Lithospheric Heterogeneity Revealed from the Envelope Analysis of Short-Period Seismograms

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1. Introduction

In short period seismograms of local earthquakes, long lasting coda waves follow the direct S arrival and the apparent duration of S waves is often much larger than the source duration time. For P-waves of teleseismic events, envelopes are broadened longer than the source duration and waves are excited in the transverse component. Analyzing those seismogram envelopes on the basis of stochastic scattering models, we are able to quantify the random heterogeneities distributed in the Earth's lithosphere: one is the scattering coefficient which phenomenological characterizes the scattering power per unit volume for the radiative transfer theory; another is the power spectral density function (PSDF) of the fractional velocity fluctuation, which is more appropriate for the wave theory in random media. Stochastic characterization and deterministic imaging such as tomography are complimentary to each other to enrich our understanding of the structure and the evolution of the solid Earth. Here we briefly review recent measurements by using statistical envelope syntheses and analytical methods.

2. Measurement of scattering coefficients on the basis of radiative transfer theory

The radiative transfer theory phenomenologically describes the scattering process of seismic energy in short periods in randomly heterogeneous media, where the scattering coefficient is the key parameter. Isotropic scattering is often assumed in many applications because of mathematical simplicity.

The multiple lapse time window analysis is to measure the scattering coefficient (loss) and intrinsic absorption of S-waves from the whole S envelopes of local earthquakes on the basis of multiple isotropic scattering model (Fehler et al. 1992). Applying this method to shallow earthquakes registered by Hi-net data, we newly made maps of those quantities in Japan (Carcole and Sato, 2010). In high frequencies (8-16 Hz), absorption is high in the west of Hokkaido and Tohoku, in Chubu, Kii peninsula and south Kyushu, and is low in eastern side of Tohoku and Kanto and north of Chugoku. In low frequencies (1-2 Hz), absorption is high in central Hokaaido, along the volcanic chain in Tohoku, in Chubu and western Japan. In high frequencies, scattering (loss) is high in the volcanic arc in Tohoku, from Niigata to Chugoku, is low in Shikoku. In low frequencies, scattering is low in western Japan but high in Kanto and north Japan. The scattering coefficient of S waves is on average 0.01 km^{-1} for 1 to 32 Hz.

In more heterogeneous region, we measured scattering coefficient in Asama volcano by using artificial explosions. The multiple isotropic scattering model including PS conversions (Sato, 1994) well explains the temporal variation of the spatial distribution of seismic energy, where the energy transfer from P to S waves is important. The estimated scattering coefficient for S wave is as large as about 1 km^{-1} for 8-16 Hz (Yamamoto and Sato, 2010).

Figure 1 summarizes those scattering coefficients newly measured with those measured in various areas in the world. Scattering coefficients estimated are from 0.001 km^{-1} to 0.05 km^{-1} in the lithosphere. The scattering coefficient beneath volcanoes is two order larger and those in the mantle at lower frequencies (Lee et al. 2003, 2006) are two or three order smaller than those in the lithosphere.

3. Measurement of the PSDF of fractional velocity fluctuation

Markov approximation for the parabolic wave equation in random media

Envelope broadening is well explained by multiple forward scattering due to random velocity inhomogeneities. When the wavelength is smaller than the correlation distance of random media, wave propagation is governed by the parabolic type equation. The Markov approximation, which is a stochastic extension of the split step algorithm, directly derives the mean square envelopes for the incidence of an impulsive wavelet or for an impulsive radiation from a point source. The excitation of transverse component for P waves is also derived (Emoto et al. 2010). According to this approximation, the PSDF of fractional velocity fluctuation controls the frequency dependence and distance dependence of the envelope broadening. From the inversion analysis of S envelopes of microearthquakes in northern Japan, we find that PSDF is larger and the spectral decay rate is smaller beneath Quaternary volcanoes (line 4.1 and 4.2) compared with those in the fore-arc side of the volcanic front (lines 3.1, 3.2, and 3.3) as shown in Figure 2 (Saito et al. 2005, Takahashi et al. 2009).

