

Passive estimation of scattering and intrinsic absorption parameters at 18 active volcanoes in Japan using envelopes of seismic ambient noise cross-correlation functions

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1. Introduction

Estimating seismic scattering and intrinsic absorption parameters, which are measures of medium heterogeneity, is important for understanding the complex structure in shallow regions of volcanoes. In recent years, seismic ambient noise cross-correlation functions (CCFs) have been used instead of records of natural earthquakes or active seismic experiments to estimate those parameters (e.g., Hirose et al., 2019; Hirose et al., 2020; van Dinter et al., 2020). This passive approach possibly allows us to estimate scattering and intrinsic absorption parameters in previously unmeasured regions and frequency bands. In this study, we apply the passive estimation method proposed by Hirose et al. (2019) to 18 active volcanoes in Japan and measure those parameters of Rayleigh waves.

2-1. Data

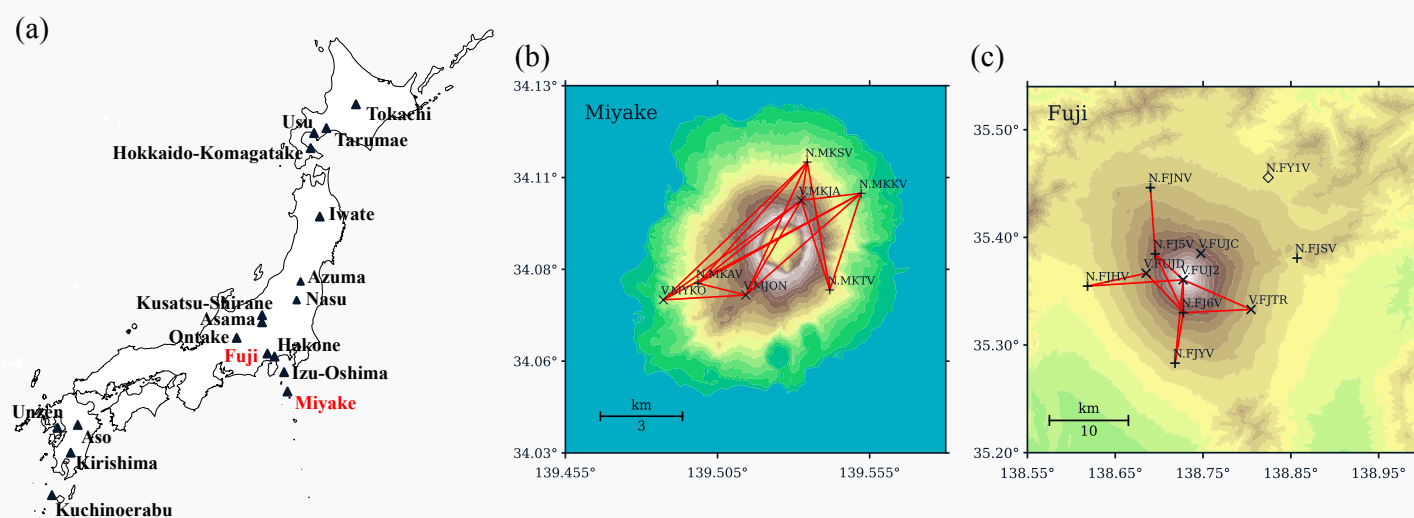


Figure 1. (a) Locations of 18 active volcanoes. Distributions of seismometers at (b) Miyakejima and (c) Mt. Fuji. Red lines indicate station pairs used on the estimation of scattering and intrinsic absorption parameters at 0.5-1 Hz band.

