Earthquake Research in China

Volume 24, Number 3, 2010

Characteristics of S-wave Envelope Broadening in the Changbaishan Tianchi Volcano[1]

Fan Xiaoping[1)], Li Qinghe[1)], He Haibing[2)], Yang Congjie[1)], and Jin Shumei[1)]

1) Earthquake Administration of Jiangsu Province, Nanjing 210014, China
2) Earthquake Administration of Zhenjiang City, Zhenjiang 212001, China

High-frequency S-wave seismogram envelopes of microearthquakes broaden with increasing travel distance, a phenomenon known as S-wave envelope broadening. Multiple forward scattering and diffraction for the random inhomogeneities along the seismic ray path are the main causes of S-wave envelope broadening, so the phenomenon of S-wave envelope broadening is used to study the inhomogeneity of the medium. The peak delay time of an S-wave, which is defined as the time lag from the direct S-wave onset to the maximum amplitude arrival of its envelope, is accepted to quantify S-wave envelope broadening. 204 small earthquake records in Changbaishan Tianchi volcano were analyzed by the S-wave envelope broadening algorithm. The results show that S-wave envelope broadening in the Changbaishan Tianchi volcano is obvious, and that the peak delay time of S-wave has a positive correlation with the hypocenter distance and frequency of the S-wave. The relationships between the S-wave peak delay time and the hypocenter distance for different frequency bands were obtained using the statistics method. The results are beneficial to the understanding of the S-wave envelope broadening phenomena and the quantitative research on the inhomogeneities of the crust medium in the Changbaishan Tianchi volcano region.

Key words: Changbaishan Tianchi volcano; S-wave envelope broadening; Peak delay time of S-waves

INTRODUCTION

Scattered seismic waves carrying much information on the fine properties of inhomogeneities in the lithosphere are induced by random inhomogeneities in the lithosphere. This scattering information is useful for learning about the medium inhomogeneity of the crust. The root mean

[1] Received on July 14, 2009; revised on November 16, 2009. This project was sponsored by the National Key Technology R&D Program (2006BAC01B04) and the Joint Earthquake Science Foundation (A08026, A07138), China.

square (RMS) envelope broadening of seismic wave seismograms with increasing travel distance is called seismic wave envelope broadening (Sato, 1989; Sato, et al., 1998; Saito, et al., 2002). It is generally agreed that diffraction and multiple forward scattering are the main causes of seismic wave envelope broadening (Sato, 1998; Saito, et al., 2002). The envelope broadening of S-wave seismograms with increasing travel distance could be a powerful tool for the quantitative study of random velocity inhomogeneity in the lithosphere. The peak delay time of an S-wave (t_p), defined as the time lag from the direct S-wave onset to the maximum amplitude arrival of its envelope (Takahashi, et al., 2007), can be used to quantify the phenomena of S-wave envelope broadening. The duration time of the S-wave envelope can be accepted to evaluate scattering intensity and describe the degree of inhomogeneity (Gusev, et al., 1999a, 1999b). Presuming spatially uniform random inhomogeneities in his target regions, Obara (Obara, et al., 1995) analyzed the S-wave's peak delay time for microearthquakes for 1 ~ 10Hz bands, and found significant inhomogeneity of the crust medium under the volcanic front in the Kanto-Tokai area, Japan. Takahashi (Takahashi, et al., 2007) studied the inhomogeneity of Quaternary volcanoes in northeastern Japan by the peak delay time of S-wave envelopes, and found strongly inhomogeneous regions which may be related to dykes and melting by ascending magma.

The Changbaishan Tianchi volcano is one of the regions where volcano activity is very intense in China (Liu Ruoxin, et al., 1992). Scientists in China studied the activity of the Changbaishan Tianchi volcano by many means, including earthquake observation (Wu Jianping, et al., 2002, 2004, 2005, 2007), electrical sounding and deep seismic exploration (Zhang Xiankang, et al., 2002; Zhao Jinren, et al., 2003; Liu Zhi, et al., 2005). Their results revealed that there were obvious medium inhomogeneities in the crust beneath the Changbaishan Tianchi volcano which may be related to the distribution of magma pocked. After analyzing the S-wave envelope broadening of microearthquakes in Changbaishan Tianchi, we obtained the characteristics of S-wave envelope broadening. The results are important for understanding the inhomogeneity of the shallow crust medium in the Changbaishan Tianchi volcano region, and also laid a foundation for quantitative study on medium inhomogeneity by seismic wave scattering.

