Magnetic storms recorded by broadband seismometers

Yutaka IDO, Ichiro KAWASAKI, Ryokei YOSHIMURA and Takuro SHIBUTANI.
Research Center for Earthquake Prediction, Disaster Prevention Research Institute, Kyoto University, Uji, Kyoto, Japan

Abstract

It seems that globally distributed broadband seismometers record large magnetic storms. In the past decade, many slow slip events with various time scales were detected on the subduction interface in the circum-Pacific region. However, no slow earthquakes of a time scale of tens of minutes to hours have been detected. After thorough inspection of the broadband records of the global seismic network, we find two anomalous events in August 13, 2000 and October 29, 2003, signals of which simultaneously appeared on the broadband seismic records within 10 minutes at many stations of the network. Their predominant periods are around 500 s. We compare the broadband seismic records with the geomagnetic records, both bandpass-filtered between 100-600 s, at Alert in the Canadian Arctic and find a high waveform similarity between them, leading to the conclusion that two anomalous events were magnetic storms.

Introduction

In the past decade, there were reports on the occurrence of slow slip events on various spatial sizes ranging from tens to hundreds of kilometers and on various time scales ranging from days (an order of 10^5s) to years (10^8s), mainly on subduction interface in Japan (e.g. Shearer (1994), Kawasaki, et al. (1995), Heki et al. (1997), Sagiya et al. (1997), Hirose et al. (1999), Hirose et al. (2000) and Kawasaki (2001)) and circum-Pacific subduction zones (e.g. Dragert et al, (2001)). Recently, Schwartz and Rokosky (2007) gave a full review. However, there have been no reports on slow earthquakes on time scales ranging from tens of minutes (10^3s) to hours (10^4s), that are longer than the source duration of Mw8 class great earthquakes which is of the order of 10^2 s and shorter than the slow slip events mentioned above. We call these undetected events of time scales from tens of minutes (10^3s) to hours (10^4s) slow earthquake in this study to distinguish from the slow slip events of time scales from days (10^5s) to years (10^8s). Search for the slow earthquakes is the original aim of our thorough inspection of the broadband seismic records of IRS/IDA. There are two types of broadband seismometers, STS-1 and STS-2, in operation in IRS/IDA. Their sensitivities to ground velocity being flat in the frequency ranges 0.0027 Hz (360 s)—10 Hz and 0.0083 Hz (120 s)—50 Hz, respectively.

Top trace of Fig.1 is the vertical component broadband record at PFO, southern California, of an Mw 7.1 Kuril earthquake, with around 700 s of S-P time. Lower traces are waveforms convolved with source duration times from 40 s to 600 s. This figure tells us that waveforms due to slow earthquakes of long source duration times do not have the appearance of ordinary seismic waves consisting of P waves, S waves and surface waves. We should keep this in mind when searching for the signals of slow earthquakes.

In the process of searching for slow earthquake, we have run across magnetic storms. This is a report on the discovery of magnetic storms on the broadband seismograms.

===== Fig.1. Seismic record at PFO ================

Synchronous anomalous signals

Fig.2 shows the distribution of 17 stations of IRIS/IDA Global network of broadband seismometers, which are selected to uniformly cover the Earth's surface. In order to search for slow earthquakes, we carry out a grid search as follows.

（1）We apply a bandpass-filter（100s to 1000 s）to the vertical component records.

（2）We make up record sections in which seismograms are arranged in the order of travel times of Rayleigh waves with a propagation velocity of 4.0 km/s, assuming that slow earthquakes occurred at one of grids with one degree spacing on the Earth's surface.

（3）We expect to be able to judge that, a slow earthquake occurred near the grid, if we can identify any signals in the record section propagating with the Rayleigh wave velocity.

===== Fig.2 17 selected stations of IRIS/IDA network =========

After a thorough grid search for the period from 1999 to 2003, we are left with a few cases in which signals propagated with the velocity of 4.0 km/s, suggesting the occurrences of slow earthquakes mainly at transform faults in the south Pacific. Their travel time differences should scatter by up to 1 hour on the whole Earth.

Surprising is that anomalous signals appeared simultaneously at most of stations within around 10 minutes of August 13, 2000 as shown in the vertical component records at the selected 17 IRIS/IDA stations in Fig. 3, although the S/N ratios vary from station to station. We call them Synchronous Anomalous Signals or SASs hereafter. Though not shown here, the SAS is less clear on the horizontal component records, noise levels of which are significantly higher than vertical component records（e.g., Berger et al, 2004）. All of records dealt in this article are vertical component for seismic records and total component for geomagnetic records which are compared with the seismic records in the following sections.

===== Fig.3 Vertical component record at IRIS/IDA stations =====

Fig.4 shows the SASs at 5 stations in four major continents, at which the SASs are clearer among the 17 stations in Fig.3. The stations are ALE in N. American, NNA in S. American, SUR in

African, and ESK and OBN in Eurasia continents.

They have the following characteristics:

(1) simple waveforms of a few cycles of **a harmonic** oscillation with predominant period of around 500 s,

(2) high degree of waveform similarity, although the polarities are opposite for some stations,

(3) small arrival time differences of less than 10 min on the whole Earth.

