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Preseismic ULF effect and possible interpretation

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Abstract
We present the results of ULF magnetic field observation at Karimshino station (Kamchatka, Russia). Using a case study we discovered an effect of suppression of ULF intensity about 2-6 days before rather strong and isolated seismic shocks (magnitude M = 4.6-6.6). It is revealed for nighttime and the horizontal component of ULF field (G) in the frequency range 0.01-0.1 Hz. Then we prove the reliability of the effect by computed correlation between G (or $1/G$) and especially calculated seismic indexes K_s for the rather long period of observation from June 2000 to November 2001. Our recent data confirm the validity of the effect. We show here a similar result during a period of frequent strong seismic activity in April-May 2002. It is highly probable that the effect observed is connected with the increase in plasma density perturbations inside the ionosphere, which are induced by preseismic water and gas release at the ground surface and following energy transportation into the ionosphere by atmospheric gravity waves. Two models are discussed and computed: the first is a decrease of penetration coefficient of Alfven waves from the magnetosphere due to a turbulent increase in effective Pedersen conductivity in the ionosphere, and the second is a change in wave number (k) distribution of source ionospheric turbulence. One of the mechanisms or both could be responsible for the observed 2-3 times suppression of ULF magnetic field noise at the ground.

Key words *Ultra-Low Frequency emission – seismicity – Alfven waves*

1. Introduction

It is now recognized that analysis of seismic data, even sophisticated, is not sufficient to resolve two essential problems of geodynamics: what are the mechanisms of earthquakes (EQs) origin and how can large EQs be forecast? In such a situation an importance of nonseismic methods is evident. One of them is the variation of magnetic field in the Ultra-Low Frequency (ULF) range 0.01-10 Hz.

This effect was first reported by Fraser-Smith *et al.* (1990) in connection with Loma-Prieta, 1989 (USA) large EQ (magnitude M_s = 7.1) and by Molchanov *et al.* (1992), Kopytenko *et al.* (1993) in association with Spitak, 1987 (former Soviet Union) EQ (M_s = 6.9). Fraser-Smith *et al.* (1990) were lucky to observe at a distance of 7 km from EQ epicenter and found that ULF magnetic intensity increased about 14 days before EQ, then it depressed several days ahead and once again it increased strongly at 4 h before the main shock and continued at a high level after EQ. They

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found the clearest effect in the frequency band $F = 0.01\text{-}0.1$ Hz. Molchanov *et al.* (1992), Kopytenko *et al.* (1993) observed ULF variation at a distance of 130 km from the EQ epicenter and noted only the last stage of the process: an increase in ULF intensity in time period from 3 h before to several days after EQ.

Subsequent research on this subject was mainly produced in Japan. Hayakawa *et al.* (1996a) reported results of observation the ULF magnetic field variations before the great EQ at Guam, 1993 ($M_s = 8.0$) at an epicenter distance 65 km. They suggested analyzing the polarization ratio $R = Z/H$ in frequency band 0.01-0.05 Hz and found that this parameter increased about 1 month before EQ but returned to the regular level after it. Later Hayakawa *et al.* (1999) considered the data once again and showed that slope of ULF spectrum (fractal number) was also changed before the EQ. Hattori *et al.* (2002) reported observation of ULF magnetic variation around date of two Kagoshima, 1997 large EQs ($M = 6.5$ and $M = 6.3$) at a distance about 60 km from both epicenters. They also analyzed the polarization ratio and found its increase about 1 month before EQ date. They could not find this signature at the far-distance stations with the same equipment. Kopytenko *et al.* (2002) observed ULF magnetic variations using network of stations situated in the Izu and Chiba areas of Japan. They discussed results related to EQ swarm during June-July, 2000 with the strongest shock $M_s = 6.4$ in the middle of the swarm. Epicenter distances to the stations changed from 70 to 150 km and the authors focused on the polarization ratio near frequencies $F_1 = 0.1 \pm 0.005$, $F_2 = 0.01 \pm 0.005$ and $F_3 = 0.005 \pm 0.003$ Hz. It was shown that ratio $R(F_3)/R \cdot (F_1)$ sharply increases just before the start of strong seismic activity, while amplitudes of Z and G component variations and Z/G ratio defined in a frequency range F_2 during night time intervals (00-06 LT) begin to increase ~1.5 months before the period of the seismic activity.

In this paper, we consider ULF perturbations in temporal scale from several hours to a few days and focus on the time correlation of our data with seismicity. Some results of observations have already been published (Molchanov *et al.*, 2003). Here we briefly review the previous results (Section 2) and present new observational evidence of the preseismic ULF effect (Section 3). Furthermore we discuss the possible explanation of the effect (Section 4).

2. Previous results

During 1999-2000, in addition to the existing seismic and geophysical observations, Russian and Japanese scientists established a special observatory at Karimshino site (52.94°N, 158.25°E) in Kamchatka (Far-Eastern Russia). Its main purpose was to study a correlation of seismic activity with electromagnetic and other nonseismic phenomena. The main advantage of this station is quiet electromagnetic environment that allows us to use rather sensitive equipment and to check some theoretical ideas. The regular recordings have been underway since June 2000 and some information about Karimshino station has already been published (Gladyshev *et al.*, 2002; Uyeda *et al.*, 2002).

Our three-component induction magnetometer measures the geomagnetic field variations in the frequency range 0.003-40 Hz. The sensitivity threshold is better than 20 $pT/Hz^{1/2}$ at frequency 0.01 Hz. It corresponds to 0.02 $pT/Hz^{1/2}$ at frequencies above 10 Hz. Here we analyze results in the interval from June 24, 2000 to February 25, 2001 (the first interval duration of 7 months) and second interval from February 26, 2001 to September 16, 2001 (during of about 6 months). So, the whole period of the observation has a duration of about 13 months. As mentioned before in this paper we are presenting results on variation with scale more than several hours which is why we use two hour averaging of the data.