1 S-WAVE ENVELOPE BROADENING IN THE INHOMOGENEOUS MEDIUM

The RMS envelope of S-wave in an inhomogeneous medium broadens with increasing travel distance, called S-wave envelope broadening. The von Kármán-type random medium was used to interpret the phenomena of S-wave envelope broadening. Fig. 1 is the schematic diagram of S-wave envelope broadening in the von Kármán-type random medium, where the longitudinal and horizontal coordinates represent the model size, and the color bar on the right represents the velocity difference of model. The size of model, velocity fluctuation (ε), background velocity of model (V_0), wave length of S-wave (λ) and model autocorrelation length (α) are 25km × 25km, 0.05, 2km/s, 1.0km, and 5.0km, respectively. The velocity scope of the S wave is from 1.8km/s to 2.8km/s. The model shows strong inhomogeneity, and the difference of velocity is in both horizontal and longitudinal directions. The waveform excited by the point source at 0km changes clearly due to the effect of change of model velocity. Fig. 1 is the schematic diagram of the S-wave and its RMS envelope at 7.5km, 12.5km and 20.5km. The waveform of the S-wave becomes complex with increasing travel distance, for example, the onset of maximum amplitude enlarges, the high frequency code appears and its RMS envelope broadens. The multiple forward scattering and diffraction due to random inhomogeneities along the seismic ray path are major sources for the S-wave envelope broadening (Sato, 1998, 2002).

The peak delay time of the S-wave, which is defined as the time lag from the direct S-wave onset to the maximum amplitude arrival of its RMS envelope (Takahashi, et al., 2007), is accepted to quantify the phenomena of S-wave envelope broadening. Fig. 2 is schematic diagram of the peak delay time of the S-wave envelope. The large and small peak delay times of the S-wave can reveal the strength of scattering and inhomogeneity of the medium.

