Tectonophysics 665 (2015) 92–100

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

A new approach to obtaining a 3D shear wave velocity model of the crust and upper mantle: An application to eastern Turkey

Jonathan R. Delph *, George Zandt, Susan L. Beck

Department of Geosciences, University of Arizona, 1040 E. 4th Street, Tucson, AZ 85721, USA

ARTICLE INFO

Article history:
Received 4 May 2015
Received in revised form 21 September 2015
Accepted 23 September 2015
Available online 9 October 2015

Keywords:
Continental lithosphere
Seismic imaging techniques
Eastern Mediterranean
Neotectonics

ABSTRACT

We present a new approach to the joint inversion of surface wave dispersion data and receiver functions by utilizing Common Conversion Point (CCP) stacking to reconcile the different sampling domains of the two datasets. Utilizing CCP stacking allows us to suppress noise in the data by waveform stacking, and correct for backazimuthal variations and complex crustal structure by mapping receiver functions back to their theoretical location. When applied to eastern Turkey, this approach leads to a higher resolution image of the subsurface and clearly delineates different tectonic features in eastern Turkey that were not apparent using other approaches. We observe that the slow seismic velocities near the Karliova Triple Junction correlate to moderate strain rates and high heat flow, which leads to a rheologically weak crust that has allowed for the upward propagation of Miocene and younger volcanics near the triple junction. We find seismically fast, presumably rigid blocks located in the southeastern Anatolian Plate and Arabian Plate are separated by a band of low shear wave velocities that correspond to the East Anatolian Fault Zone, which is consistent with the presence of fluids in the fault zone. We observe that the Arabian Plate has underthrust the Eurasian Plate as far as the northern boundary of the Bitlis Massif, which can explain the high exhumation rates in the Bitlis Massif as a result of slab break-off of the Arabian oceanic lithosphere. We also find a shallow (~33 km) anomaly beneath eastern Turkey that we interpret as a localized wedge of mantle that was underthrust by a crustal fragment during the collision of Arabia and Eurasia. These observations are possible because of the high-resolution images obtained by combining common conversion point receiver function stacks with ambient noise dispersion data to create a data-driven three-dimensional shear wave velocity model.

1. Introduction

Imaging how the crust and upper mantle deform in response to stresses is critical to the understanding of Earth's tectonic processes. A widely used and relatively high-resolution seismic method to do this is through receiver function analysis (Langston, 1979). This method isolates P-to-S-wave conversions at impedance contrasts in the Earth to recover Earth structure immediately beneath a seismic station. However, receiver function analysis suffers from an inherent non-uniqueness with respect to the absolute shear wave velocities that are responsible for the resulting receiver function profile (Ammon et al., 1990). More recently, the development of ambient noise tomography (ANT) has led to the accurate recovery of short period Rayleigh waves sensitive to absolute shear wave velocities in the crust and uppermost mantle, which were previously difficult to obtain via earthquake-generated surface waves (Shapiro et al., 2005). Dispersion data obtained from surface wave inversions are widely used to recover the shear wave velocity structure of the Earth through shear wave inversions, but suffer from their own non-uniqueness, as the broad sensitivity kernels of Rayleigh waves sample a wide range of depths depending on their frequency (Fig. 1) and thus are not ideal for imaging sharp velocity discontinuities. Inverting these two datasets separately results in an inverse problem with a large number of models that satisfy the data, which can lead to biases in velocity models due to their strong dependence on poorly constrained *a priori* models.

The joint inversion of surface wave velocities and receiver functions has resulted in a vast improvement in the calculation of shear wave velocity models by utilizing each method's individual strengths (Julia et al., 2000; Özalabey et al., 1997). Receiver functions constrain the depth to boundaries and their associated velocity contrasts, while Rayleigh wave dispersion data constrain the absolute shear wave velocities between the boundaries. By utilizing both receiver functions and high frequency surface wave dispersion data, many studies have been successful in gaining insight into crustal structure at a resolution unprecedented before the development of this joint technique (Shen et al.,

* Corresponding author.
E-mail addresses: jrdelph@email.arizona.edu (J.R. Delph), gzandt@email.arizona.edu (G. Zandt), slbeck@email.arizona.edu (S.L. Beck).

