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Anomaly disturbances of the magnetic fields before the strong earthquake in Japan on March 11, 2011

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ABSTRACT

One of the strongest earthquakes, with magnitude M 8.9, occurred at the sea bottom near to the east coast of Japan on March 11, 2011. This study is devoted to the investigation of anomaly disturbances in the main magnetic field of the Earth and in ultra-low frequency magnetic variations (F <10 Hz) observed before this earthquake. Secular variations of the main geomagnetic field were investigated using three-component 1-h data from three magnetic observatories over the 11-year period of January 1, 2000, to January 31, 2011. The Esashi and Mizusawa magnetic stations are situated northwest of the earthquake epicenter, at distances of around 170 km to 200 km, and the Kakioka observatory is situated southwest of the earthquake epicenter, at a distance of about 300 km. During this period, there were four local anomalies in the secular variations. The last anomaly was the biggest, which began around 3 years prior to the earthquake moment. All of the anomalies can be most distinctly recognized, in the form of differences in the corresponding magnetic components at these remote magnetic stations. For investigations of the ultra-low frequency magnetic field disturbances, three-component 1-s data at two magnetic stations (Kakioka and Uchiura) were used. The Uchiura station is situated 119 km south of Kakioka, at a distance of about 420 km from the earthquake epicenter. Data from the time interval of February 18, 2011 to March 10, 2011 (only at night-time: 01:00 to 04:00 local time) were investigated in a wide frequency range. In the frequency range of 0.033 Hz to 0.01 Hz, there was the clearest anomaly, seen as a decrease in the correlation coefficients of the corresponding magnetic components at these two stations, from February 22, 2011. Differences in the Z components showed an increase, and became positive after this date. This might suggest that the ultra-low frequency lithospheric source appeared north of the Kakioka station. Outside this specified frequency range, the anomalies were not well defined.

1. Introduction

One of the strongest earthquakes, with a magnitude M_w 8.9 (Japan Meteorological Agency classification), occurred at the sea bottom near the east coast of Japan on March 11, 2011. This earthquake triggered a devastating tsunami that killed over 15,000 people. We have studied the precursors of this earthquake in the secular variations of the main geomagnetic field and in the ultra-low frequency (ULF) magnetic disturbances.

It is now evident that during the preparation period prior to a strong earthquake, ULF (F <10 Hz) lithospheric magnetic emissions with a noise-like character originate from around the site of the forthcoming earthquake [Kopytenko et al. 1990, 1993, 2001, 2003, 2007, 2009, Bernardi et al. 1991, Molchanov et al. 1992, Hayakawa et al. 1996, Kawate et al. 1998, Molchanov and Hayakawa 1998, 2008, Ismaguilov et al. 2001, 2002, Hattori 2004, Fraser-Smith 2009]. The intensities of the lithospheric ULF disturbances are very weak (usually <0.1 nT), but when we can observe these emissions, the epicentral distances can extend up to 100 km or more [Fraser-Smith 2009, Hayakawa et al. 2007] before strong earthquakes (M >6). Modern high-sensitivity magnetometers can detect these weak signals from the lithospheric sources, although there is a problem with strong artificial electromagnetic noise, especially in the industrial areas of Japan. Additionally, there are ULF geomagnetic pulses of ionospheric origin that can have high amplitudes during disturbed geomagnetic periods. Therefore, before an earthquake moment, we can usually observe a superposition of ULF emissions from different sources at the Earth surface.