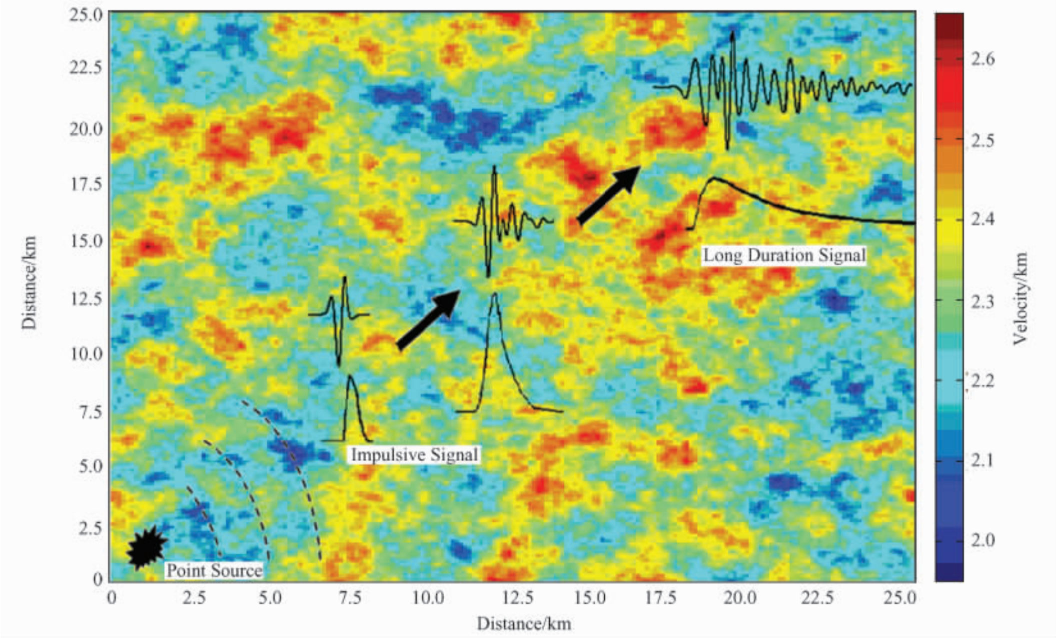

Fig. 1
Schematic diagram of S-wave envelope broadening in inhomogeneous medium

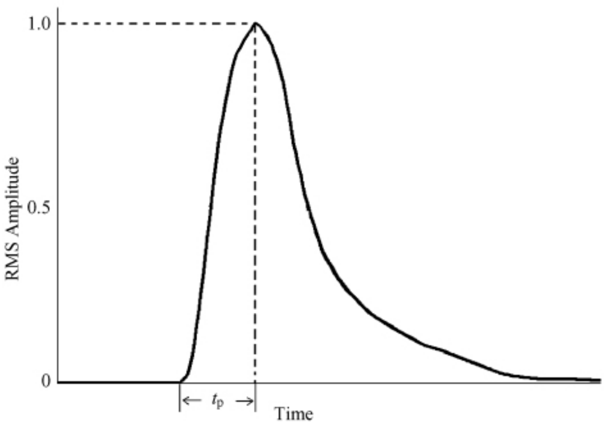

Fig. 2
Schematic diagram of the peak delay time of S-wave envelope

2 DATA AND PROCESSING

Institute of Geophysics, China Earthquake Administration, observed the seismicity in the Changbaishan Tianchi volcanic area from 2002 to 2005 using several broadband digital seismographs which have flat response to the ground motion velocity from 0.05Hz to 30Hz. The seismic stations were operated in continuous mode with a sampling rate of 125 samples per second at each channel. Fig. 3 is the distribution map of temporary seismic stations (triangles) and epicenters (circles). The research area is marked by a square. In order to get a reliable S-wave peak delay time, 204 velocity records with clear S-wave onset and precise relocation were analyzed by the algorithm of S-wave envelope broadening. We measured the peak delay time t_p as follows. We first convolved the recording system's response with two horizontal components of velocity seismograms to calculate the RMS envelope for the two components in four frequency bands, 2Hz ~ 4Hz, 4Hz ~ 8Hz, 8Hz ~ 16Hz and 16Hz ~ 30Hz. The envelopes are smoothed by applying a moving time window with a width twice the centre period of each frequency band. Then we measured t_p in seconds starting from the S-wave onset to the maximum amplitude arrival of its envelope.

3 CHARACTERISTICS OF S-WAVE PEAK DELAY TIME

3.1 Relationship between the Peak Delay Time of S-wave and Its Travel Distance

The travel distance is one of key factors affecting the peak delay time of S-waves from the definition of S-wave envelope broadening. The original seismic records and 4Hz ~ 8Hz RMS envelope of earthquakes (T_0: 2002-08-20 T13:52:06, $M_L = 2.0$, $H = 2.8$km) with different epicenter distances are shown in Fig. 4. The figures (a), (b), (c), and (d) in Fig. 4 are the original seismic records (above) and 4Hz ~ 8Hz RMS envelope (down) for WD1, WD3, WD8,