First of all we have produced the spectrum of ULF intensity for each magnetic field component (H, D, Z) in the 7 frequency bands: $F = 0.003\text{-}0.01$ Hz (channel 1), $F = 0.01\text{-}0.03$ Hz (channel 2), $F = 0.03\text{-}0.1$ Hz (channel 3), $F = 0.1\text{-}0.3$ Hz (channel 4), $F = 0.3\text{-}1.0$ Hz (channel 5), $F = 1.0\text{-}3.0$ Hz (channel 6) and $F = 3.0\text{-}5.0$ Hz (channel 7). We found a conventional corre-

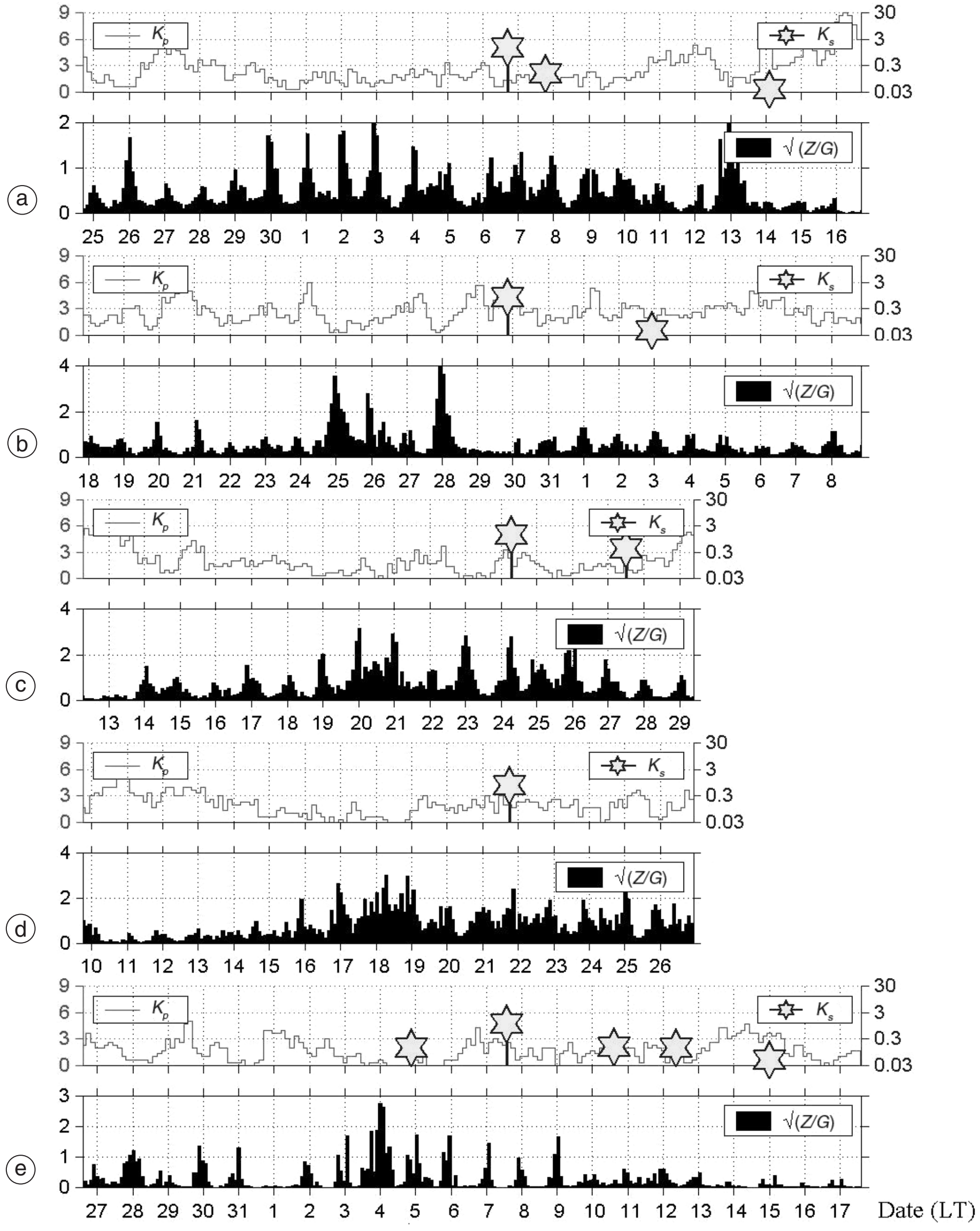


Fig. 1a-e. Variation of impedance ratio at channel 2 near the date of the EQs with the following parameters: panel a) – July 6, 2000, M = 6.0, distance D = 762 km, K_s = 1.4; panel b) – July 29, 2000, M = 4.9, distance D = = 195 km, K_s = 0.8; panel c) – August 23, 2000, M = 4.6, distance D = 112 km, K_s = 1.35 ; panel d) – November 21, 2000, M = 5.1, distance D = 170 km, K_s = 0:75 ; panel e) – February 7, 2001, M = 5.6, distance D = = 210 km, K_s = 1.15. Vertical grid lines are for local midnightofeachday of observation. The intervals in panels c) and d) are shorter due to lack of data.

