original data) and that with Green's function derivatives are convolved.
2. The seismogram obtained in (1.) and the Green's function derivatives are convolved in time (trace by trace), generating a new data which has only the multiple reflections of the original data.
3. An adaptive filter must be applied in order to settle the amplitudes from the multiple reflections of (2.).
4. The seismogram obtained in (3.) and the seismogram that contain primaries and multiples are subtracted.

With this extrapolated data, the primary reflections are turned into first-order free-surface multiples. The multiple reflections that were already in the data are turned into second-order free-surface multiples. The arrival time of the constructed events coincides with the time of the multiple in the original data; however, there is a change in the amplitude of the multiples generated (Verschuur, 2006).

Examples

In this first modeling, synthetic model was used with three flat and parallel layers with 1500m/s, 2000m/s and 2500m/s, respectively, as shown in the Figure 3.

The model has a horizontal length og 3km and depth of 2.25km. The mesh used in this model has uniform spacing equal to 7.5 m. In order to increase the stability of the algorithm and reduce the numerical dispersion, a time interval was used equal to 3ms. Each seismogram has total time equal to 3.6s.

The prediction process is held for an original seismogram (Figure 4 (b)) with primaries and multiples, recorded at a depth z = 37.5 m for a source applied to all points at the same depth. Green’s functions derivatives must be calculated for all points at z = 750m. Figure 4 (a) shows the seismogram related to the Green's function derivative for a wave plane shot in the first layer. The goal is to extrapolate the reflections of the original data (convolving it with the Green’s function), transforming primary reflections into first-order free-surface multiples, these into second-order multiples and so on. This extrapolation can be interpreted as the wave field propagation along the water layer such that, the primaries are turned into first-order reverberations.

A convolution process was applied between the seismogram of Figure 4 (a) and (b). In this first convolution process, the primary and multiple reflections are shifted in time. This is equivalent to extrapolating the wave field recorded on the surface to the first layer. This shift is proportional to the time the wave takes to propagate from the surface to the ocean-bottom.

The next step is to convolve the result of the first convolution process with the Green's function derivative. This convolution will extrapolate the wave field (which was extrapolated to the seabed in the previous step) to the surface. According to the reciprocity theorem, it is possible to use the same Green’s function derivative from the previous extrapolation. This step will complete a round trip in the first layer, thereby generating the multiple reflections of the free-surface. This new data will have only multiple reflections related to the first layer matching in time and position with the multiples in the original data, however, of high amplitude and reversed phase, precluding their subtraction. To scale the amplitude of this data, and then to achieve the attenuation, applied was an adaptive Wiener filter of the *Seismic Unix* (SU) package, called *Sushape*, which set the amplitudes of the multiple reflections in accordance with traces of the original data (primaries and multiples – Figure 5 (a)). With the filtered data, the amplitudes were adjusted, allowing the subtraction (Figure 5 (b)).

In the next example, the model, with three dip layers, has a horizontal length equal to 3km and 2.25km depth and the same modeling properties of the previous example. The same process was used in order to predict and attenuate free-surface multiples. The results are shown in Figure 6.

Conclusions

After subtracting, it is possible to determine that many multiples have not been fully removed. However, the remaining signal does not influence the data as much as before, allowing the identification of signals that could be reliable. It can be concluded that the method of prediction and removal of multiple reflections related to the first layer using the wave field extrapolation considerably eased first-order free-surface multiples in the original data. It was observed that the application of adaptive filter enabled the scaling of the amplitudes and subsequent attenuation of the multiple; however, it has generated some noise.