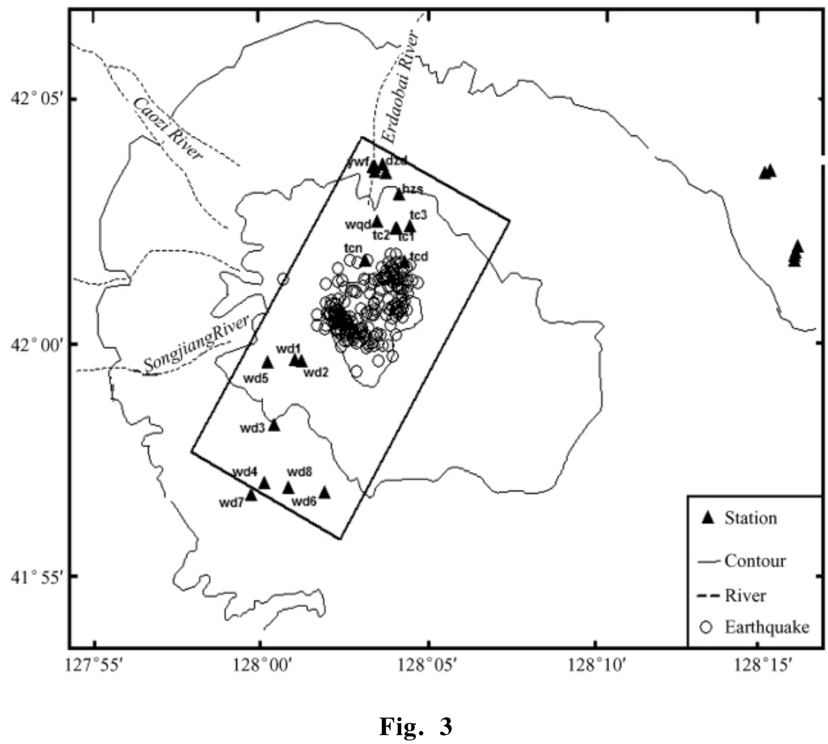

Fig. 3

Map of the Changbaishan Tianchi volcanic area showing locations of temporary seismic stations (triangles) and epicenters (circles) (Research area is encircled by square) and WD7 stations, and the position of arrow, circle and the character of t_p in Fig. 4(a), (b), (c), and (d) represent the onset, the maximum amplitude and the value of the peak delay time of the S-wave. The positions of WD1, WD3, WD8, and WD7 are shown in Fig. 3. We can see from Fig. 4 that: (1) with the increasing travel distance, the waveform of S-wave becomes more complex, the secondary seismic phases get richer, and the duration of code wave is longer; (2) the peak delay time of the S-wave becomes gradually larger with increasing travel distance. The relationships between the peak delay time of the S-wave and its hypocenters are shown in Table 1. From Fig. 4 and Table 1, the relationship between and the peak delay time of the S-wave and its hypocenters shows a positive correlation, but is not simply linear; (3) the change rate of the S-wave's peak delay time is greater. The change rates of the S-wave's peak delay time are not a steady value, which reveals medium inhomogeneity in the S-wave path. If the medium is homogeneous, the contribution of the epicenter distance per kilometer to the peak delay time of S-wave will be consistent. The greater the difference of change rate of S-wave peak delay time, the greater the difference of medium property between the observation stations, and the sharper the inhomogeneity of medium.

