Geophys. J. Int. (2003) **153,** F1–F5

FAST TRACK PAPER

Shear wave statics using receiver functions

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Accepted 2003 February 6. Received 2003 January 22; in original form 2002 July 8

SUMMARY

We extend the seismological receiver function method to the exploration seismic domain to solve the problem of shear wave statics for multicomponent data. The method relies on cross-correlation or deconvolution of pressure with radial component traces in the common-receiver domain followed by a stacking step. This procedure is repeated for each receiver, resulting in a profile of high-resolution stacked receiver functions; events corresponding to shallow mode-converted waves constrain the shear wave static. The method is applied to a line of commercial multicomponent seabed seismic data and gives results in good agreement with a conventional statics method, although results along some other lines require additional interpretation. In contrast to seismological receiver function analysis, the main converted wave energy in the receiver functions originates from reflection at shallow interfaces rather than conversion of upgoing wavefields.

Key words: deconvolution, explosion seismology, receiver functions, statics, *S* waves.

1 INTRODUCTION

Multicomponent technology has been successfully introduced to the seismic exploration industry during the last decade. Efficient acquisition of multicomponent data in marine environments (i.e. seabed) is now possible with cables of densely spaced receivers; each consisting of a hydrophone and three orthogonal geophones. The industry has become aware of the advantages of recording mode-converted waves. One problem, however, that the exploration industry experiences, in applying multicomponent technology, is the distortive effect of the near surface on the deeper reflected wavefield. The near surface, both in seabed and land acquisition, is generally associated with low, laterally varying shear wave velocities. On land, the *P*-wave velocity can also be low. These properties often lead to large *P*- and *S*-wave traveltime perturbations in the deeper reflected wavefield, which vary from receiver to receiver. These perturbations, known as statics, can lead to a significant loss of high frequencies in subsequent processing and complicate event correlation in combined *PP* and *PS* interpretation (Gaiser *et al.* 2001).

In this paper, we extend the receiver function method to the exploration seismic domain to solve the shear wave statics problem for multicomponent data. Although we focus our discussion on seabed seismic data, the proposed method should also work for land multicomponent data.

2 RECEIVER FUNCTIONS IN SEISMOLOGY

The receiver function method is a well-known method for investigating the structure of the Earth's crust and upper mantle. It relies on the observation of mode-converted waves in the coda or as a precursor of teleseismic body-wave phases, resulting from mode-conversion at major crustal or upper-mantle discontinuities (Phinney 1964; Burdick & Langston 1977). The receiver function, formed by deconvolution of the vertical from the radial component, exploits the natural separation of the *P* waves on the vertical and *S* waves on the radial component. The effects of the deconvolution are twofold: first, it works as a designature operation since the spectrum of the *P* wave on the vertical component is not affected much by the crustal structure. Secondly, the *S* waves are shifted in time, relative to the arrival of the *P* event. Typically, receiver functions are inverted for a horizontally layered model using the Thomson–Haskell propagator matrix formalism (e.g. Ammon *et al.* 1990; Paulssen *et al.* 1993). In the simplest implementation, however, they provide a measure of the difference in traveltime between the main phase and the mode-converted branches through the upper mantle or crust. Tangential receiver functions can provide information on the dip of the main converters and anisotropy within the crust and upper mantle (Zhang & Langston 1995; Levin & Park 1997). Recent receiver function studies use exploration seismic methods that stack and migrate receiver functions obtained for phases arriving with varying ray parameters (Gurrola *et al.* 1994; Ryberg & Weber 2000).

3 STATICS USING RECEIVER FUNCTIONS

The natural separation of *P* waves on the vertical and *S* waves on the horizontal components is also well known for industrial multicomponent data. This suggests that, by applying the receiver function method to exploration seismic data, information concerning the compressional and shear wave properties of the near surface can be obtained. In particular, we consider here the difference between the *P*- and *S*-wave statics.

We focus on seabed seismic data because both source-side and *P*-wave statics are considered insignificant for this environment. More importantly, since the shear wave velocities in the seabed are extremely low, with V_p/V_s velocity ratios up to 10 in the upper 25 m (Hamilton 1976; Rodriguez-Suarez & Stewart 2000), the events in the receiver function are dominated by the shear wave traveltime and hence are a direct measure of the *S* statics. When the *P*-wave traveltime through the near surface cannot be neglected, the *P* statics must be found separately and added to the traveltime differences given by the receiver functions.

