Shallow subsurface mapping using Receiver Functions

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Abstract

Near-receiver P/S mode conversions following the first-arrivals can be used to constrain the shallow subsurface in refraction and reflection profiles with multicomponent recording. The method is based on the well-known in teleseismic seismology Receiver Function (RF) technique, which uses the deconvolution of the radial with the vertical component to isolate the responses of the near-receiver structures. When applied to a wide-angle crustal dataset recorded in a fjord in SE Alaska and W British Columbia, P-wave polarization analysis of the first-arrivals revealed a significant deviation of 20-50º from the source-receiver plane. Therefore, 3-component data rotation was required to correctly separate the P-wave from the transversely-polarized phase following the first arrivals in ~60-400 ms. This phase was interpreted as due to the P/S mode conversions on the basement-sediment contact, in agreement with the MCS reflection imaging. Comparison of these results also suggest a V_P/V_S ratio of the sediments equal to ~2.5. Based on these observations, we suggest that mode conversions in the first-arrivals coda could also be utilized to map the shallow subsurface as well as for derivation of S-wave statics in reflection seismology.

Introduction

Whenever a P-wave strikes a near-receiver velocity interface with significant S-wave velocity contrast at oblique incidence, it generates a converted P/S wave that also propagates forward and contributes to the coda of the P-wave arrivals. The amplitudes of these arrivals depend upon the angle of incidence of the primary P wave and on the contrast in elastic properties across the interface. Although the P/S converted phases will show stronger amplitudes on the horizontal component as compared to the vertical component, yet these arrivals are difficult to interpret in a raw seismogram because the waveform contained is a composite of source and P-to-S converted phases and their reverberations. Information about the near-receiver structure could be extracted by isolating the source signature and its propagation path effect from the composite waveform. This could be accomplished by employing the "receiver function" deconvolution, which is obtained by deconvolving the vertical-component recordings from the radial component. This deconvolution results in an impulse response of the near-receiver structure, dominated by the forward P/S conversion and P-wave multiples. From the travel time lag of the converted phase relative to the primary first arrival (δt_{PS}), the depth to the converting interface can be estimated (Figure 1):

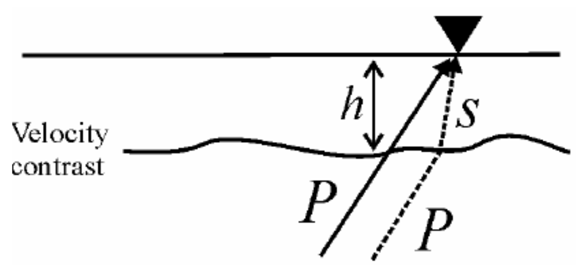

Figure 1. Ray diagram of a direct P and its converted P/S phase from a distant source.

$$h \approx \frac{\delta t_{PS}}{1/V_S - 1/V_P} \qquad (1)$$

The depth mapping approach (1) is widely used in teleseismic seismology (e.g., Vinnik, 1997). Recently, Morozov and Smithson (2002) applied it to recordings from an ultra-long range refraction/reflection profile using Peaceful Nuclear Explosions in Russia and showed that the P/S travel-time lags could be utilized to map the thickness of the sediments along the profile.

In order to test the method on a more conventional seismic dataset and also to evaluate its potential in exploration imaging, we applied it to the wide-angle crustal data from a joint U.S.-Canadian experiment ACCRETE. The 140-km long refraction/reflection wide-angle seismic line was acquired in SE Alaska and British Columbia in 1994 using the airgun array of R/V Maurice Ewing as the seismic source. The shots were made at 50-100 m interval and the corresponding arrivals were recorded by a land-based array of ~60 IRIS/REFTEKS 3-component seismographs from the Incorporated Research Institutions for Seismology. To date, ACCRETE represents one of the best-quality wide-angle datasets including excellent S-wave recordings.

