

A Study of Seismic Structure beneath Shikoku Island Revealed by

Receiver Function and Ambient Noise Tomography Analyses:

Insight from MCMC-based Joint Inversion

「MCMC に基づく レシーバー関数と常時微動トモグラフィー解析
による四国下の地震波速度構造に関する研究」

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Chapter 1 Introduction

Seismic anisotropy serves as a critical observable linking microscale rock fabrics and stress fields to measurable seismic wavefield signatures, providing unique insights into deformation and geodynamic processes within the solid Earth. This introductory chapter establishes the foundational concepts and context for investigating anisotropy in subduction zones, with a focus on the Nankai Trough beneath Shikoku Island, Japan.

A central challenge in anisotropy studies is the isolation of depth-dependent contributions, as signals from shallow sedimentary layers and crustal heterogeneity can masquerade as deeper structure features in common seismic methods. This chapter reviews the mechanisms of anisotropy, including shape-preferred orientation and lattice-preferred orientation, and key observational phenomena like shear-wave splitting. It highlights how advances in dense arrays and waveform modeling support the probing of Earth's interior.

The review then focuses on the specific context of the Nankai subduction zone beneath Shikoku Island, Japan—the target area of this thesis. Despite the region's significance for understanding megathrust earthquakes and slow earthquake phenomena (e.g., tectonic tremor, low frequency earthquake, slow slip), its fine-scale anisotropic velocity structure remains poorly resolved. The spatially heterogeneous seismic activity in Shikoku presents a key opportunity to investigate potential correlations between anisotropic patterns and the distribution of slow earthquakes.

This thesis aims to address these gaps by integrating three complementary methods: Receiver Function (RF) analysis for deep interfaces and anisotropy, Ambient Noise Tomography (ANT) for high-resolution shallow crustal anisotropic imaging, and Markov Chain Monte Carlo (MCMC) joint inversion to unify constraints into a robust velocity model. Key innovations include applying the Bayesian Information Criterion to RF analysis to mitigate overfitting, utilizing across-

sea station pairs in ANT to enhance resolution, and incorporating anisotropic parameters into a predeveloped MCMC code. This chapter thereby sets the scientific and methodological framework for the subsequent investigative chapters.

Chapter 2 Integrated Approach of Receiver Function and Shear Wave Splitting analyses

This chapter aims to utilize receiver function and shear-wave splitting analyses, focusing primarily on the converted P_S phases generated at the oceanic Moho, to produce a map of anisotropy distribution across the entire Shikoku region for the first time, spanning from the oceanic Moho to the surface. Teleseismic data recorded by Hi-net stations were employed to compute receiver functions, which were then aligned and plotted into profiles based on back-azimuth. During the calculation of each receiver function via the iterative time-domain deconvolution method, the Bayesian Information Criterion was applied to constrain waveform overfitting. Since dipping interfaces can generate signals on the transverse component of receiver functions, similar to anisotropic media, this chapter integrates receiver functions from all back-azimuths to extract anisotropy parameters (delay time and fast polarization direction, FPD), thereby minimizing the potential contamination from dipping interfaces on the anisotropy analysis.

The measured delay times show a median value of 0.06 s with a median absolute deviation of 0.04 s across the study area. Near the northeastern and southern coasts of Shikoku, the fast polarization directions are sub-parallel to the plate convergence direction, contrasting with the predominantly sub-perpendicular pattern observed in the island's interior. Western Shikoku exhibits a strong sub-perpendicular FPD pattern relative to the convergence direction, which may reflect the influence of serpentinization within the underlying mantle wedge. These results provide initial insights into the integrated anisotropic characteristics of the Shikoku region. However, the absence of constraints on the shallow anisotropic velocity structure limits the precise assessment of the entire anisotropic pattern. This gap necessitates the high-resolution imaging of the shallow crustal structure, which will be addressed in the following chapter.

Chapter 3 Ambient Noise Tomography Analysis

To address the limited resolution of shallow structures in Chapter 2, this chapter employs ambient noise tomography to characterize the shear-wave velocity and azimuthal anisotropy structure of the upper crust (<10 km) beneath Shikoku Island with high spatial resolution. We utilized two years of continuous waveform data recorded by the dense Hi-net seismic array in southwestern Japan. Since the average water column thickness of about 100 m within the study area has a negligible influence on surface wave dispersion at periods of 2–7 s, cross-sea station pairs were included in the ambient noise tomography analysis, significantly enhancing ray path coverage across Shikoku. By extracting and inverting Rayleigh wave phase velocity dispersion curves, we obtained a three-dimensional shear-wave velocity model.

