ANOMALY DISTURBANCES OF SECULAR MAGNETIC FIELDS AND ULF MAGNETIC VARIATIONS BEFORE THE STRONGEST EARTHQUAKE IN JAPAN ON MARCH 11, 2011

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Abstract. The strongest earthquake (EQ) with magnitude $M=9$ happened under a sea bottom near the Japan east coast on March 11, 2011. Secular variations of the main geomagnetic field were investigated by means of three-component 1-hour data at three magnetic observatories during 11-year period of 01.01.2000-31.01.2011. Magnetic stations Esashi and Mizusawa are situated northwest of the EQ epicenter at distances ~170–200 km and the observatory Kakioka is situated southwest of the EQ epicenter at distance ~300 km. During the period, we found four local anomalies in the secular variations. All anomalies are most distinctly recognized in the form of differences of corresponding magnetic components at these remote magnetic stations. It was found that four seismic active zones were aroused near the magnetic stations Esashi and Mizusawa before (0.5-1 year) the four local anomalies. The last anomaly is the biggest one that had begun ~3 years prior to the EQ moment.

For investigation of the ULF magnetic field disturbances three-component 1-sec data at two magnetic stations (Kakioka and Uchiura) were used. The Uchiura station is situated south of Kakioka at a distance 119 km and at a distance of ~420 km from the EQ epicenter. Data from the time interval of 18.02 - 10.03, 2011 (only night times 01-04 LT) were investigated in a wide frequency range. It was found that in the frequency range of $F=0.033 – 0.01$ Hz there was observed the clearest anomaly as a decrease in correlation coefficients of corresponding magnetic components at these two stations from 22.02, 2011. Differences of Z components exhibited an increase and became positive after this date. It may suggest that the ULF lithospheric source appeared north of the Kakioka station. Outside the specified frequency range, the anomalies are not well defined.

1. Introduction

The strongest earthquake (EQ) with magnitude $M_w=9$ (JMA classification) took place under a sea bottom near the Japan east coast on 11.03, 2011. The EQ triggered a devastating tsunami that killed very many people. We study precursors of this EQ arising in the secular variations of the main geomagnetic field and in the ULF magnetic disturbances.

In the present time it is evident that during a strong EQ preparation period ULF ($F$(frequency) < 10 Hz) lithospheric magnetic emissions with noise-like character originate in a forthcoming EQ hearth (Kopytenko et al. [1990, 2001, 2003, 2007], Bernardi et al. [1991], Molchanov et al. [1992], Hayakawa et al. [1996], Kawate et al. [1998], Molchanov and Hayakawa [1998, 2007, 2008], Ismaguilov et al. [2001, 2002], Hattori [2004]). Intensities of the lithospheric ULF disturbances are very weak (usually $< 0.1$ nT), but the epicentral distances when we can observe these emissions may extend up to 100 km or more (Fraser-Smith [2009], Hayakawa et al. [2007]) before strong EQs (M>6). Modern high-sensitive magnetometers can detect the weak signals from the lithospheric sources, but there is a problem with strong artificial electromagnetic noise, especially in the industrial area of Japan. Additionally there exist ULF geomagnetic pulsations of ionospheric origin with high amplitude during disturbed geomagnetic periods. So, before the EQ moment we usually observe at the Earth’s surface a superposition of the ULF emissions from different sources.

The natural ULF geomagnetic variations have the ionospheric sources. At the Earth’s surface the registration points are usually at large distances from the ionospheric sources (many hundred kilometers) and the ULF disturbance gradients along the Earth’s surface are very small and depend on a 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 registration point and their gradients are greater than those of the natural pulsation (Kopytenko et al. [2000, 2003]). Therefore, differential methods of data processing are very appropriate to detect the lithospheric signals. A 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). It allows us to find local anomalies in the ULF magnetic field gradients and
phase velocities before the EQ moment and to estimate the direction to a strong EQ epicenter during “EQ preparation phase”.

2. Secular variations of the main geomagnetic field

A yellow biggest star in Fig.1 schematically marks the epicenter of the EQ. White triangles in Fig.1 stand for magnetic stations at Kakioka (abbreviated as KAK, $\phi=36.23^\circ, \lambda=140.19^\circ$), Esashi (ESA, $\phi=39.112^\circ, \lambda=141.204^\circ$), Mizusawa (MIZ, $\phi=39.237^\circ, \lambda=141.355^\circ$), and Uchiura (UCU, $\phi=35.16^\circ, \lambda=140.20^\circ$). The observatories ESA and MIZ are situated northwest of the EQ epicenter at distances ~170 – 200 km. The distance between the ESA and MIZ is equal to 19 km, and the distance between ESA and KAK is 332 km. The epicentral distance to the KAK station is about 300 km.

Fig.1. Location of magnetic stations (white triangles) and areas of strong seismic activity (yellow stars) during the period of 01.01.2000 – 31.01.2011.