===== Fig.4 7 hour records at 5 stations in four continents =======

Figs.5 and 6 show 7 hour records on the same day at GRSN stations in Germany and at F-net stations in Japan, respectively. The overall correlation between the waveforms is fine, showing high peak-to-peak correspondence. Especially, the correlation is high within each network.

===== Fig.5 7 hour records at GRSN stations in Germany ========

===== Fig.6 F-net stations in Japan =====================

Core modes

The observation that small arrival time differences within around 10 min on the whole Earth leads us to a suggestion that their sources might be in the core. If this is true, peaks of many of seismic core-modes should be recognized in the spectra of the records. Core modes are eigenoscillations whose oscillation energy is mostly in the core. Eigen functions of two core modes are shown in Fig.7 computed by DISPER80 (Saito, 1988).

===== Fig.7 eigen functions of core-modes ================

Fig.8 shows the power spectra of the broadband seismic records at ALE (Alert, Canada) and KDA (Kuranda, Alasaka in USA), where SAS is clear as shown in Fig.3. Vertical broken lines indicate eigenfrequencies of core modes such as 2S2 (eigenperiod of around 1060 s), 3S3 (700s), 5S1 (580 s), 3S4 (540 s), 3S5 (445 s), 6S2 (410 s), 4S6 (377 s) and 4S7 (330 s) and some other modes which have some oscillation energy in the core. nSm defines one of eigenmodes of spheroidal oscillation with a radial degree n and spherical harmonic degree m. Eigenfunctions are computed using Fortran program DOSPER80 of Saito (1988)

===== Fig.8 power spectra at ALE and KDA ==============

After a thorough inspection of the spectra, there are no meaningful spectral peaks of the core modes. Thus, we conclude that the excitation sources of the SAS were not in the core.

Magnetic storms

The other possible source would be in the outer space. Left and right panels in Fig.9 are the original and bandpass-filtered one-day records of total component of magnetometer at ALE Geomagnetic Observatory and the broadband seismometer at ALE IRIS/IDA station, respectively, in the Canadian arctic region on August 13, 2000, when there was a strong geomagnetic storm. The two sites are about 2 km apart.

===== Fig.9 Records at ALE ===========================

Fig.10 shows 7 hour records of the total component of the magnetometer and the broadband seismometer both at ALE with a bandpass filter between 200 s and 600 s. The correlation coefficient of the waveforms is around 0.8. From the close waveform similarity, we can conclude that the SASs in the broadband seismometer records are due to the geomagnetic storm.

===== Fig.10 7 hour records at ALE ====================

There was another great geomagnetic storm on October 29, 2003. The upper trace in Fig.11 is 7.5 hours of broadband record at TKO in Kyushu Island（Takaoka, 31.89N, 131.23E）of F-net. The middle trace is the same seismogram deconvolved with the instrumental response of the broadband seismometer with a bandpass−filter between 50 s and 2500 s. The bottom trace is a total component of the geomagnetic record at KNY（Kanoya, Kyushu, Japan, 31.408N, 130.880E）of Japan Meteorological Agency（JMA）, filtered in the same period range. Thus, there is a remarkable waveform similarity between the geomagnetic record and seismic records deconvolved with instrumental response. The close waveform similarity between the middle and the bottom traces leads us to the conclusion that SAS in the broadband seismometer were due to the geomagnetic storm.

===== Fig.11 7 hour records at TKO and KNY ============

Ishii-type strainmeter（Ishii et al., 2003; Asai et al., 2005）measures deformation of a vessel placed in a borehole. Their sensitivity is theoretically flat down to 0 Hz（DC component）. It is equipped with magnification devices and geomagnetic sensors but not equipped with a magnetic shield. As previously noted, it well records geomagnetic storms **(Ishii et al., 2003; Asai et al., 2005)**. Now, we show for the first time that broadband seismometers in the period range of up to a few thousand seconds also record magnetic storms.

Puzzling observations

We should note the following puzzling observations.

No SASs were recorded at some stations of low level of seismic noises. The upper trace in the upper panel of Fig.12 is a 5 hour seismic record at NSK（Nishiki, Yamaguchi Pref., Japan）at a time of magnetic storm on October 29, 2003, whereas the lower trace is a seismic record at KNM（Kanayama, Gifu Pref., Japan）in which the SAS is not seen in spite of low seismic noises. The two sites are only about 500 km apart.

===== Fig.12 5 hour seismic records showing no synchronous signal ==========

The SAS display reverse polarity at some of stations. Upper and lower traces in the lower panel of Fig.12 are 5 hour seismic records at TKO（Takaoka, Miyazaki Pref., Japan）and IGK（Ishigaki, Okinawa-Pref., Japan）, showing opposite polarity.　They are about 1000 km apart.

Left panel in Fig.13 shows the correlation coefficients between the broadband seismic records at a time of magnetic storm on October 29, 2003 at the F-net stations and the magnetometer records at KAK（Kakioka JMA Geomagnetic Observatory, Ibaraki Pref., Japan）, where red color indicates high correlation.　Right panel displays relative noise levels at the broadband seismic stations, where red color means low seismic noise level.　We should note that the geomagnetic storm was not recorded at low noise stations red-circled in the central part of Honshu Island.　In other words, sensitivity to the geomagnetic storm varies from station to station.