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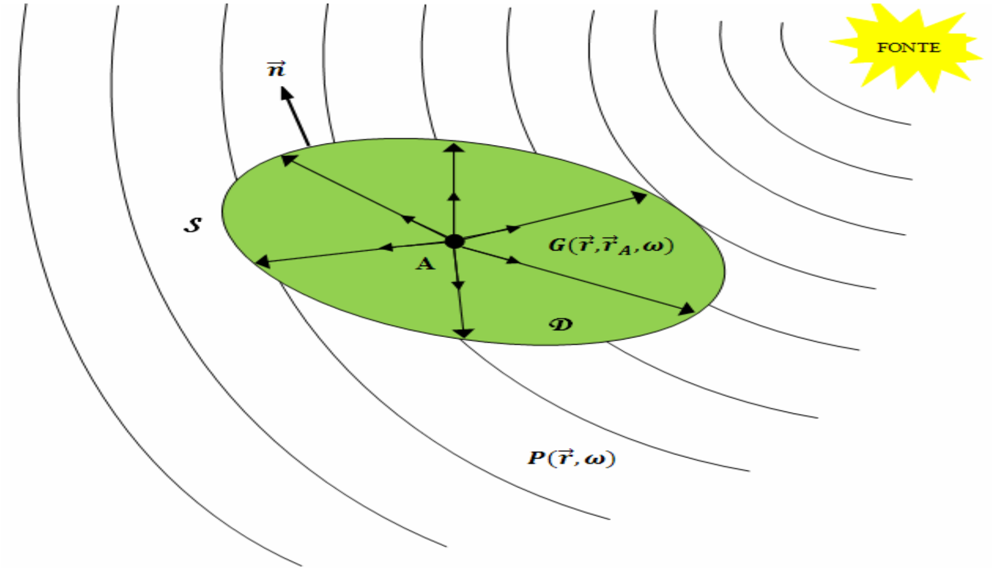

Figure 1. Illustration of the concept behind the Kirchhoff-Helmholtz Integral.

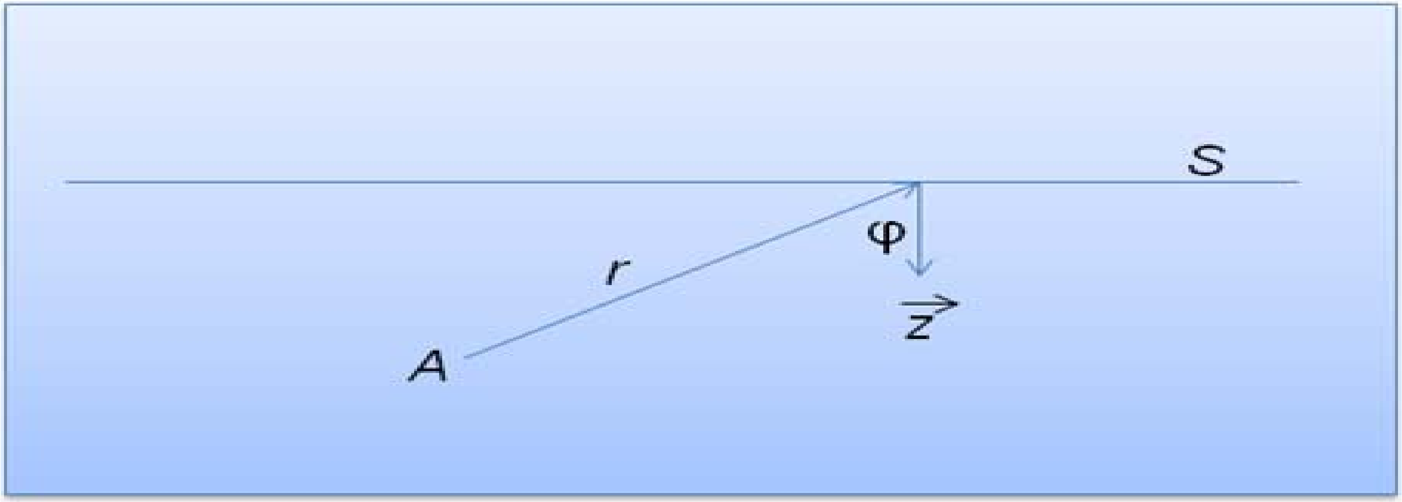

Figure 2. Simplification for the seismic case configuration.