Polarization Analysis

In order to investigate the presence of P/S converted waves in the first-arrival coda, 3-Component hodogram (particle motion diagram) analysis was carried out. Hodogram is a plot of the particle trajectory resulting from the wave propagation as a function of time. From the Hodogram plot (Figure 2), a change in particle motion within the few hundred msec is apparent indicating the P/S conversions. The upper right panel is a plot of amplitudes for horizontal components as seen from above. Similarly, the bottom right panel is the plot of the amplitudes between vertical and rotated radial component. The red axes are the principal axes of the cross-energy matrix.

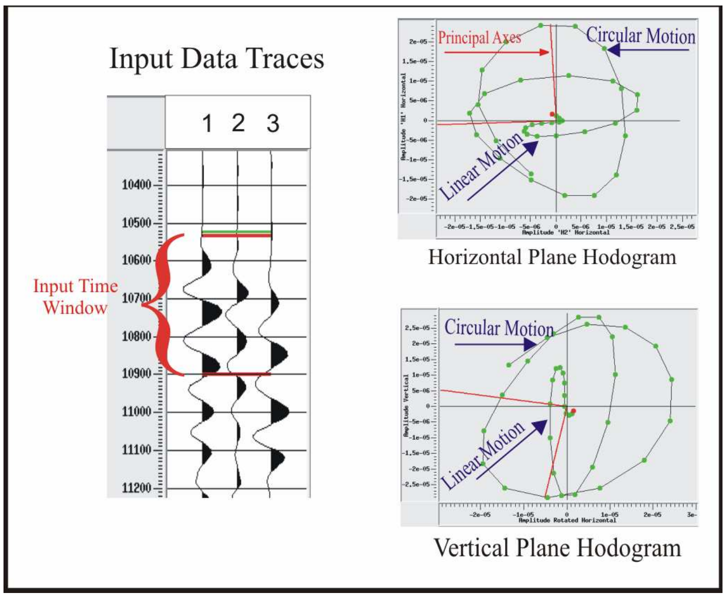

Fig. 2. Hodogram showing the polarization change in the first-arrivals coda. Note the change from linear to circular motion after ~60 ms.

The objectives of the hodogram display are two-fold: 1) to verify the presence of the P/S converted waves within following the first-arrivals and 2) to select the time window for P-waves to measure the polarization. After this, the data are rotated according to the dominant direction of this measured polarization.

P-wave Polarization Measurements

Polarization is the principal direction of particle motion resulting from the wave propagation. The primary objective of measuring the polarization of the primary waves was to separate it from the secondary scattered (P/S) wave. After the direction of the predominantly linear motion was established, the component axes were rotated so that the new component 1 was aligned in the direction of the P-wave polarization. This procedure optimizes the separation of P-waves from S-waves.

Polarization was measured by the principal component method. Fig. 3 shows the azimuths of P-wave polarization measured at station 19 from the different shots along the fjord. The middle graph is a plot of the polarization angles subtracted from the near-receiver shore azimuth (35˚). The polarizations of the primary P waves appear to be are determined by the shore azimuth and are virtually insensitive to the source azimuth as the shots move from north to south. As the shot line passes the station 19, the water depth (blue line on right panel) increases from 300 to 600 m, and the polarization azimuth differs by ~20˚ off the shore azimuth. The polarization behavior along the source-receiver offset demonstrates that in order to isolate and maximize the S-wave energy on the horizontal components, P-wave polarization within the first arrivals must be carefully measured and corrected for.

Receiver Function Deconvolution

After the 3-C data rotation along the dominant direction of P-wave polarization, the component-1 was deconvolved from the remaining transverse components to remove the influence of the source and propagation path effects. The resulting Receiver Function sections (Figure 4) shows a clear travel-time lags between P- and P/S converted phases. Since this time is constant within ~20 ms, we interpreted the arrival as associated with the vicinity of the receiver.