An assumption we make, which has been confirmed to be approximately valid by synthetic modelling (van Manen 2001) is that the difference in *P*- and *S*-wave traveltime through the near surface at a given receiver location becomes constant at medium-to-far offsets. This assumption is aided by the low shear wave velocities in the seabed, which result in near vertical *S*-wave propagation for a large range of incidence angles. It enables us to take advantage of the large amount of data present in a typical seismic survey by stacking receiver functions obtained for different offsets at the same receiver. We also use long time windows for the receiver function calculation, containing not a single event, but a range of reflections.

An example of a pair of events, recorded in a seabed seismic setting, that can be analysed using receiver functions is shown in Fig. 1(a). In Fig. 1(b) the receiver function methodology is illustrated using the near-offset data obtained for the model and events shown in Fig. 1(a). For simplicity no multiples were included in the synthetic modelling.

4 DATA PROCESSING

We now propose a seismic processing flow to find the *S* statics based on the receiver function method and illustrate the processing on a line of commercial multicomponent seismic data acquired on the North Sea continental shelf.

4.1 Pre-processing

Before receiver functions are calculated, the data must be rotated into radial–transverse coordinates (with respect to the source), to maximize the projection of the shear waves on the radial component. Furthermore, the data must be sorted into common-receiver gathers. In Figs 2(a) and (b), pressure and radial component recordings are shown for a typical common-receiver gather. The shot spacing is 50 m. Although the receiver function calculation can be performed in any domain, this is the natural domain because all energy arriving at the same receiver probes the same near-surface structure. Pre-processing typically also includes muting or gaining part of the input data.

4.2 Receiver function calculation

The second step is the calculation of receiver functions for a range of source–receiver offsets in the common-receiver gather. The receiver functions are calculated using a stabilized deconvolution technique known as the water level method (Langston 1979). It works in the frequency domain by filling the troughs of the denominator in the spectral division up to a fraction, *c*, of its maximum, to prevent the division from exploding. Typically, we use a value $c = 0.05$ when calculating receiver functions for real data. The result of calculating receiver functions using the pressure and radial component data shown is displayed in Fig. 2(c). We calculate receiver functions using the pressure instead of the vertical component. The main results that will be shown, have also been obtained using the vertical component,