=====　Fig.14　correlation coefficients and noise levels　=========

So far, we can find no orrelations of the puzzling observations with such factors as the azimuth of STS sensors, strike and length of vaults, and latitude and longitude of stations.

In March 13, 1989, a large geomagnetic storm triggered troubles in the electric power supply system in eastern Canada and about 6 million people were put under power failure in Quebec for 9 hours（e.g., Appenzeller, 1992）.　To prevent such a disaster, geomagnetists are trying to forecast geomagnetic storms.　One of the difficulties seems to be the poor spatial coverage of magnetometers on the Earth.　The broadband seismometer network could be used in future to complement the spatial coverage of the magnetometer network.

Concluding remarks

We conclude that the close waveform similarity between the geomagnetic records and broadband seismic records as seen in Fig.10 and 11 proves that the SAS is the record of the variation of magnetic field due to geomagnetic storms.

Although it is previously known that geomagnetic storm is a source of long period noises in seismic records (ref?), we suppose that our report may be the first one on the geomagnetic storms actually recorded by globally distributed modern geophysical instruments other than geomagnetometers, based on close similarity of waveforms.

Acknowledgement

We express our sincere thanks to Prof. S. Uyeda for critically reading the manuscript and to IRIS, GRSN and F-net for broadband seismic records and to the Geological Survey of Canada and JMA Kakioka Magnetic Observatory for geomagnetic records.

References

Appenzeller, T., Hope for Magnetic Storm Warnings, Science, 922-924, DOI: 10.1126/science.255.5047.922, 1992.

Asai, Y., M. Okubo, H. Ishii, H. Aoki, T. Yamauchi, Y. Kitagawa and N. Koizumi, Co-seismic strain-steps associated with the 2004 off the Kii peninsula earthquakes-Observed with Ishii-type borehole strainmeters and quartz-tube extensometers, Earth Planets Space, 57, 309-314, 2005.

Berger, J., P. Davis and G. Ekstrom, Ambient noise: a survey of the global seismographic network, J. Geophys. Res., 109, doi.10.1029/2004JB003408, 2004.

Dragert, H., K. Wang, and T. S. James, A silent slip event on the deeper Cascadia subduction interface, Science, 292, 1525-1528, 2001.

Heki, K., S. Miyazaki and H. Tsuji, Silent fault slip following an interplate thrust earthquake at the Japan Trench, Nature, 386, 595-597, 1997

Hirose, H., K. Hirahara, F. Kimata, N. Fujii, and S. Miyazaki, A slow thrust slip event following the two 1996 Hyuganada earthquakes beneath the Bungo Channel, southwest Japan, Geophys. Res. Lett., 26, 3237-3240, 1999.

Hirose, I, I. Kawasaki, Y. Okada, T. Sagiya, and Y. Tamura, A silent earthquake of December 9, 1989, in the Tokyo bay, as revealed by the continuous observation of crustal movements in the southern Kanto district, central Japan, Zisin, 53, 11-23, 2000 in Japanese.

Ishii, H., T. Yamauchi, Y. Asai, M. Okubo, S. Matsumoto and H. Aoki, Continuous multi-component monitoring of crustal activities by a newly developed instrument installed in a 1200 m depth borehole - the deepest multiple observation in the world consisting of stress, strain, tilt, seismic waves, geomagnetism, temperature, JSS01/30A/D-011, IUGG, 2003.

Kawasaki, I., Y. Asai, Y. Tamura, T. Sagiya, N. Mikami, Y. Okada, M. Sakata, and M. Kasahara, The 1992 Sanriku-Oki, Japan, ultra-slow earthquake, J. Phys. Earth, 43, 105-116, 1995.

Kawasaki, I., Y. Asai, and Y. Tamura, Space-time distribution of interplate moment release including slow earthquakes and the seismo-geodetic coupling in the Sanriku-oki region along the Japan trench, Tectonphysics, 300, 267-283, 2001.

Sagiya, T., Anomalous Transients in Crustal Movements of the Boso Peninsula, Japan - Is it a Slow Earthquake? , Transactions, American Geophysical Union, 1997 Spring Meeting, 78, 17 suppl., s214-s214, 1997.

Saito, M., DISPER80: A subroutine package for the calculation of seismic normal-mode solutions, in Seismological algorithms, Academic Press, USA, 1988.

Schwartz, S. Y. and J. M. Rokosky, Slow slip events and seismic tremor at circum-Pacific subduction zones, Rev. Geophys., **45**, RG3004, 2007.

Shearer, P. M., Global seismic event detection using a matched filter on long-period seismogram, J. Geophys. Res., 99, 13,713-13,725, 1994.