- A three-component short-period seismometer with a natural frequency of 1 Hz is installed at each station. All the seismograms are recorded with a sampling frequency of 100 Hz.
- Continuous seismic records over 1 year (3 components)
- 0.5-1 Hz, 1-2 Hz, 2-4 Hz

2-2. Calculation procedure of seismic ambient noise CCFs

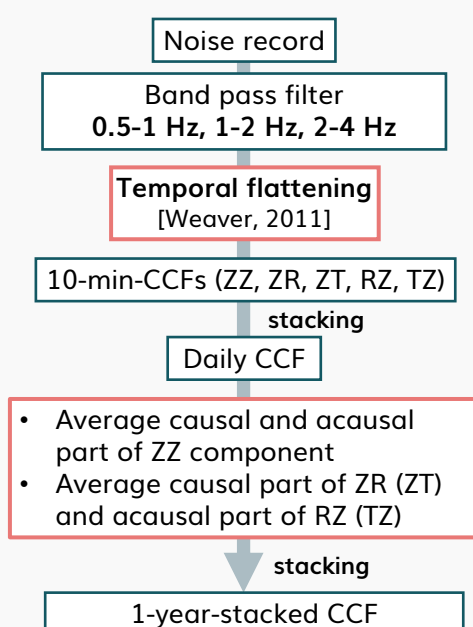


Figure 2. Calculation procedure of seismic ambient noise CCFs.

We apply the **temporal flattening technique** (Weaver, 2011) to the seismic ambient noise data for reducing the effect of temporal fluctuations of noise levels.