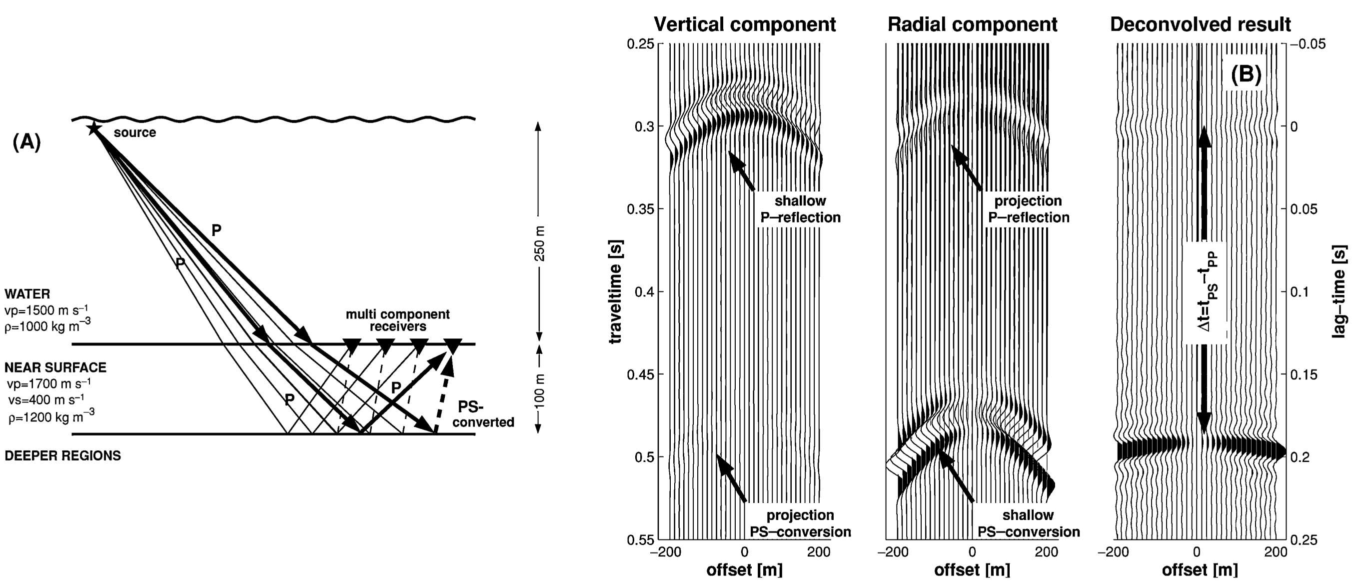

Figure 1. The receiver function methodology in a seabed reflection seismic setting. (a) Downgoing energy reflects and partially mode-converts at a shallow interface in the seabed. Shear wave legs are dashed. (b) Synthetic data and receiver functions for the model and events shown on the left (no multiples included in the modelling). The receiver functions provide the difference between the *P*- and *S*-wave traveltimes through the near surface.

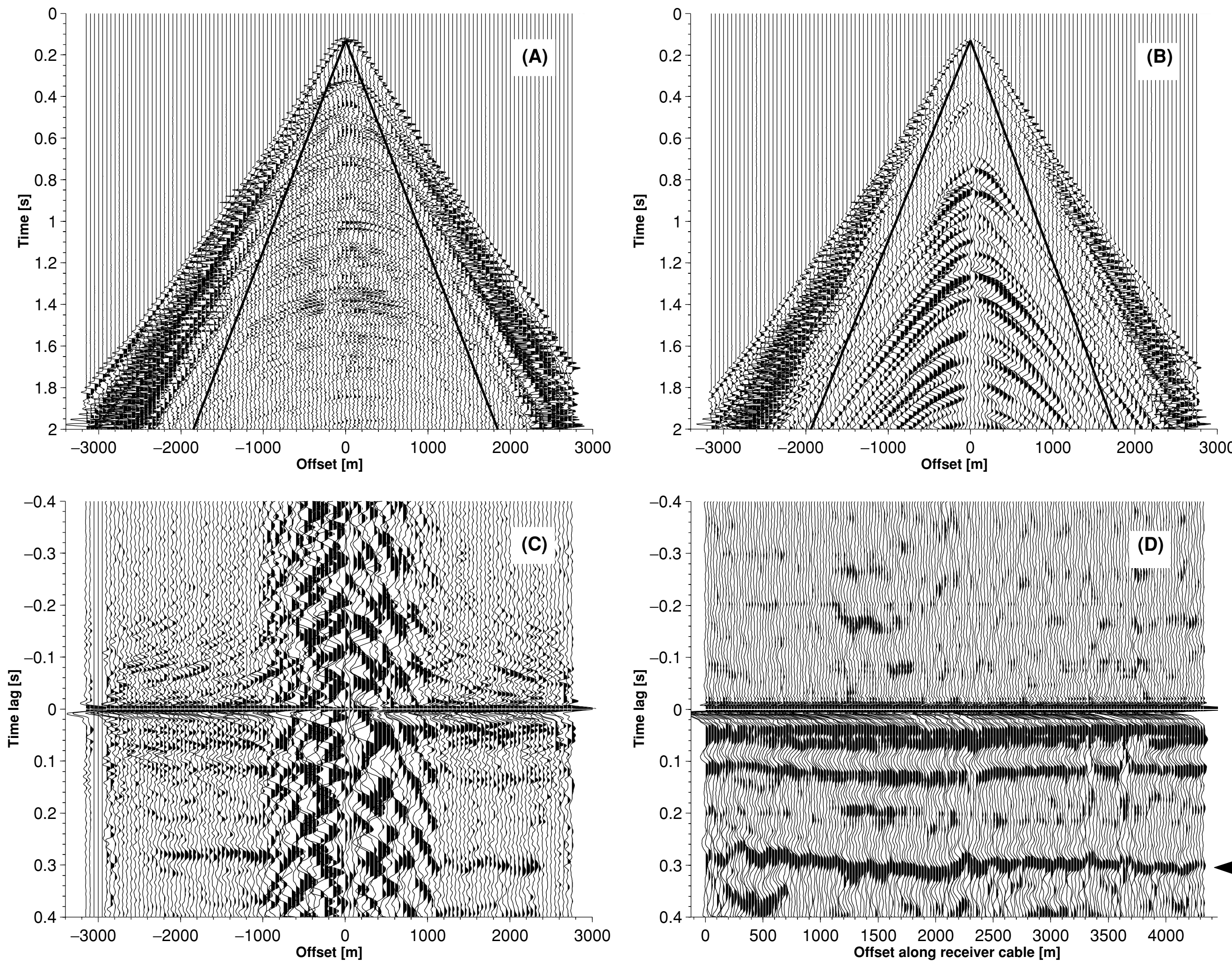

Figure 2. Typical common-receiver gather data with a t^2 gain applied. (a) Pressure recording. (b) Radial component of particle velocity. (c) Receiver function gather, obtained by deconvolution of the pressure from the respective radial component traces. (d) Profile of stacked receiver functions. The arrow denotes the event that was picked and corresponds to the shear wave statics.

