Shallow 3D shear wave velocity structure beneath China revealed by joint inversion of Rayleigh wave ellipticity and receiver function

Xiao Xiao[1](xiaox17@mail.ustc.edu.cn), Shihua Cheng[1], Lianxing Wen[2,1]

1. Laboratory of Seismology and Physics of Earth's Interior; School of Earth and Space Sciences, University of Science and Technology of China
2. Department of Geosciences, State University of New York at Stony Brook

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1. Introduction

Shallow shear wave velocity structure plays essential role in earthquake hazard assessment, seismic imaging and geodynamic simulation. However, for China, it remains poorly constrained due to sparse data coverage for traditional body wave and surface wave tomography methods. To resolve it, Rayleigh wave ellipticity or ZH ratio, mainly sensitive to local shallow shear wave velocity (Vsv) model, and P wave receiver function (RF), reflecting discontinuities, are used to jointly constrain the shallow Vsv structure extending to 8 km from surface with a Markov Chain Monte Carlo (MCMC) method in this study.

2. Project overview and Data coverage

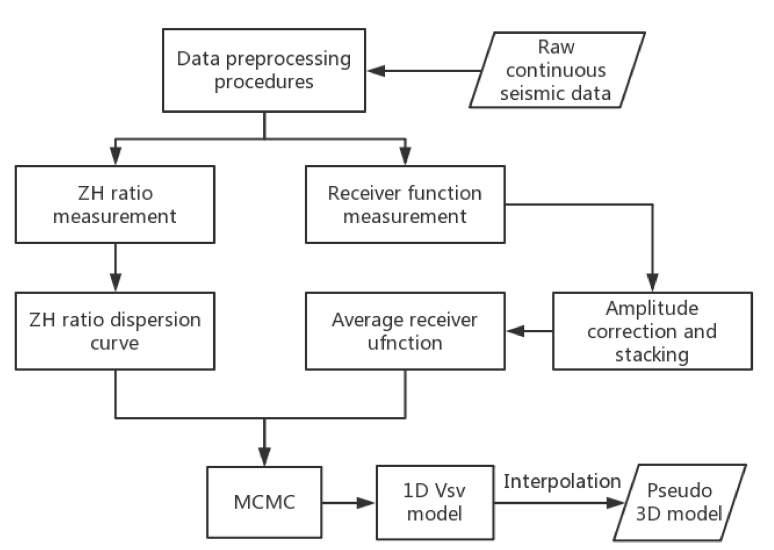

Fig. 1: Flowchart of the entire project.

