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Characteristics of the stress and barometric seismograms produced by the 2011 Tohoku Earthquake (*M*9.0) and vertical movements derived from barometric seismograms

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Abstract

High-quality data concerning the Tohoku Earthquake (*M*9.0) on March 11, 2011, were obtained from the deep borehole observation network (maximum depth of 1030 m; epicentral distance of approximately 600 km) of the Tono Research Institute of Earthquake Science. In addition to data acquired via seismometers, stress meters, and strain meters, barometric seismograms were recorded by several barometers that are usually used for weather observations. We examined the characteristics of barometric and stress seismograms and compared them to the data obtained using broadband seismometers, finding a shared feature: large amplitudes and long-period waveforms began with the arrival of surface waves. We also investigated the relationship between vertical movements observed with GPS and barometric variations and discovered that the barometric variations were related to the differential of vertical movements, while the vertical movements corresponded to the integral of barometric variations. All these results demonstrate that vertical movements at observation points can be computed from the barometric variations observed at those points.

Keywords: Stress seismograms, Barometric seismograms, 2011 Tohoku Earthquake (*M*9.0), Vertical movements derived from barometric seismograms, Water pressure seismograms, STS seismograms

Background

The phrase "barometric seismogram" is used in the title and throughout the paper. We define "atmospheric pressure changes caused by an earthquake" as "barometric seismograms" hereafter. In research based on microbarograph data concerning pressure changes associated with the 2003 Tokachi-Oki Earthquake in Japan (Watada et al. 2006), the relationship between seismic velocities and barometric variations has been investigated using the records obtained with a velocity seismograph.

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Most of the broadband seismic data were out of scale for the Tohoku Earthquake, which occurred on March 11, 2011, because the magnitude was over 8 (*M*9.0). However, the stress meters, strain meters, and barometers installed for the deep borehole observation network (maximum depth 1030 m; epicentral distance of approximately 600 km) at the Tono Research Institute of Earthquake Science (TRIES) could capture some high-quality data. Several barometers usually used for weather observation (F4711, Yokogawa Denshikiki. Co., Ltd.)—inexpensive microbarographs—were able to record the barometric seismograms caused by the earthquake. The GPS observations conducted near our observation sites by the Geospatial Information Authority of Japan (GSI) captured vertical movements attributable to the earthquake. We investigated the features of the recorded stress and barometric seismograms as well as the relationship between the barometric variations and vertical movements.

TRIES observation sites

Earthquakes have been studied at TRIES using instruments developed by our group (Ishii et al. 1997, 2002) for comprehensive observations in deep boreholes. These instruments, having built-in strain meters, tilt meters, seismometers, magnetometers, and a thermometer, can be used in a borehole at around 1 km depth, enabling a thorough and accurate observation to be conducted in an environment less susceptible to noise. It also enables continuous observation of stress variations, as it incorporates a recently developed borehole stress meter (Ishii and Asai 2015). Figure 1 shows the distribution of some of observation sites (SN-3, TRIES, MIZ, STG200.TOS, BYB, and TOKI-GPS). The STG200 observation site was located inside the Mizunami Underground Laboratory (MIU; http://www.jaea.go.jp/04/tono/miu_e/). The MIU consists of a main shaft 6.5 m in diameter and a ventilation shaft 4.5 m in diameter. The ventilation shaft is positioned 40 m away from the main shaft and is connected to the main shaft via horizontal shafts placed at 100-m intervals down to a depth of 500 m.

The observations at STG200 were made in a borehole excavated 20 m below the horizontal shafts at a depth of 200 m. The data used in this study are as follows: barometer records (at SN3 and STG200), water pressure records (at STG200), stress records (at STG200), vertical movements observed with GPS (at TOKI by GSI), acceleration record (at TOS), and STS seismogram (at MIZ). STS is a name of broadband seismometer manufactured by Streckeisen Company.