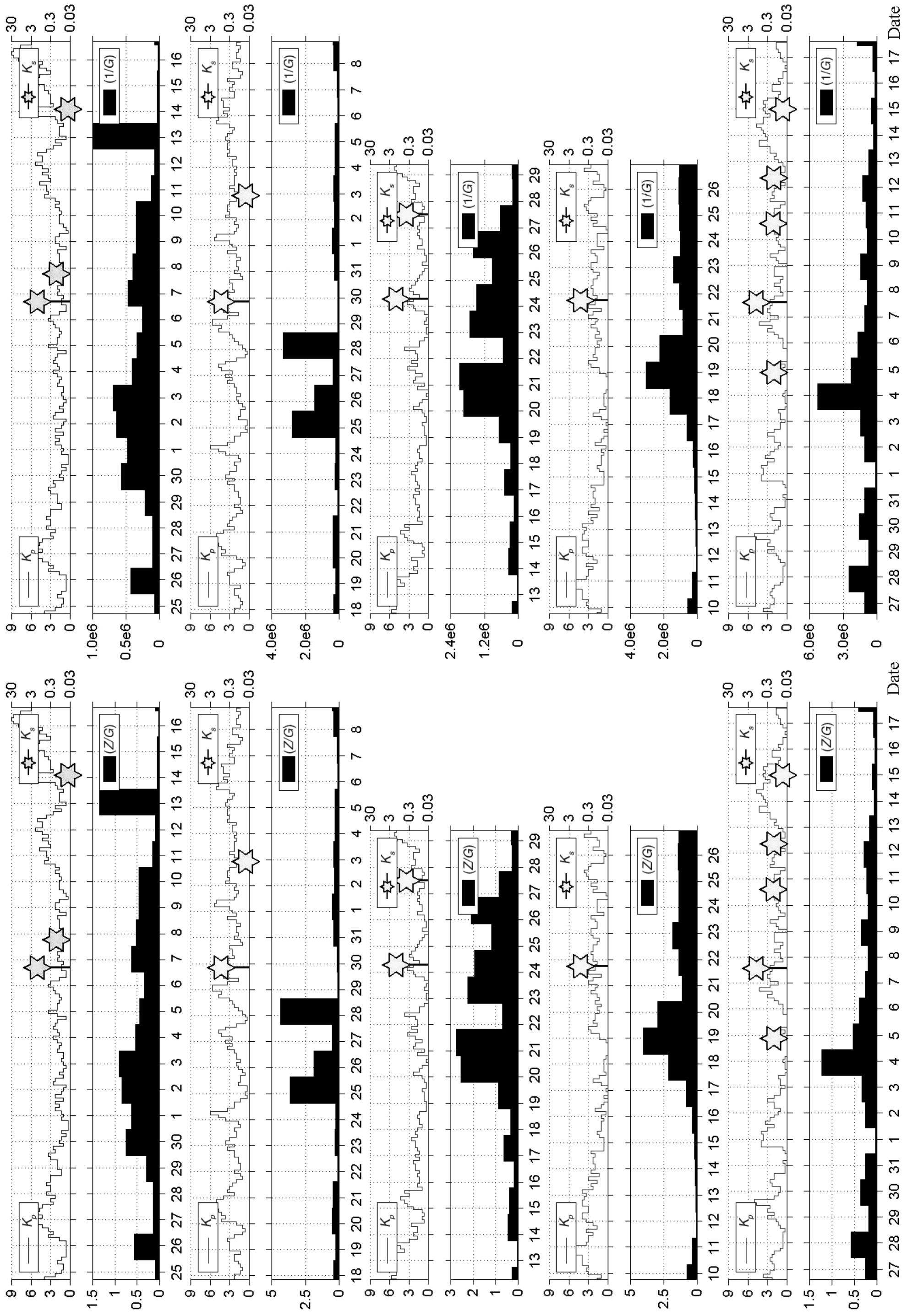


Fig. 2. Z/G values (*left* panels) and $1/G$ values (*right* panels) after 1 day averaging for the same cases as in fig. 1a-e.

lation with K_p index of magnetic activity and evident daily variation, especially in channels 1, 2, 3. But we did not find any clear correlation with a specially developed index of seismicity K_s, which includes dependence on magnitude and distance to earthquake (EQ) epicenter and which is proportional to seismic energy released near the observation site (see Molchanov *et al.*, 2003).

Then we apply the method of polarization ratio, which was discussed in many papers since Hayakawa *et al.* (1996a) and which is reduced to analysis of $Z^{1/2}/G^{1/2}$ ratio in our research. In contrast with amplitude analysis, some correlation with K_s was found at least for the frequency channels 2 and 3 and near the date of large K_s values. We demonstrate several cases in fig. 1a-e, each case during time interval ± 14 days around the EQ date and presentation is centered on the corresponding date. For simplicity, we present only channel 2 (F= =0.01-0.03 Hz). It is obvious that nighttime values of $Z^{1/2}/G^{1/2}$ show an increase at about 2-7 days time period before EQ date. An important question arises immediately: what does increase in Z component or decrease of G component or both mean? First of all, we examined the behavior of Z component and found it reveals mainly seasonal changes and sometimes it is exposed to small man-made perturbations but does not show correlation with seismicity. To clarify this we present Z/G values and $1/G$ values after 1 day averaging in fig. 2 for the same cases as in fig. 1a-e. As a result, we concluded that the effect observed is a depression of horizontal ULF magnetic field several days before EQ. The effect was not found for all the events being masked by the dominant magnetospheric component of amplitude variation of the geomagnetic field on the Earth surface. Maybe, for some events the difference of parameters of EQs can be important. To check it we analyzed the geographical distribution of the casual EQs and discovered that correlated cases are mainly concentrated near the sea shore.