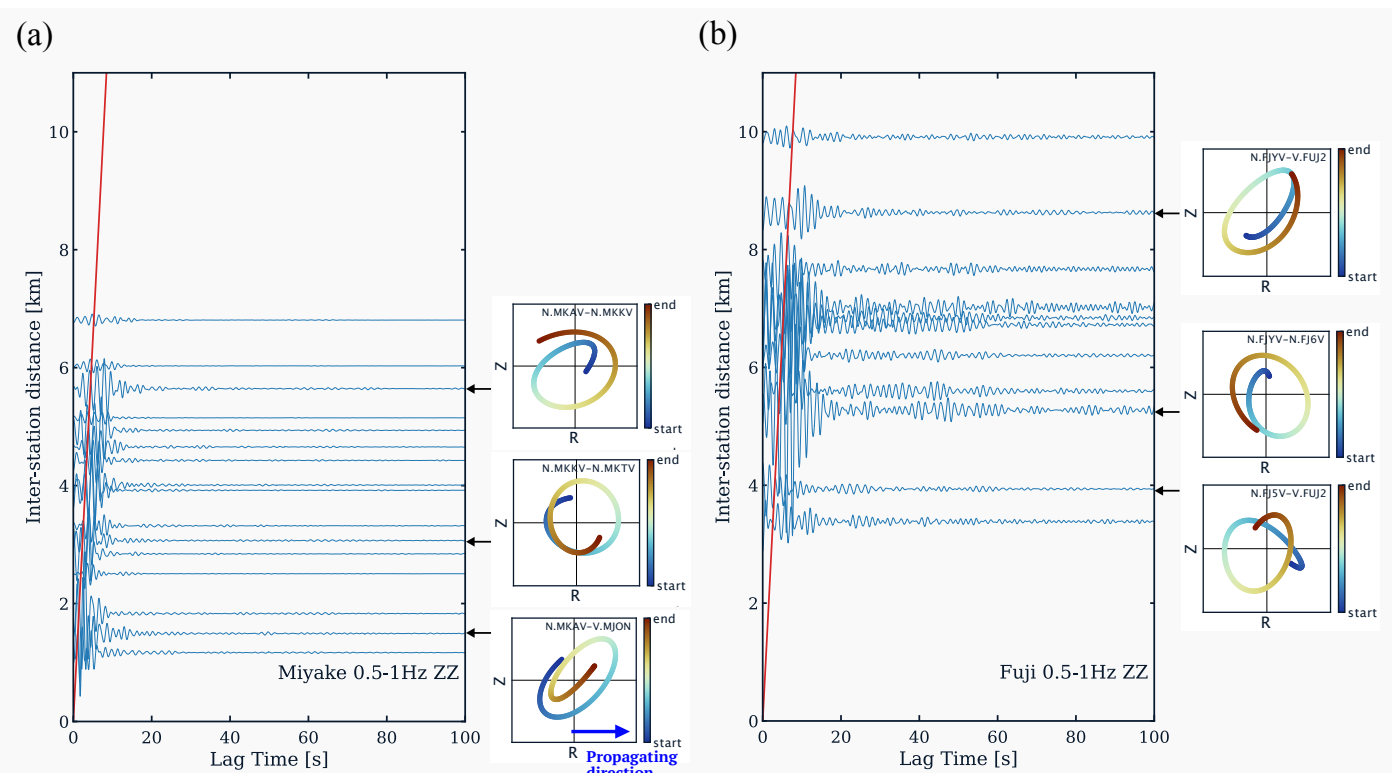


Figure 3. Record sections of 1-year-stacked seismic ambient noise CCFs on vertical-vertical (ZZ) component in 0.5-1 Hz band at (a) Miyakejima and (b) Mt. Fuji. The red straight lines represent arrival times of direct Rayleigh waves assuming their velocities to be 1.3 km/s. The three small panels beside the each record-section are examples of particle motions on the radial-vertical (R-Z) plane around the direct Rayleigh wave arrivals.

Particle motions on the radial-vertical plane are retrograde
-> Rayleigh waves are predominant on seismic ambient noise CCFs.

2-3. Estimation method of scattering and intrinsic absorption parameters

The best-fit values of the scattering mean free path ℓ and the intrinsic absorption parameter b ($b = Q_l^{-1}\omega$) of Rayleigh wave are estimated by modeling the space-time distributions of energy densities with the 2-D radiative transfer theory (Hirose et al., 2019).

$$SSR = \sum_{i=1}^6 \sum_{j=1}^N \left(\log_{10} E_{obs}(t_i, j) - \log_{10} E_{syn}(t_i, j) \right)^2 \rightarrow \text{minimize}$$

E_{obs} : Sum of mean squared (MS) envelopes for three components (ZZ, RZ & ZR, ZT & TZ).

E_{syn} : The 2-D radiative transfer model for scalar waves which assumes isotropic scattering and source radiation in an infinite medium (e.g., Shang and Gao, 1988; Sato, 1993).

$$E_{syn}(r, t) = \frac{e^{-ct\ell^{-1}}}{2\pi cr} e^{-bt} \delta\left(t - \frac{r}{c}\right) + \frac{e^{\ell^{-1}(\sqrt{c^2 t^2 - r^2} - ct)}}{2\pi \ell \sqrt{c^2 t^2 - r^2}} e^{-bt} H\left(t - \frac{r}{c}\right)$$