Kawasaki（e-mail: kawasaki@rcep.dpri.kyoto-u.ac.jp）

Figure captions

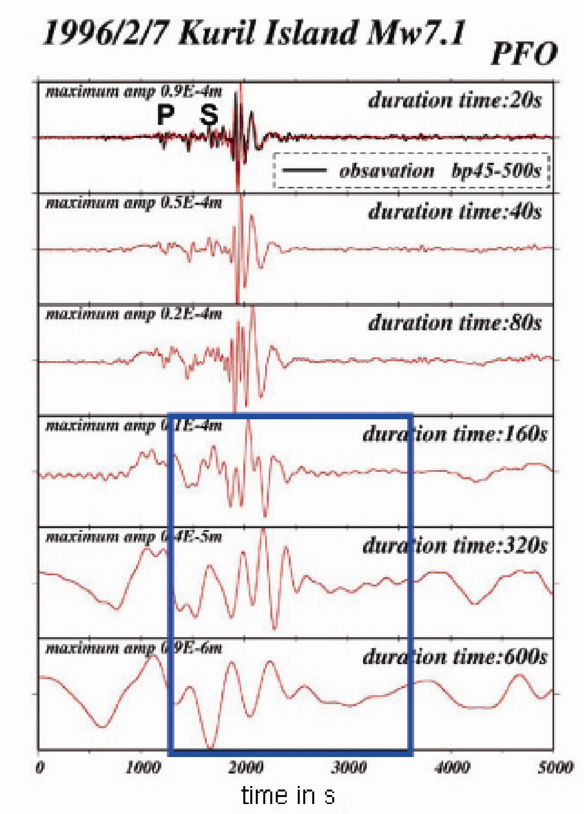

Fig.1. Top red and black traces are synthetic and observed vertical component broadband seismic record at PFO, southern California, due to the Mw 7.1 Kuril earthquake. Lower red traces are synthetic waveforms convolved with various source duration times of 20 s to 600 s. Horizontal time scales are arbitrary. Blue rectangle illustrates presumed waveforms of slow earthquakes.

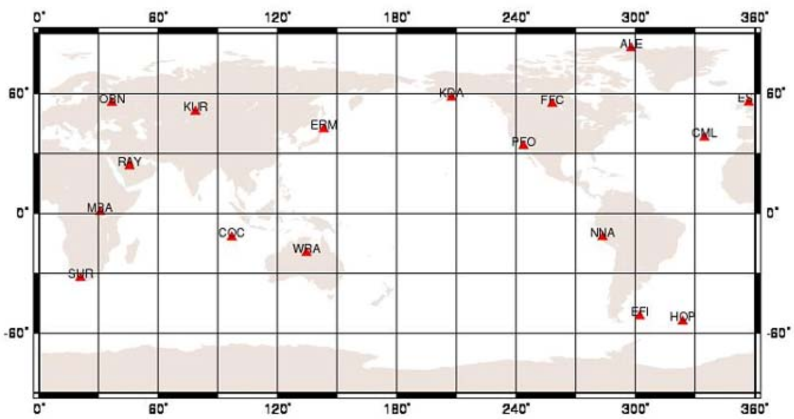

Fig.2. Distribution of 17 stations of IRIS/IDA Global network of broadband seismometers, which are selected to uniformly cover Earth's surface.

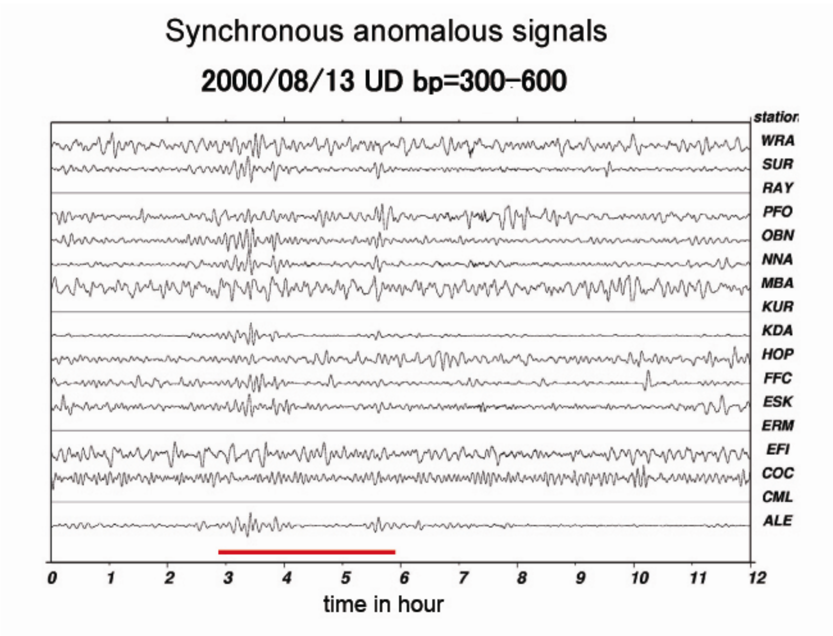

Fig.3. Vertical component broadband seismic records at the 17 IRIS/IDA stations in August 13, 2000, which are bandpass-filtered between 300 s and 600 s. The synchronous anomalous signal can be recognized within the three hour time window shown by bold bar.