Then we checked the reliability of the effect by correlation analysis. At the beginning we construct the set of normalized deviations as the following:

$$\delta G_i = \left(G_i - \langle G_i \rangle\right) / \langle G_i \rangle$$
$$\delta\left(1/G_i\right) = \left(1/G_i - \langle 1/G_i \rangle\right) / \langle 1/G_i \rangle$$

where i is number of the frequency channel, i = = 1, 2, 3 and $\langle G \rangle$, $\langle 1/G \rangle$ denotes running mean with 1 month window. Taking into considera-

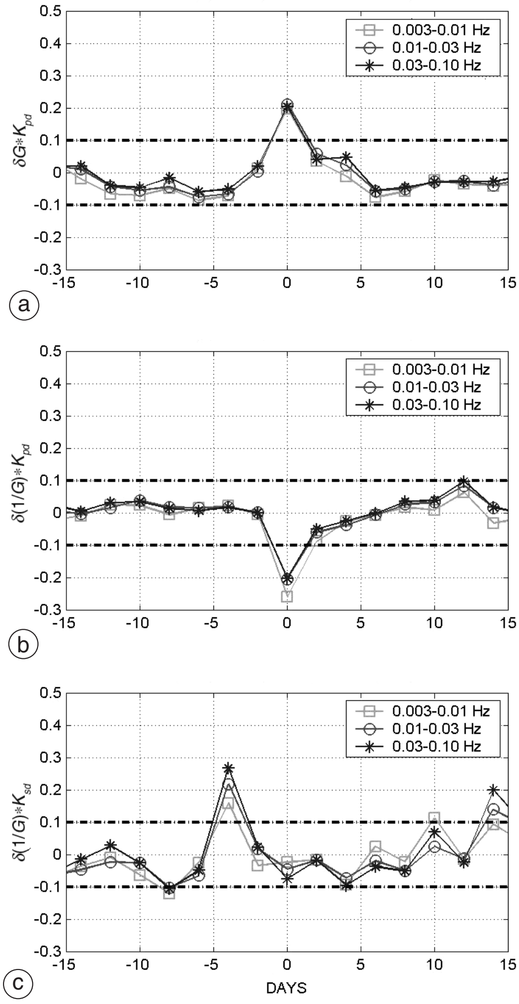


Fig. 3a-c. Cross-correlation of (a) $\delta G{*}K_{pd}$, b) $\delta(1/G){*}$ $*K_{pd}$ and (c) $\delta(1/G){*}K_{sd}$ in a range of ±15 days for whole 13 months period of observation and different frequency bands.

tion that our expected effect has a temporal scale order of several days, we produce 2 days averaging of δG_i and $\delta(1/G_i)$, which leads to values $\delta_2 G_i$, $\delta_2(1/G_i)$, and find $K_{sd} = \sum K_s$ per day, $K_{pd} = \sum K_p$ per day. Due to a clear daily variation of ULF spectrum in the selected channels, $\delta_2 G_i$ is mainly related to daytime ULF intensity,but $\delta_2(1/G_i)$ is mainly related to night-time ULF intensity. As a next step we computed correlation functions $F_{1i}(\tau) = \delta_1 G_i * K_{sd}$, $F_{2i}(\tau) = \delta_1(1/G_i) * K_{sd}$, $F_{3i}(\tau) = \delta_1 G_i * K_{pd}$ and $F_{4i}(\tau) = \delta_1(1/G_i) * K_{pd}$ using conventional programs, where τ is determined in the interval ± 14 days. The negative value of τ corresponds to the preseismic period and the positive τ-value is for the postseismic period in our formulation.

Firstly, we present a correlation of ULF intensity with global ionosphere-magnetosphere activity (fig. 3a,b). An obvious correlation is observed both for daytime ULF intensity (fig. 3a) and for the night-time values (fig. 3b). It is evident that both day-time and night-time ULF intensity is proportional and concurrent to K_p index. This correlation is understandable. We call a correlation reliable if it reveals for all the intervals and at least twice out of a reliability margin at the whole interval, which is about ± 0.1. Based on this point a correlation in fig. 3a,b is reliable.

Then we show a correlation of ULF intensity with seismic index K_s (fig. 3c). Due to our criteria, night-time suppression of ULF intensity near value $\tau \sim -4$ days looks a reliable effect. This conclusion coincides with the result of case study. Note that reliability of seismo-associated ULF suppression effect is comparable with the reliability of the well-known effect of connection between ULF variation and K_p index of global magnetic activity.

3. New observational results

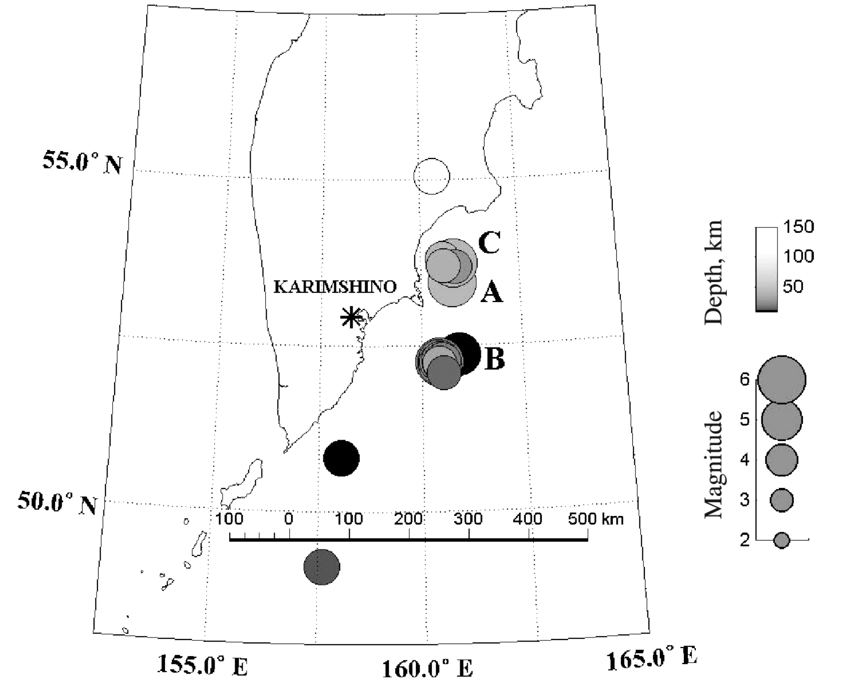
Previous results were obtained for a period of rather moderate seismic activity, $K_s \leq 3$ (see fig. 1a-e). However, since late autumn of 2001 the activity intensified in the vicinity of our station. In this situation, statistics of the preseismic effect do not change essentially but a new feature appears just near the date of strong EQs.