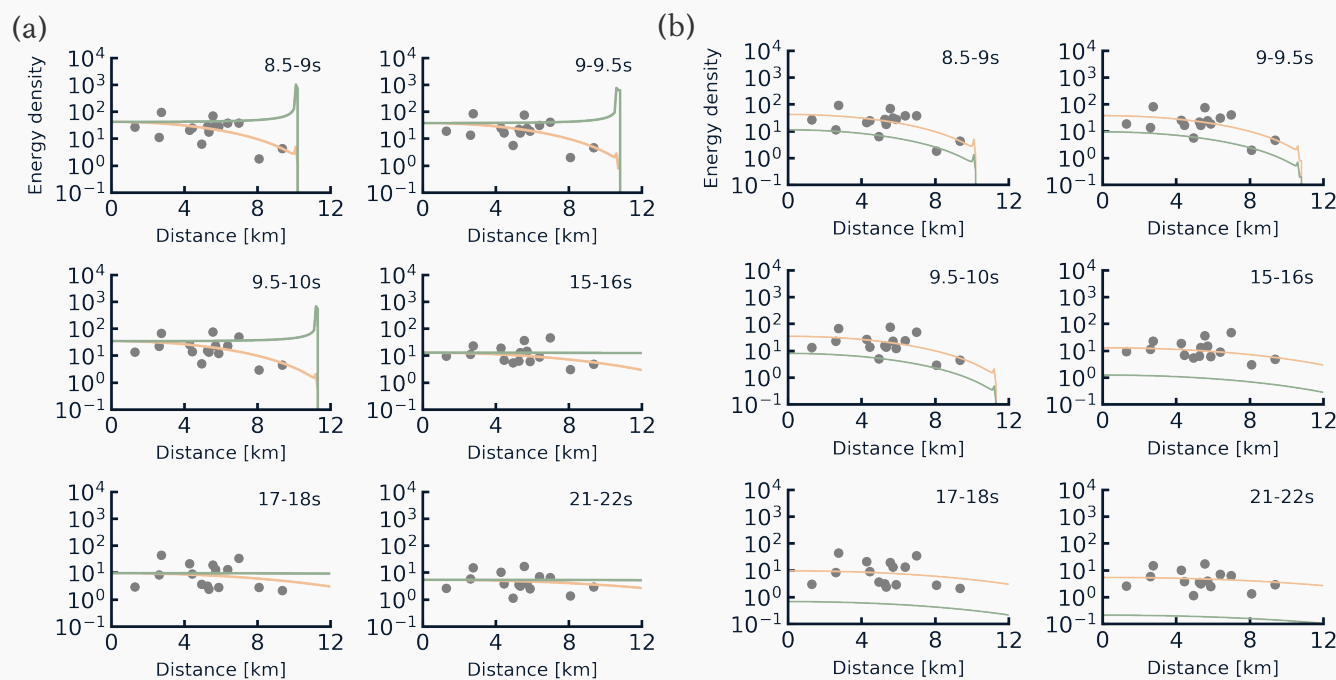


Figure 4. Theoretical curves for (a) two different scattering mean free path (pink: $\ell=1.6$ km and $b=0.09$ s⁻¹, green: $\ell=10$ km and $b=0.09$ s⁻¹) and for (b) two different intrinsic absorption parameter (pink: $\ell=1.6$ km and $b=0.09$ s⁻¹, green: $\ell=1.6$ km and $b=0.24$ s⁻¹).

- **Scattering mean free path ℓ controls spatial gradient of energy densities**
- **Intrinsic absorption parameter b is defined as a decreasing speed of energy level**