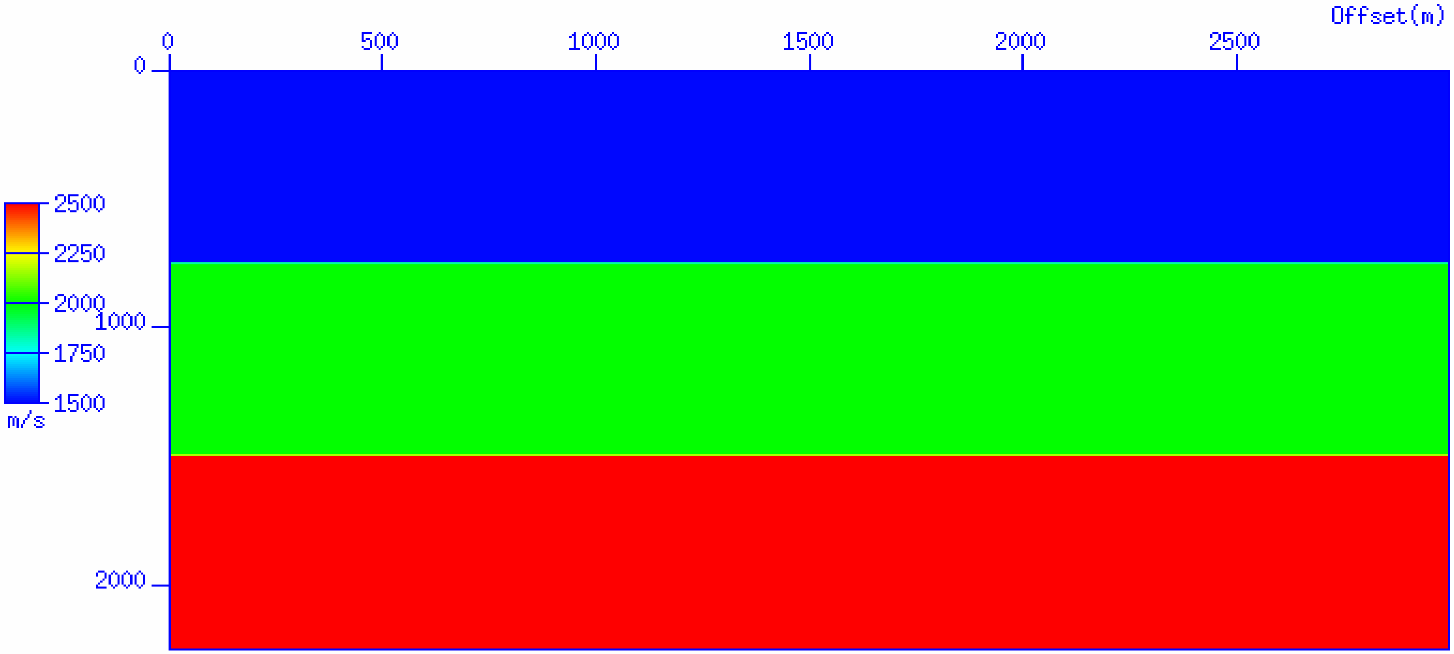

Figure 3. Synthetic model with three flat and parallel layers.