Three components (H, D, Z) of the secular variations of the constant magnetic field at the ESA and KAK magnetic stations during 11-year period (01.01.2000-31.01.2011) are plotted in Fig.2. 1-hour data were used for plotting the figure. The data were received from WDC. The data were averaged using 24-point window in order to delete SQ daily variations. The secular variations in Fig.2 are very similar in KAK and ESA with the scales used in Fig.2. It is seen from the figure that Z components at this magnetic stations increase after the year of 2006, D components decrease and H components slowly decrease during the whole 11-year period. A vertical line in Fig.2 marks the EQ moment. Daily sum of Kp-indices reflect magnetic activity in Fig.2 (top panel). Evidently, the secular time variations in the six lower curves are seen to be not connected with magnetic activity.

It is very complicated to find any precursors of EQs using the source data presented in Fig.2. We will use differential values for this purpose. Differences of the corresponding magnetic components of two pairs of the remote magnetic stations (ESA-MIZ, ESA-KAK) are plotted in Fig.3. The bottom curve of Fig.3 is the difference $dZ(EM) = Zesa – Zmiz$. The second curve from the bottom is $dZ(EK) = Zesa – Zkak$, and so on. Magnitudes of EQs (USGS classification) are mapped at the top part of Fig.3. Only EQs with $M\geq4$ and with epicentral distances $<150$ km from the ESA station were taken into account. Anomaly variations with duration in 1 – 3 years and 1 – 5 nT amplitude are distinctly seen on the six lower curves. More exactly the anomalies are seen in the second panel from the top, in which we plot the ratio of the vertical component difference to the horizontal component difference: $dZ(EM)/dH(EM) = (Zesa – Zmiz)/(Hesa – Hmiz)$. Black arrows under this curve mark moments of the anomalies, and red arrows above the curve mark moments of seismic shocks with $M\geq6$. It is apparent that the shocks have a delay of 1 - 3-year relative to the start of the magnetic anomaly. Latest and the most distinct anomaly is found to occupy the longest time interval, and it increased before the strongest EQ. The seismic activity areas during the 11-year period are presented in Fig.1 by yellow stars. Magnitudes of the strongest seismic shocks are indicated inside the stars. After the anomaly of the year of 2002 EQ epicenters took place ~ 100 km south of the ESA station near Sendai city. In the years of 2005 – 2007 EQ hearths were situated under a sea bottom at a distance ~150-200 km southeast of the ESA. In the year of 2008 EQ epicenters were situated very close to the ESA and MIZ stations (~50 km southwest of the ESA station). After the year of 2009, seismic activity was displayed under a sea bottom approximately as in the years of 2005-2007.
Fig. 2. Daily sum Kp-indices (top panel) and secular variations of three components of main geomagnetic field during the period of 01.01.2000 – 31.01.2011. Vertical line marks the EQ moment.

3. Discussion and summary

Two geomagnetic poles closest to Japan in the secular variation are situated in the 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 six curves represented in Fig. 2, we can conclude that the space scale of the variations is very big. In addition, the global geomagnetic activity has not an influence on the secular variations (see Fig. 2). Therefore, the anomalies observed in Fig. 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 (ratio of the vertical component difference and the horizontal component difference for the ESA and MIZ) mark four anomalies discovered. The red arrows indicate moments of the EQs with M≥6 (USGS classification). Apparently, the shocks have one–three year delay relatively to the start of the magnetic anomaly. Moreover, these EQs were situated in different zones of seismic activity (yellow stars in Fig. 1). The seismic zone (M=7.0) appeared after the magnetic anomaly in 2002. It was located ~ 100 km south of the ESA station near Sendai city. An average depth of the seismic hypocenters was ~37 km (we consider shocks with M≥4). The magnetic anomaly of the year of 2005 existed before the beginning of seismic activity under a sea bottom at a distance ~150-200 km southeast of the ESA (M=6.9). An average depth of the seismic hypocenters was ~54 km. During the year of 2008 EQ(M=6.0) epicenters were situated very close to the ESA and MIZ stations, and an average depth of the seismic hypocenters was ~18 km. After the year of 2009 seismic activity was displayed under a sea bottom more eastern than in the years of 2005-2007 and an average depth of the seismic hypocenters was 36 km. The seismic activity in 2005-2007 and after 2009 was situated in the subduction area, and it was probably connected with the Pacific Plate movement (Simon [2011]). The seismic activity with bigger depth usually exhibits a tendency to appear earlier almost in all subduction zones (Molchanov [2011]). We considered only EQs with M≥4 and found that seismic activity was absent in the subduction zone during 2007 – 2009.

Beginnings of the anomalies in the total magnetic field vector before the EQs were observed earlier (Sasai and Ishikawa [1980]; Mogi [1985]). These authors interpreted the effect as a local change of the conductivity in the Earth’s crust. Really the tectonic movements lead to the generation of an increased temperature and consequently to higher conductivity in the EQ hearth region. Telluric currents reallocate near the high conductivity local region and create a magnetic anomaly at the Earth’s surface. Sign of the
Fig. 3. Magnitudes (M≥4) of EQs (top panel) during the period of 01.01.2000 – 31.01.2011. Differences (dH, dD, dZ) of corresponding magnetic components of pairs of remote magnetic stations (Esashi-Mizusawa(EM) and Esashi-Kakioka(EK), six lower curves). Ratio dZ/dH for Esashi and Mizusawa magnetic stations (second from top). Black arrows mark moments of the anomalies, and red arrows indicate moments of seismic shocks with M≥6.