3. Results

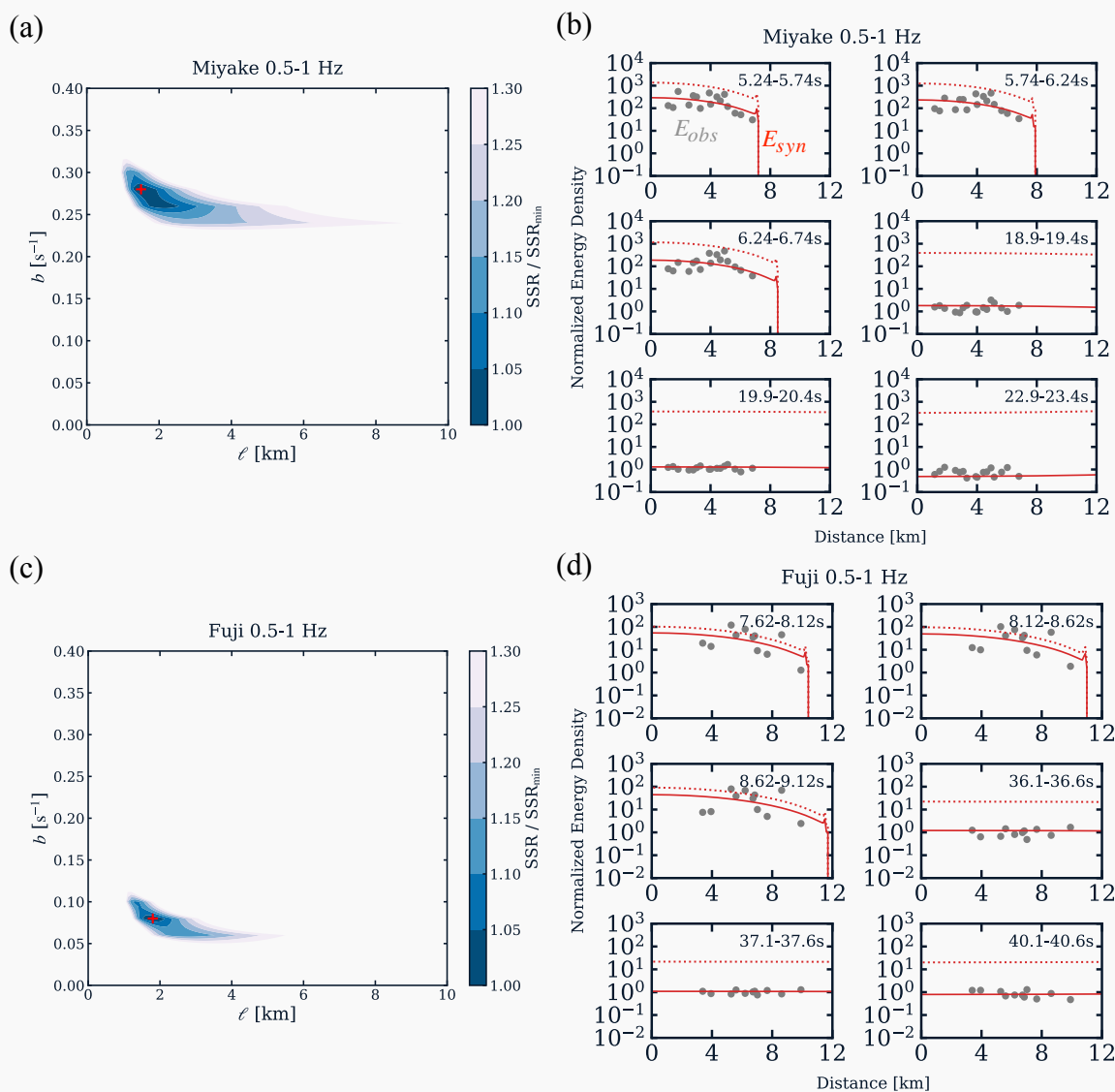


Figure 5. (a) The result of grid-search in 0.5-1 Hz band at Miyakejima. (b) Space-time distributions of energy densities. (c)-(d) Similar to (a) and (b), but at Mt. Fuji.

Best-fit values of ℓ

-> 1.2–3.3 km (0.5-1 Hz), 0.6-3.0 km (1-2 Hz), 0.8-3.4 km (2-4 Hz)

Best-fit values of b

-> $1.5 \times 10^{-3} - 3 \times 10^{-2}$ (0.5-1 Hz), $7 \times 10^{-4} - 2 \times 10^{-2}$ (1-2 Hz), $3 \times 10^{-4} - 1.5 \times 10^{-2}$ (2-4 Hz)

Table 1. Best-fit values of ℓ and b at all volcanoes and frequency bands. Value ranges in brackets indicate 95 % confidence intervals. γ_{Sc} and γ_l represent frequency dependencies of Q_{Sc}^{-1} and Q_l^{-1} ($Q_{Sc}^{-1} = c/\ell\omega$ and $Q_l^{-1} = b/\omega$).