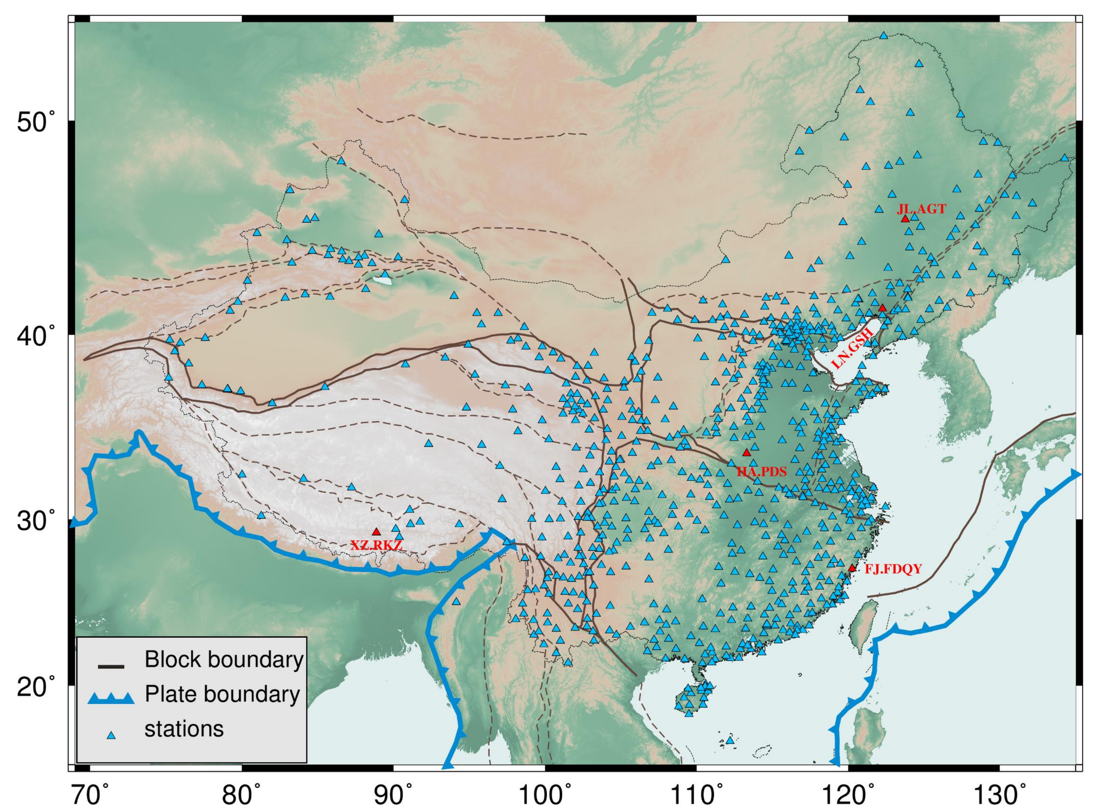

Fig. 2: Spatial distribution of seismic stations. Seismic stations used in this study are shown as triangles. Five seismic stations, identified as red triangles, are used to illustrate the joint inversion method in **Sec. 4**. Boundaries of the primary (black solid lines) and secondary (black dashed lines) blocks come from Zhang et al, 2005.

Our project mainly consists of three stages, including data preprocessing, measurement of azimuth averaged ZH ratio and RF and 3D Vsv model construction (**Fig. 1**). At the beginning, we removed instrumental responses from the continuous waveforms and teleseismic records. Then, ZH ratio dispersion curves and RFs are measured from these preprocessed data (demonstrated in **Sec. 3**). In the following step, they were jointly used to constrain local 1D Vsv profile with a MCMC method (**Sec. 4**). Finally, all inverted 1D Vsv models and associated uncertainties were interpolated to construct the final pseudo 3D Vsv model (**Sec. 5**).

Our dataset in this study contained 3-year continuous waveforms, ranging from 2015 to 2017, and 4-year teleseismic records, between 2012 and 2015, of 767 3-component seismic stations, operated by China Earthquake Administration (**Fig. 2**). These data are provided by China Earthquake Data Center.

4. Joint inversion of ZH ratio and RF

As azimuth averaged ZH ratio and RF are mostly sensitive to local shallow 1D isotropic Vsv strcture, we only searched Vsv profile extending to 20 km (reliable till to about 8 km) as the maximum period of ZH ratio dispersion curve we used is 9.5 s.

