Tsuji *et al. Earth, Planets and Space (2018) 70:146*
https://doi.org/10.1186/s40623-018-0917-2

Earth, Planets and Space

EXPRESS LETTER

Open Access

Secular and coseismic changes in S-wave velocity detected using ACROSS in the Tokai region

Shuhei Tsuji[1*], Koshun Yamaoka[2], Ryoya Ikuta[3], Takahiro Kunitomo[2], Toshiki Watanabe[2], Yasuhiro Yoshida[4] and Akio Katsumata[5]

Abstract

We discovered a secular change in the travel time of direct S-waves over a 10-year observation period by means of continuous operation of an artificial and stable seismic source, called Accurately Controlled Routinely Operated Signal System (ACROSS), which is deployed in the central part of Japan along the Nankai Trough. We used 13 High Sensitivity Seismograph Network Japan (Hi-net) stations around the ACROSS source to monitor the temporal variation in travel time. Green's functions were calculated for each station daily from March 29, 2007, through October 30, 2017. Secular advance in the temporal variation in travel time was seen for the whole operation period, in addition to a steplike delay associated with the 2011 Tohoku earthquake. We estimated the rate of secular change and the amount of coseismic step by modeling the transfer function of S-waves with a linear trend and the coseismic step of the 2011 Tohoku earthquake. Distance dependences of the travel time changes can be explained as a combination of common bias and dispersion for each station, for both the secular and coseismic changes. This can be interpreted as a randomly distributed change in seismic velocity over the range of the observation region. An azimuthal dependence exists for both changes and shows larger changes in the NE–SW direction than in the NW–SE direction from the ACROSS source.

Keywords: Seismic wave velocity change, Coseismic change, Secular change, Artificial seismic source, ACROSS, 2011 Tohoku earthquake

Introduction

Temporal variation in the propagation property of seismic waves has been studied to understand the state of the subsurface medium under various tectonic circumstances. Changes in seismic velocity are basically caused by the density variation of cracks or pores in the medium and the degree of fluid saturation in those cracks and pores (Nur 1971; O'Connell and Budiansky 1974; Hadley 1976). Therefore, stress/strain, which changes crack density, and pore pressure, which changes fluid saturation, can be detected by measuring variation of seismic velocity. This is one reason why temporal variation of seismic velocity has long been an interest in relation to earthquake generation processes, in which stress/strain and pore pressure govern the triggering process of earthquakes (e.g., Terakawa 2014).

Laboratory, theoretical, and field studies have been carried out to understand the cause of seismic velocity changes attributable to various conditions in the subsurface medium. Laboratory experiments have revealed the influences of stress, cracks/pores, and pore fluid on seismic propagation (e.g., Birch 1960; Nur and Simmons 1969; Dewhurst and Siggins 2006; Bonnelye et al. 2017). Velocity increases with stress/strain and fluid saturation, and stress sensitivity depends on the aspect ratio of the crack and/or fluid saturation. Theoretical expressions for the seismic propagation properties of rock including cracks have been studied (e.g., O'Connell and Budiansky 1974; Popp and Kern 1994; Kame et al. 2014), and

*Correspondence: stsuji@seis.nagoya-u.ac.jp
[1] Graduate School of Environmental Studies, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan
Full list of author information is available at the end of the article

the effects of crack density, fluid saturation, pressure, and strength on seismic velocity have been formulated. Field experiments using artificial seismic sources have been carried out to detect a temporal change of seismic velocity. Temporal change of seismic velocity associated with earth tide and/or barometric pressure change is detected with the use of vibrators, air guns, and piezoelectric transducers (De Fazio et al. 1973; Reasenberg and Aki 1974; Leary et al. 1979; Yamamura et al. 2003; Niu et al. 2008).

Furthermore, Kumazawa and Takei (1994) proposed the idea of using a very accurate and stable artificial seismic source to detect change in seismic velocity with high sensitivity. They proposed the Accurately Controlled Routinely Operated Signal System (ACROSS) seismic source, which generates a seismic signal with the rotation of an eccentric rotor that is accurately synchronized to a GPS clock to achieve both short- and long-term stability of signal. Yamaoka et al. (2001) demonstrated variation of travel time with a resolution of 0.1 ms, and Ikuta et al. (2002) were the first to detect coseismic change of seismic velocity induced by the strong motion of earthquakes using ACROSS with a 15-month observation period. Ikuta and Yamaoka (2004) interpreted the coseismic change as being caused by a breakage of bedrock induced by an increase in pore pressure excited by strong ground motion through an analysis of anisotropic changes of seismic velocity and strain.

In recent years, field measurement of temporal change in seismic velocity has been attempted more extensively using natural seismic sources, such as ambient noise. The coda wave interference method is widely used (Sawazaki et al. 2009; Clarke et al. 2013; Brenguier et al. 2014). A sudden decrease in seismic velocity associated with earthquakes is being observed widely (e.g., Sawazaki and Snieder 2013; Hobiger et al. 2016) and is commonly being interpreted as an effect of the breakage of subsurface bedrock or sediments.

The principal advantage of ACROSS is its stability of signal, which has been utilized for monitoring the temporal variation of seismic velocity (Yamaoka et al. 2001; Saiga et al. 2006; Yamaoka et al. 2014). This study presents the results of a 10-year monitoring with an ACROSS vibrator at the Morimachi site in the Tokai region, central Japan. During the operation period, we detected a secular variation as well as a coseismic change during the 2011 Tohoku earthquake of S-wave at regional scale within a range of 30 km.