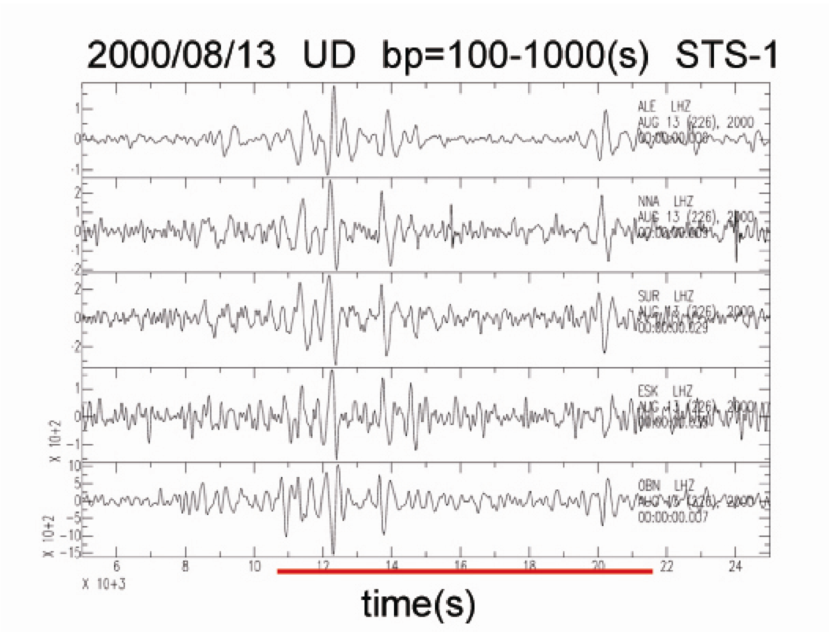

Fig. 4. Seven hour broadband seismic records at 5 stations in four major continents, at which the synchronous anomalous signal is clear among the 17 stations in Fig.3.

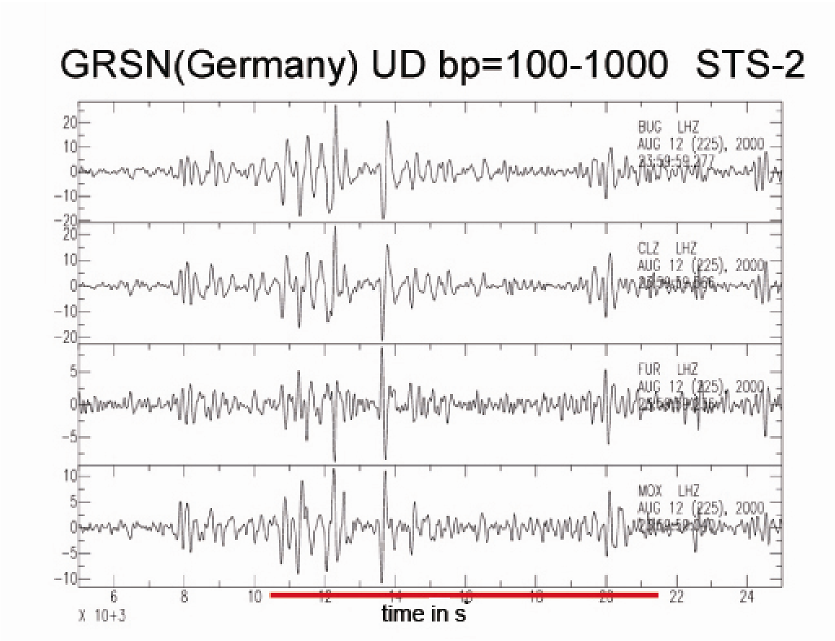

Fig.5. Seven hour broadband seismic records including SAS at GRSN stations in Germany.

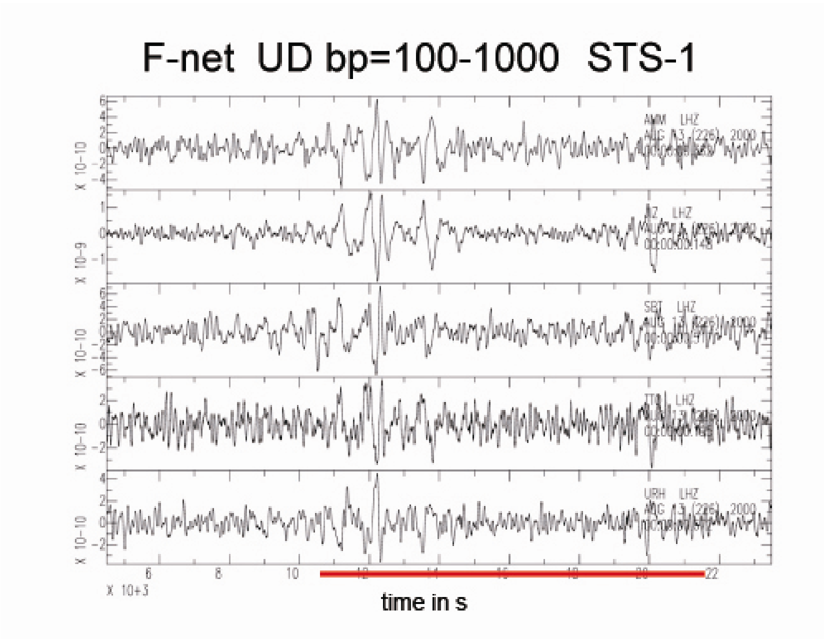

Fig.6. Seven hour broadband seismic records including SAS at F-net stations, Japan.