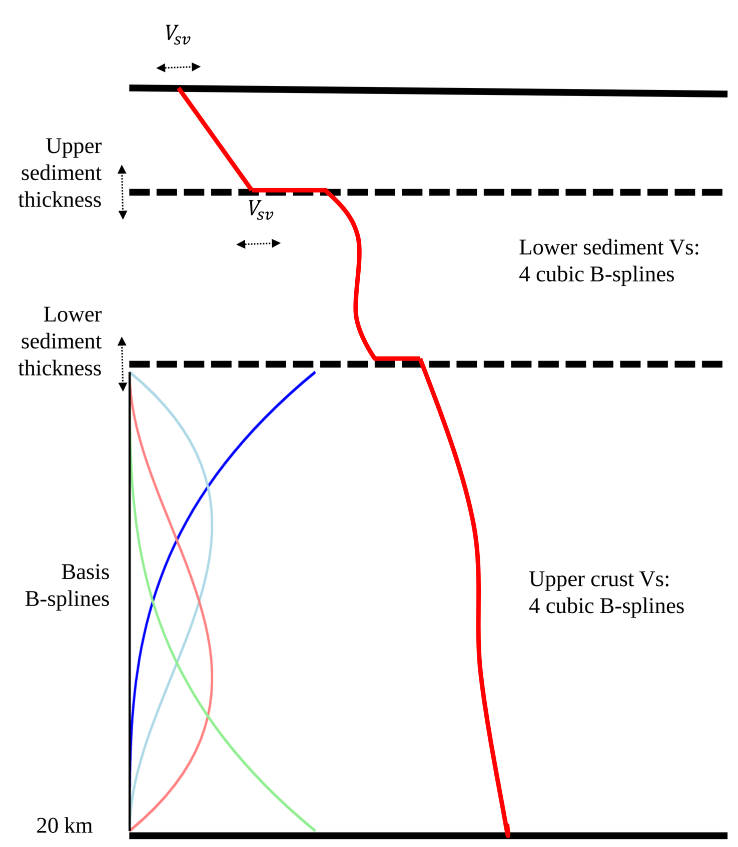

Fig. 6: Model parameterization illustration. The 1D Vsv model, stacked by the upper, lower sediment and the upper crust layers. It totally contains 12 independent parameters, including thicknesses of the upper and lower sediment layer, shear wave velocities of the topmost and bottom of the upper sediment layer, 4 cubic B-spline coefficients depicting Vsv profile in the lower sediment layer and another 4 coefficients describing Vsv variation in the upper crust layer. Four curves at the bottom left corner demonstrate the shape of B-spline basis functions used to expan the Vsv profiles.

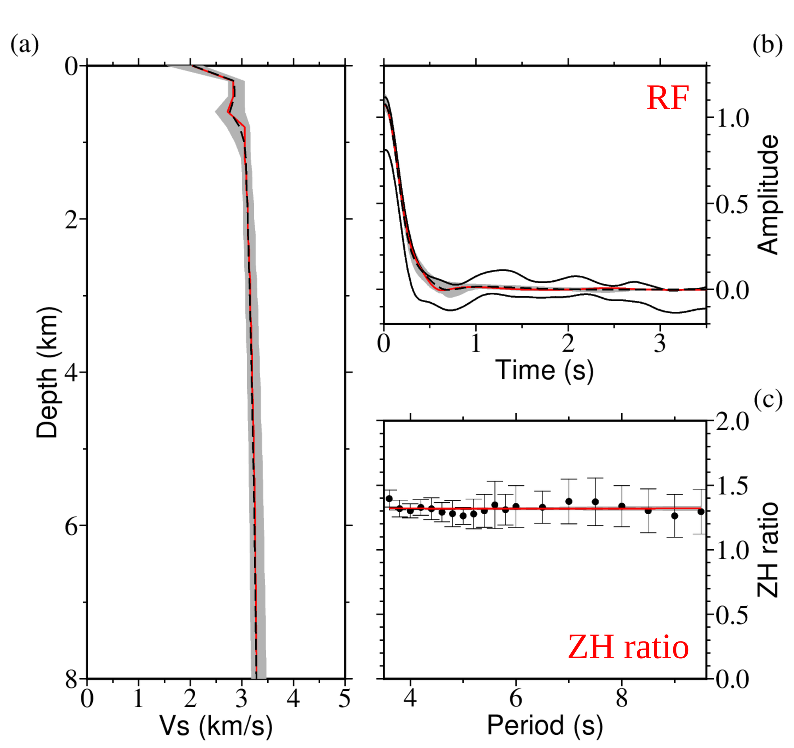

Fig. 7. Joint inversion of ZH ratio and RF for station FJ.FDQY, locating at the south China craton. (a) The 95% confident interval of all acceptable models is shaded with grey. Mean of these models is shown as black dashed line while representative model is plotted in red. (b) Two parallel black solid lines enclose estimated uncertainty of RF. The grey area indicates 95% confidence interval of synthetic RFs from all accepted models and their mean is identified as the black dashed line. Synthetic RF of the representative model is shown with red. (c) The grey area also indicates 95% confident interval of all synthetic ZH ratio curves. The mean of them is identified as dashed black line while the red line represents synthetic ZH ratio curve from the representative model.

We modified misfit function in bayesian Monte-Carlo joint inversion method (Shen et al, 2013) to use ZH ratio dispersion curve and RF, simultaneously. The resulting misfit function is defined as

$$S_{joint}(\boldsymbol{m}) = \alpha S_{ZH} + \beta S_{\mathrm{RF}} = \alpha \sum_{i=1}^{N} \frac{(ZH(\boldsymbol{m})_i - DZH_i)^2}{\delta_i^2} + \beta \sum_{j=1}^{M} \frac{(RF(\boldsymbol{m})_j - DRF_j)^2}{s_j^2}$$

where the S_{ZH} is summation of uncertainty-weighted norm-2 data misfit between predicted ZH ratio curve $ZH(\boldsymbol{m})$ and observed one DZH. Similarly, S_{RF} is defined as summation of uncertainty-weighted norm-2 data misfit over all time steps for RF. α and β repsent relative weight between ZH ratio and RF, choosen as 10 and 0.25 respectively through trial and error. Practically, we used 1D Vsv model from (Shen et al, 2016) as initial model, applied the MCMC method to approaching the representative model, defined as the nearest sampled model to the average of model assemble, and accepted several models near it to assess model uncertainty.