Experiment

ACROSS source and transfer functions

In this study, we used an ACROSS source deployed at Morimachi in the Tokai region, central part of Japan (Fig. 1). The ACROSS source was installed so that its axis of rotation was oriented vertically to produce horizontal force. It was designed to generate a larger force at a lower frequency, that is 1.8×10^5 [N] at 7.5 Hz, than any other ACROSS source in operation in Japan. In our experiment, the ACROSS source was operated between 3.5 Hz and 7.5 Hz with frequency modulation at an interval of 50 s.

We calculated transfer functions (Green's functions) by deconvolution of the signal observed at each seismic station with the force excited by the ACROSS source, which is theoretically calculated using the operation parameters of the source. As the modulation period of 50 s produces spectral peaks with an interval of 0.02 Hz, 201 discrete frequencies can be used. The deconvolution produces transfer functions in the frequency domain, and those in the time domain are obtained by inverse Fourier transformation.

We synthesize linear excitation by a linear combination of the signals of clockwise and counterclockwise rotations with appropriate phase shift (Saiga et al. 2006; Yamaoka et al. 2014). For this purpose, the direction of rotation was switched every 2 h, and neighboring two transfer functions are used.

In this study, we used the daily transfer functions of about 10 years, from March 29, 2007, to October 31, 2017. The daily transfer functions were calculated from the observation data for each day with the weighted stacking method (Nagao et al. 2010), in which the reciprocal of the data variance is used for the weight. The operation of the ACROSS source sometimes stopped due to system maintenance, malfunction, or power outrage. We analyzed operation logs, in which rotational frequency and mass position are recorded every second, to identify the periods of normal operation. About 60% of the observation period was identified as being available for our analysis.

The Tokai region, where the ACROSS source is deployed, is a source region of large interplate earthquakes between the subducting Philippine Sea Plate and the crust of the Japan Archipelago. The Philippine Sea Plate pushes the Tokai region northwestward and generates compressional strain in the NW–SE direction (Sagiya et al. 2000; Henry et al. 2001; Kumar et al. 2002). We may expect to detect temporal change associated with the subduction processes by monitoring the propagation of seismic waves in this region.

Seismic stations and calibration

We used High Sensitivity Seismograph Network Japan (Hi-net) stations around the ACROSS source as receivers. Hi-net is a dense earthquake observation network operated by the National Research Institute for Earth

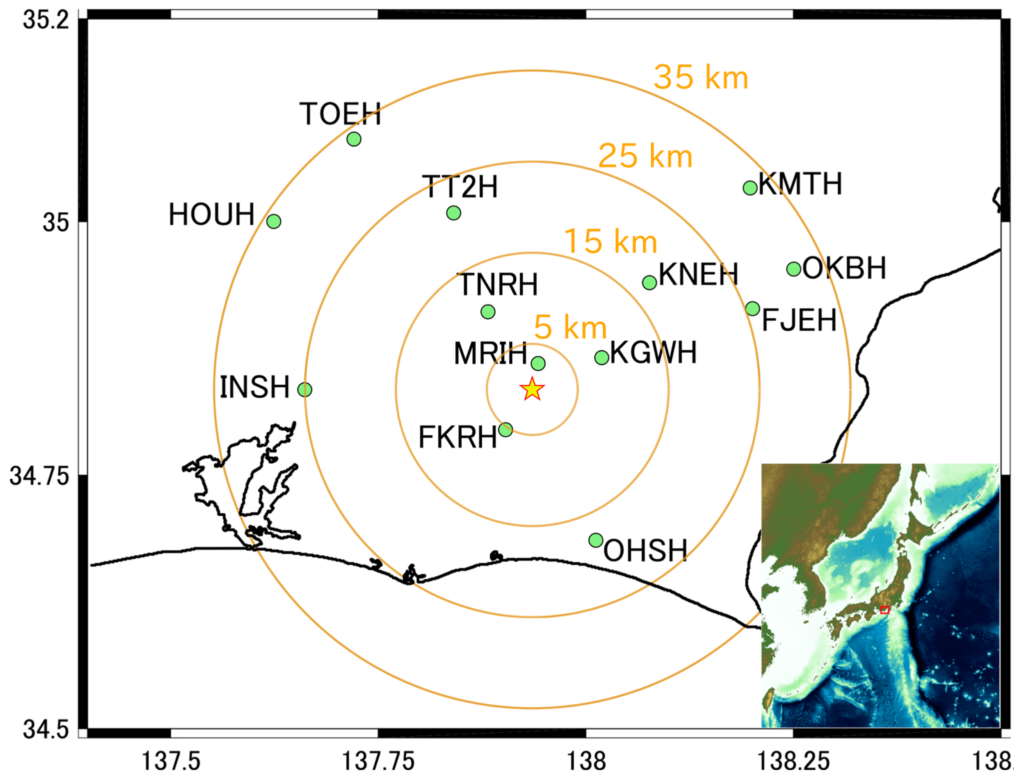

Fig. 1 Location of the ACROSS source and seismic stations. Yellow star denotes the ACROSS source used in this study. Green circles represent the Hi-net stations used in this study. The inset map identifies the area of the main map

Science and Disaster Resilience (NIED), with sampling rate of 100 Hz. We selected 13 stations based on the signal-to-noise ratio (SNR) of the signal from the ACROSS source (Fig. 1).

The use of Hi-net digital records requires attention to measure temporal change of travel time with high accuracy. Kunitomo (2014) found that the timing of digital sampling of Hi-net occasionally shifts, resulting in false temporal change of travel time. The time shift of sampling can occur when data loggers are reset for maintenance. He developed a method to correct the sampling timing using a sensor calibration signal that is synchronized to a GPS clock. In this analysis, we applied his method for correcting the sampling timing of Hi-net data (Additional file 1). A similar problem arises when Hi-net data loggers are replaced. In this case, we could not use the correction method developed by Kunitomo (2014) because different calibration timings are adopted for different types of data loggers. Therefore, we made a correction by assuming no change in travel time due to change in structure from shortly before to shortly after data logger replacement (Additional file 2). We calculated phase difference, which reflects travel time change, for all frequency signals of the ACROSS upon data logger replacement. We selected 5–20 days within one month before and after the replacement and avoided the 3–7 days after a rainfall because rainfall can change travel time (Ikuta et al. 2002).