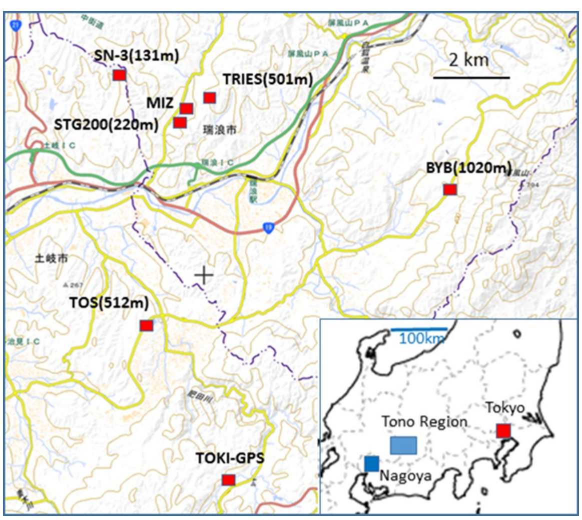

Fig. 1 Distribution of some of the borehole observation sites of the Tono Research Institute of Earthquake Science and of the GPS observation site (TOKI-GPS) of the Geospatial Information Authority of Japan in the Tono Region. The values show the depth of the boreholes. MIZ is a horizontal tunnel site. The map is modified from "GSI maps", http://maps.gsi.go.jp/)

Observation records

Figure 2 shows the data obtained during the March 11, 2011, earthquake. Time on the horizontal axis is expressed as Japan Standard Time for all figures. When "*units/full" appears in a figure, it means that the full scale of the vertical axis corresponds to * units for all figures. The data acquired by the stress meters, water pressure meters, and barometers as well as the vertical movement data all show that large variations began when S waves arrived. In addition, the waveforms with long periods and high amplitudes appeared between 14:50 and 14:51 in all of the data obtained from the stress meters, water pressure meters, and barometers. Time variations for lower six seismograms at a time from 14:49 to 14:51 show similar waveforms in spite of different observation factors. The water pressure variations observed at STG200 were almost identical to the vertical stress variations observed at STG200, although they were of opposite polarities (Ishii and Asai 2015).

Comparison of data obtained with stress meters with data obtained by STS seismometers

Figure 3 shows the data recorded with the STS seismometer at the MIZ observation site and the data obtained with the stress meter at the TOS observation site (512 m deep). The waveforms obtained by the STS seismometer were out of scale for large-amplitude waves, whereas this was avoided for the waveforms obtained with the stress meter. The sequence for both waveforms during the period between the initial activity and the arrival of surface waves (14:48–14:50) was very similar, and STS seismogram was out of scale after 14:50. The highest observed amplitude of the stress seismogram was around 300 kPa, but the dynamic range of the stress meter was from 100 Pa to approximately 2 MPa (100 Pa is equivalent to the weight of a 1-cm water column over 1 cm^2). Also, unlike an STS seismometer, a stress meter can measure variations from zero frequency though a seismometer cannot and is especially effective in predicting the generation of a tsunami associated with long-period movements at the earth's crust around an epicenter.

Barometric variations derived from vertical movements

Because we obtained vertical movement data observed using GPS by GSI in addition to the records obtained with barometers, stress meters, water pressure meters, and seismometers, the relationship between the vertical