The natural ULF geomagnetic variations have ionospheric sources. At the Earth surface, the recording points are usually at large distances from the ionospheric sources (many hundreds of kilometers), and the ULF disturbance gradients along the Earth surface are very small and depend on the distance from the sources [Ismaguilov et al. 1992, Kopytenko et al. 2000, 2003]. On the other hand, the local lithospheric ULF sources are situated much closer to the recording point, and their gradients are greater than those of the natural pulses [Kopytenko et al. 2000, 2003]. Therefore, differential methods of data processing are particularly appropriate to detect these lithospheric signals. The phase-gradient method [Kopytenko et al. 2000, 2001, 2003, 2007, 2009, Ismaguilov et al. 2001, 2002] is based on the data at three remote magnetic stations (ULF magnetic gradientometers). These allow us to find local anomalies in the ULF magnetic field gradients and phase velocities before the earthquake moment, and to estimate the direction to a strong earthquake epicenter during the 'earthquake preparation phase'.

2. Experimental results

2.1. Secular variations of the main geomagnetic field

Figure 1 shows a schematic representation of the epicenter of this earthquake (Figure 1, largest yellow star). The white triangles in Figure 1 indicate the magnetic stations at Kakioka (KAK; $\phi = 36.23°$, $\lambda = 140.19°$), Esashi (ESA; $\phi = 39.112°$, $\lambda = 141.204°$), Mizusawa (MIZ; $\phi = 39.237°$, $\lambda = = 141.355°$), and Uchiura (UCU; $\phi = 35.16°$, $\lambda = 140.20°$). The ESA and MIZ observatories are situated northwest of the earthquake epicenter, at distances of 170 km to 200 km from it. The distance between ESA and MIZ is 19 km, and

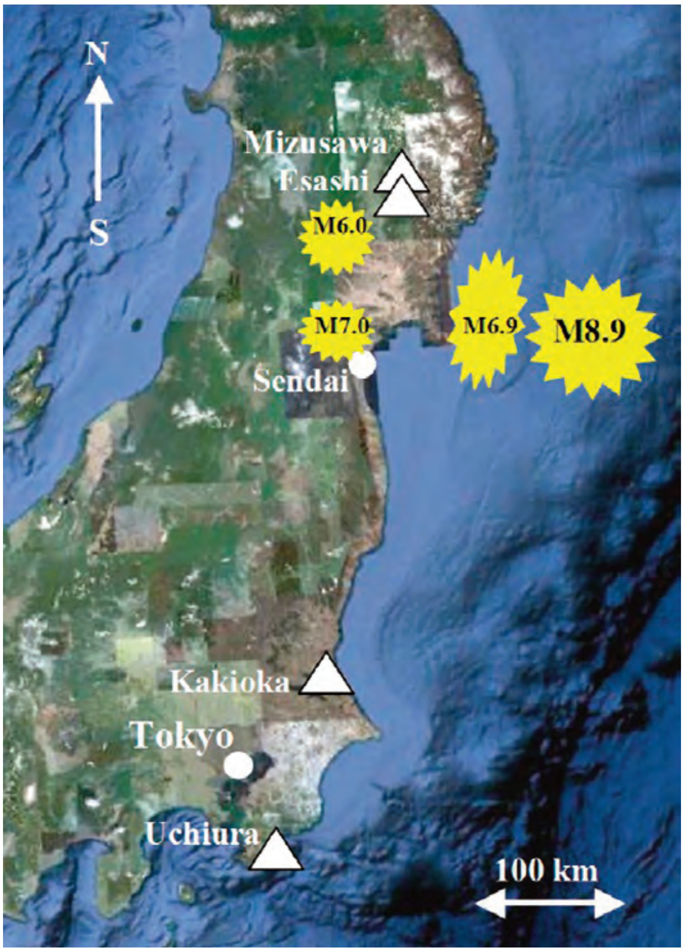

Figure 1. Location of the magnetic stations (white triangles) and the areas of strong seismic activity (yellow stars) during the period of January 1, 2000, to January, 2011.