Analysis

We calculated transfer functions that were used for reference in the analysis of temporal variation by averaging all the available daily transfer functions in the operation period. The weighted stacking method (Nagao et al. 2010) was also applied using the daily noise levels which is evaluated using the spectral signal between the peaks of ACROSS signal for the weights. The signal from the ACROSS source could be identified for stations as far as 160 km from the source. However, we only used data from 13 stations, mainly due to SNR for the short time period.

We estimated the temporal variation of the transfer function for S phase because the ACROSS source at Morimachi, which vibrates horizontally, efficiently excites S-waves. We identified S phase in the reference transfer functions with the help of the Japan Meteorological Agency (JMA) 2001 travel time table (Ueno et al. 2002). A three-second long portion was selected based on the arrival time according to the JMA table and the amplitude of the reference wave, as shown in Fig. 2. Daily deviation of transfer function was calculated by dividing the S-wave part of the transfer function by that of the reference transfer function in the frequency domain. A 20% Hanning window in the time domain was used for picking out S phase for daily and reference transfer functions.

Figure 3 shows the daily deviation of travel time at eight representative stations. The deviation of travel time from the reference was calculated with a weighted average using the phase deviation at each frequency component as

$$\delta t = \frac{\sum_j \overline{A}_j \frac{\delta \phi_j}{\omega_j}}{\sum_j \overline{A}_j} \tag{1}$$

where ω_j is angular frequency of jth spectral peak, $\delta\phi_j$ is the phase deviation at ω_j, and $\overline{A}_j$ is the amplitude of the reference S phase transfer function at ω_j. Most of the

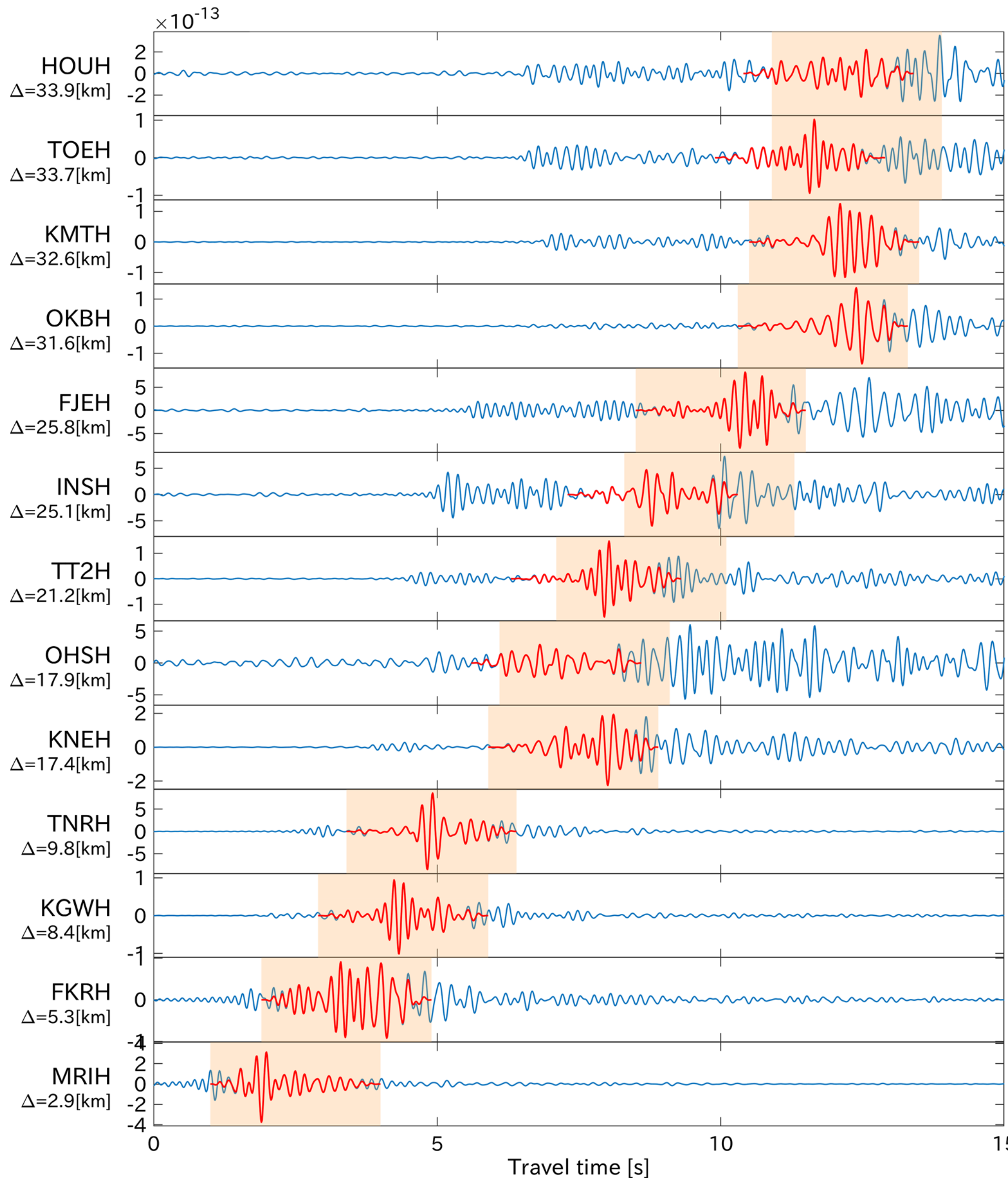

Fig. 2 Reference transfer functions. Reference transfer functions, which were obtained by averaging all of the daily transfer functions at each station, are shown by blue lines. The area shaded in orange color shows the 3-s window from the arrival time of S-waves in the JMA 2001 travel time table. Red lines show the reference wave that we used