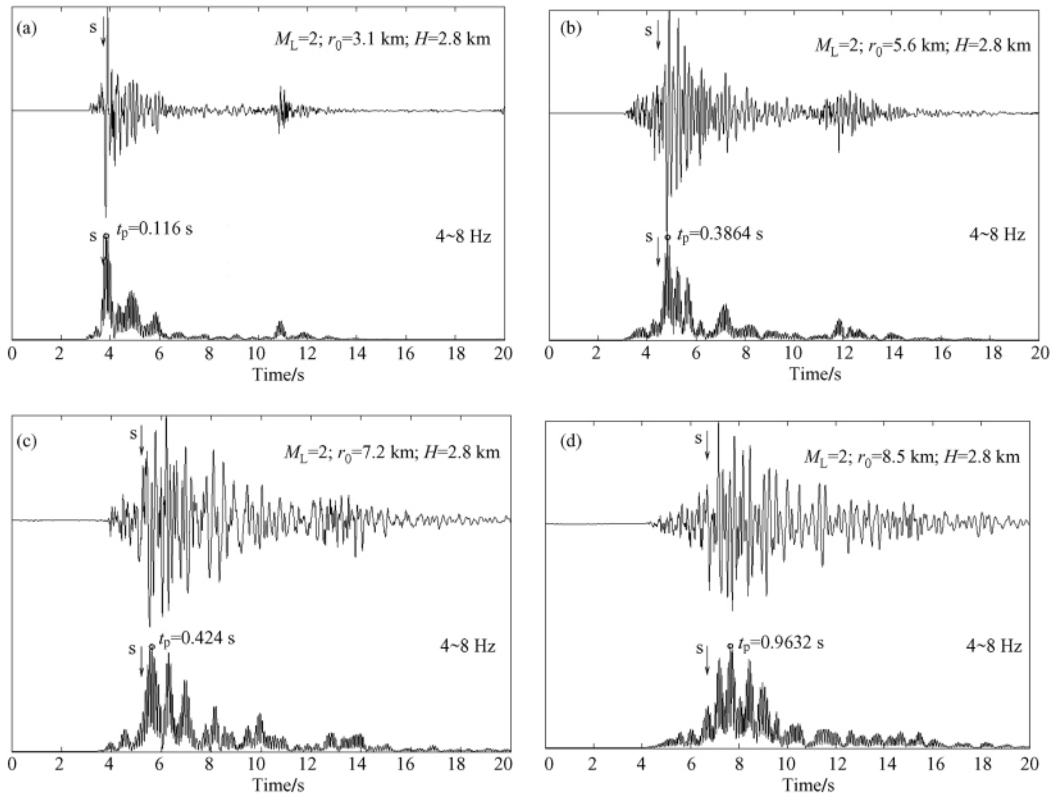

Fig. 4

Original seismic records (above) and its 4Hz ~ 8Hz RMS envelope (down) of earthquake (T_0:2002-08-20 T13:52:06, M_L = 2.0, H = 2 = 2.8km) for different hypocenters

(a) WD1 station; (b) WD3 station; (c) WD8 station; (d) WD7 station

Table 1 Statistics of the peak delay time of S-wave envelope and its change rate at different epicenter distances

Station	r_0 (km)	t_P (s)	t_p/r_0
WD1	3.1	0.118	0.0380
WD3	5.6	0.386	0.0689
WD8	7.2	0.424	0.0588
WD7	8.5	0.963	0.1132

3.2 Relationship between the Peak Delay Time of S-wave and Frequency

Observations and research results have revealed that S-wave frequency is also one of the important factors affecting the peak delay time. The original seismic records and the 2Hz ~ 4Hz, 4Hz ~ 8Hz, 8Hz ~ 16Hz, and 16Hz ~ 32Hz RMS envelopes of the earthquake (T_0: 2002-08-20 T13:52:06, M_L = 2.0, H = 2.8km) for WD3 station are shown in Fig. 5. The position of the arrow and circle in Fig. 5 represents the onset of the S wave and the value of the peak delay time, respectively. The relationship between the peak delay time and its frequency shows positive

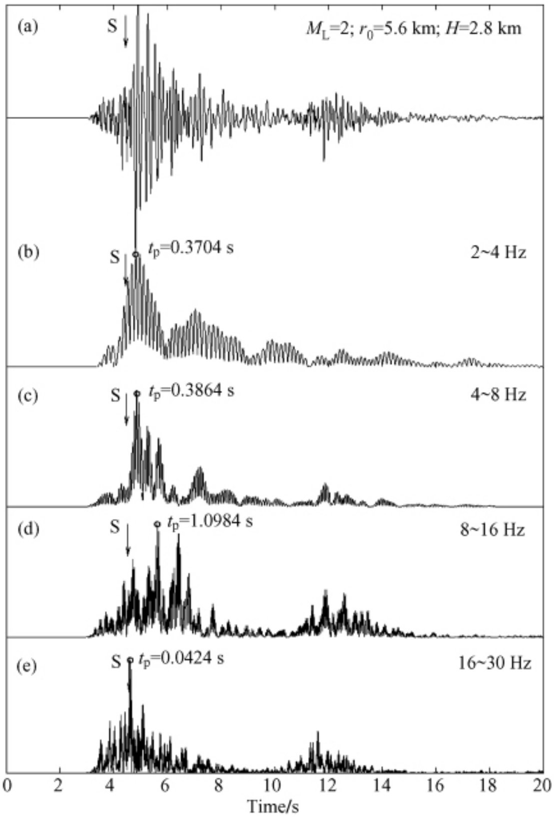

Fig. 5

Original seismic record and its 2Hz ~ 4Hz, 4Hz ~ 8Hz, 8Hz ~ 6Hz, and 16Hz ~ 30Hz RMS envelopes of earthquake (T_0: 2002-08-20 T135206, M_L = 2.0, H = 2.8km) for WD3 station