Let us consider it for the period from April 17, 2002 to May 17, 2002, including several strong EQs with $M_s > 5$. Two of them happened near the sea shore A (April 26, $M_s = 5.8$, distance $D = 180$ km, $K_s = 7.5$) and C (May 8, $M_s = 6$, distance $D = 195$ km, $K_s = 10.4$), the others occurred further from the shore, including B (May 3, $M_s = 5.2$, distance $D = 190$ km, $K_s = 1.8$) (fig. 4a). Impedance ratio in channels 1, 2, 3, 4 is presented in fig. 4b. Preseismic signature 3-4 days before event A and 3-5 days before event C can be noted. It is similar to previous results and in the same manner as earlier we check that it is due to a decrease of G-component of the ULF magnetic field. In contrast, an increase in the impedance ratio near the date of the EQs is connected here with an increase in Z-component, which can be considered in conventional terms of ULF radiation from underground seismic source.

4. Possible interpretation of the preseismic ULF effect

It was usually supposed that seismo-associated ULF variations could be either due to direct radiation from EQ origin zone (Fenoglio *et al.*, 1995; Molchanov and Hayakawa, 1995) or due to a change in geoelectric conductivity inside and near the EQ zone, which leads to a change

Fig. 4a,b. a) Map of EQ's with $M_s > 4$ from April 17, 2002 to May 17, 2002, including several strong EQs with $M_s > 5$. Two of them have happened near the sea shore A (April 26, $M_s = 5.8$, distance $D = 180$ km, $K_s = 7.5$) and C (May 8, $M_s = 6$, distance $D = 195$ km, $K_s = 10.4$) the others occurred further from the shore, including B (May 3, $M_s = 5.2$, distance $D = 190$ km, $K_s = 1.8$). b) Impedance ratio in channels 1, 2, 3, 4 is presented. Preseismic signature 3-4 days before event A and 3-5 days before event C can be noted.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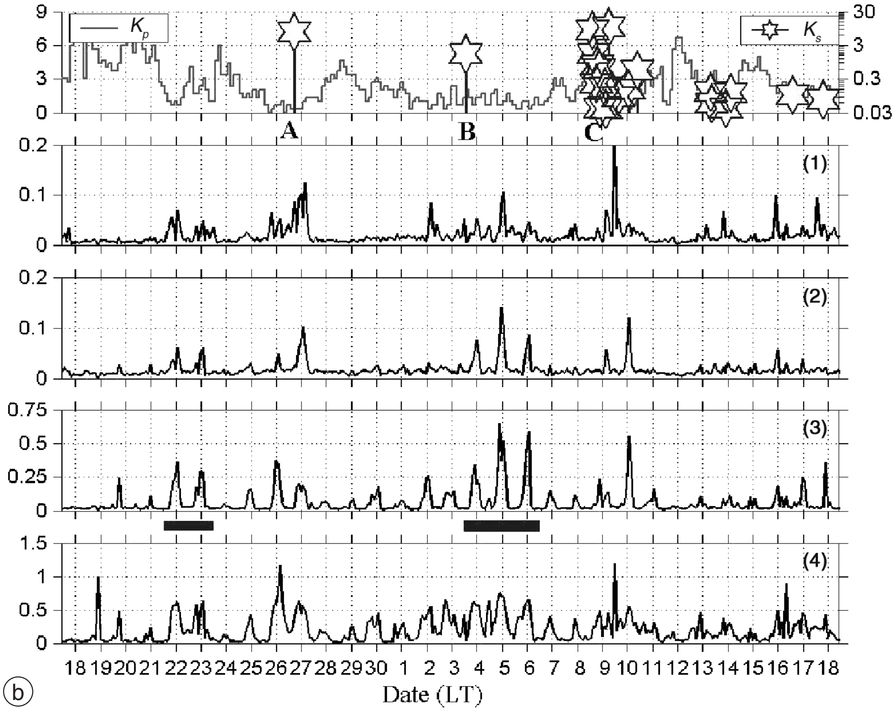
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b

in ULF waves generated by ionospheric sources (*e.g.,* Merzer and Klemperer, 1997). The first mechanism is not compatible with our observational results on preseismic effect because it predicts a preseismic increase in ULF intensity. Indeed, we observed such an increase near the date of several strong EQ shocks (see fig. 4b). Probably the interval of ULF increase could be extended essentially for the very large EQs up to a few days as reported earlier (see Section 1). An explanation by preceding change in the ground conductivity is also not very attractive for us because long-term magnetotelluric observation in U.S.A. and Japan did not show any correlation with seismicity (see, *e.g.,* Park, 1997). It seems that suppression of ULF magnetic variation happened not inside the ground but in the lower ionosphere. A hint might be in the results of monitoring of the upper atmosphere and ionosphere around EQ date by VLF transmitter signals, reported by Hayakawa *et al.* (1996b) and Molchanov *et al.* (2001). They found clear perturbations of the atmosphere-ionosphere boundary several days before large EQs at nighttime or during night-to-day transition (so-called terminator time). Molchanov *et al.* (2001) provide arguments that water and gas eruptions before EQs could origin «mosaic» and «twinkle» spots of atmospheric temperature and density variations leading to the generation of Atmospheric Gravity Waves (AGW) turbulence. There are reports on increased intensity of ionospheric irregularities (so called *E*-spread and *F*-spread events) several days before large EQs (see, *e.g.*, review by Meister *et al.*, 2002). As considered by Mareev *et al.* (2002) AGW produce turbulent variations of density and electric field in the lower ionosphere with horizontal scales order of AGW source size near the ground (~ 50-150 km). Alperovich *et al.* (2002) showed that AGW perturbations inside the ionosphere can modify plasma conductivity, especially Pedersen type (along electric field of the perturbation).