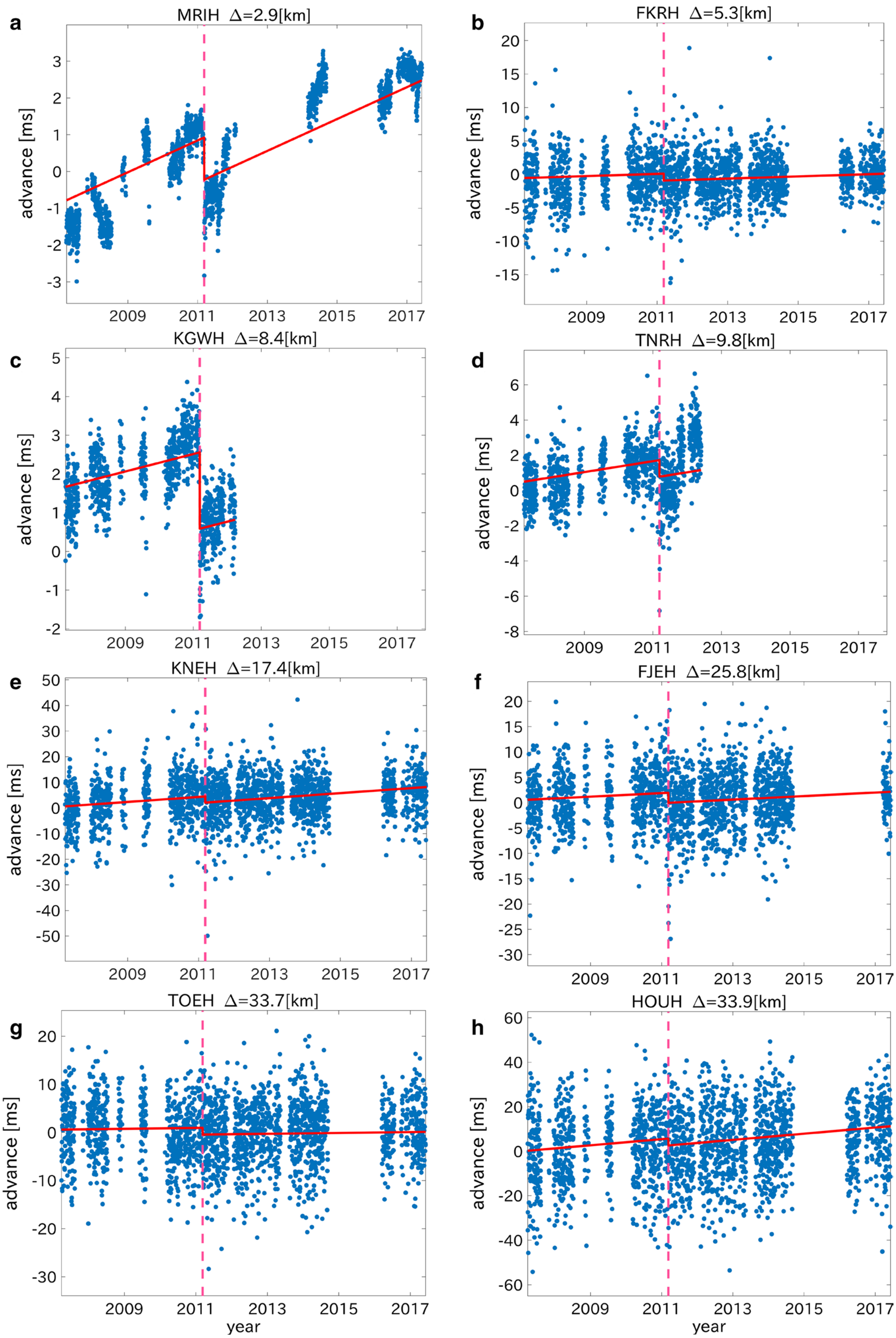

Fig. 3 Travel time deviations at eight representative stations. Blue dots show daily deviation of travel time, and red solid lines show estimated travel time deviation with our model. The broken lines show the time of the 2011 Tohoku earthquake

stations in Fig. 3 show secular advance throughout the observation period and a steplike delay at the time of the Tohoku earthquakes that occurred on March 11, 2011.

As secular advance and coseismic step are commonly recognizable for the stations with good SNR, we modeled this variation with a simple equation to examine whether these characteristics held for the stations with lower SNR. We adopted the following equation on the deviation of travel time as a function of calendar time:

$$\delta\tau_k = aT_k + b\cdot H\left(T_k - T_{eq}\right) + c \quad (2)$$

where T_k is the calendar time in year from the beginning of the operation of the ACROSS, $\delta\tau_k$ is the deviation of the travel time at T_k, a is the rate of secular change, b is the amount of step at T_{eq}, which is the time of the Tohoku earthquake, H is Heaviside's step function, and c is a constant.

We estimated three parameters, a, b, and c, which minimize the sum of the squared distance between data and model on the complex plane in the frequency domain, by the nonlinear least square method. The sum of the squared distance to minimize is given by the following equation.

$$\sum_k \frac{\sum_j \overline{A}_j \left|D_{jk} - e^{i\omega_j\delta\tau_k}\right|^2}{\sum_j \overline{A}_j} \to \text{min.} \quad (3)$$

where $\overline{A}_j$ is the amplitude of the reference transfer function at jth frequency ω_j and D_{jk} is the daily deviation of the transfer function, which is complex number, at kth date at ω_j. In this model, we assume that the amplitude of deviation for each component is unity. The estimation errors were calculated from errors of the daily deviation of transfer functions, which were estimated by the noise level at each frequency component. Thus, we were able to estimate parameters and their errors even at the stations with low SNR.