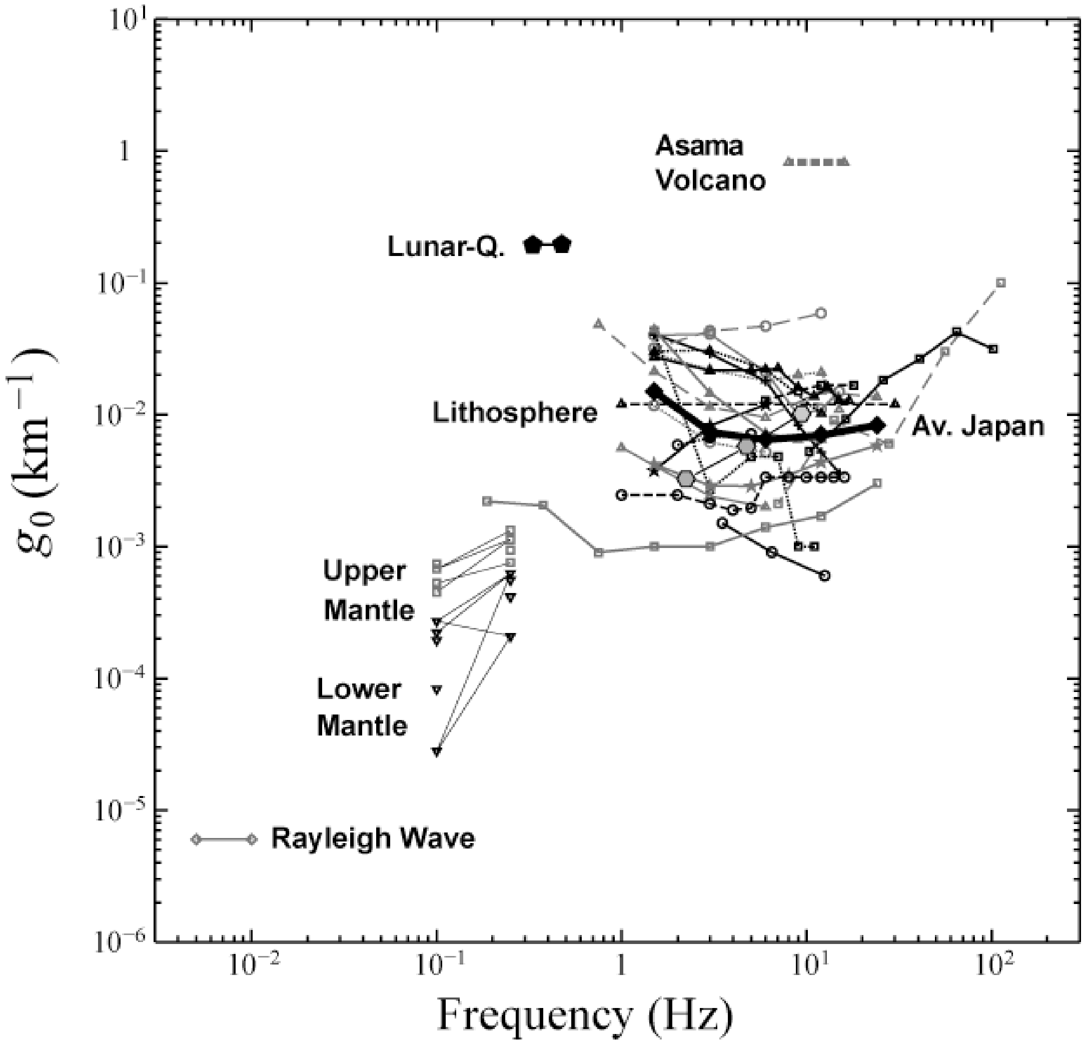

Figure 1. Summary of scattering coefficients of S waves [Courtesy of K. Emoto].