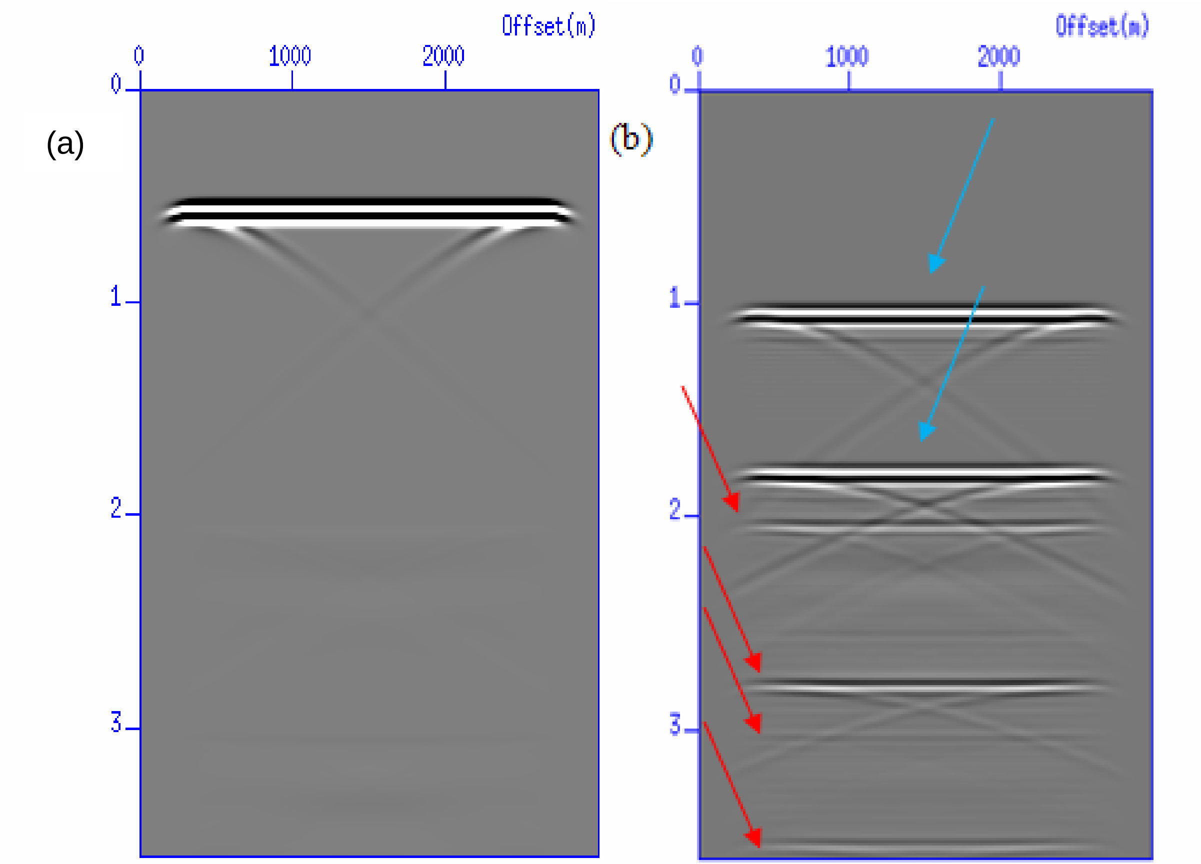

Figure 4. Synthetic seismograms: (a) Green's Function derivative (b) original data – primaries (blue arrows) and multiples (red arrows).

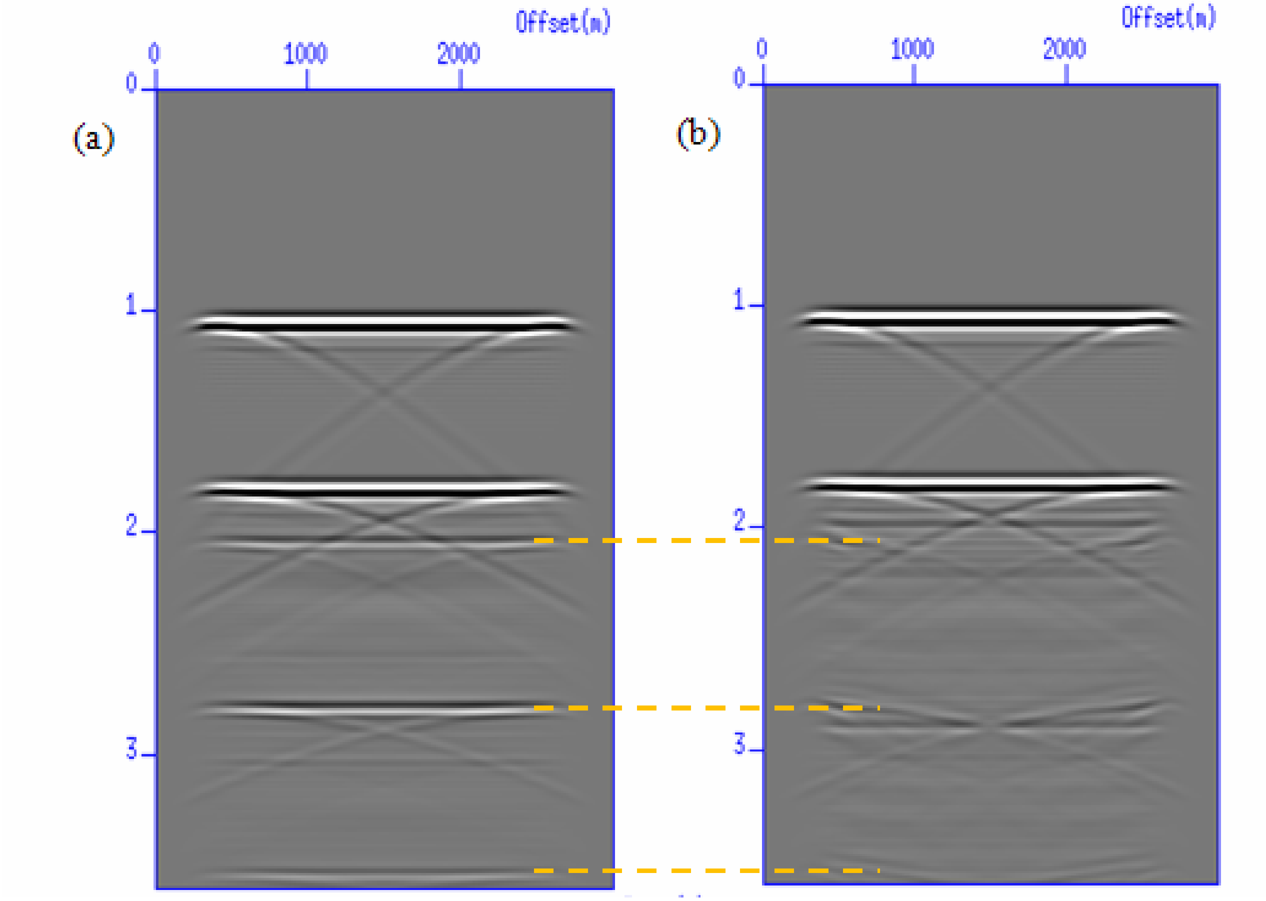

Figure 5. Second extrapolation: (a) original data and (b) original data after multiple attenuation.