Results and discussion

Estimated travel time changes

Positive rates of secular change throughout the observation period and coseismic delays at the time of the Tohoku earthquake were observed at most of the stations (Fig. 4). The plotted travel time changes are the mean of the two horizontal components with radial source excitation. The rates of the secular change ranged from 0.0 to 1.4 ms/year, and the amounts of coseismic step at the Tohoku earthquake ranged from −4.0 to 0 ms (Additional file 3). These changes correspond to 0.0–2.2×10^{-2}%/year and 6.0–0.0 $\times 10^{-2}$% of velocity change with reference to the JMA table. Similar results were obtained using transverse source excitation.

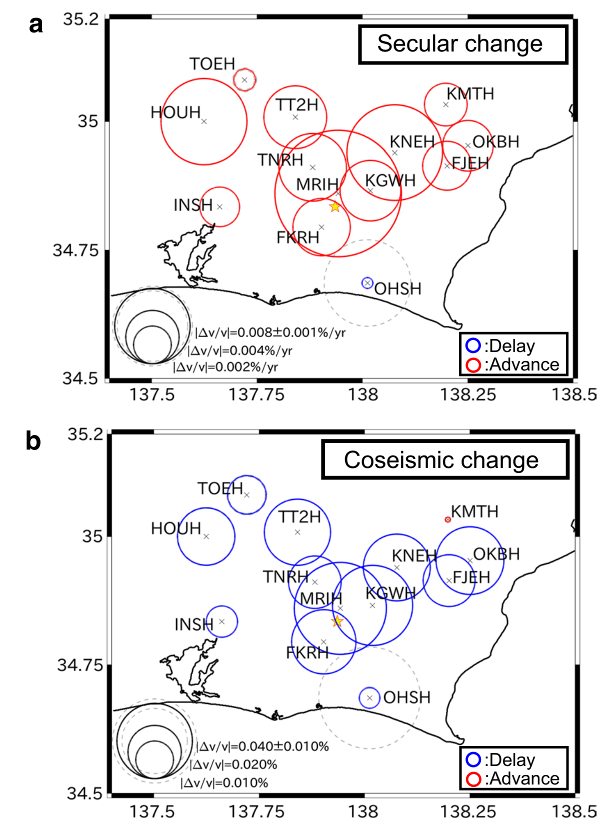

Fig. 4 Estimated secular and coseismic change. Secular change rate (**a**) and coseismic step (**b**) estimated by the model fitting to the daily transfer functions. Blue and red circles indicate delay and advance, respectively. The relative magnitudes of coseismic step and secular change are represented by the area of the solid circles. The dashed circle attached to each solid circle shows the estimation error

The secular change lasting 10 years has not been reported previously, although the same order of coseismic change has been observed. The coseismic delay at the time of the Tohoku earthquake was observed widely by the coda wave interferometry method (e.g., Minato et al. 2012; Brenguier et al. 2014). In the Tokai region, −0.02–0% velocity changes were estimated by Brenguier et al. (2014). Our analysis is consistent with their result, but it reveals smaller deviation with better resolution. In contrast to the coseismic change, little is known about the secular change of seismic velocity in terms of both observation and origin.

Distance and azimuthal dependence

To clarify the nature of the travel time changes we observed, their distance dependences were examined. If the change occurs uniformly in the space of this area, the travel time changes would be expected to increase or decrease linearly with distance. Figure 5a and c shows