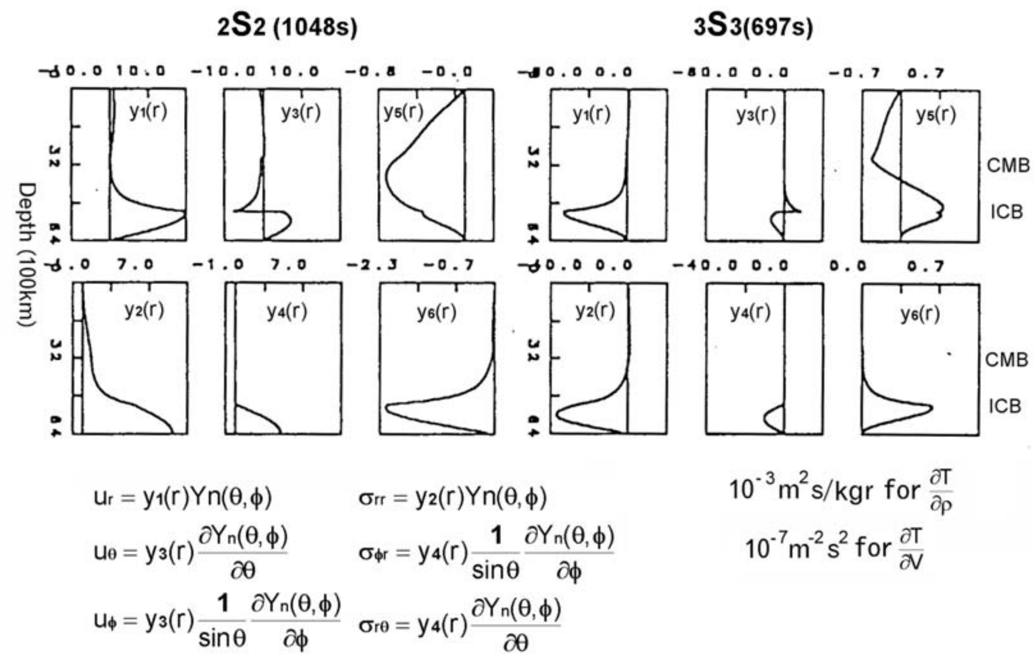

Fig.7. Eigenfunctions of three core modes as a function of depth. Horizontal axis is relative amplitude. Vertical axis is a depth. T, C and U are an eigenperiod, a phase and a group velocities, respectively. (r,θ,φ) are spherical polar coordinates. $Yn(\theta,\varphi)$ is spherical harmonics of angular order of n. Eigenfunctions of $y_2(r)$ to $y_6(r)$ are normalized by $y_1(r{=}r_o)$ where r and ro are a distance from the center and a radius of the Earth, respectively. ρ and ξ are density and anisotropy parameter, respectively. V_P and V_S denote P and S wave velocities, respectively. Subscripts H and V denote horizontal and vertical propagation directions, respectively. CMB and ICB on the right sides of each panel denote the core-mantle and the inner-outer core boundaries, respectively.

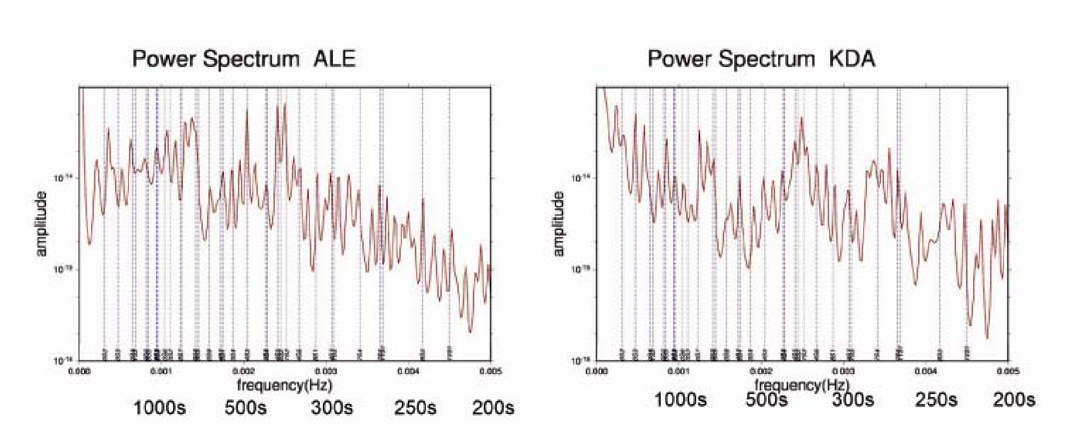

Fig.8. Power spectra of the broadband seismic records at ALE (Alert, Canada) and KDA (Kuranda, Australia), at which SAS is clear in the time domain records as in Fig.3. Vertical broken lines indicate eigenfrequencies of the core modes and some other modes that have some oscillation energy in the core.