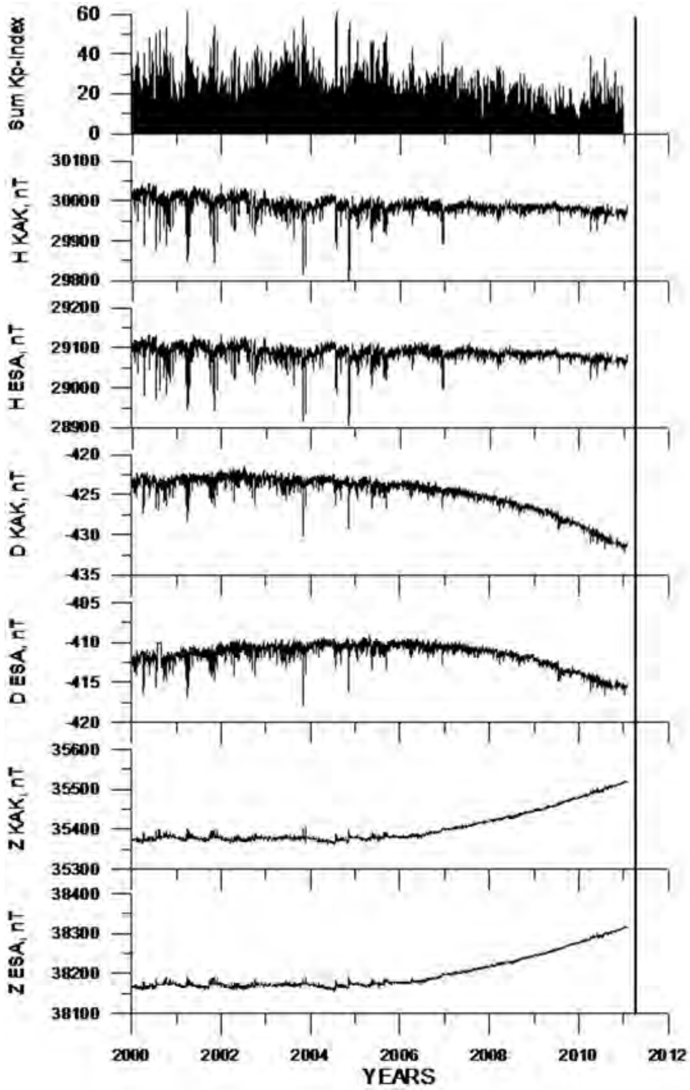

Figure 2. Daily sum of the Kp indices (top panel) and secular variations of the three components of the main geomagnetic field during the period of January 1, 2000 to January 31, 2011. The vertical line marks the earthquake moment.

the distance between ESA and KAK is 332 km. The epicentral distance to the KAK station is about 300 km.

Three components (H, D, Z) of the secular variations of the constant magnetic field at the ESA and KAK magnetic stations over an 11-year period (January 1, 2000, to January 31, 2011) are plotted in Figure 2, as the 1-h data. These data were received from the World Data Centre (http://swdcwww.kugi.kyoto-u.ac.jp/index.html). The data were averaged using a 24-point window, to delete SQ daily variations. The secular variations in Figure 2 are very similar at KAK and ESA at the scales shown in Figure 2. It can be seen from Figure 2 that the Z components at these magnetic stations increased after 2006, the D components decreased, and the H components slowly decreases during the whole of this 11-year period. The vertical line to the right in Figure 2 marks the earthquake moment. In Figure 2 (top panel), the daily sum of the Kp indices reflects the magnetic activity. The Kp index is usually calculated using the level of the 'magnetic quiet days' as the 'zero' level. However, the magnetic quiet days level is the level of the secular variation, so that Kp reflects the activity of the ionosphere-magnetosphere sources, and these are not connected with the lithospheric sources. Evidently, the secular time variations in the six lower curves in Figure 2 are not connected with the ionosphere-magnetosphere magnetic activity.