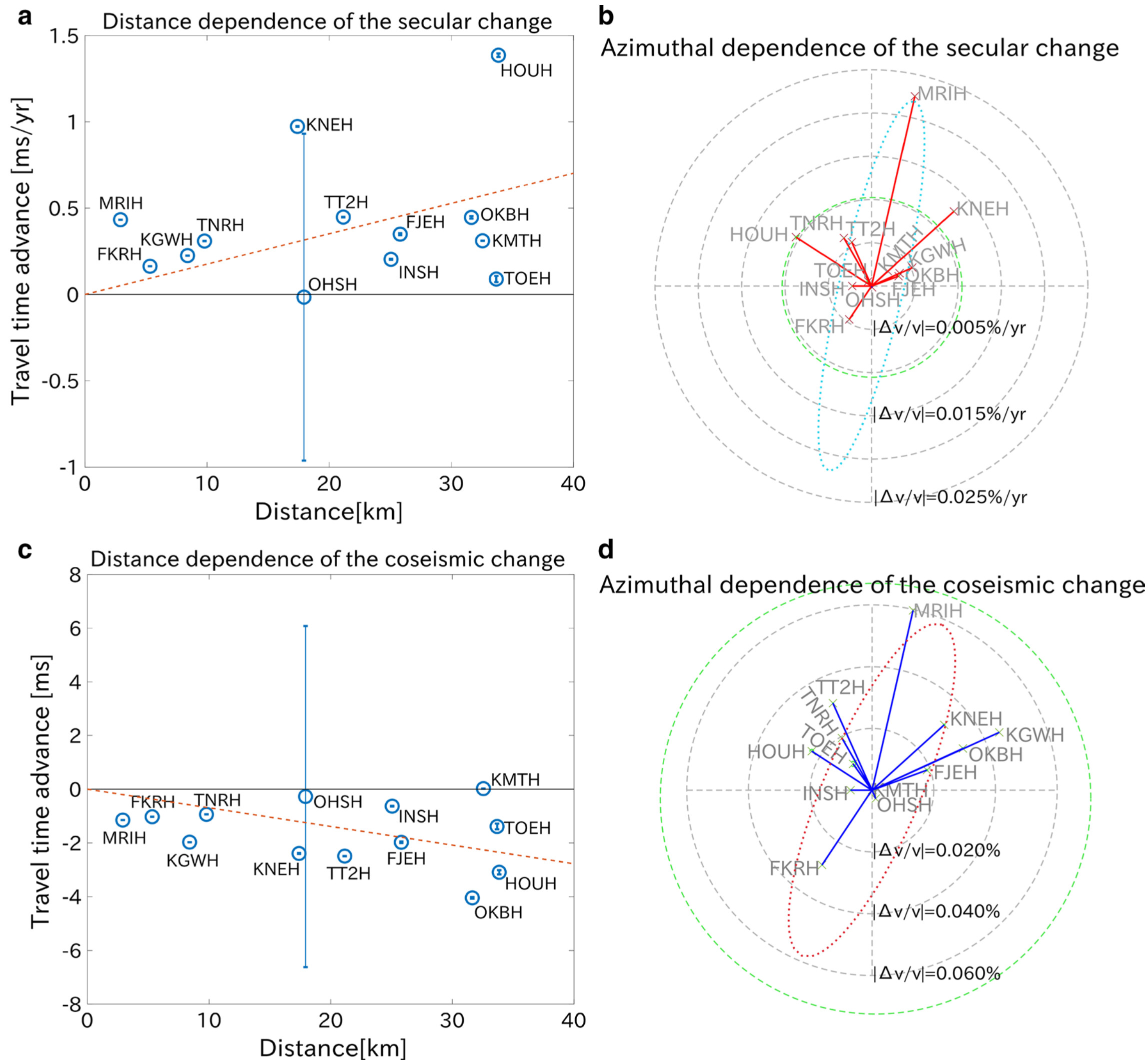

Fig. 5 Distance and azimuthal dependence. Distance dependence (**a**, **c**) and azimuthal dependence (**b**, **d**) of coseismic and secular change. In **a**, **c**, coseismic steps and rate of secular changes are plotted against distance from the ACROSS source. Yellow broken lines show regression line. In **b**, **d**, coseismic steps and rate of secular changes are plotted against the azimuthal direction of the stations with reference to the ACROSS source. Green dashed circles show errors. The distribution of velocity changes for each station is approximated with blue and red ellipse. Travel time change was converted to velocity change using the JMA 2001 travel time table

the distance dependence of travel time for the secular and coseismic changes. In this result, the data points are roughly plotted in a triangular region extending in the positive direction for the secular changes and the negative direction for the coseismic changes. The results can be interpreted as a spatial velocity variation scattering around positive and negative bias for secular and coseismic change, respectively. This means that the sensitivity for the secular and coseismic effects differs from place to place, although they change in the same direction.

Azimuthal dependences of the secular and coseismic changes are also a key to understanding the origin of the change. We plotted the rate of secular velocity change and the amount of coseismic velocity change as a function of the azimuthal angles of each station with respect to the location of the ACROSS source. As a result, the magnitudes of the changes at stations located in the NE direction were larger than those of stations in the NW direction for both changes (Fig. 5b and d). The fitting of the distributions of velocity changes with an ellipse shows that the direction of the major axis for the secular and the coseismic changes is approximately N13°E and N23°E, respectively.

Possible causes of the coseismic and secular changes

Coseismic delays are widely observed at the time of an earthquake and interpreted with respect to several mechanisms, pore pressure change, stress change, and breakage of rocks. For example, Ikuta and Yamaoka (2004) detected coseismic delay and gradual recovery in about one week using an ACROSS vibrator and interpreted the phenomena, by referring to a strain observation, as pore pressure increase in groundwater caused by the strong shaking of an earthquake. Olivier et al. (2015) detected permanent seismic velocity changes around an underground mine with ambient seismic noise correlations and interpreted these changes as having been caused by a stress change induced by excavation by blasting. Sawazaki and Snieder (2013) reported good a correlation between S-wave delay and maximum dynamic strain by the Tohoku earthquake and attributed it to a breakage of shallow rocks by the strong shaking of the earthquake.

Considering these results, the coseismic change detected in this study can be caused by stress change and/or rock breakage by the Tohoku earthquake. The possibility of pore pressure increase can be excluded because the coseismic step remained for a long time during the observation period. In the case of pore pressure change, short recovery of velocity is expected due to diffusion of pore pressure, as in the case of Ikuta and Yamaoka (2004). In contrast, travel time changes caused by stress change (Olivier et al. 2015) or rock breakage (Hobiger et al. 2012; Sawazaki and Snieder 2013) often remained for very long periods of time.

The secular change detected in this study may have been caused by the healing process of rock and/or by stress buildup due to subduction. Considering that the secular change continued for 10 years with the same tendency, it is difficult to interpret it by a gradual change of pore pressure. However, the healing process or stress change can explain such a continuous 10-year change. The healing process in subsurface material causes stiffness increase that leads to increase in seismic velocity. Precipitation of chemical components on crack surfaces in rock and compaction in shallow layers are examples of possible healing mechanisms. These processes can reduce crack density, resulting in increased rigidity and seismic velocity (O'Connell and Budiansky 1974). This interpretation can also explain the random distribution of the distance dependence. Increase in seismic velocity may differ depending on the original porosity or the damage caused by the last breakage, causing variation of velocity changes from place to place. Stress increase caused by subduction of the Philippine Sea Plate can also close cracks, which causes velocity increase.

The azimuthal dependence of the temporal velocity changes can reflect the anisotropic nature of crack distribution in this region. In case of isotropic distribution, NW–SE compression of strain rate that is observed in this region would induce maximum velocity change in NW–SE, which is inconsistent with our observation. On the other hand, any direction can be maximum in the velocity change for anisotropic medium, according to the preferred orientation of cracks. Hence, our observation may indicate that cracks oriented preferably in NE–SW prevail, though geological evidences supporting the crack orientation are not found yet. The anisotropic distribution of cracks can also explain negative correlation between the secular and the coseismic change if we can assume that the both changes result from closure and opening of the same cracks.