although at a higher noise level. We restrict the range of time-lags in the receiver functions to [−0.4, 0.4] s. This range should be chosen according to the shear wave static delays expected. Note the complicated behaviour in the central part of the receiver function gather.

In contrast with receiver functions in global seismology the seismic receiver functions contain significant energy at negative time-lags. This is due to the mixture of arrivals with different slownesses in a single pressure/radial component trace and affects the receiver functions both at positive and negative times. It masks the signal at positive time-lags. To quantify this noise, we calculate a signal-to-noise (S/N) ratio based on the ratio of rms energies at positive and negative time-lags. We find the 'poor' pre-stack S/N ratio of 1.1361. At large offsets, however, some flat events *can* be seen at approximately 0.1 and 0.3 s.

4.3 Stacking receiver functions

Following the calculation of receiver functions for a particular receiver gather, the receiver functions are stacked. The amplitude of the stacked trace is normalized by the number of input receiver functions. No moveout correction is applied before stacking. Note that the application of a moveout correction requires knowledge of a near-surface velocity model. In principle, such a model could be obtained by velocity spectrum stacking of receiver functions in the slowness domain (Gurrola *et al.* 1994). However, this process is time consuming and synthetic modelling (van Manen 2001), as well as the flat events in the receiver function gather, suggest that a moveout correction is not necessary.

4.4 Plotting and picking

The process of calculating and stacking receiver functions is repeated for all 174 receivers. Because the stacked receiver functions only contain events related to near-surface structure, shallow, mode-converted waves measuring the shear wave static should be visible in a profile of these stacked receiver functions and be able to be picked. The result is shown in Fig. 2(d). Note how the events at 0.1 and 0.3 s, already visible in Fig. 2(c), are amplified through the stacking. When we re-calculate the S/N ratio based on rms energies at positive and negative time-lags we find 2.7989. The stacking has removed a significant part of the (a-causal) noise associated with the mixture of slownesses in the input data. The event at 0.3 s was picked and is compared against a conventional *S*-statics solution, obtained