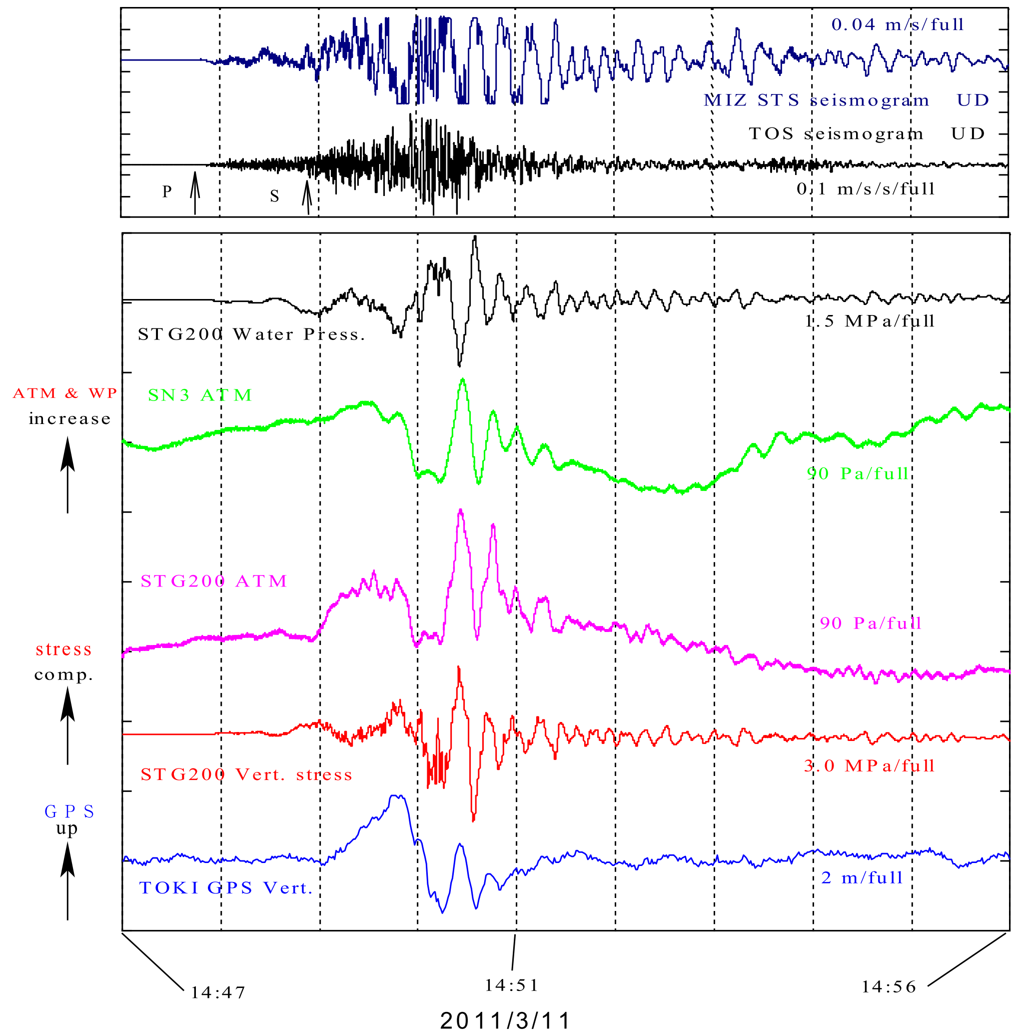

Fig. 2 The data recorded at each observation site at the time of the Tohoku Earthquake that occurred on March 11, 2011. In order from *top* to *bottom*: *MIZ* vertical component observed with the STS seismometer, *TOS* vertical component observed with the accelerometer, *STG200* hydraulic pressures, *SN3* data recorded by the barometer, *STG200* data recorded by the barometer, *STG200* data obtained from the vertical component of the stress meter, and *TOKI-GPS* vertical movements

movements and barometric pressure changes was studied. The upper portion of Fig. 4 shows the time variation of the observed vertical movement with about maximum 40-cm upheaval. According to Watada et al. (2006), data obtained with a velocity seismometer and data obtained with a microbarometer are similar around the time of arrival of Rayleigh waves. In other words, changes in velocities at the ground surface and changes in atmospheric pressure are similar.