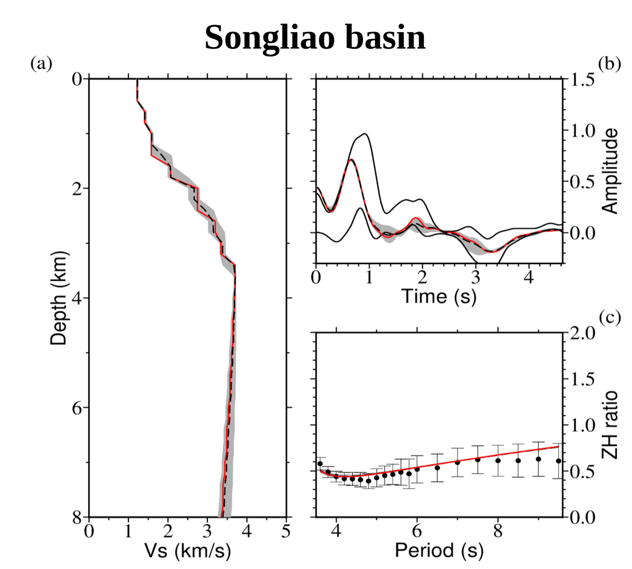

Fig. 8: The same as Fig. 7, but for station JL.AGT.

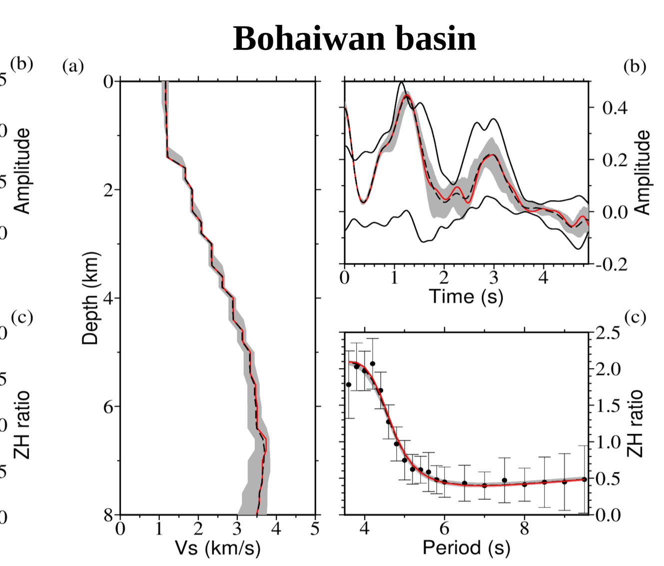

Fig. 9: The same as Fig. 7, but for station LN.GSH.

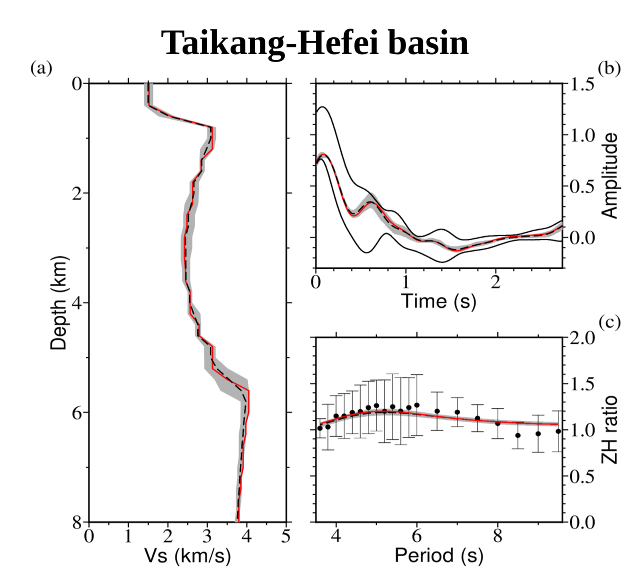

Fig. 10: The same as Fig. 7, but for station HA.PDS.