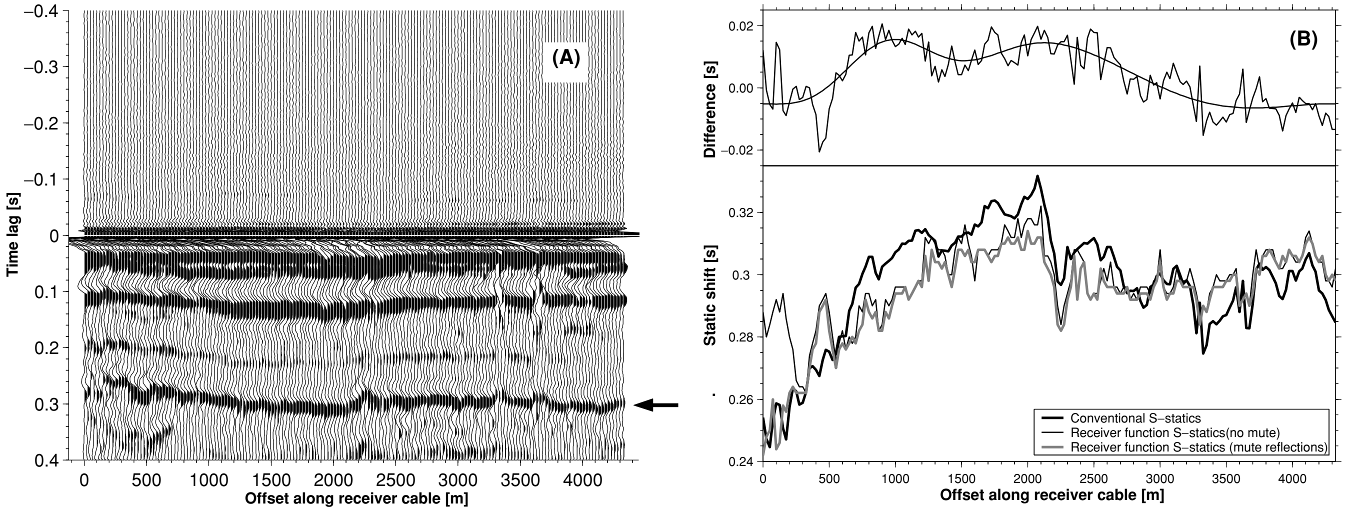

Figure 3. (a) Profile of stacked receiver functions when the central cone of reflected energy is muted from the input data. The arrow denotes the event that was picked and corresponds to the shear wave statics. (b) Comparison of the *S* statics obtained with the residual statics method (thick black) and the receiver function methodology (thin black & grey). In the top panel the difference between the receiver function statics (reflection data muted) and the residual statics is shown. The smooth line emphasizes the, dominantly long-wavelength, mismatch.

using the residual statics method, in Fig. 3(b). Note the good agreement between the receiver function statics and the residual statics. In the top panel the difference and its dominant long-wavelength behaviour is shown.

5 ORIGIN OF THE SHEAR WAVE STATIC SIGNAL

To test which part of the data contributes most to the statics event observed in the receiver functions, a simple muting experiment was done. The central cone of reflection data was muted from the input data. The black solid lines in Figs 2(a) and (b) indicate the top mute boundary. Subsequently, the processing was repeated. The resulting profile of receiver functions is shown in Fig. 3(b). Note that the results have an even higher S/N ratio (S/N = 7.9373, based on the ratio of rms energies at positive and negative time-lags). The general features, however, remain unchanged. We conclude that the central cone of reflection data does not contribute significantly to the shear wave statics event in the stacked receiver function profile. The inverse muting experiment confirms this conclusion. In contrast with the receiver function method in seismology, mode-conversion of upgoing wavefields does not seem to play a significant role in the formation of the events observed in the receiver function profiles. The re-picked receiver function statics curve is again compared with the residual statics solution in Fig. 3(b).

6 DISCUSSION

We attribute the lack of transmitted energy in the receiver functions to the small incidence angles, and hence, small conversion coefficients involved with the central cone of reflection data. In other survey areas, however, such energy may result in a significant signal. We explain the signal observed in the receiver function profile by *PS* waves, mode-converted upon reflection at shallow interfaces and the accompanying *P* reflections (Fig. 1). We also consider the possibility of head-waves propagating along shallow interfaces, emitting both *P* and *S* waves upward into the near surface. Such waves have been observed on land (Lash 1986) and also lead to static traveltime differences, as observed at far offsets. The other arrivals in the receiver function profile could be due to additional contrasts in the seabed or due to internal *P*-wave reverberations—more research is needed to investigate this.

We have repeated the processing on several other lines of data, with mixed results. For some lines, the long-wavelength match between the arrivals in the receiver functions and the conventional shear wave statics solution was poor. One explanation for poorer results could be that the *P* waves involved reflect at different locations from the *PS*-converted waves (Fig. 1), leading to lateral averaging and significant *P*-wave traveltimes that can no longer be neglected. Note that although other methods exist to find the shear wave statics, they either are limited to waterdepths of less than ∼75 m and long-wavelength variations (inversion of Scholte waves) or can suffer from cycle skips and have problems constraining the long-wavelength variations (residual statics). Our method seems to provide mainly the short-wavelength variations. Finally, we have also tested cross-correlation of pressure and radial component data, because our main interest is in phase information. The results were similar to those obtained using stabilized deconvolution, but were inferior in S/N ratio.

7 CONCLUSION

We have demonstrated the potential of the receiver function method in an exploration and production seismic setting to investigate the near surface and the distortive effect it has on the deeper reflected wavefield. In the simplest approach, the receiver function method can give information concerning the shear wave statics. These traveltime perturbations generally limit multicomponent seismic data quality. A data processing flow was proposed and tested on a line of commercial multicomponent seabed seismic data. The processing gave results consistent with a conventional statics solution, although results along some other lines (not shown) require further investigation. The receiver function method, using tangential components, also has potential in exploration seismics to estimate anisotropy in the near-surface and to image shallow dipping interfaces. Amplitudes of receiver functions can potentially provide information on anelastic (shear wave) attenuation.

ACKNOWLEDGMENTS

We thank Everhard Muyzert and Valerie le Mezo for valuable input. The suggestions of an anonymous reviewer were appreciated. Finally, we thank WesternGeco for permission to publish these results.

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