In this present study, we differentiated the observed vertical movements and converted them into ground motion velocities, obtaining the black line shown in the lower portion of Fig. 4. The red and green lines show the barometric seismograms observed at SN-3 and STG200, respectively. The shapes of those lines are similar to the shape of the line derived from the differential of vertical movements, indicating that barometric variations are proportional to the velocities of vertical movements at the ground surface. A differentiated vertical movement of 0.11 m/s corresponds to barometric variations of 50 Pa. Watada et al. (2006) explained the observed pressure change by (air density) × (sound velocity in air) × (ground vertical velocity). The present case can be explained in the same way.

Vertical movements derived from barometric variations

We then investigated the vertical movements derived from barometric variations. We used the barometric

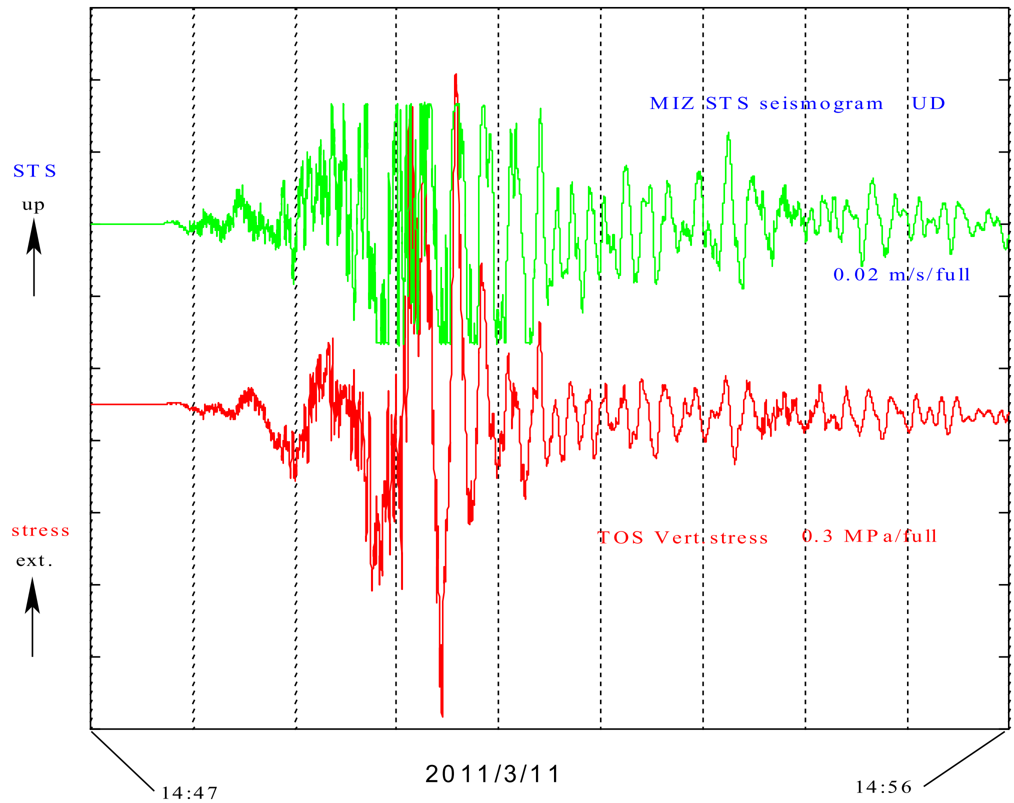

Fig. 3 Comparison of the data observed during the Tohoku Earthquake on March 11, 2011. The *upper portion* shows the vertical component observed with the STS seismometer at the MIZ observation site, and the *lower portion* shows the vertical stress component observed with the stress meter at STG200

variation data observed at SN-3 and STG200 and the vertical movement data that were observed with GPS at TOKI-GPS (Fig. 1). Previously, it was discussed how the observed vertical movements differentiated over time were similar to the barometric variations observed at SN-3 and STG200; here, we discuss the observed barometric variations related to a time integral. The upper portion of Fig. 5 shows the barometric variations observed at SN-3 and STG200. The barometric variations observed at SN-3 and STG200 with respect to a time integral are shown with a red and a green line, respectively, in the lower portion of Fig. 5. The integration was conducted after the elimination of secular changes in atmospheric pressure. The black line shows the observed vertical movements at TOKI-GPS. As the figure demonstrates, the vertical movements derived from the barometric variations integrated over time are similar to the observed vertical movements, indicating that vertical movements can be computed from observed barometric variations. A barometric variation of 5 hPa s corresponds to a vertical movement of 2 m.