Radiative Transfer theory with the Born scattering coefficients

By using the Born approximation for random elastic media, we can derive nonisotropic scattering coefficients, which is a function of the PSDF of fractional velocity fluctuation. By using the raditiave transfer theory with the Born scattering coefficients, we are able to synthesize vector wave envelopes. By applying this method, PSDFs are estimated from S envelopes in Norway (line 6, Przybilla et al. 2009) and from P and S envelopes in Nikko, Japan (line 7, Yoshimoto et al. 1997). Lines 1.1 and 1.2 are PSDF in the lithosphere and the upper mantle and that in the lower mantle revealed from P envelopes of teleseismic events (Shearer and Earle, 2004).

3. Summary

The scattering coefficient is a key parameter to characterize phenomenologically the medium heterogeneity. Scattering coefficients for S waves are of the order of 0.01 km^{-1} on average in the lithosphere. Scattering coefficient beneath volcanoes is two order larger and those in the mantle are two or three order smaller than those in the lithosphere. It will be necessary to measure the scattering coefficients for PS conversion scattering. It will be interesting to develop theories, which adopt conversion scattering between surface waves and body waves. PSDF of the fractional velocity fluctuation is important for the quantitative description of the medium heterogeneity in relation with wave propagation. PSDF decreases according to a power of wavenumber at large wavenumbers, where the exponent ranges from –3.4 to –4.2. Reported measurements of PSDF well discriminate the difference between the mantle and the lithosphere in global scale, and that between volcanoes and the curst in regional scale. It will be necessary to develop more accurate inversion methods for the evaluation of PSDF.

Acknowledgements

The author would like to express sincere thanks to T. Nishimura, E. Carcole, M. Yamamoto, and T. Takahashi, W. S. Lee and K. Emoto for their collaboration in those measurements.

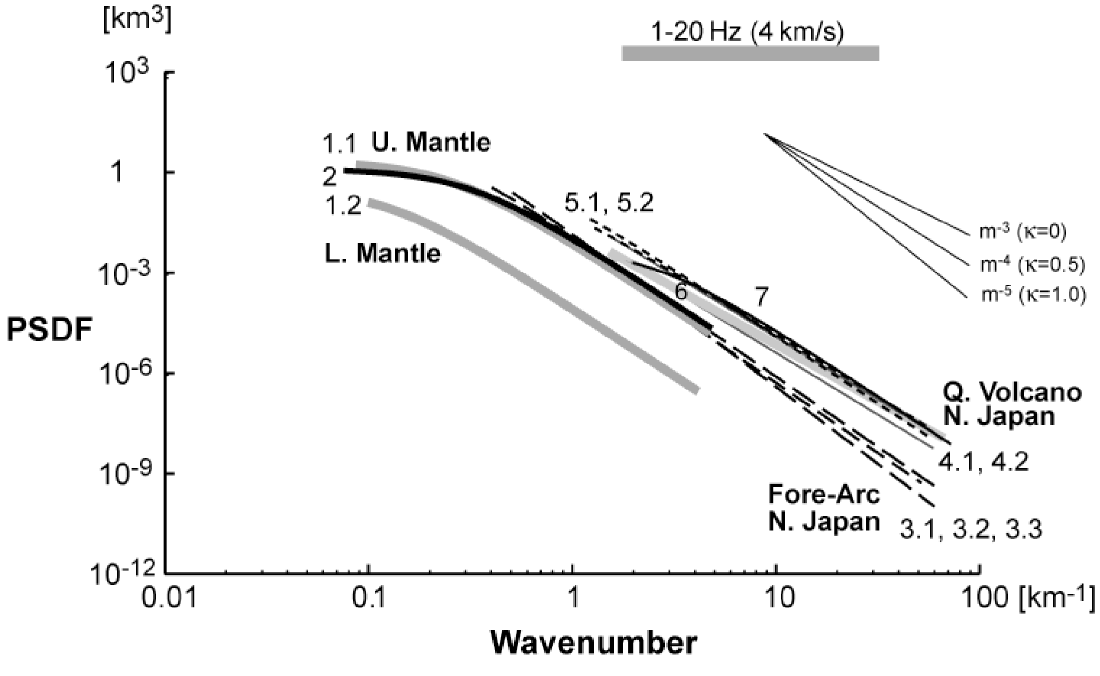

Figure 2. Summary of PSDFs of the fractional velocity fluctuation revealed from the analysis of S and P wave envelopes.