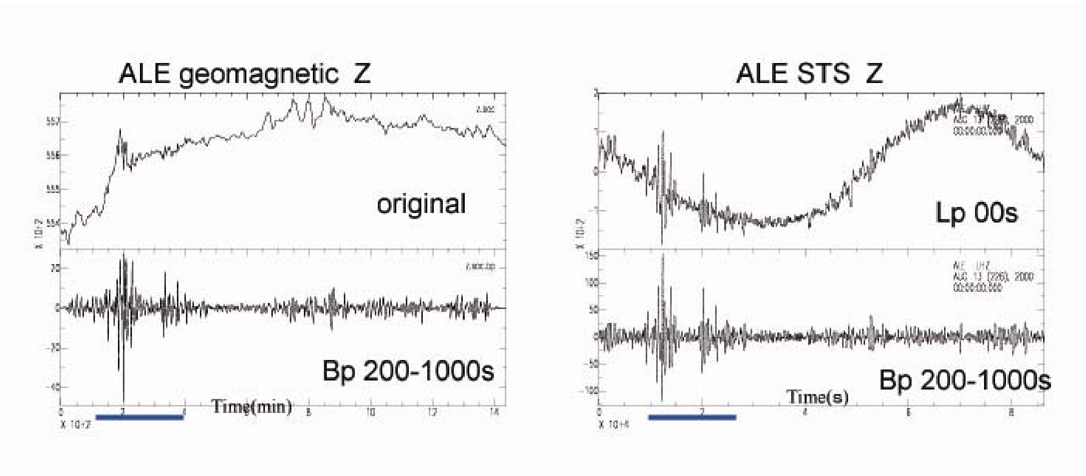

Fig.9. Left and right panels are original and bandpassed-filtered one-day records of magnetometer at ALE Geomagnetic Observatory and STS broadband seismometer at ALE IRIS/IDA station, respectively, both in Canadian Arctic region in August 13, 2000, when there was a strong magnetic storm. The two sites are located about 2 km apart.

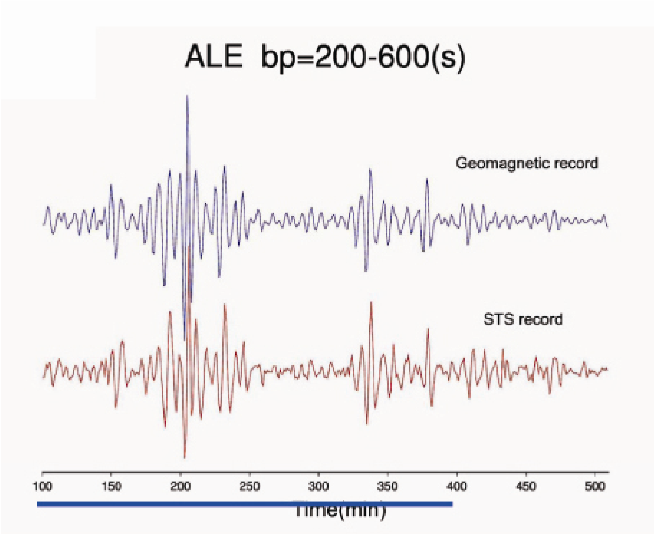

Fig.10. Seven hours records of the magnetometer and the broadband seismometer both at ALE in the Canadian Arctic region with bandpass filter between 200 s and 600 s. Correlation coefficient of waveforms is around 0.8.

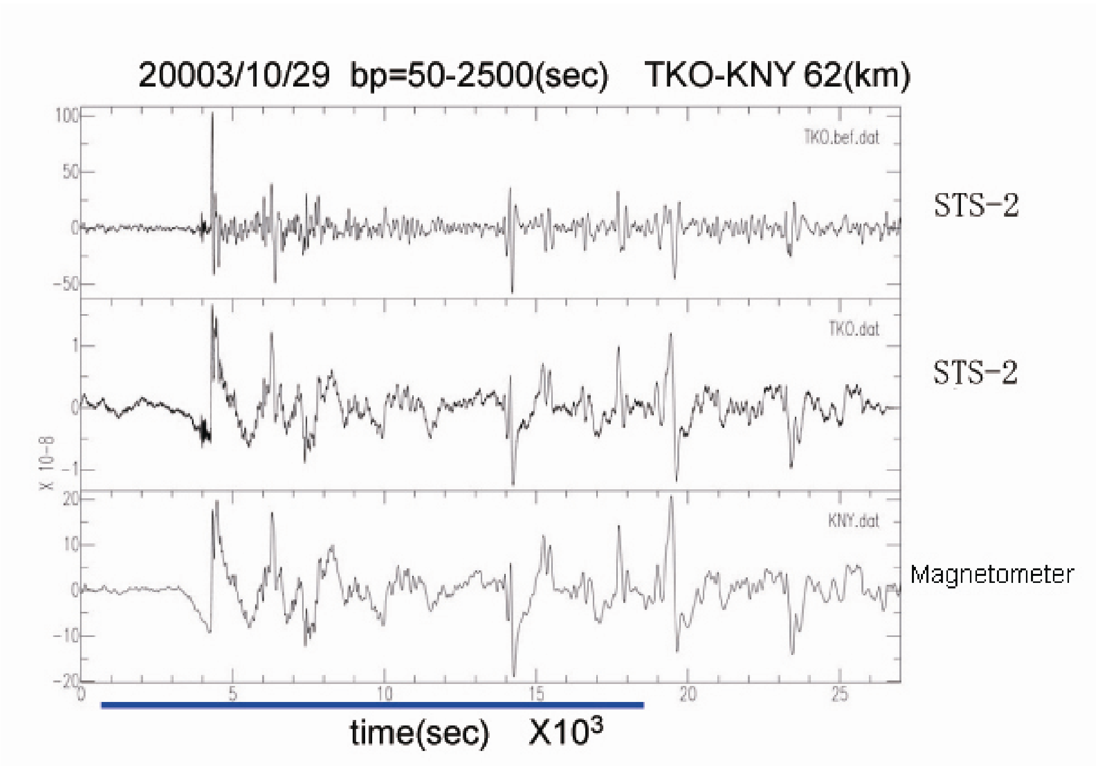

Fig.11 An upper trace is 7.5 hours of broadband seismic record at TKO（Takaoka, Kyushu, Japan）of F-net. A middle trace is a seismogram deconvolved with the instrumental response of with a bandpass filter between 50 s to 2500 s. A bottom trace is a magnetic record at KNY（Kanaya, Kyushu, Japan, 31.408, 130.880）of Japan Meteorological Agency（JMA）, bandpass-filtered in the same period range.