So, for explanation of ULF field suppression before EQ we considered two models: first is a decrease of penetration coefficient of Alfven waves from the magnetosphere due to turbulent increase of effective Pedersen conductivity in the ionosphere, and second is a change in wave number (k) distribution of source ionospheric turbulence. We assume that the ULF magnetic field at the ground $\boldsymbol{b}_g$ is sum of the fields from two generation regions: the magnetosphere, in which downgoing Alfven waves generate with amplitude b_m above ionosphere, and the ionosphere, in which turbulent electric fields $\Delta\boldsymbol{E}_i$ generate with random phase ($\langle\Delta\boldsymbol{E}_i\rangle = 0$).

The cartesian coordinates with the z-axes vertical upward is used. The main geomagnetic field $\boldsymbol{B}_0 = B_0\hat{z}$. The electromagnetic field is expanded over the harmonics $\sim \exp(-i\omega t + i\boldsymbol{k}_\perp \boldsymbol{r})$ where $\boldsymbol{k}_\perp = k_x\hat{\boldsymbol{x}} + k_y\hat{\boldsymbol{y}}$. Let the x-axes be directed along the $\boldsymbol{k}_\perp$, $k_x = \boldsymbol{k}_\perp \equiv k$, $k_y = 0$. The following relationship can be written for the electromagnetic field in the ionosphere and on the Earth surface:

$$b_{xg}^2(\omega) = \int T_A(\omega,k)\, b_m^2(\omega,k)\, dk + \\ + \int T_{ix}(\omega,k)\frac{\Delta E_{ix}^2(\omega,k)}{C_A^2}\, dk + \\ + \int T_{iy}(\omega,k)\frac{\Delta E_{iy}^2(\omega,k)}{C_A^2}\, dk. \qquad (4.1)$$

Here T_A is the penetration coefficient of the Alfven wave and T_{ix}, T_{iy} are the penetration coefficients of the normalized electric field of the ionospheric turbulence. Furthermore, we take into consideration that under the above assumptions and real conductivity of the atmosphere $b_{yg}/b_{xg} << 1$.

In the first model, we neglect the input of the ionospheric turbulence and produce full wave computations using IRI-90 ionospheric profiles at midnight under the quiet conditions. The procedure of computation is described in many papers beginning from (Hughes and Southwood, 1976). Assuming

$$b_m(\omega,k) = b_m(\omega)\,\delta(k - k_1) \qquad (4.2)$$

where δ is Dirac function and k_1 is determined by peculiarities of Alfven wave generation and propagation in the magnetosphere. Then in correspondence with results of Alperovich *et al.* (2002) we suppose that ionospheric turbulence induced by seismicity leads to increased effective Pedersen conductivity. Results are present-

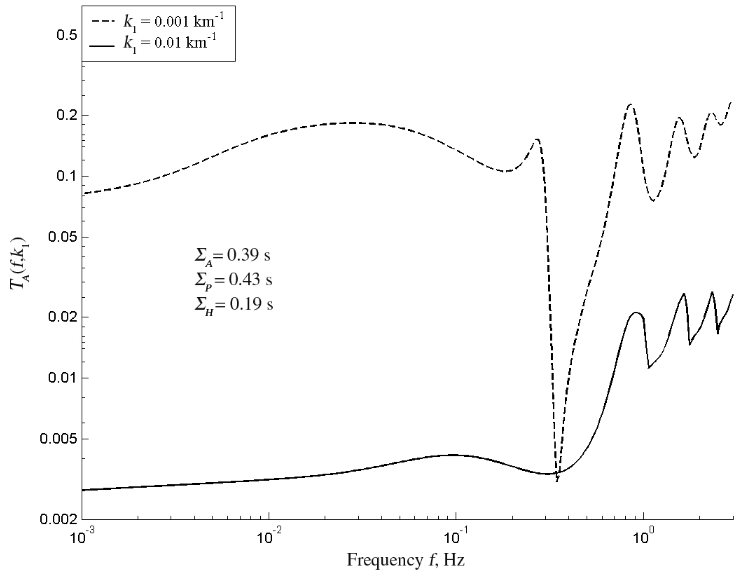

Fig. 5. Dependence of T_A (ω, k_1) obtained from the full wave solution using IRI-90 ionospheric profiles at midnight under the quiet conditions. Σ_P and Σ_H are integral Pedersen and Hall conductivities. Σ_A is the Alvfen wave conductivity. The oscillating regime at high frequencies is the manifestation of the ionospheric Alfven resonance.

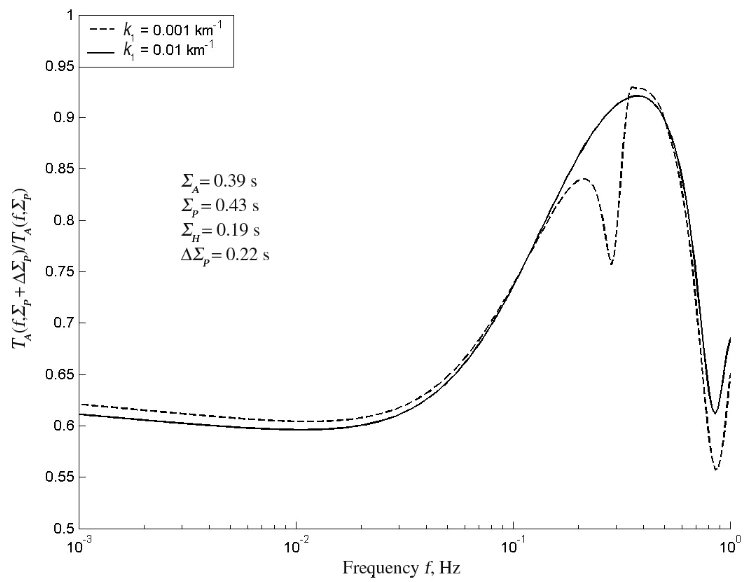

Fig. 6. The frequency dependence of the ratio of the penetration coefficients in the disturbed ionosphere to one in the undisturbed ionosphere calculated as shown in fig. 5.