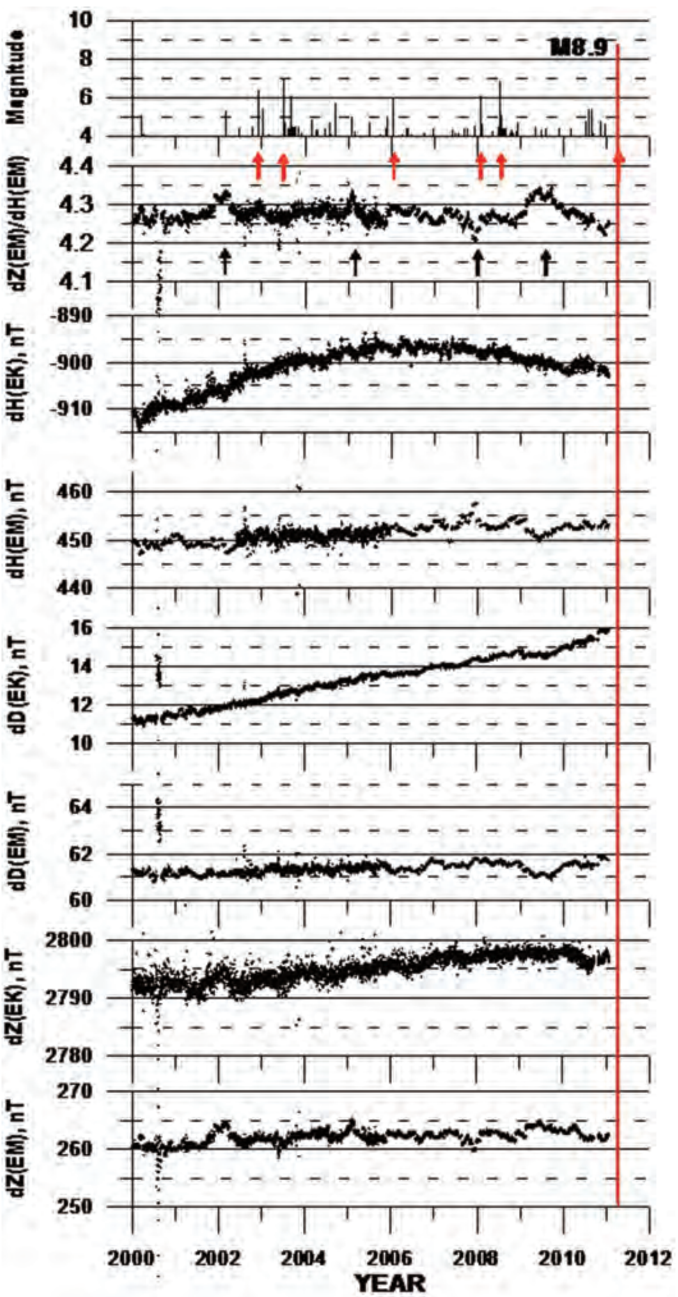

Figure 3. Magnitudes (M ≥ 4) of earthquakes (top panel) during the period of January 1, 2000 to January 31, 2011. The differences (dH, dD, dZ) of the corresponding magnetic components of pairs of remote magnetic stations (Esashi-Mizusawa – EM and Esashi-Kakioka – EK) (six lower curves). Ratio dZ/dH for the Esashi and Mizusawa magnetic stations (second from top). Black arrows mark moments of the anomalies, and red arrows indicate the moments of seismic shocks with M ≥ 6.