Volcano	Frequency band	ℓ [km]	b [s ⁻¹]	γ_{Sc}	γ_l	c [km/s]
Tokachi	0.5–1 Hz	1.7 (1.1-3.0)	0.14 (0.13-0.15)	1.00	0.40	1.6
	1–2 Hz	2.4 (1.4-6.1)	0.14 (0.13-0.15)			
	2–4 Hz	1.7 (1.1–2.8)	0.32 (0.29-0.33)			
Tarumae	0.5–1 Hz	1.2 (1.1-1.6)	0.24 (0.23-0.27)	1.06	1.79	1.2
	1–2 Hz	1.3 (1.1-1.8)	0.12 (0.11-0.13)			
	2–4 Hz	1.3 (1.2-1.8)	0.08 (0.05-0.11)			
Usu	0.5–1 Hz	1.3 (1.1-1.7)	0.20 (0.17-0.19)	1.10	1.50	1.0
	1–2 Hz	0.7 (0.6-0.9)	0.20 (0.19-0.23)			
	2–4 Hz	1.2 (1.1-1.4)	0.10 (0.09-0.11)			
Hokkaido-Komagatake	0.5–1 Hz	1.2 (1.1-1.4)	0.24 (0.21-0.25)	1.00	1.50	1.2
	1–2 Hz	0.9 (0.8-1.1)	0.18 (0.15-0.21)			
	2–4 Hz	1.2 (1.1-1.4)	0.12 (0.11-0.13)			
Iwatesan	0.5–1 Hz	2.2 (1.8-2.9)	0.08 (0.07-0.09)	1.12	0.60	1.6
	1–2 Hz	2.1 (1.6-2.8)	0.08 (0.05-0.11)			
	2–4 Hz	2.6 (1.9-3.8)	0.14 (0.13-0.15)			
Azuma	0.5–1 Hz	2.4 (1.8-3.6)	0.12 (0.09-0.13)	0.97	1.13	1.5
	1–2 Hz	2.0 (1.6-2.8)	0.14 (0.13-0.15)			
	2–4 Hz	2.3 (1.6-4.5)	0.10 (0.07-0.13)			
Nasu	0.5–1 Hz	2.4 (1.9-3.1)	0.14 (0.13-0.15)	1.06	1.00	1.5
	1–2 Hz	3.0 (2.4-3.8)	0.14 (0.13-0.15)			
	2–4 Hz	2.6 (2.2-3.2)	0.14 (0.13-0.15)			
Kusatsu-Shirane	0.5–1 Hz	2.7 (2.1-3.9)	0.14 (0.11-0.17)	0.67	0.82	1.2
	1–2 Hz	2.2 (1.6-3.3)	0.14 (0.11-0.17)			
	2–4 Hz	1.7 (1.6-1.9)	0.18 (0.15-0.19)			
Asama	0.5–1 Hz	3.3 (2.4-5.6)	0.08 (0.07-0.09)	0.88	0.84	1.4
	1–2 Hz	1.5 (1.3-1.9)	0.10 (0.09-0.11)			
	2–4 Hz	2.8 (2.1-4.3)	0.10 (0.09-0.11)			
Fuji	0.5–1 Hz	1.8 (1.4-2.3)	0.08 (0.07-0.09)	1.23	1.21	1.3
	1–2 Hz	2.1 (1.6-2.9)	0.08 (0.07-0.09)			
	2–4 Hz	2.3 (1.8-3.1)	0.06 (0.05-0.07)			
Hakone	0.5–1 Hz	1.6 (1.3-1.9)	0.20 (0.17-0.23)	0.73	1.37	1.6
	1–2 Hz	1.6 (1.4-1.8)	0.10 (0.09-0.11)			
	2–4 Hz	1.1 (0.8-1.6)	0.12 (0.07-0.15)			
Izu-Oshima	0.5–1 Hz	2.7 (1.8-3.5)	0.22 (0.19-0.25)	0.42	1.44	1.2
	1–2 Hz	1.2 (0.9-1.6)	0.16 (0.13-0.19)			
	2–4 Hz	1.2 (1.1-1.4)	0.12 (0.11-0.13)			
Miyake	0.5–1 Hz	1.6 (1.2-2.1)	0.28 (0.27-0.29)	0.56	1.50	1.3
	1–2 Hz	0.6 (0.5-0.7)	0.18 (0.17-0.21)			
	2–4 Hz	0.8 (0.6-1.0)	0.14 (0.13-0.15)			
Ontake	0.5–1 Hz	2.5 (1.8-3.4)	0.18 (0.15-0.21)	0.97	1.29	2.0
	1–2 Hz	2.1 (1.8-2.8)	0.14 (0.13-0.15)			
	2–4 Hz	2.4 (1.8-3.5)	0.12 (0.07-0.17)			
Aso	0.5–1 Hz	2.0 (1.6-2.4)	0.12 (0.09-0.15)	1.04	0.63	1.6
	1–2 Hz	2.1 (1.8-2.8)	0.14 (0.13-0.15)			
	2–4 Hz	2.1 (1.6-2.9)	0.20 (0.19-0.21)			
Unzen	0.5–1 Hz	1.9 (1.4-2.8)	0.20 (0.17-0.23)	0.88	1.37	1.2
	1–2 Hz	1.8 (1.4-2.4)	0.12 (0.11-0.13)			
	2–4 Hz	1.6 (1.2-2.0)	0.12 (0.11-0.13)			
Kirishima	0.5–1 Hz	2.6 (2.2-3.3)	0.14 (0.13-0.15)	1.19	0.90	1.5
	1–2 Hz	2.0 (1.6-2.4)	0.16 (0.15-0.17)			
	2–4 Hz	3.4 (2.2-7.5)	0.16 (0.11-0.21)			
Kuchinoerabu	0.5–1 Hz	1.4 (1.1-1.9)	0.30 (0.27-0.33)	0.60	1.00	1.2
	1–2 Hz	1.3 (0.9-2.1)	0.26 (0.23-0.29)			
	2–4 Hz	0.8 (0.6-1.2)	0.30 (0.23-0.29)			