http://dx.doi.org/10.1016/j.tecto.2015.09.031
0040-1951/

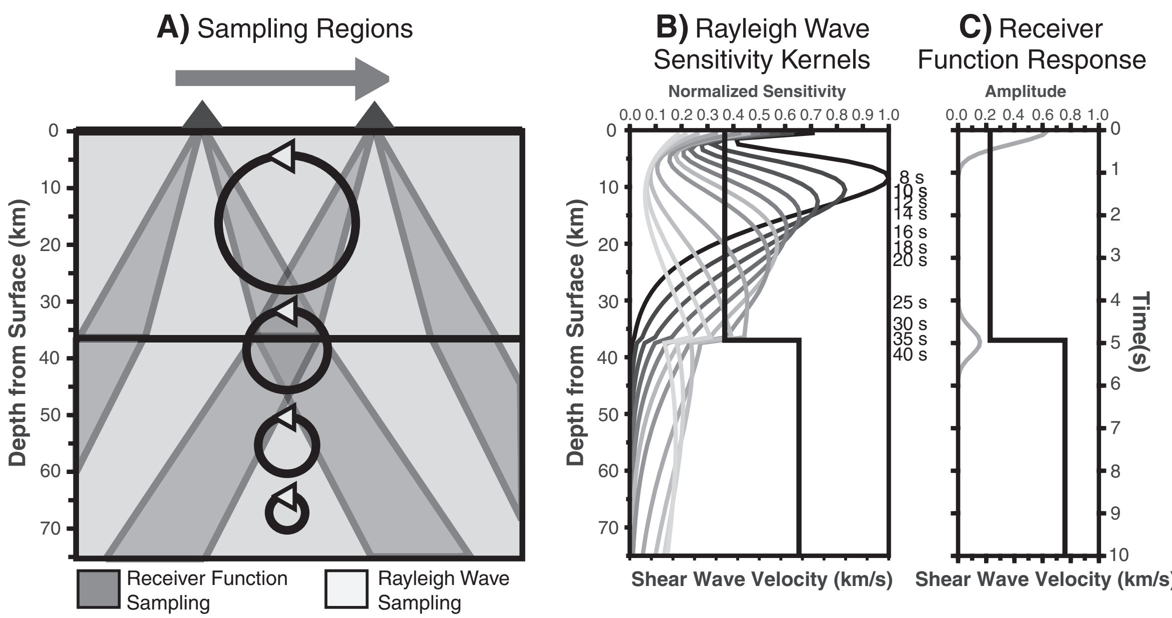

Fig. 1. (A) Sampling regions of receiver functions (dark gray cones) and Rayleigh waves (light gray background). Rayleigh waves sample the entire region, while receiver functions are limited by station distribution. Black, circular arrows show conceptual particle motion of a Rayleigh wave as it propagates to the right. (B) Sensitivity kernels for Rayleigh waves at different periods for a simple 1D shear wave velocity model (black line). (C) Radial receiver function response to a velocity contrast at depth (shown by black line representing velocity structure).

2013b; Ward et al., 2014). However, the sampling regions and resolutions of these two datasets are vastly different (Fig. 1), and must be reconciled before presenting models of shear wave velocity via this technique.

Past studies have attempted to reconcile the different sampling regions of these two techniques using different approaches. The most common approach is the single-station joint inversion (Julia et al., 2000; Kgaswane et al., 2009). This approach uses all receiver functions recorded at a single station, accounts for differences in ray parameter, and constrains shear wave velocities using a surface wave dispersion curve from a gridpoint near the station location. This results in the approximation of a 1D shear wave velocity profile as a function of depth beneath each individual station. This approach, however, suffers when large backazimuthal variations exist beneath an individual station. Shen et al. (2013a) attempted to account for backazimuthal variation via "harmonic stripping", which ideally creates azimuthally independent receiver functions. If a 3D velocity model is sought, joint inversion studies generally interpolate the single-station velocity profiles between stations (Liu et al., 2014; Shen et al., 2013b), leading to a 3D velocity model that is dependent on the interpolation method as opposed to a data-driven 3D velocity model. Ward et al. (2014) approached the single-station joint inversion slightly differently, using a multistep inversion approach. First, individual receiver function were inverted for a shear wave velocity profile at a given station, and a mean shear wave velocity profile and uncertainty was obtained which reflected variations in receiver functions largely due to noise and backazimuthal variations. The mean profiles at each station were then interpolated throughout the study area, and a shear wave inversion was performed to ensure the resulting shear wave velocity volume fit all available dispersion data. This method is an improvement in creating a 3D volume of shear wave velocities using a joint inversion approach, but may suffer from the inversion of contaminating noise in individual receiver functions, which may lead to spurious velocity information that is later propagated through the model via mathematical interpolation. Conversely, Chai et al. (2015) smoothed receiver function waveforms over large distances to obtain a low-noise receiver function containing information about first-order discontinuities. This leads to a good first-order model at the cost of local heterogeneities, and thus resolution.

In this paper, we present a new approach to the joint inversion problem to develop a more robust 3D shear wave velocity model. We utilize common conversion point (CCP) stacking (Dueker and Sheehan, 1997), which is widely used to create 3D volumes of receiver function amplitude as a function of depth to gain insight into impedance contrasts in the Earth. By using a depth-to-time migration on the resulting 1D amplitude profiles created by CCP stacking, we can create receiver functions that account for backazimuthal variations, dampen noise, mitigate the dependence of receiver function data on station location, and lead to a high-resolution data-driven 3D shear wave velocity model when jointly inverted with dispersion data.

2. Methods: the creation of CCP-derived receiver functions

CCP stacking creates a 3D amplitude volume throughout a study area by averaging receiver functions that fall in a grid cell (or bin) after being ray-traced along theoretical raypaths assuming an average velocity model for an area. The average amplitudes in the volumes represent the location of discontinuities in the crust and mantle, successfully accounting for backazimuthal variations beneath a station, albeit rather smoothly. Commonly in the CCP method, the grid spacing and information in individual bins is user-defined by the radius of the bin and the bin spacing, which constrains the data that is used in the solution for amplitude in that bin.

In order to extract a receiver function for each gridpoint from our CCP stacks, we must have a continuous amplitude profile as a function of depth. Due to the localization of raypaths beneath individual stations at shallow depths, bins are often empty between stations if the bin width is less than station spacing. In an attempt to alleviate this issue and create a more continuous image of the shallow crust, we allow our predefined bin width to dilate until a minimum number of raypaths is incorporated into the bin. We use true receiver function amplitudes (i.e. non-normalized), migrate the receiver functions to depth for the CCP stacking analysis using a regional 1D velocity model, and then extract a vertical receiver function amplitude profile for each gridpoint as a function of depth. Then, a depth-to-time migration is performed using the average ray parameter in the uppermost bin and the same 1D regional velocity model used for ray-tracing and time-to-depth migration in order to minimize the effect that an incorrect velocity model might have on the resulting CCP-derived receiver functions. To avoid aliasing in the CCP-derived receiver functions, we must choose thin CCP depth bins so that