It is very difficult to find any precursors of earthquakes using the source data presented in Figure 2. We will use differential values for this purpose. The differences in the corresponding magnetic components of the two pairs of the remote magnetic stations (ESA-MIZ, ESA-KAK) are plotted in Figure 3. The bottom curve of Figure 3 is the difference dZ(EM) = Zesa – Zmiz. The second curve from the bottom in Figure 3 is dZ(EK) = Zesa – Zkak, and so on. The magnitudes of earthquakes (as the US Geological Survey classification) are indicated at the top of Figure 3. Only earthquakes with M >4 and with epicentral distances <150 km from the ESA station were taken into account. Anomaly variations with durations of 1 year to 3 years and of 1 nT to 5 nT amplitude are distinctly seen on the six lower curves. More exactly, the anomalies are seen in the second panel from the top of Figure 3, which shows the ratio of the vertical component difference to the horizontal component difference: dZ(EM)/dH(EM) = (Zesa – Zmiz)/(Hesa – Hmiz). The black arrows under this curve mark the moments of the anomalies, and the red arrows above the curve mark the moments of seismic shocks with M ≥6. It is apparent that the shocks have a delay of 1 year to 3-years relative to the start of the magnetic anomalies. The latest and the most distinct anomaly shows the longest time interval, and it increased before the strongest earthquake. The seismic activity areas during the 11-year period are shown in Figure 1 with the yellow stars, with their magnitudes indicated inside the stars. After the anomaly of 2002, there was an earthquake epicenter about 100 km south of the ESA station, near Sendai city. In 2005 to 2007, the earthquake sites were situated at the sea bottom at a distance of about 150 km to 200 km southeast of the ESA station. In 2008, an earthquake epicenter was situated very close to the ESA and MIZ stations (about 50 km southwest of the ESA station). After 2009, seismic activity was seen at the sea bottom, approximately as in 2005 to 2007.

2.2. ULF magnetic disturbances

In previous studies, anomaly manifestations in amplitudes, gradients and phase velocities of the ULF magnetic disturbances have been found for 1 month to 3 months before strong earthquakes [Kopytenko et al. 2001, 2003, 2007, 2009, Ismaguilov et al. 2001, 2002]. In these studies we used the data from three magnetic stations situated at the top of a triangle at the Earth surface, spaced at distances of 4 km to 6 km (ULF magnetic gradientometer). The gradient vectors were directed to the local lithospheric source of the ULF variations, and the phase velocity vectors were directed to the opposite side.

In the present study we used the 1-s data from the Uchiura magnetic station (UCU), which is situated at a distance of about 420 km from the earthquake epicenter and from the KAK observatory (KAK station epicenter distance, about 300 km). The distance between UCU and KAK is 119 km, as seen in Figure 1. The data from a time interval of