4. Discussions

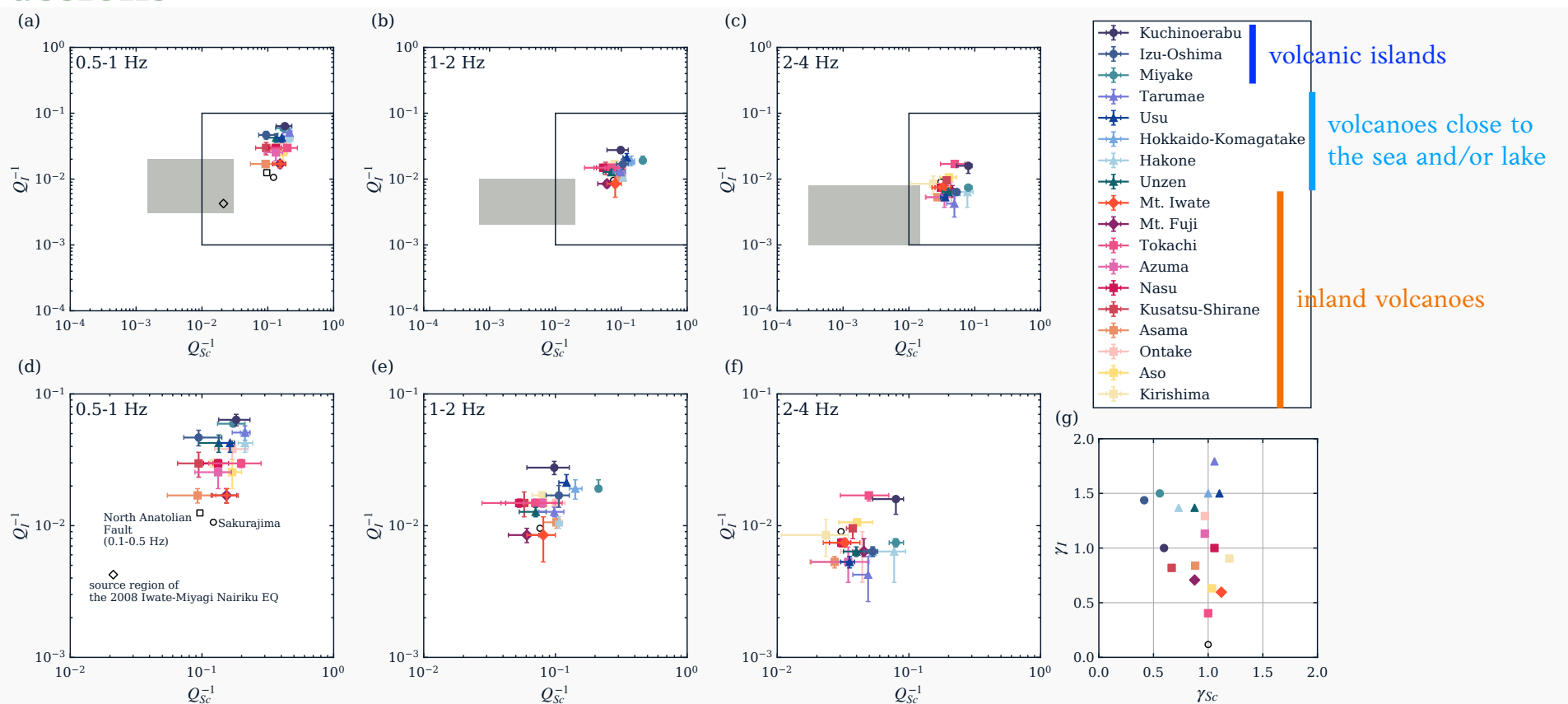


Figure 6. Estimated values of scattering attenuation factor Q_{sc}^{-1} and intrinsic attenuation factor Q_l^{-1} at the (a) 0.5-1 Hz, (b) the 1-2 Hz band, and (c) the 2-4 Hz bands. (d)-(f) Enlarged views of (a)-(c). (g) Frequency dependences of Q_{sc}^{-1} and Q_l^{-1} . The opened circled, squares, and diamonds in the panels (a)-(f) represent estimated attenuation factors estimated by the passive method in Sakurajima volcano (Hirose et al., 2019), the North Anatolian Fault (van Dinther et al., 2020), and the source region of the 2008 Iwate-Miyagi Nairiku EQ (Hirose et al., 2020).

Common features

- **Estimated Q_{sc}^{-1} ($Q_{sc}^{-1} = c/\ell\omega$) at the 18 volcanoes are 2 orders of magnitudes of larger than those in the non-volcanic regions.**
-> Many previous studies have reported such strong medium heterogeneities in the shallow parts of volcanoes. For example, Asama volcano, Japan ($\ell \approx 1.1$ km at 8-16 Hz band; Yamamoto and Sato, 2010), Usu volcano, Japan ($\ell \approx 1.0$ km at 4-20 Hz band; Prudencio et al., 2017), and Stromboli volcano, Italy ($\ell \approx 0.2$ km at 4 Hz ; Prudencio et al., 2015).
- **Estimated Q_l^{-1} ($Q_l^{-1} = b/\omega$) at the 18 volcanoes are at most one order of magnitude larger than those in the non-volcanic regions.**
-> Shito et al. (2020) estimated scattering attenuations beneath active volcanoes in Kyushu, Japan, which are about 2-3 orders of magnitudes larger than those in other areas. On the other hand, intrinsic attenuation factors are only one order of magnitude larger than those in other areas.