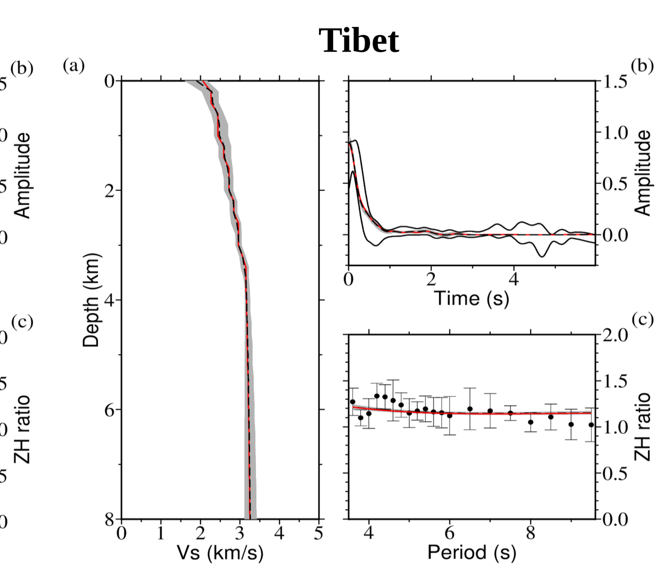

Fig. 11: The same as Fig. 7, but for station XZ.RKZ.

3.Measurement of ZH ratio and RF

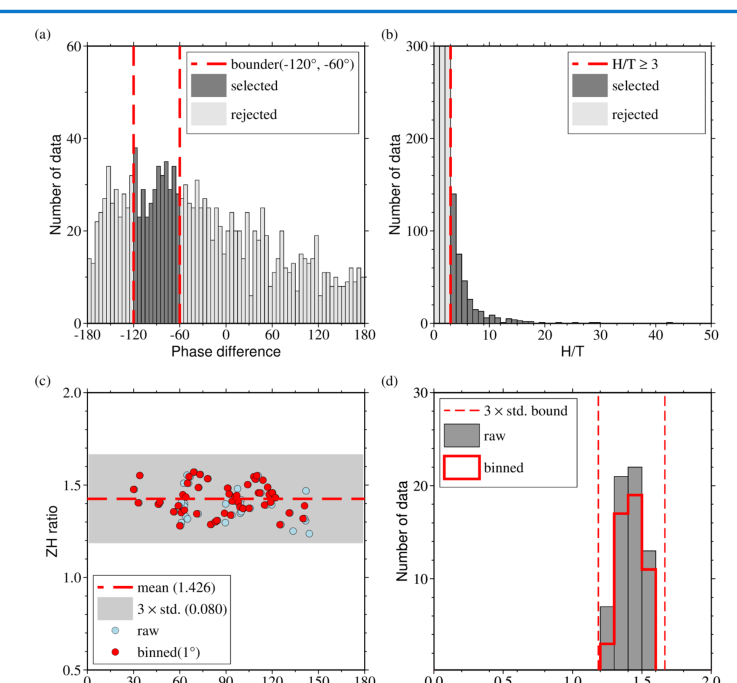

Fig. 3: Measurement of seasonal ZH ratio at period 5.4s for seismic station FJ.FDQY from Feb. to Apr. in 2016. (a) Histogram of phase-shift angles between the horizontal and vertical components. Data segments with phase shift between -60° and -120° (two dashed lines) are selected to derive Rayleigh wave ellipticity. (b) Histogram of amplitude ratio between quasi radial and transverse components (H/T). Only segments with H/T higher than 3 (red dashed line) are kept. (c) Azimuth distribution of ZH ratio for segments selected (blue dots) and azimuth bin-stacked (red dots). (d) Histogram of the raw (grey) and binned (red) ZH ratios. Two dashed lines enclose three standard deviation region from the average of binnned ZH ratios.