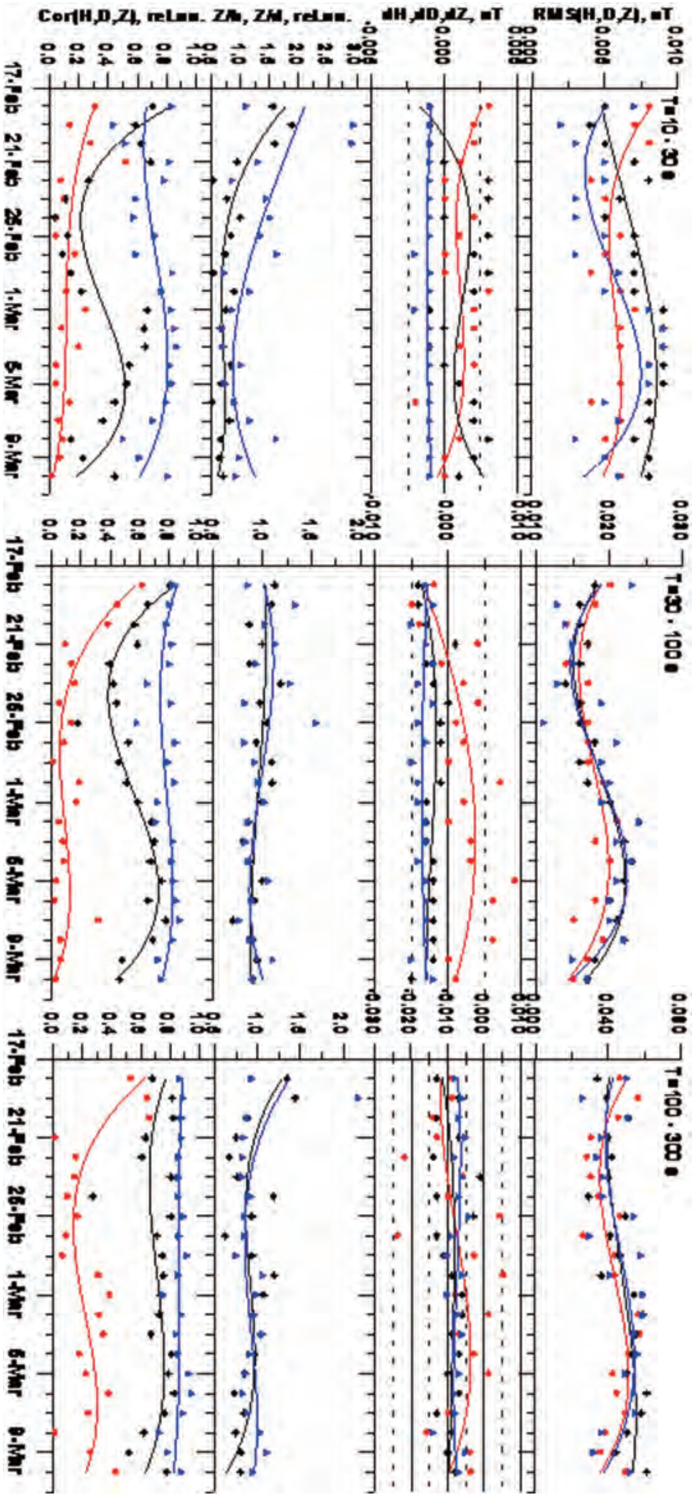

Figure 4. RMS of the three magnetic components (Kakioka observatory) during the period of February 18, 2011 to March 10, 2011 (top curves). Differences (dH, dD, dZ) of the corresponding magnetic components of a pair of remote magnetic stations (Kakioka-Uchiura, second from top). Cor(H,D,Z), as the correlation coefficients of the corresponding magnetic components of the Kakioka and Uchiura stations. Blue squares, H; black crosses, D; and red circles, Z component. Ratios Z/h (blue squares) and Z/d (black crosses), vertical component divided by the horizontal one (Kakioka, second from bottom).

February 18, 2011 to March 10, 2011 were used (for the last three weeks before the earthquake). As during the day-time the man-made noise in Japan is very high, only the night-time data were used (01:00 to 04:00 local time). The data were initially filtered using a band-pass filter for different period ranges of the ULF variations: 10 s to 30 s, 30 s to 100 s, and 100 s to 300 s. The results of this data processing are presented in Figure 4, where the filled blue squares represent the H magnetic component, the black crosses, the D component, and the filled red circles, the Z component. The following values are plotted in Figure 4, from top to bottom:

– The root mean square (RMS) of the magnetic components at the KAK station;

– The differences dH = Hkak – Hucu, dD = Dkak – Ducu, dZ = Zkak – Zucu;

– The ratios Z/h (blue squares) and Z/d (black crosses), as the vertical component divided by the horizontal one for the KAK station;

– Cor(H,D,Z), as the correlation coefficients of the corresponding magnetic components of these remote stations.

The period range of 30 s to 100 s in Figure 4 is more interesting than the other period ranges shown. The correlation coefficients of the Z components of the KAK and UCU magnetic stations sharply decreased 18 days before the earthquake moment (March 11, 2011). The differences in the Z components increased and became positive. Outside this specified frequency range, the anomalies are not so well defined. Ratios Z/h, Z/d → Z/H, Z/D decrease towards the earthquake moment, and the RMS values changed according to the variations in the magnetic activity throughout the entire period range.