Conclusions

We analyzed the travel time variation of S-waves in the Tokai region, central Japan, for 10 years, from March 29, 2007, to October 31, 2017. We detected travel time variation as a secular advance and a coseismic steplike delay at the time of the 2011 Tohoku earthquake at most stations. The rates of secular changes were 0.0–1.4 ms/year with errors of 0.0–0.9 ms/year, and the coseismic delays were −4.0 to 0 ms with errors of 0.0–6.4 ms.

The distance dependence can be explained by a combination of common bias and random dispersion for each station. This can be interpreted as spatially random distribution of velocity variation and positive and negative bias of secular and coseismic changes, respectively. The magnitude of velocity changes was larger at stations located in the NE–SW direction than at stations in the NW–SE direction for both the secular and coseismic changes, which suggests healing and breakage as a cause of the velocity change.

Additional files

Additional file 1. Date and amount of the time shift corrections with Kunitomo (2014)'s method.

Additional file 2. Date and amount of the time shift corrections at the replacements of data loggers.

Additional file 3. Secular and coseismic change for each station.

Authors' contributions

ST carried out the analyses and drafted the manuscript. KY supervised ST and developed the theories for model fitting. RI provided the basic idea of secular change and provided a program for transfer function. TK maintained the ACROSS source. TW maintained daily stacking, and YY and AK managed the operation of the ACROSS source. All authors read and approved the final manuscript.

Author details

[1] Graduate School of Environmental Studies, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan. [2] Earthquake and Volcano Research Center, Graduate School of Environmental Studies, Nagoya University,

Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan. [3] Faculty of Science, Shizuoka University, 836 Oya, Suruga, Shizuoka 422-8529, Japan. [4] Meteorological College, Kashiwa, Chiba 277-0852, Japan. [5] Meteorological Research Institute, Nagamine, Tsukuba, Ibaraki 305-0052, Japan.

Acknowledgements
We used continuous waveform data from Hi-net operated by the NIED. We used JMA travel time table and daily precipitation data.

Competing interests
The authors declare that they have no competing interests.

Availability of data and materials
Hi-net data are retrieved from NIED webpage (https://hinetwww11.bosai.go.jp/nied/appli/?LANG=en). JMA 2001 table is available in the JMA Web site (http://www.data.jma.go.jp/svd/eqev/data/bulletin/catalog/appendix/trtime/tjma2001.zip). Daily precipitation data are retrieved from the JMA Web site (http://www.data.jma.go.jp/gmd/risk/obsdl/index.php).

Publisher's Note
Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Received: 14 June 2018 Accepted: 5 September 2018
Published online: 14 September 2018