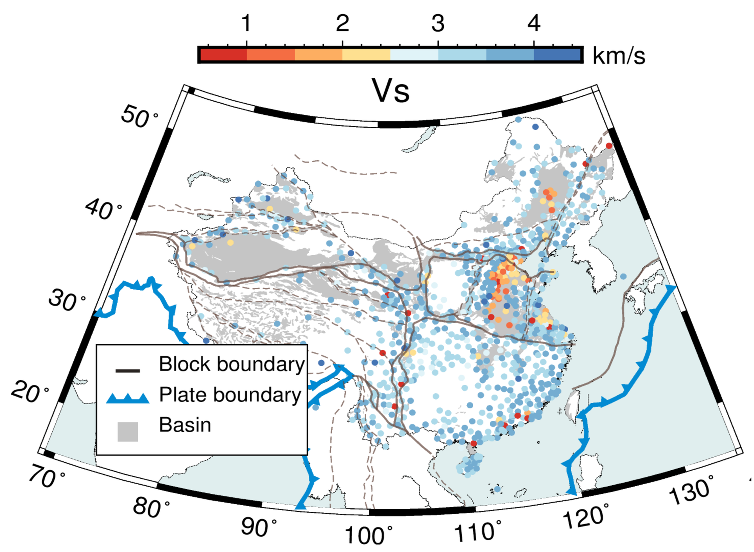

Fig. 4: Estimated near-surface shear velocities

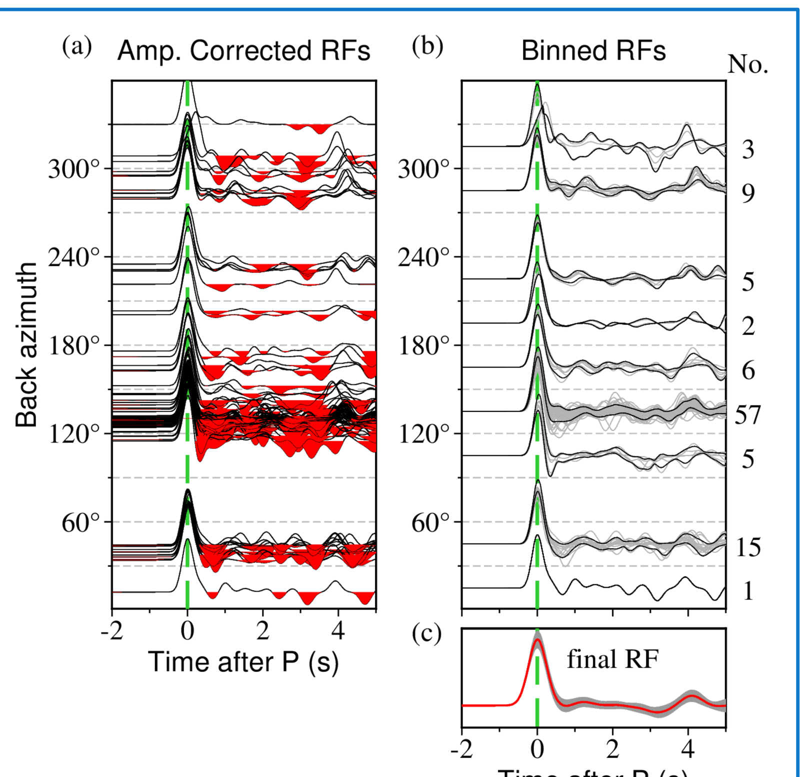

Fig. 5: Stacking procedure of the RFs for station FJ.FDQY. (a) Total 103 amplitude corrected RFs used for stacking. (b) The RFs (grey lines) shown in (a) are stacked with 30° bins in back-azimuth. Two black lines show the uncertainty region estimated from the mean and one standard deviation for stacking in each bin. Numbers listed rightside indicate numbers of RF stacked in each bin. (c) The average RF (red line) of thoses mean RFs in bins and uncertainty region (grey area).

5. Shallow pseudo 3D Vsv model

1D Vsv models inverted based on previous joint inversion method are interpolated to construct the finl pseudo 3D Vsv model.