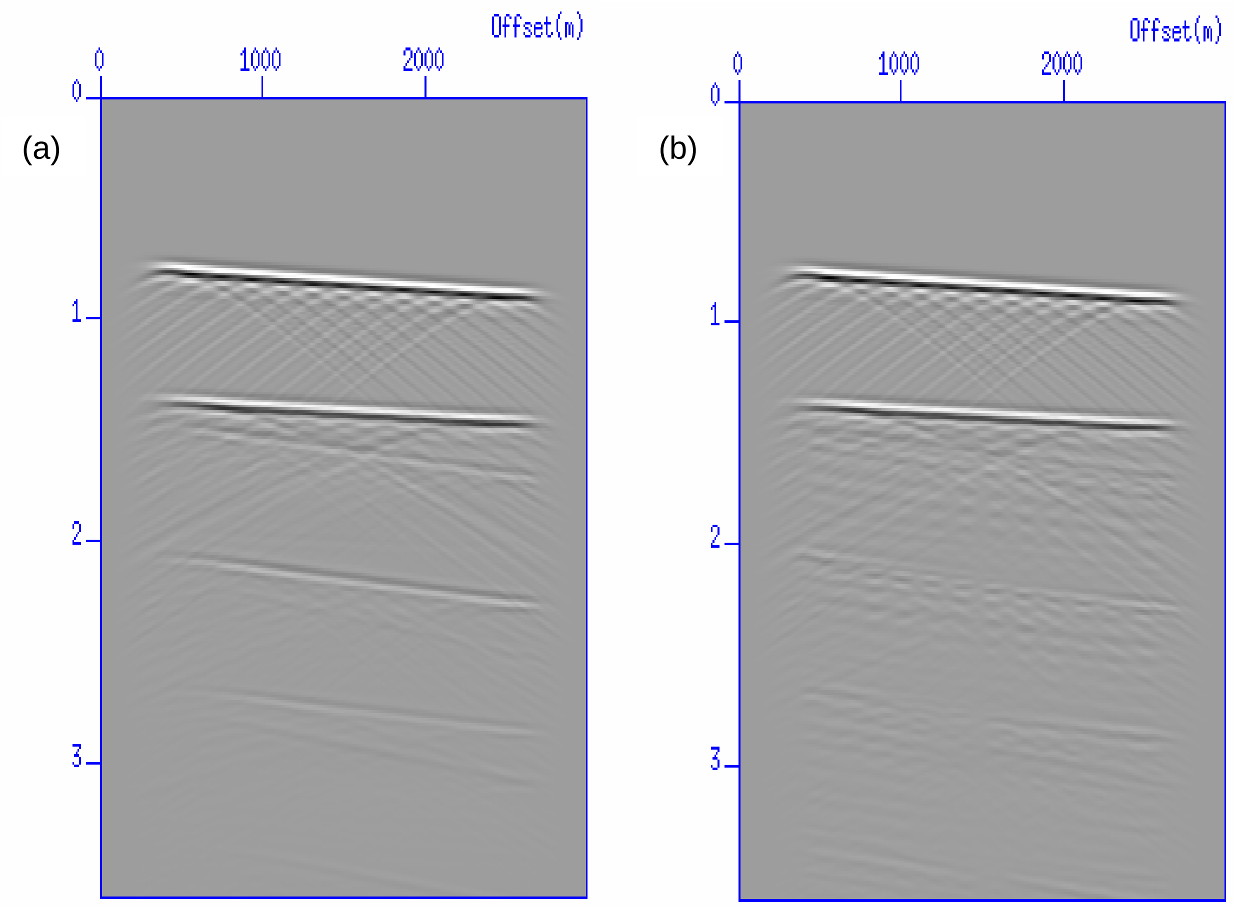

Figure 6. Synthetic dip model: (a) original data and (b) original data after multiple attenuation.