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Review

A review on the analysis of the crustal and upper mantle structure using receiver functions

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ABSTRACT

The discontinuities in the earth such as Moho, lithosphere–asthenosphere boundary (LAB), 410 and 660 km discontinuities, are characterized with an abrupt jump in velocities of P and S waves. The depths of these discontinuities are an important parameter to investigate tectonic evolution in the lithosphere. Receiver functions technique with teleseismic events is very suitable for studying the crust and upper mantle structure beneath stations, thus becoming one of the standard tools for such study. The principle of receiver functions is to separate the converted Ps or Sp phases generated at the discontinuities beneath stations in the case that the direct P or S is a delta function. In this paper, the methods of receiver function analysis are collected from literatures. We introduce the coordinate transform technique for the separation of Ps or Sp waves, the deconvolution algorithm to extract P and S receiver functions, the waveform fitting method to invert for S-wave velocity structure, the stacking technique to improve signals, and the migration from time series to depth domain. With some illustrative examples, the care that should be taken in study of the crustal and upper mantle structure using receiver functions are summarized.

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1. Introduction

According to plate tectonic theory, high-viscous lithosphere that moves over low-viscous asthenosphere is divided laterally into several mobile plates, with their lateral boundaries marked by seismicity. The lower boundary of the lithosphere, i.e., the litho sphere–asthenosphere boundary (LAB) is not marked by seismicity, but is observed with geophysical means (Kind et al., 2012). The Moho, LAB, 410 and 660 km discontinuities have an abrupt jump in velocities of P and S waves. Although the LAB is a first order feature in the geodynamic sense, it is only a weak interface in the seismic sense (Dziewonski and Anderson, 1981; Kennett and Engdahl, 1991) because velocity does not vary abruptly across this interface. In the last decades, travel-time curve is a classic seismic observation which is used to invert for the velocity-depth model. With this curve, not only the existence of a liquid outer core has been shown by Gutenberg (1914), but also a low velocity asthenosphere has been introduced into the global seismic model (Gutenberg, 1959a, 1959b). Another technique is wide angle observation which means the horizontal part of a travel path is much larger than the vertical part. Although that technique is effective to explore crustal structure, it has difficulty in identifying a lower velocity zone which makes seismic wave tend to bend toward the inner earth (Kind et al., 2012). During the recent 30 years, seismic tomography technique (body wave or surface wave) was frequently applied to study the upper mantle (e.g. Kanamori and Press, 1970; Knopoff, 1972), and it is sensitive to gradual variation in velocity but not quite sensitive to sharp discontinuity, and thus it is not quite effective for exploring sharp discontinuity (Kind et al., 2012). The lateral resolution of regional surface wave tomography is at 300–400 km, while the vertical resolution is at 30–50 km (Rychert and Shearer, 2009). Although teleseismic body wave tomography has a better lateral resolution, but it is worse in vertical resolution (McKenzie and Priestley, 2008; Priestley and Tilmann, 2009).

Teleseismic P waveform contains information of the Ps phase and multiple reverberations converted at discontinuities in the crust and upper mantle beneath station. Thus separation of the Ps conversion phase and PpSs + PsPs multiple phases from the direct P wave is an effective approach to inversion for the S wave velocity structure beneath the station (Langston, 1977; Vinnik, 1977). The essential concept and original form of receiver function methodology came from Phinney (1964), who modeled spectral amplitude ratios of teleseismic P waves using the ratio of Fourier spectral amplitude of the vertical displacement to that of the radial displacement of incoming P waves. The major advantage of that innovation is that knowledge of the incident P waveforms are not required. Regretfully, Phinney (1964) did not step further to transform his results from the frequency domain to the time domain, such that the timing and amplitude of individual phases with the spectral ratio method remained unknown. The breakthrough was achieved by Langston (1977). He directly modeled the observations in the time domain by estimating the effective source function. This improvement provided the stability and ease of interpretation by comparing synthetic seismograms in the time domain directly to the data. Later on, he developed a deconvolution technique to equalize effective source time functions and to remove the instrumental response, and named the deconvolved radial components in the time domain as receiver function (Langston, 1979). Moreover, by spectral division of the radial and vertical components (the deconvolution), he extracted the receiver function from the long-period body wave of teleseismic events. Owens et al. (1984) applied the technique to broadband waveform and extracted the receiver functions. In the last 30 years, the analysis method of receiver function has been developed from separation of S and P wave (Langston, 1979; Owens et al., 1984; Ammon et al., 1990; Ligorría and Ammon, 1999), waveform fitting (e.g. Ammon, 1991) and time-depth transform (Dueker and Sheehan, 1997, 1998), to the stacking and migration technique (e.g. Yuan et al., 1997), becoming a major tool for investigating the lateral variation of discontinuities in crust and upper mantle. Since the beginning of 1990s, three large passive seismic experiments have been carried out by the international INDEPTH group along a north–south profile across Tibet, with the major goal being investigation of the fate of the colliding Indian and Euria-asian plates beneath the Tibetan plateau. The results from receiver functions showed that the Moho has been observed very well along the entire profile and the subducting Indian LAB was found to reach the central Tibet at depth 250 km. In the northern Tibet, a relatively shallow LAB was observed at depth 100 km, close to the LAB depth in central Europe (Yuan et al., 1997; Kind and Yuan, 2010). Rychert and Shearer (2009) have compiled a global map of the LAB using P receiver functions recorded at permanent seismic stations. They concluded that the depth of LAB is about 70 km beneath oceans, about 80 km in orogenic regions and Phanerozoic platforms, and about 90 km in Precambrian shields. Lawrence and Shearer (2006) stacked P wave receiver functions for 118 global seismic stations to yield new estimate of the thickness of mantle transition zone (measured by the depth difference between the 410- and 660-km discontinuities), with a globally average of 242 ± 2 km.

The P receiver function technique has existed for more than thirty years and has been established to be a robust technique for study of the structure of the crust and upper mantle. The motivation of this paper is to review the advancement of the receiver function technique in the last 30 years, and to summarize different analysis methods of receiver function. For each method, the principle is briefly and clearly described. The procedures of the receiver function analysis are illustrated with several computational or observational examples. Especially, the attention and care with the use of these methods are given.

2. Receiver function technique

2.1. Separation of P and S waves

When a seismic wave is incident on a discontinuity between two different solids, a part of the wave will be transmitted and another will be reflected. Moreover, there is a mode conversion. An S wave (here is called Ps phase), which follows the direct P wave with S wave speed, will be generated when a P wave is incident on the discontinuity. Similarly, an incident S wave will generate a P wave (here is call Sp phase) which is transmitting with a P wave speed and is running ahead the incident S wave. These different type phases are both recorded at the same station. If their incident angles and the speeds have been given, the discontinuity depth where the conversion mode are generated can be determined from the differential arrival times of these phases. Since the converted phase is a different type from the incident wave, it is dominantly recorded on a component different from the incident

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