Conclusions

Figure 6 shows all the above-mentioned data, i.e., the variations observed during 14:48–14:52 on March 11, 2011, when the Tohoku Earthquake occurred. The upper portion shows the data captured with the STS vertical seismometer (1) and the data recorded by the vertical components of the stress meter (2). The lower portion shows the observed barometric variations (3 and 4), the barometric variations derived from the vertical movements (5), the vertical movements derived from the barometric variations (6 and 7), and the vertical movements observed with GPS (8). The analysis of these data demonstrates that barometric variations caused by a gigantic earthquake like the Tohoku Earthquake can be observed with a standard barometer and that vertical movements can be derived from barometric variations.

Figure 6 clearly indicates that:

1. Large variations began with the arrival of S waves (at around 14:49) for all observation factors.

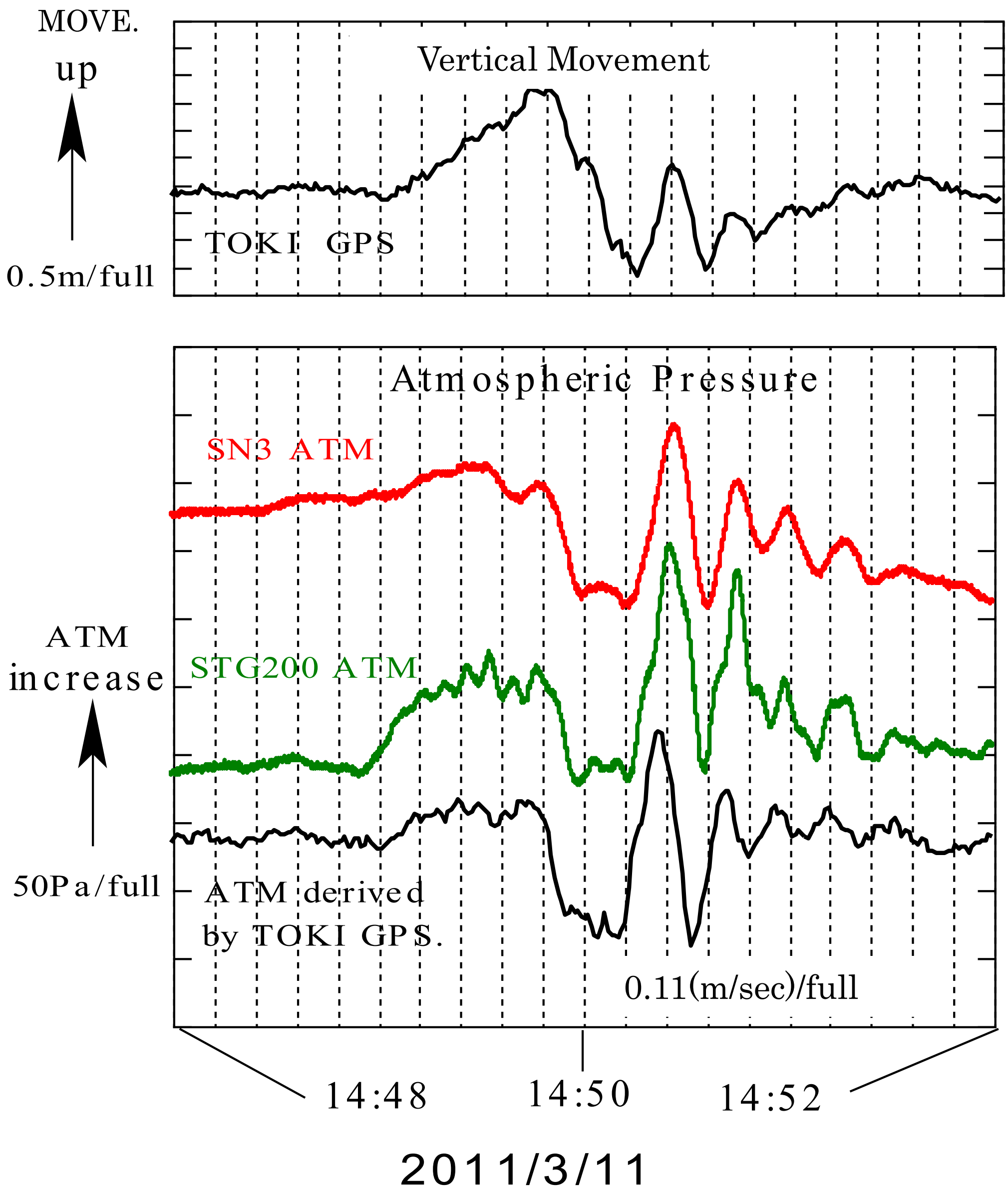

Fig. 4 Comparison between the barometric variations derived from the vertical movements observed at the time of the Tohoku Earthquake on March 11, 2011, and the observed barometric variations. The *upper portion* shows the vertical movements at the TOKI-GPS observation point. In the *lower portion*, the *red line* shows the barometric record at the SN-3 observation point, the *green line* shows the barometric record at the STG200, and the *black line* shows the barometric variations computed by differentiating the vertical movements observed at TOKI-GPS

2. Data from both the stress meter and the barometer show large amplitudes and long-period waveforms from 14:50:12 to 14:50:48 (marked with a horizontal arrow). Large amplitudes and long-period waveforms like this are observed by water pressure meters, barometers, stress meters, and vertical movements, but not by seismometers. These data will yield useful information about earthquake mechanisms in the future.
3. The vertical movements (6 and 7) computed from the integrals of the observed barometric variations (3 and 4) nearly match the observed vertical movements (8).