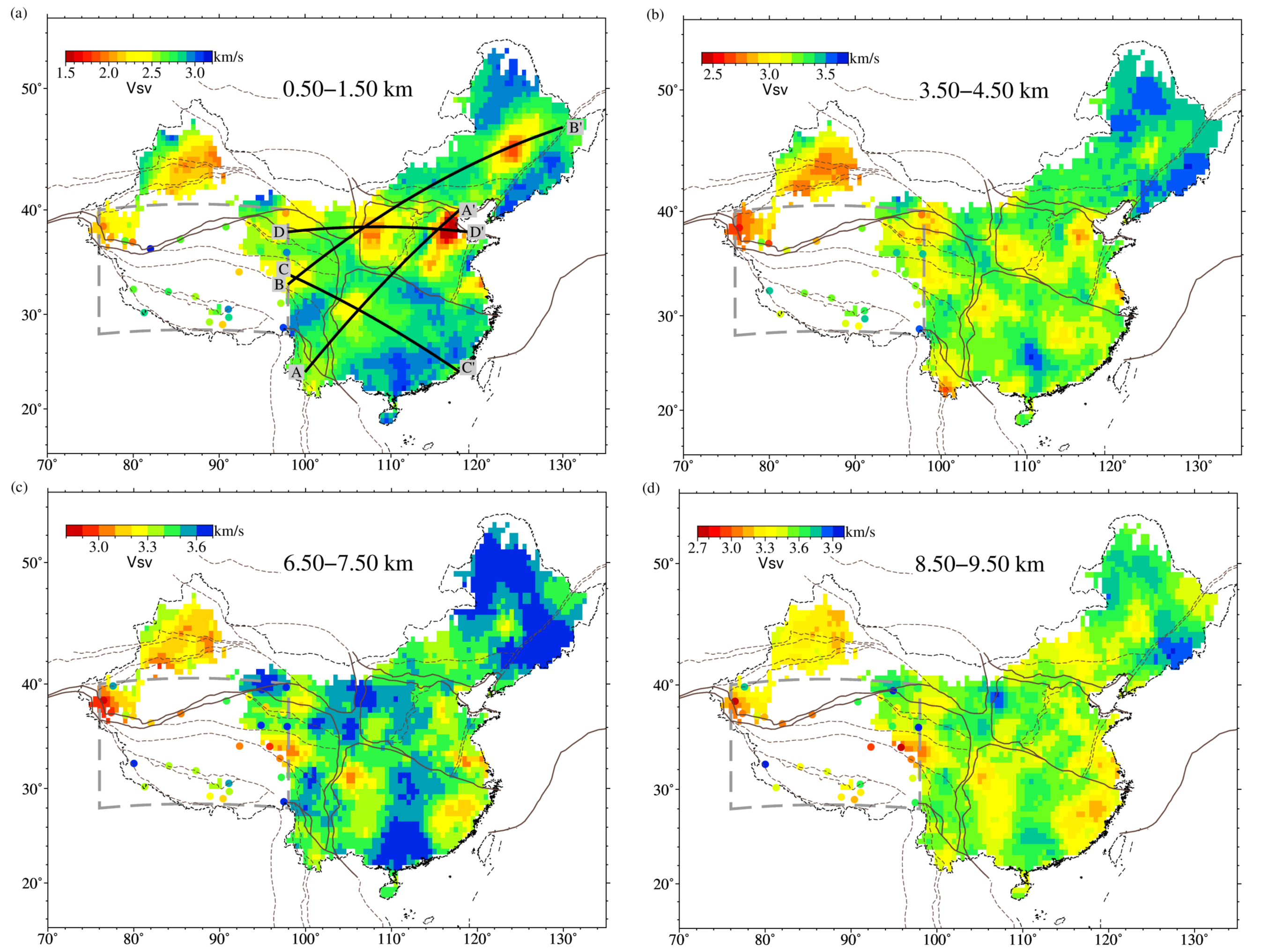

Fig. 12: Map views of interpolated 3D Vsv model at different depths. (a) The averaged Vsv structure among the depth range 0.5 – 1.5 km. The thick-black lines show location of transects in **Fig. 13**. The grey dashed lines enclose Tibet area and the solid circles are indicative of uninterpolated average Vsv over this depth range beneath seismic stations. (b), (c), and (d) are the same as (a), but for depth range 3.5 – 4.5 km, 6.5 – 7.5 km and 8.5 – 9.5 km, respectively.