(a) original seismic record; (b) 2Hz ~ 4Hz RMS envelope; (c) 4Hz ~ 8Hz RMS envelope; (d) 8Hz ~ 16Hz RMS envelope; (e) 16Hz ~ 30Hz RMS envelope). The position of the arrow is S-wave onset. The position of the circle is the peak value of the S-wave envelope correlation from Fig. 5, and the peak delay time becomes larger with increasing frequency. When the frequency bands are 2Hz ~ 4Hz, 4Hz ~ 8Hz and 8Hz ~ 16Hz, the peak delay time is 0.3704s, 0.3864s, 1.0984s, respectively. However, when the frequency is 16Hz ~ 30Hz, the peak delay time decreases to 0.0424s. One of the reasons for the S-wave peak delay time of decrease at 16Hz ~ 30Hz may be instrument response, which has flat response to ground motion velocity from 0.05Hz to 30Hz, where 30Hz is its upper limit of frequency. Another reason may be the change of medium properties around the WD3 station. The property of medium around WD3 could be thought of as homogeneous in 16Hz ~ 30Hz.

The frequency of the S wave's peak delay time reveals the multi-scale characteristics of inhomogeneity. The contribution of inhomogeneities to strength of scattering is different when an inhomogeneity with given size is responding to scattered seismic waves at different frequency bands. If the size of inhomogeneity is almost equal to seismic wavelength, the contribution of inhomogeneity to strength of scattering is greater.

3.3 Characteristics of the Peak Delay Time of S-wave

We find from above that the frequency and the travel distance are important factors affecting the size of the S wave's peak delay time. The peak delay times at 2Hz ~ 4Hz, 4Hz ~ 8Hz, 8Hz ~ 16Hz and 16Hz ~ 32Hz were obtained after analyzing 204 velocity records using the S-wave envelop broadening method. Fig. 6 shows observed peak delay times against epicentral distances in the logarithmic scale for each frequency band (a: 2Hz ~ 4Hz, b: 4Hz ~ 8Hz, c: 8Hz ~ 16Hz, d: 16Hz ~ 30Hz). Black dots in Fig. 6 represent the peak delay times. Black lines in Fig. 6 represent the linear regression lines of peak delay times against epicentral distances r_0 in each frequency band. Numeral values in each bin σ represent the standard deviation of peak delay time. The regression lines of peak delay time and epicentral distances are listed as follow.

$$\log t_p^t [2 \sim 4\mathrm{Hz}] = -2.6721 + 1.2218 \log r_0 \quad (1)$$

$$\log t_p^t [4 \sim 8\mathrm{Hz}] = -2.4919 + 1.0607 \log r_0 \quad (2)$$

$$\log t_p^t [8 \sim 16\mathrm{Hz}] = -2.2332 + 0.9256 \log r_0 \quad (3)$$

$$\log t_p^t [16 \sim 30\mathrm{Hz}] = -1.6726 + 0.5356 \log r_0 \quad (4)$$

We can conclude from Fig. 6 and equations (1), (2), (3), and (4) that:

(1) The peak delay time and epicentral distances in the logarithmic scale show a linear relationship. Although the observed peak delay time is scattered within the range of epicentral distance, the general trend of peak delay time vs. epicentral distance is linear in the logarithmic scale. The change rate of peak delay time with epicentral distance decreases gradually with increasing frequency. The peak delay times caused multiple forward scattering and diffraction for the random inhomogeneities along the seismic ray path could be thought of as parameters to evaluate the strength of scattering. So, the decrease slope in equations (1), (2), (3) and (4) in the high frequency band suggests the decreasing of scattering strength of the S-wave by inhomogeneities, and the properties of medium become generally homogeneous.

(2) The peak delay time of an S-wave is related to frequency. The regression coefficients of peak delay time and epicentral distances are different in different frequency bands. The standard deviation and dispersion of peak delay time decrease gradually with increasing frequency, and the dependence of peak delay time on frequency also gradually decreases with increasing frequency.

4 RESULTS AND DISCUSSION

The 204 small earthquake records in the Changbaishan Tianchi volcano region were analyzed by the S-wave envelope broadening algorithm based on the theory of S wave envelope broadening.