Results

Figure 5 compares the sediment thickness measured by MCS (multichannel seismic reflection) to the travel-time lags between P- and its P/S converted phase. Since the sediment thickness was measured within the offset range of 1-3 km where the thicknesses vary from 50-200 m, we took an average value of 100 m as the depth error. The uncertainty in travel-time picking was estimated as ~20 ms. As Figure 5 shows, for all stations except #53, linear relation (1) with V_P=2500 m/s and V_P/V_S=2.5, describes the relationship between δt and sediment depth satisfactorily. This shows that the observed transversely-polarized phase is indeed the P/S mode conversion generated on the sediment-basement contact.

Potential Applications

Two important applications of P/S mode conversions in the first-arrival coda are suggested by this study. First, 3-component first-arrival waveforms can be used to map the shallow subsurface not only in wide-angle but also in seismic exploration. Generally, the near-surface weathering layer shows characteristics which can be interpreted in terms of low, laterally varying P- and S-wave velocities. Therefore, strong P/S converted waves would be generated at the base of this layer, and these phases could be utilized to map its thickness.and/or V_P/V_S ratios.

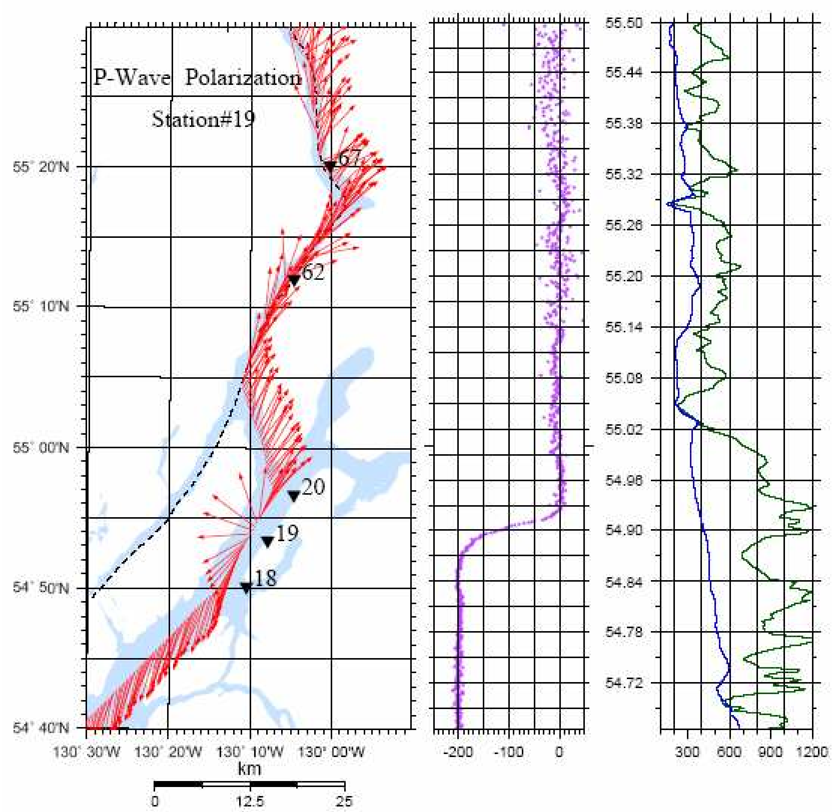

Figure 3. P-wave polarization azimuths from station 19

In another application, P/S mode conversions could help to solve the S-wave statics problem. Standard refraction analysis by which the P-wave statics are obtained could be virtually difficult for the S-waves because they arrive on the background of P-wave reflectivity making accurate picking of their onset times problematic. At the same time because of their slower velocities and typically high V_P/V_S ratios within the weathering layer, the S-wave statics could be 2-10 times higher than the P-wave statics.

From equation (1):

$$\delta t_S = \delta t_P + \delta t_{PS}$$

Thus, given the P-wave statics determined from conventional P-wave processing and P- to P/S conversion lag times measured from the analysis above, the S-wave statics could be derived.