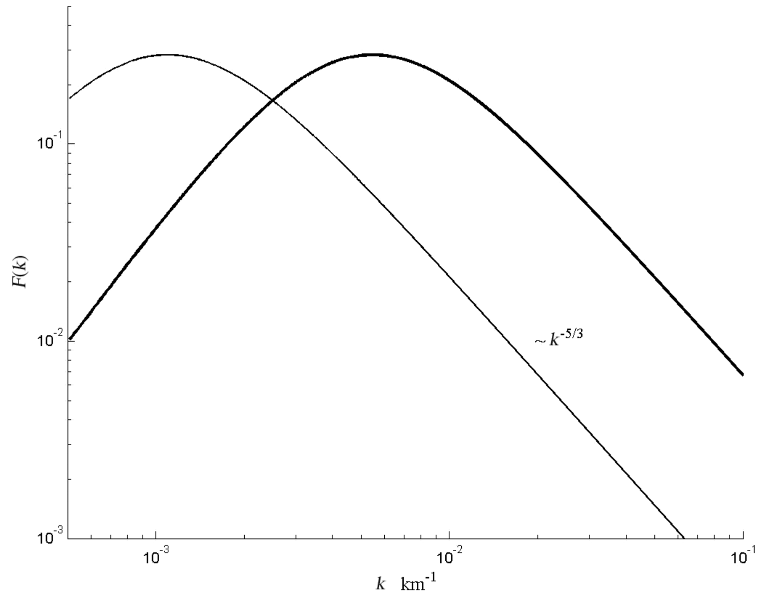

Fig. 7. Supposed distribution of the ionospheric turbulence in k-space. Thin line is for regular distribution (k_2^{-1} = 1000 km) thick line is for seismo-induced k-distribution (k_2^{-1} = 200 km).

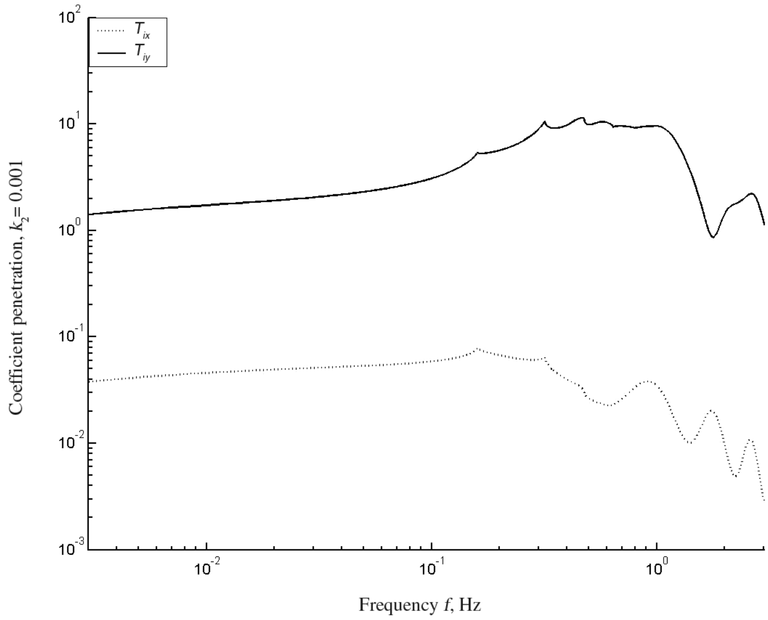

Fig. 8. Integrated penetration coefficients $T_{ix}(f, k_2)$ and $T_{iy}(f, k_2)$.

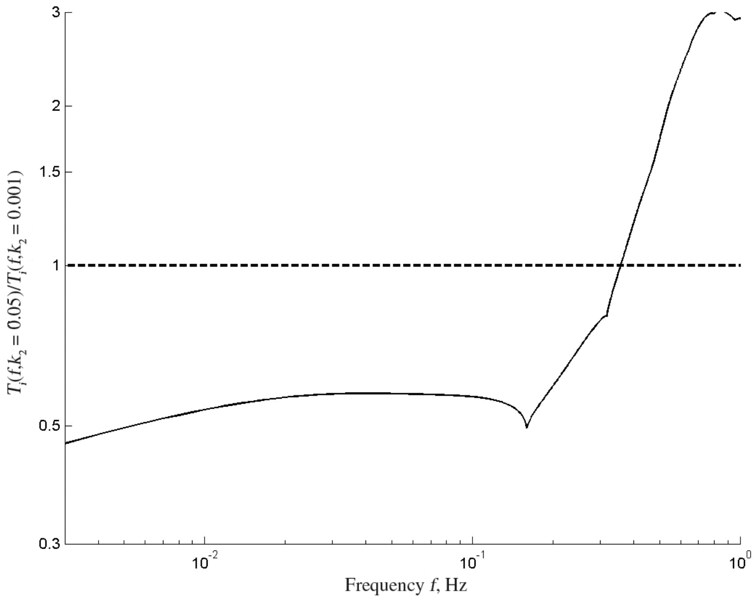

Fig. 9. Change in the common penetration coefficient $T_i(f, k_2)$ due to modification of the main scale of the turbulence k_2.

ed in figs. 5 and 6. Dependence of $T_A(\omega, k_1)$ is shown in fig. 5. The frequency dependence of the ratio of the penetration coefficients in the disturbed ionosphere to one in the undisturbed ionosphere is shown in fig. 6. It is clear from the figure that the magnetic field on the Earth surface at frequencies below ~ 10^{-1} Hz decreases with growth of Pedersen conductivity.