An anomaly depends on the relative location of the magnetic stations relative to a seismic active area (Sasai and Ishikawa [1980]). Additionally, during an EQ preparation period a surface slope can change due to tectonic processes. A change in magnetic sensor orientation is a possible another reason for the anomaly generation. For instance, a tilting of the sensor at 0.01° leads to 6.6 nT change in the horizontal magnetic component.

Molchanov and Hayakawa [1998] supposed that the generation of ULF seismogenic electromagnetic emissions is a natural consequence of micro fracturing process. In this theory, intensity of the ULF emissions exponentially increases with frequency of the emission. From the other side attenuation of the emissions in the Earth’s crust depends on distance, conductivity and inversely proportional to the square root of the emission frequency. The KAK and UCU magnetic stations are situated at large distances from the EQ hearth (~300 km and ~420 km), therefore mostly long period disturbances are expected to be observed at these stations. An industrial noise is very high in the higher frequency region of the ULF emissions.

The lowest curves in Fig. 4 represent correlation coefficients of corresponding magnetic components of the KAK and UCU magnetic stations for period ranges of 3-10 s, 30-100 s, and 100 – 300 s. The used values are a mean value for nighttime interval 01 - 04 LT. We observe sharp decreases in the coefficients before the EQ moment of 11.03.2011. Kopytenko et al. [2009] found an increase in the correlation coefficients before the moment of EQ at the Boso peninsula in 2002. Nevertheless, a situation in that case was different. Magnetometers at the Boso peninsula were spaced at a small distance (~5 km). The lithospheric emissions arrived at the magnetic stations with very close phases because the phase velocity of ULF disturbances propagation is very high (tens km/s) and the correlation coefficients have to increase when we expect an increase in the intensity of lithospheric emissions. In the present case the distance between the UCU and KAK is equal to 119 km, so that the lithospheric source had ~300 km length (Simon et al. [2011]). Therefore, the lithospheric emissions arrived at the magnetic stations KAK and UCU with different phases and the correlation coefficients must decrease when an intensity of the lithosphere emissions increases. H
and D magnetic components of the ULF emissions are mostly connected with the ionospheric sources. The Earth’s crust has a greater influence on Z component than on horizontal ones (Kovtun [1980]). It is seen from Fig.4 that in the period range of T = 30 – 100 s the clearest anomaly as a decrease in correlation coefficients was observed from 22.02.2011.

**Fig.4.** RMS of three magnetic components (Kakioka observatory) during the period of 18.02 - 10.03.2011 (top curves). Differences (dH, dD, dZ) of corresponding magnetic components of a pair of remote magnetic stations (Kakioka-Uchiura, second from top). Corr(H,D,Z) – correlation coefficients of corresponding magnetic components of Kakioka and Uchiura stations. Blue squares - H, black crosses - D and red points - Z component. Ratios Z/h (blue squares) and Z/d (black crosses) - vertical component divided by horizontal one (Kakioka, second from bottom).

The top parts of Fig.4 represent RMS of three magnetic components registered at the KAK observatory. Geomagnetic disturbances took place on 18.02.2011 and on 01-07.03.2011, and RMS values reflect magnetic activity of magnetosphere-ionosphere origin as it is seen in Fig.4. Differential values (B_{KAK} - B_{UCU}) must be proportional to RMS values if we assume that sources of the ULF magnetic variations are in the ionosphere (dB = B1 - B2 = B1(1-k), here B2 = kB1). The amplitudes of natural magnetic variations are usually higher than those of magnetic emissions of the lithospheric origin but the gradients are very small because of very long wavelength. The differences in Fig.4 (second curves from the top) have to be proportional to the RMS (in a case of natural variations). However, we observe a more complicated picture especially in the period range 30 – 100 s. It is likely that besides the natural sources there arise additional ULF disturbance sources. Positive differences of Z component (Z and D components for the period range 10 – 30 s) signify that the ULF magnetic disturbance sources are situated north of the KAK observatory. Ratios Z/h and Z/d are found to have decreased toward the EQ moment (second curve from the bottom). Similar time variations of the ratios were observed earlier (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 the industrial noise, for F<0.0033 Hz – due to high amplitudes of the natural disturbances).

Summarizing the above-mentioned results we can conclude the followings.

- During the period of 2000-2011 we found four local anomalies in the secular variations. The last anomaly is the biggest one and it had begun ~3 years prior to the EQ moment. All anomalies are most distinctly seen in the form of differences of corresponding magnetic components at these remote magnetic stations.
- It was found that in a frequency range of F=0.033 – 0.01 Hz there was observed the clearest anomaly as a decrease in correlation coefficients of corresponding magnetic components of remote two stations from 22.02.2011. The differences of Z components increased and became positive after this date. It seems that the ULF lithospheric source appeared north of the Kakioka station. Outside the specified frequency ranges, the anomalies are not well defined.

**References**