The median anisotropy amplitudes (for values exceeding 0.1%) across different depth layers are 1.95%, 2.04%, 2.05%, 1.92%, and 1.62% for the depth ranges of 0.9–1.9 km, 1.9–4.0 km, 4.0–6.7 km, 6.7–9.3 km, and 9.3–12 km, respectively. The predominant fast-axis orientations beneath Shikoku vary from northeast-southwest to east-west and southeast-northwest. Notably, the fast-axis orientations exhibit segmental variations along the Median Tectonic Line. We interpret the azimuthal anisotropy derived from ANT as primarily stress-induced, while not excluding the influence of fault systems near major faults.

This chapter provides crucial constraints on shallow crustal shear-wave velocity and anisotropy. Furthermore, to construct an integrated anisotropic model extending from the surface to the oceanic crust, it is necessary to combine the shallow constraints presented here with the receiver function information from Chapter 2.

Chapter 4 Markov Chain Monte Carlo-based joint inversion

This chapter constructs a shear-wave velocity and anisotropy model with clear depth resolution, extending from the crust to the subducting slab beneath Shikoku, by jointly inverting the receiver function data from Chapter 2 and the surface wave dispersion data from Chapter 3. Special attention is given to the converted Ps phases generated at the oceanic Moho to deduce the geometric configuration of the Philippine Sea Plate. We employ a Markov Chain Monte Carlo framework for probabilistic joint inversion. This method effectively accounts for the trade-off between interface depth and velocity in the receiver functions by incorporating the shallow crustal velocity constraints from Chapter 3, while quantitatively assessing model uncertainty.

By interpolating the Moho depths beneath individual stations, the derived PHS plate geometry, approximated by offsetting the Moho by a standard oceanic crustal thickness, suggests a relatively gentle dip angle beneath eastern Shikoku. Specifically, the subduction of the PHS plate beneath eastern Shikoku follows a shallower and

gentler trajectory ($\sim 6\text{--}8^\circ$), extending farther north beneath the Seto Inland Sea, which diverges from existing models. Our analysis reveals systematic along-strike variations in the distribution of both mantle earthquakes and low-frequency earthquakes, which are closely linked to the thermal structure and fluid processes associated with the subducting slab.

Chapter 5 General Discussion

This chapter synthesizes the findings from receiver function analysis, ambient noise tomography, and joint inversion to present an integrated model linking seismic structure, anisotropy, and slow earthquakes in Shikoku.

Key conclusions are: (1) A newly shallower geometry of the subducting Philippine Sea plate is proposed, suggesting an explanation of the along-strike variation of low-frequency earthquakes (LFEs) and tremors. (2) Upper crustal anisotropy is predominantly stress-induced, while localized trench-parallel anisotropy in the northwest likely indicates serpentinization in the mantle wedge. (3) Slow earthquakes (tremors and LFEs) primarily occur in regions of low intrinsic anisotropic intensity.

The synthesis demonstrates that multi-scale anisotropy is critical for decoupling the lattice-preferred orientation in the deeper mantle from the dominant stress field in the crust. These results directly supply the variations of anisotropy for further analysis on the spatial distribution of slow earthquakes, providing structural evidence for understanding the mechanism of seismicity in the Nankai subduction zone. Methodological limitations are also discussed to highlight areas for future methodological refinement.

Chapter 6 General Conclusion

This chapter summarizes the key findings of this doctoral dissertation, which presents a comprehensive, multi-method seismic investigation of Shikoku Island. By integrating receiver function analysis, ambient noise tomography, and Markov Chain Monte Carlo joint inversion, we resolve the anisotropic structure and propose a revised geometric configuration for the subducting Philippine Sea (PHS) plate. Our principal conclusions are twofold: (1) The PHS plate subducts at a shallower, gentler angle ($\sim 6\text{--}8^\circ$) beneath eastern Shikoku than previously thought, extending farther north. This new geometry provides a structural framework that elucidates the along-strike migration patterns of tectonic tremor and low-frequency earthquakes (LFEs), linking an LFE gap in eastern Shikoku to thermally driven early fluid exhaustion. (2) Multi-scale anisotropy analysis reveals that crustal anisotropy is dominant and stress-induced, while weak, trench-parallel anisotropy in the northwestern mantle wedge likely indicates

serpentinization influenced by dehydration. Critically, tremor and LFE activity is concentrated in regions of low intrinsic anisotropy. Collectively, this work establishes direct links between slab geometry, multi-scale anisotropic fabric, and the spatiotemporal distribution of slow earthquakes, advancing the understanding for the Nankai subduction zone.