References
Birch F (1960) The velocity of compressional waves in rocks to 10 kilobars: 1. J Geophys Res 65:1083–1102. https://doi.org/10.1029/JZ065i004p01083
Bonnelye A, Schubnel A, David C, Henry P, Guglielmi Y, Gout C, Fauchille AL, Dick P (2017) Strength anisotropy of shales deformed under uppermost crustal conditions. J Geophys Res Solid Earth 122:110–129. https://doi.org/10.1002/2016JB013040
Brenguier F, Campillo M, Takeda T, Aoki Y, Shapiro NM, Briand X, Emoto K, Miyake H (2014) Mapping pressurized volcanic fluids from induced crustal seismic velocity drops. Science 345(80):80–82. https://doi.org/10.1126/science.1254073
Clarke D, Brenguier F, Froger JL, Shapiro NM, Peltier A, Staudacher T (2013) Timing of a large volcanic flank movement at Piton de la Fournaise Volcano using noise-based seismic monitoring and ground deformation measurements. Geophys J Int 195:1132–1140. https://doi.org/10.1093/gji/ggt276
De Fazio TL, Aki K, Alba J (1973) Solid Earth tide and observed change in the in situ seismic velocity. J Geophys Res 78:1319–1322. https://doi.org/10.1029/JB078i008p01319
Dewhurst DN, Siggins AF (2006) Impact of fabric, microcracks and stress field on shale anisotropy. Geophys J Int 165:135–148. https://doi.org/10.1111/j.1365-246X.2006.02834.x
Hadley K (1976) Comparison of calculated and observed crack densities and seismic velocities in westerly granite. J Geophys Res 81:3484–3494. https://doi.org/10.1029/JB081i020p03484
Henry P, Mazzotti S, Le Pichon X (2001) Transient and permanent deformation of central Japan estimated by GPS 1. Interseismic loading and subduction kinematics. Earth Planet Sci Lett 184:443–453. https://doi.org/10.1016/S0012-821X(00)00335-6
Hobiger M, Wegler U, Shiomi K, Nakahara H (2012) Coseismic and postseismic elastic wave velocity variations caused by the 2008 Iwate–Miyagi Nairiku earthquake, Japan. J Geophys Res Solid Earth 117:1–19. https://doi.org/10.1029/2012JB009402
Hobiger M, Wegler U, Shiomi K, Nakahara H (2016) Coseismic and post-seismic velocity changes detected by passive image interferometry: comparison of one great and five strong earthquakes in Japan. Geophys J Int 205:1053–1073. https://doi.org/10.1093/gji/ggw066
Ikuta R, Yamaoka K (2004) Temporal variation in the shear wave anisotropy detected using the Accurately Controlled Routinely Operated Signal System (ACROSS). J Geophys Res B Solid Earth 109:1–15. https://doi.org/10.1029/2003JB002901
Ikuta R, Yamaoka K, Miyakawa K, Takahiro K, Mineo K (2002) Continuous monitoring of propagation velocity of seismic wave using ACROSS. Geophys Res Lett 29:1627. https://doi.org/10.1029/2001GL013974
Kame N, Nagata K, Nakatani M, Kusakabe T (2014) Feasibility of acoustic monitoring of strength drop precursory to earthquake occurrence. Earth, Planets Space 66:1–12. https://doi.org/10.1186/1880-5981-66-41
Kumar KV, Miyashita K, Li J (2002) Secular crustal deformation in central Japan, based on the wavelet analysis of GPS time-series data. Earth, Planets Space 54:133–139. https://doi.org/10.1186/BF03351713
Kumazawa M, Takei Y (1994) Active method of monitoring underground structures by means of Accurately Controlled Rotary Seismic Source (ACROSS). 1. Purpose and principle. Abstruct Seismol Soc Japan p 158
Kunitomo T (2014) An improvement in the precision of measuring seismic travel time changes with the use of the hi-net data. Zisin (J Seismol Soc Jpn 2nd ser) 66:97–112. https://doi.org/10.4294/zisin.66.97
Leary PC, Malin PE, Phinney RA, Brocher T, Voncolln R (1979) Systematic monitoring of millisecond travel time variations. J Geophys Res 84:659–666. https://doi.org/10.1029/JB084iB02p00659
Minato S, Tsuji T, Ohmi S, Matsuoka T (2012) Monitoring seismic velocity change caused by the 2011 Tohoku-oki earthquake using ambient noise records. Geophys Res Lett 39:1–6. https://doi.org/10.1029/2012GL051405
Nagao H, Nakajima T, Kumazawa M, Kunitomo T (2010) Stacking strategy for acquisition of an ACROSS transfer function. In: Handbook of geophysical exploration: seismic exploration. Pergamon, pp 213–227
Niu F, Silver PG, Daley TM, Cheng X, Majer EL (2008) Preseismic velocity changes observed from active source monitoring at the Parkfield SAFOD drill site. Nature 454:204–208. https://doi.org/10.1038/nature07111
Nur A (1971) Effects of stress on velocity anisotropy in rocks with cracks. J Geophys Res 76:2022–2034. https://doi.org/10.1029/JB076i008p02022
Nur A, Simmons G (1969) The effect of saturation on velocity in low porosity rocks. Earth Planet Sci Lett 7:183–193. https://doi.org/10.1016/0012-821X(69)90035-1
O'Connell RJ, Budiansky B (1974) Seismic velocities in dry and saturated cracked solids. J Geophys Res 79:5412–5426. https://doi.org/10.1029/JB079i035p05412
Olivier G, Brenguier F, Campillo M, Roux P, Shapiro NM, Lynch R (2015) Investigation of coseismic and postseismic processes using in situ measurements of seismic velocity variations in an underground mine. Geophys Res Lett 42:9261–9269. https://doi.org/10.1002/2015GL065975
Popp T, Kern H (1994) The influence of dry and water saturated cracks on seismic velocities of crustal rocks—a comparison of experimental data with theoretical model. Surv Geophys 15:443–465. https://doi.org/10.1007/BF00690169
Reasenberg PA, Aki K (1974) A precise, continuous measurement of seismic velocity for monitoring in situ stress. J Geophys Res 79:399–406. https://doi.org/10.1029/JB079i002p00399
Sagiya T, Miyazaki S, Tada T (2000) Continuous GPS array and present-day crustal deformation of Japan. Pure appl Geophys 157:2303–2322. https://doi.org/10.1007/PL00022507
Saiga A, Yamaoka K, Kunitomo T, Watanabe T (2006) Continuous observation of seismic wave velocity and apparent velocity using a precise seismic array and ACROSS seismic source. Earth, Planets Space 58:993–1005. https://doi.org/10.1186/BF03352604
Sawazaki K, Snieder R (2013) Time-lapse changes of P- and S-wave velocities and shear wave splitting in the first year after the 2011 Tohoku earthquake, Japan: shallow subsurface. Geophys J Int 193:238–251. https://doi.org/10.1093/gji/ggs080
Sawazaki K, Sato H, Nakahara H, Nishimura T (2009) Time-lapse changes of seismic velocity in the shallow ground caused by strong ground motion shock of the 2000 Western-Tottori earthquake, Japan, as revealed from coda deconvolution analysis. Bull Seismol Soc Am 99:352–366. https://doi.org/10.1785/0120080058
Terakawa T (2014) Evolution of pore fluid pressures in a stimulated geothermal reservoir inferred from earthquake focal mechanisms. Geophys Res Lett 41:7468–7476. https://doi.org/10.1002/2014GL061908
Ueno H, Hatakeyama S, Aketagawa T, Funasaki J, Hamada N (2002) Improvement of hypocenter determination procedures in the japan meteorological agency. Q J Seismol 65:123–134
Yamamura K, Sano O, Utada H, Takei Y, Nakao S, Fukao Y (2003) Long-term observation of in situ seismic velocity and attenuation. J Geophys Res Solid Earth 108:1–15. https://doi.org/10.1029/2002JB002005

Yamaoka K, Kunitomo T, Miyakawa K, Kobayashi K, Kumazawa M (2001) A trial for monitoring temporal variation of seismic velocity using an ACROSS system. Isl Arc 10:336–347. https://doi.org/10.1111/j.1440-1738.2001.00332.x

Yamaoka K, Miyamachi H, Watanabe T, Kunitomo T, Michishita T, Ikuta R, Iguchi M (2014) Active monitoring at an active volcano: amplitude-distance dependence of ACROSS at Sakurajima Volcano, Japan. Earth, Planets Space 66:32. https://doi.org/10.1186/1880-5981-66-32