The peak delay time of an S-wave is accepted to quantify the phenomenon of S-wave envelope broadening. The results show that S-wave envelope broadening recorded in the Changbaishan Tianchi volcano is obvious. The peak delay time has a positive correlation to frequency and epicentral distance, that is to say, the peak delay time increases with the increasing of frequency and epicentral distance, but the dependence of peak delay time on frequency also decreases gradually with increasing frequency. The peak delay time and epicentral distances in the logarithmic scale show a linear tread.

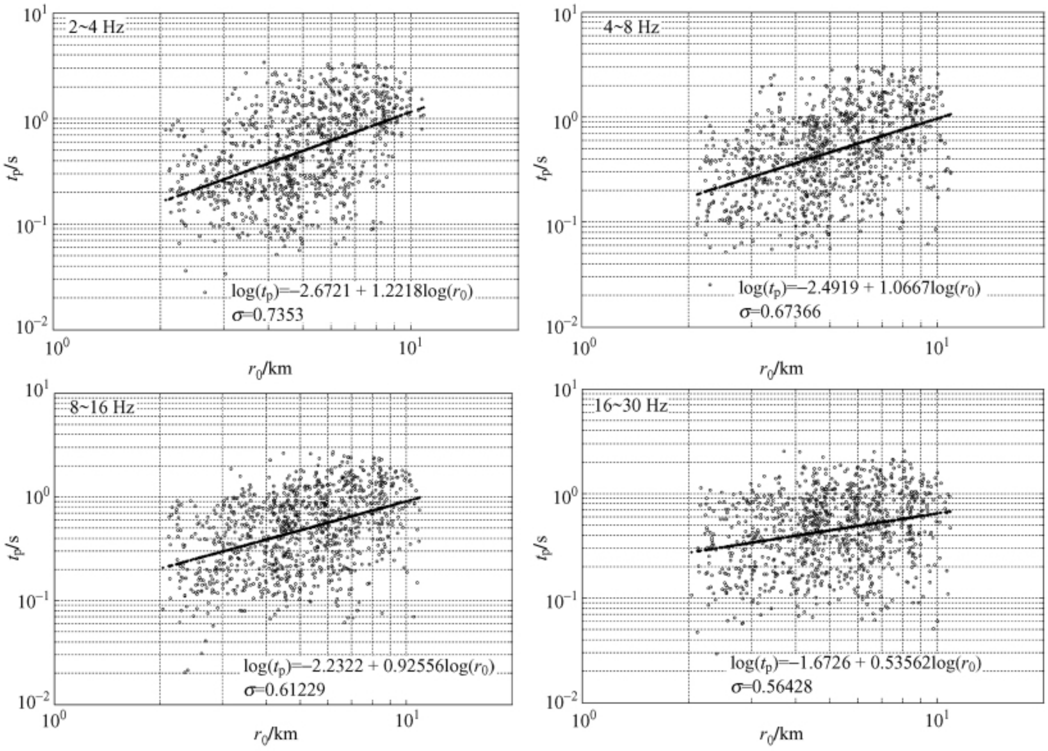

Fig. 6

Relationship between S-wave envelop peak delay times and epicentral distance

(Gray dots represent the S-wave envelope peak delay times in this study. Black lines are regression lines)

Multiple forward scattering and diffraction for the random inhomogeneities along the seismic ray path are the main factors causing S-wave envelope broadening and one of causes of wave code production. In fact, the degree of seismic wave envelope broadening reveals the mode and strength of effect of inhomogeneities on the propagation of seismic waves, and also contains information on the properties, positions and size of inhomogeneities. Thus, the characteristics of seismic wave envelope broadening in the research regions reveal the space and strength characteristics of inhomogeneities. The relationships of seismic wave envelope broadening to frequency and epicentral distances by statistical algorithms are the foundation for quantitative or qualitative studies on medium inhomogeneity.

ACKNOWLEDGMENTS

The authors are grateful to Prof. Wu Jianping of the Institute of Geophysics, CEA, for offering data for this study.

This paper has been published in Chinese in the journal of *Seismology and Geology*, Volume

31, Number 4, 2009.

REFERENCES

Gusev A. & Abubakirov I. R. Vertical profile of effective turbidity reconstructed from broadening of incoherent body-wave pulses (I. General approach and the inversion procedure [J]. *Geopyhs. J. Int.*, 1999a, 136: 295 ~ 308.