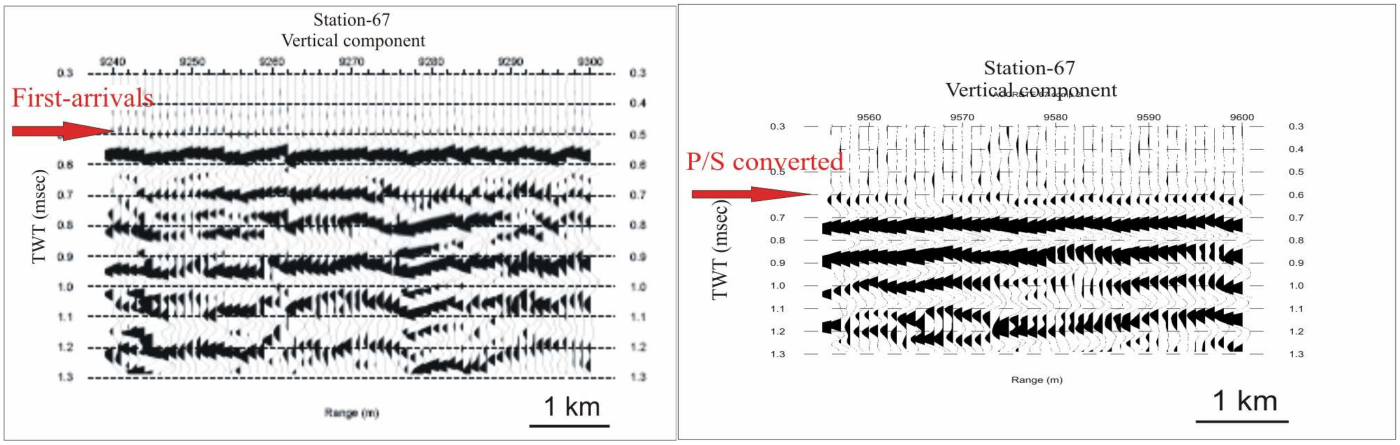

Figure 4. P-wave (left) and transverse (right) components after RF deconvolution.

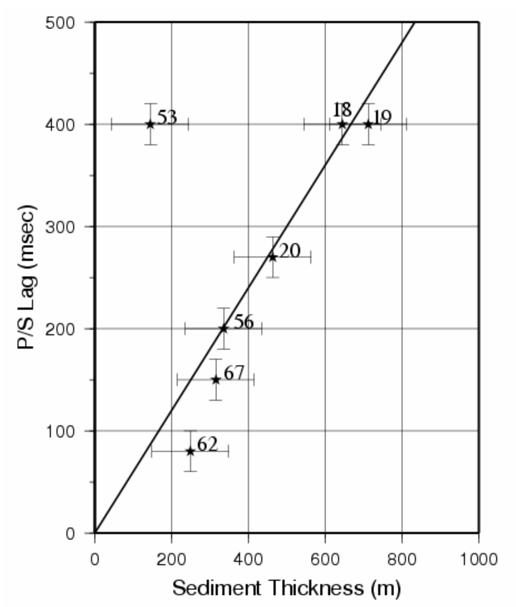

Fig. 5. Comparison of the P/S travel time lags to sediment thickness along the profile

Conclusions

The polarization change and the observed linear dependence between the time lags of the secondary phases and the near-receiver sediment thicknesses in ACCRETE records suggest that:

1) P/S mode conversions in the first-arrival coda can be identified by analyzing 3-component particle motion.
2) Receiver Function technique can be successfully used to constrain the thickness of the low-velocity (sedimentary) near the receivers.
3) The RF technique also carries high promise in 3-component seismic exploration, with high density of recording and redundancy of subsurface coverage. For known depths to the S-wave velocity contrast, V_P/V_S ratio could be estimated by correlating them to the P/S conversion time lags

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