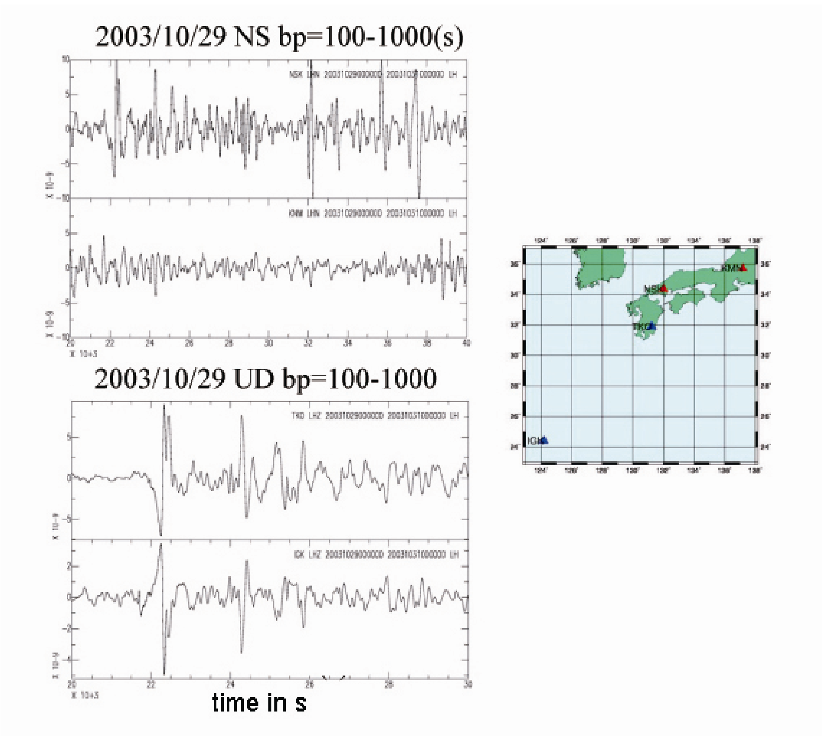

Fig.12. (a) Upper and lower traces in the upper panel are a 5 hour seismic records at NSK（Nishiki, Yamaguchi Pref., Japan） and at KNM（Kanayama, Gifu Pref., Japan）in which the synchronous anomalous signal is not seen while noise level as seismic record is low.　They are about 500 km apart.　(b) Upper and lower traces in the lower panel are 5 hour seismic records at TKO（Takaoka, Miyazaki Pref., Japan）and IGK（Ishigaki, Okinawa-Pref., Japan）, showing opposite polarity. They are about 1000 km apart.

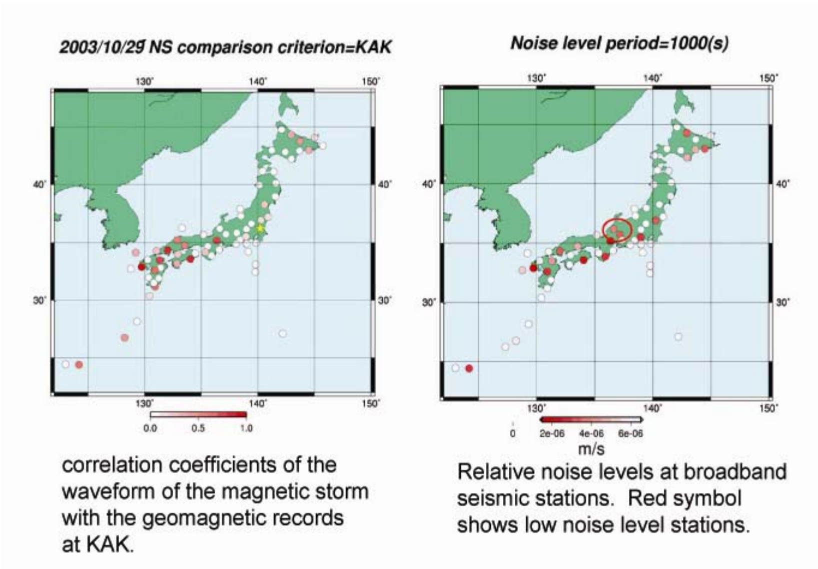

Fig.13. (a) Left panel displays correlation coefficients of the waveform of the magnetic storm at broadband seismic stations with the magnetometer records at geomagnetic station KAK（Kakioka, Ibaraki Pref., Japan）. Red symbols indicate high correlation. (b) Right panel displays relative noise levels at broadband seismic stations. Red symbol shows low noise level. At stations of red circle in the central part of Honshu Island where noise level is low, the magnetic storm was not recorded