Gusev A. & Abubakirov I. R. Vertical profile of effective turbidity reconstructed from broadening of incoherent body-wave pulses (II. Application of Kamchatka data [J]. *Geopyhs. J. Int.*, 1999b, 136:309 ~ 323.

Liu Ruoxin, Li Jitai, Wei Haiquan, et al. Volcano at Tianchi lake, Changbaishan Mt. — A modern volcano with potential danger of eruption [J]. *Chinese J. Gephys.*, 1992, 25(5):661 ~ 665 (in Chinese with English abstract).

Liu Zhi, Zhang Xiankang, Wang Fuyun. 2-D crustal Poisson's ratio from seismic travel time inversion in Changbaishan Tianchi volcanic region [J]. *Acta Seismologica Sinica*, 2005, 27(3):324 ~ 331(in Chinese with English abstract).

Obara K., and Sato H. Regional differences of random inhomogeneities around the volcanic front in the Kanto–Tokai area, Japan, revealed from the broadening of S wave seismogram envelopes [J]. *J. Geophys Res.*, 1995, 100:2103 ~ 2121.

Saito T, Sato H, and Ohtake M. Envelope broadening of spherically outgoing wave in three-dimensional media having power law spectra [J]. *J Geophys Res.*, 2002, 107. doi:10.1029/2001JB000264.

Sato H. Broadening of seismogram envelopes in the randomly inhomogeneous lithosphere based on the parabolic approximation Southeast Honshu, Japan [J]. *J. Geophys Res.*, 1989, 94:17735 ~ 17747.

Sato H., Fehler M. C. *Seismic Wave Propagation and Scattering in the Heterogeneous Earth* [M]. New York: Springer-Verlag and American Institute of Physics Press, 1998. 1 ~ 3.

Takahashi T. Sato H., Nishimura T. and Obara K. Strong inhomogeneity beneath Quaternary volcanoes revealed from the peak delay analysis of S-wave seismograms of microearthquakes in northeastern Japan [J]. *Geophys. J. Int.*, 2007, 168:90 ~ 99.

Tang Ji, Deng Qianhui, Zhao Guoze, et al. Electric conductivity and magma chamber at the Tianchi volcano area in Changbaishan Mountains [J]. *Seismology and Geology*, 2001, 23(2):191 ~ 200 (in Chinese with English abstract).

Wu Jianping, Ming Yuehong, Su Wei. *Study on the Deep Velocity Structures and Seismicity in Changbaishan Tianchi Volcano Region* [A]. In: The Deep Structure and Dynamics of the Chinese Mainland. Beijing: Science Press, 2004. 859 ~ 971 (in Chinese).

Wu Jianping, Ming Yuehong, Zhang Henrong. Earthquake swarm activity in Changbaishan Tianchi volcano [J]. *Chinese J. Gephys.*, 2007, 50(4):1089 ~ 1096(in Chinese with English abstract).

Wu Jianping, Ming Yuehong, Zhang Henrong. Seismic activity at the Changbaishan Tianchi volcano in the summer of 2002 [J]. *Chinese J. Gephys.*, 2005, 48(3):621 ~ 628(in Chinese with English abstract).

Zhang Xiankang, Zhang Chengke, Zhao Jinren, et al. Deep seismic sounding investigation into the deep structure of the magma system in Changbaishan-Tianchi volcano region [J]. *Acta Seismologica Sinica*, 2002, 15 (2): 143 ~ 151 (in Chinese with English abstract).

Zhao Jinren, Zhang Xiankang, Yang Zhuoxin, et al. 3-D tomography of velocity structure in upper crust beneath the Changbaishan Tianchi volcanic region [J]. *Chinese J. Geophys.*, 2003, 46 (6):796 ~ 802 (in Chinese with English abstract).

About the Author

Fan Xiaoping, born in 1974, is an associate research professor of the Earthquake Administration of Jiangsu Province. He obtained his Doctor's degree in the Institute of Geophysics, CEA, in 2009. His major is research on the seismic wave scattering and attenuation. E-mail: nj_fxp@163.com