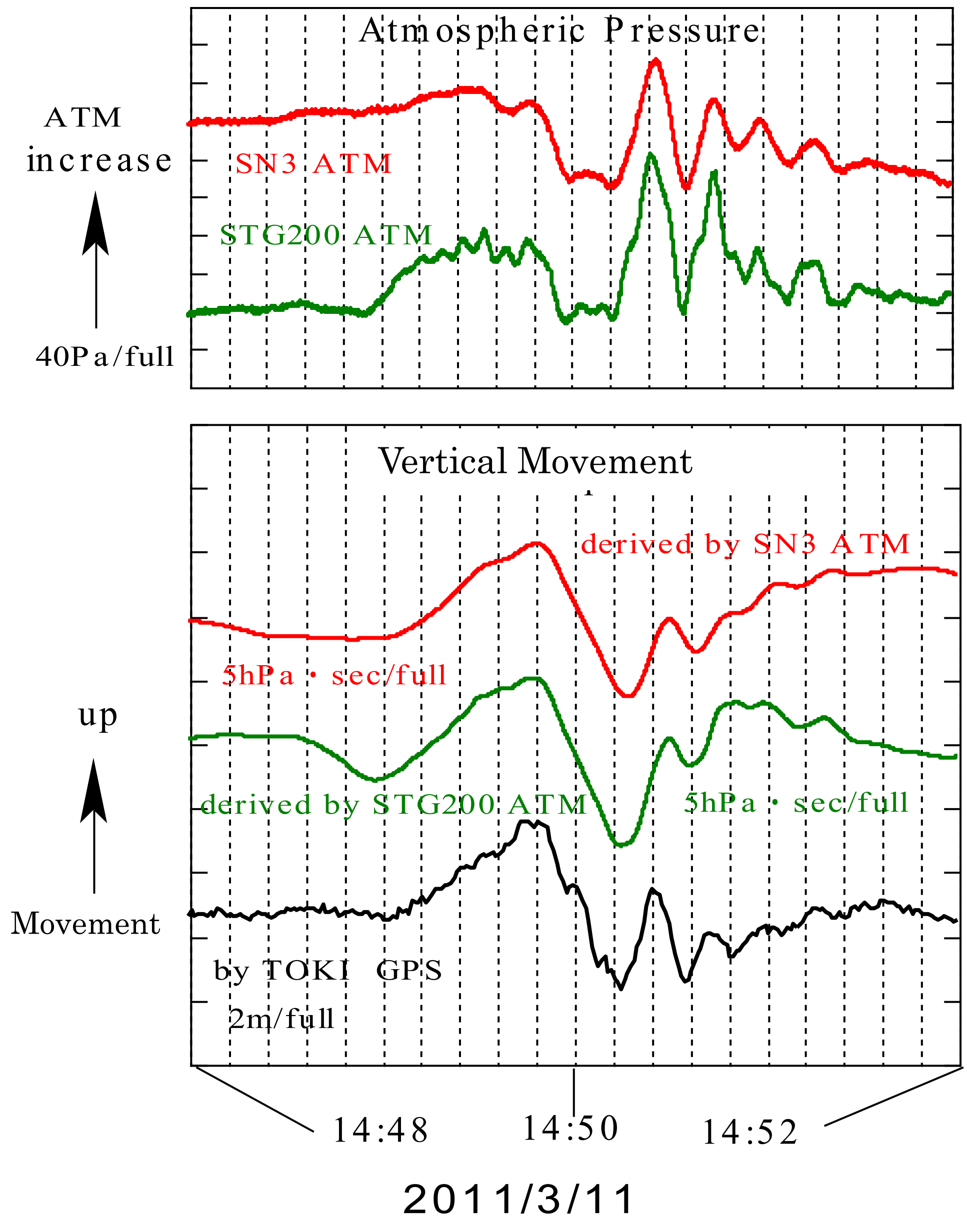

Fig. 5 Comparison between the vertical movements derived from the barometric variations observed at the time of the Tohoku Earthquake on March 11, 2011, and the observed vertical movements. The *upper portion* shows the barometric variations observed at SN3 and STG200. In the *lower portion*, the *red* and *green lines* show the vertical movements computed from time integrals of the observed barometric variations that are shown in the *upper portion*. The *black line* shows the vertical movements observed at TOKI-GPS

4. The barometric variations (5) computed through the differentiation of the observed vertical movements (8) nearly match the observed barometric variations (3 and 4).
5. The aforementioned 3 and 4 suggest that vertical movements can be estimated from barometric variation data.