Contrarily, the second model considers only the ionospheric source and neglects the input from magnetospheric Alfven waves and the change in ionosphere conductivity. For simplicity we also assume that turbulence is isotropic, *i.e.* $\Delta E_{ix}^2 = \Delta E_{iy}^2 = \Delta E_i^2$. Hence

$$b_{xg}^2(\omega) = \int T_i(\omega, k)\, \Delta E_i^2(\omega, k) / C_A^2\, dk \quad (4.3)$$

where $T_i(\omega, k) = T_{ix}(\omega, k) + T_{iy}(\omega, k)$. Then we take into account that the turbulence develops as ionospheric eigenmode, *i.e.* $\omega = \omega(k)$, $\Delta E_i^2(\omega, k) = \Delta E_i^2(k)$ and assume the following k-distribution:

$$\Delta E_i^2(k) \sim (k/k_2)^2 \Big/ \left[1 + (k/k_2)^2\right]^{11/6} \quad (4.4)$$

which is reduced to classic Kolmogorov's distribution $k^{-5/3}$ for the $k >> k_2$, where k_2 has a meaning of inverse scale (L_2) of the turbulence external source. So, we assume $k_2 = 10^{-3}$ km^{-1} (L_2 ~ 1000 km) in the usual (regular) situation and $k_2 = 5 * 10^{-3}$ km^{-1} ($L_2 = 200$ km), if the main source is AGW induced by seismicity. Both types of the distribution are demonstrated in fig. 7. Integrated penetration coefficients $T_{ix}\cdot$ $\cdot(\omega, k_2)$ and $T_{iy}(\omega, k_2)$ are shown in fig. 8, while change in the common penetration coefficient $T_i(\omega, k_2)$ due to modification of main scale of the turbulence k_2 is presented in fig. 9.

5. Discussion and conclusions

We found the effect of suppression of ULF magnetic field variations about 2-6 days before rather strong seismic shocks in a case study. It is revealed for night-time and for horizontal component intensity (G) in the frequency range 0.01-0.1 Hz. We prove a reliability of the effect by computed correlation between G (or $1/G$) and specially calculated seismic indexes K_s. Based on the simple criteria, we conclude that reliability of seismo-associated ULF suppression effect is comparable with the well-known effect of connection between ULF variation and K_p index of global magnetic activity. Using K_s in our formulation for analysis of preseismic effect means an assumption that seismic shock is a result of some dynamic process (like instability) and intensity of preseismic perturbations is proportional to the energy of seismic shock itself. Some justification of this approach is found in the well-known correlation between magnitudes of foreshocks and main shock (see, *e.g.*, Scholz, 1990).

This effect can also be supposed in the previous observations at least in those where a preseismic increase in polarization ratio had been found (see Section 1). As is shown here, a decrease of G could lead to observed increase of ratio Z/G. Note furthermore that depression of G amplitude several days before the main shock was noted in one of the first papers by Fraser-Smith *et al.* (1990).

Like some other non-seismic precursors, our effect looks a sporadic one in a case study and can be recognized only by statistics. We believe that ULF-seismicity connection becomes more clear and regular after integration on space, *i.e.* using a network of stations, which we plan to do in future.

Our interpretation of the effect is not very speculative if seismo-induced AGW influence on the ionospheric turbulence is to be believed. The connection between AGW and the turbulent variation of plasma density and electric fields inside ionosphere is well-known. It is evidenced by both ionospheric sounders and radars from the ground and in direct satellite observations (see review in the latest paper by Molchanov *et al.*, 2002). Biagi *et al.* (2003) based on 24-years hydrogeochemical observations at Kamchatka area reported a clear correlation of hot-water eruptions and change in content with the occurrence of large EQs in the time intervals from several days before EQ up to 1-2 weeks after it. Mareev *et al.* (2002) showed that even small temperature and density variations near the ground surface effectively generate AGW energy flux into the ionosphere and the time of the energy transportation is between several hours and 1 day for AGW periods from 10 min to 1-2 h and horizontal wavelengths 30-100 km. Thus our assumptions on seismo-induced modification of the ionospheric turbulence are reasonable.

As a result of our first model computations (figs. 5 and 6), we discovered that ULF signal suppression is approximately proportional to turbulent increase in Pedersen conductivityina frequency range $F < 0.1\text{-}0.2$ Hz. The result is not surprising because in this frequency range $T_A \sim \left[\Sigma_H / (\Sigma_A + \Sigma_P)\right]^2$ (Hughes and Southwood, 1976), where Σ_H, Σ_P are integral conductivities of the ionosphere and Σ_A is wave Alfven conductivity. In the higher frequency range, the effect is masked by Ionospheric Alfven resonance structure, which is evident in fig. 5 and created due to the passage of Alfven wave through the upper ionosphere. Although the frequency behavoiur of the computed effect coincides with the observed one (see fig. 6), the existence of the EQ-related intensification of the ionospheric turbulence enough to enhance the ionospheric conductivity at several ten percents is not proved. Looking now at the result of our second model computation, it can be seen that frequency and value dependence is about the same, but we are free from assumption on increased turbulence intensity. However a new assumption on the redistribution of turbulence k-spectrum after the arrival of seismo-induced AGW seems realistic but demands additional research on the nature of ionospheric turbulence. We believe that one of the models or both are helpful to explain our observed effect.

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