Different characteristics

1. **Volcanic islands and volcanoes close to the sea and/or lake have stronger intrinsic attenuations than inland volcanoes.**
2. **Frequency dependencies of Q_l^{-1} at those volcanoes are stronger than those of inland volcanoes.**
-> Water-bearing layers extending widely beneath the volcanic islands will cause strong intrinsic attenuations. For example, resistivity structures along depths at Izu-Oshima suggest low resistivity regions around 500-600 m beneath volcano (Utada and Shimomura, 1990). These low resistivity regions are interpreted as a water-bearing layer.
-> High Q_l^{-1} cause strong frequency dependencies of Q_l^{-1} .
3. **Intrinsic attenuations at Mt. Fuji and Mt. Iwate are relatively weak among the 18 active volcanoes at the 0.5-1 Hz and 1--2 Hz bands.**
-> The results of the magnetotelluric (MT) survey at Mt. Fuji suggest that there are no significant low resistivity regions at the shallow part of Mt. Fuji (Aizawa et al., 2005).
-> At the east part of Mt. Iwate, the high resistivity region extends widely. This region corresponds to accumulated lava (Aizawa et al., 2009).

5. Conclusions

This study succeeded in estimating scattering and intrinsic absorption parameters at 18 active volcanoes in Japan. Estimating these parameters separately allowed us to discuss common features and different characteristics in attenuation structures at the 18 volcanoes. The passive estimation method of scattering and intrinsic absorption parameters based on seismic interferometry can be a useful tool for estimating attenuation structures at shallow regions of the Earth's crust.