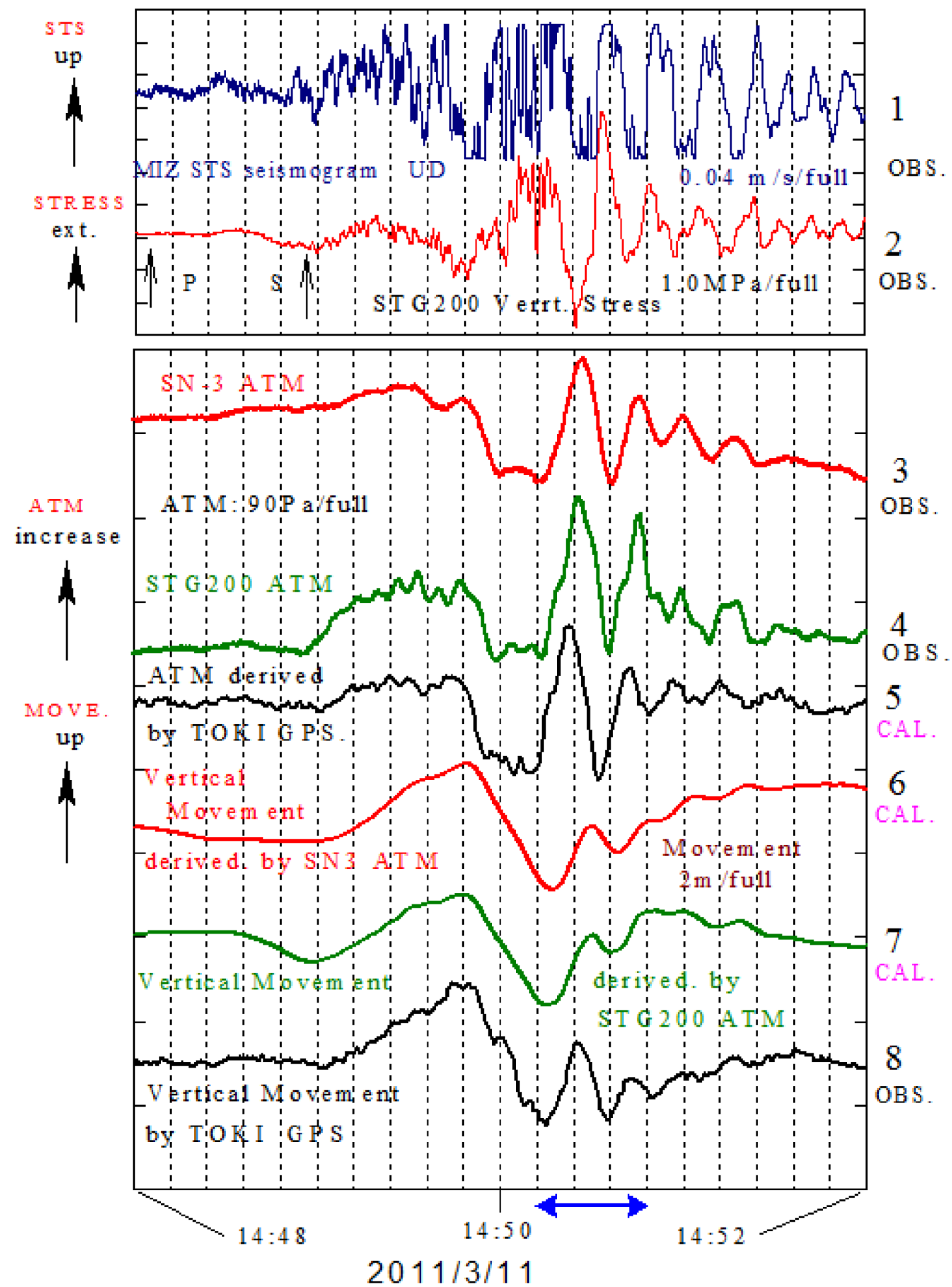

Fig. 6 List of the data recorded at the time of the Tohoku Earthquake on March 11, 2011, and the variations derived from the recorded data. *1*. Vertical variation observed by the STS seismometer at MIZ; *2*. vertical components observed by the stress meter at STG200; *3*. data observed by the barometer at SN-3; *4*. data observed by the barometer at STG200; *5*. barometric variations computed from the differentiation of the vertical movements (8) observed at TOKI-GPS; *6*. vertical movements computed from the barometric variations (3) observed at SN-3; *7*. vertical movements computed from the barometric variations observed at STG200; and *8*. vertical movements observed at TOKI-GPS. The arrow indicating the period between 14:50:12 and 14:50:48 shows the time when the stress meter, barometer, water pressure meter, and STS seismometer recorded large amplitudes

Authors' contributions

HI designed this study, analyzed the data, and wrote the manuscript. YA and HI installed the instruments (stress meters, strain meters, water pressure meters, and barometers) and maintained them, and YA helped interpretation of the data. Both authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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