3. Discussion and summary

Two geomagnetic poles in the secular variations closest to Japan are situated in eastern Siberia and in the Pacific Ocean, as based on the computations by Demina et al. [2008] using a dynamic model of sources of the main geomagnetic field. A long period displacement of these poles leads to large-space changes in the secular magnetic variations in the Japan area. When we compare the six curves shown in Figure 2, we can conclude that the space scale of the variations is very large. In addition, the global geomagnetic activity has no influence on the secular variations (see Figure 2). Therefore, the anomalies observed in Figure 3 should be local, and they have to be situated close to the ESA and MIZ magnetic stations. The black arrows under the second curve from the top in Figure 3 (ratio of the vertical component difference and the horizontal component difference for ESA and MIZ) mark four anomalies that were discovered. The red arrows indicate the moments of the earthquakes with M ≥6 (USGS classification). Apparently, the shocks have a 1 year to 3 year delay relative to the starts of the magnetic anomalies.

Moreover, these earthquakes were located in different zones of seismic activity (Figure 1, yellow stars). The seismic zone (M = 7.0) appeared after the magnetic anomaly in 2002. This was located about 100 km south of the ESA station, near to Sendai city. The average depth of the seismic hypocenter was about 37 km (we considered shocks with M ≥ 4). The magnetic anomaly of 2005 showed before the beginning of the seismic activity at the sea bottom, at a distance about 150 km to 200 km southeast of the ESA station (M = 6.9). The average depth of the seismic hypocenters was about 54 km. During 2008, the earthquake (M = 6.0) epicenter was situated very close to the ESA and MIZ stations, and the average depth of the seismic hypocenter was about 18 km. After 2009, the seismic activity was at the sea bottom in a location more eastern than in 2005 to 2007, and the average depth of the seismic hypocenter was 36 km. The seismic activity in 2005 to 2007 and after 2009 was located in the subduction area, and it was probably connected with movement of the Pacific Plate [Simon 2011]. Seismic activity at greater depths usually has a tendency to appear earlier in almost all of the subduction zones [Molchanov 2011]. We considered only earthquakes with M ≥4, and found that there was no seismic activity in the subduction zone from 2007 to 2009.

The start of the anomalies in the total magnetic field vector before the earthquakes was observed earlier [Sasai and Ishikawa 1980, Mogi 1985]. These authors interpreted the effect as a local change in the conductivity in the Earth crust. Actually, the tectonic movements lead to the generation of an increased temperature and consequently to higher conductivity in the earthquake site region. Telluric currents reallocate near to the local high conductivity region and create a magnetic anomaly at the Earth surface. The signs of the anomaly depend on the location of the magnetic stations relative to an active seismic area [Sasai and Ishikawa 1980]. Additionally, during the earthquake preparation period, a surface slope can change due to the tectonic processes. A change in the magnetic sensor orientation is another possible reason for the generation of the anomaly. For instance, a tilting of the sensor at 0.01° leads to a 6.6 nT change in the horizontal magnetic component.

Molchanov and Hayakawa [1998] assumed that the generation of the ULF seismogenic electromagnetic emissions is a natural consequence of a microfracturing process. According to this theory, the intensity of the ULF emissions increases exponentially with the frequency of the emissions. From the other side, attenuation of the emissions in the Earth crust depends on distance and conductivity, and is inversely proportional to the square root of the emission frequency. The KAK and UCU magnetic stations are situated at large distances from the earthquake site (about 300 km and 420 km, respectively), and therefore mainly long period disturbances are expected to be observed at these stations. Industrial noise is very high in the higher frequency regions of the ULF emissions.