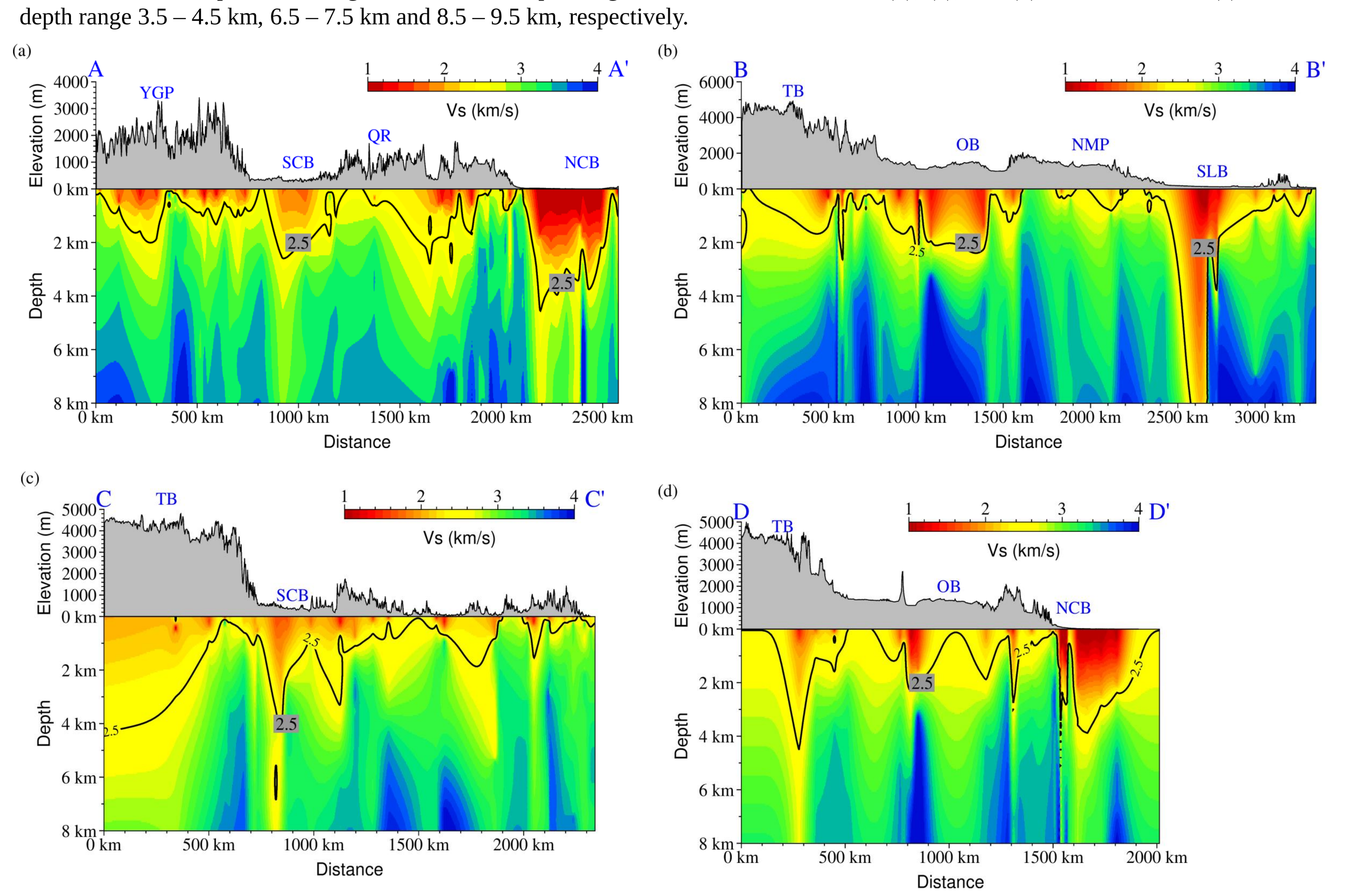

Fig. 13: Vertical transections along profiles (A − A′, B − B′, C − C′ and D − D′), denoted in Fig. 12(a). The locations of geological units are indentified with name acronym above each transect along with surface topography. [YGP: Yunnan-Guizhou plateau; SCB: Sichuang basin; QR: Qing range; NCB: north China basin; TB: Tibet; OB: Ordos block; YT: Neimenggu plateau; SLB: Songliao basin;] The thick black lines in panels represet contour of 2.5 km/s. (a) for transection A − A′, (b) for B − B′, (c) for C − C′ and (d) for D − D′.

6. Conclusions

1. Joint inversion of ZH ratio and receiver function properly constrains shallow Vsv structure, especially for the uppermost 8 km with the longest period of ZH ratio being 9.5s.
2. This study results a pseudo 3D Vsv model beneath China extending to 8 km, highly correlating with geological features. This model identifies locations and ranges of Sichuan basin, north China basin, Songliao basin, Ordors block and Subei Yellow Sea basin, Chuxiong basin and Lanping-Simao basin. In addition, it provides a reliable thickness estimation of sediment for all basins.
3. This study generates a byproduct–nearsurface shear wave velocity model, which partly reflects average shear wave velocity among depth from free surface to several kilometers beneath China.