The lowest curves in Figure 4 show the correlation coefficients of the corresponding magnetic components of the KAK and UCU magnetic stations for the period ranges of 3 s to 10 s, 30 s to 100 s, and 100 s to 300 s. The values used are the mean values for the night-time interval of 01:00 to 04:00 local time. We observe a sharp decrease in the coefficients before the earthquake moment of March 11, 2011. Kopytenko et al. [2009] found an increase in the correlation coefficients before the moment of an earthquake at the Boso peninsula in 2002. Nevertheless, the situation was different in that case. The magnetometers at the Boso peninsula were spaced at a small distance (about 5 km). The lithospheric emissions thus arrived at the magnetic stations with very close phases, because the phase velocity of the ULF disturbance propagation was very high (tens of km/s), and the correlation coefficients have to increase when we expect an increase in the intensity of the lithospheric emissions. In the present case, the distance between the UCU and KAK stations is 119 km, so that the lithospheric source was around 300 km distant [Simon et al. 2011]. Therefore, the lithospheric emissions arrived at the magnetic stations of KAK and UCU with different phases and the correlation coefficients must decrease when the intensity of the lithosphere emissions increases. The H and D magnetic components of the ULF emissions are mostly connected with ionospheric sources. The Earth crust has a greater influence on the Z component than on the horizontal ones [Kovtun 1980]. It can be seen from Figure 4 that the clearest anomaly is in the period range of T = 30 s to 100 s, as a decrease in the correlation coefficients that was seen from February 22, 2011.

The top parts of Figure 4 show the RMS of the three magnetic components recorded at the KAK observatory. Geomagnetic disturbances took place on February 18, 2011, and on March 1-7, 2011, and the RMS values reflect the magnetic activity of the magnetosphere-ionosphere origin, as is seen in Figure 4. The differential values ($B_{KAK} - B_{UCU}$) must be proportional to the RMS values if we assume that sources of the ULF magnetic variations are in the ionosphere ($dB = B_1 - B_2 = B_1(1\text{-}k)$, here $B_2 = kB_1$). The amplitudes of the natural magnetic variations is usually higher than those of the magnetic emissions of lithospheric origin, but the gradients are very small because of the very long wavelength. The differences in Figure 4 (the second curves from the top) have to be proportional to the RMS (for the case of natural variations). However, we observe a more complicated picture, especially in the period range of 30 s to 100 s. It is thus likely that besides the natural sources, there are additional ULF disturbance sources. The positive differences in the Z component (Z and D components for the period range 10 s to 30 s) signify that the ULF magnetic disturbance sources are situated north of the KAK observatory. Ratios Z/h and Z/d decreased toward the earthquake moment (Figure 4, second curves from the bottom). Similar time variations of the ratios were observed previously [Yanagihara 1972, Hayakawa et al. 1996]. Outside the specified frequency ranges, the anomalies are not so well defined (for F >0.1 Hz, due to a high level of industrial noise, for F < 0.0033 Hz, due to the high amplitudes of the natural disturbances).

In summarizing these results, we can conclude the following:

– During the period of 2000 to 2011, there were four local anomalies in the secular variations. The last of these anomalies was the biggest one, and it began about 3 years prior to the earthquake moment. All of these anomalies are most distinctly seen in the form of the differences of the corresponding magnetic components at these remote magnetic stations. The distinctive form of the anomalies in the second curve from the top in Figure 3 can be explained by a tilting of the magnetic sensors situated at the ESA and MIZ observatories during the development of the tectonic processes, or by a change in the conductivity of the anomaly zone before the earthquake. At the first stage, tectonic pressure in the subduction zone leads to an increase in the temperature and conductivity in the area of the forthcoming earthquake hypocenter. At the second stage, the increases in the numbers and sizes of microfractures lead to a decrease in the anomaly conductivity to the initial level, if there is no water at such great depths. In this case, the ratio dZ(EM)/dH(EM) will increase or decrease (depending on the anomaly disposition relative to the magnetic stations), and then the ratio will return to its initial level.

– In a frequency range of 0.033 Hz to 0.01 Hz, there was the clearest anomaly, which is seen as a decrease in the correlation coefficients of the corresponding magnetic components of the two remote stations from February 22, 2011. The differences in the Z components increased and became positive after this date. It appears that the ULF lithospheric source was north of the Kakioka station. Outside the specified frequency ranges, the anomalies are not well defined. To determine the epicenter position of a forthcoming earthquake, ULF magnetic gradientometers need to be used [Kopytenko et al. 2001, 2003, 2007, 2009, Ismaguilov et al. 2001, 2002].

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