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Precursory behavior of fractal characteristics of the ULF electromagnetic fields in seismic active zones before strong earthquakes

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Abstract

It is now recognized that the earthquake hazard systems evolve naturally to the self-organized critical (SOC) state, in which the system is very sensitive to any external perturbations, and when the large avalanches (strong earthquakes) are probable events. Since the principal feature of the SOC state is fractal organization of the output parameters both in space (scale-invariant structure) and in time (flicker noise or $1/f$ noise) we can use fractal methods to investigate the evolutionary processes in the earthquake hazard system at different stages of the catastrophic event preparation. Here we apply fractal methods for extraction of earthquake precursory signatures from ULF ($f = 0.001$–1 Hz) geomagnetic data obtained in seismic active regions before strong earthquake events. We focus our attention on the massive Guam earthquake of August 8, 1993 ($M = 8$, depth = 60 km), and on a swarm of Japanese earthquakes of June–August 2000 occurred near Izu Peninsula ($M > 6$, depth $\approx$ 10 km). We analyze scaling (fractal) characteristics of ULF geomagnetic fields registered in the area less than 100 km from the earthquake epicenters, study their dynamics as approaching the earthquake dates, and compare the results obtained in both regions. Three methods have been applied to calculate scaling parameters (spectral exponents and fractal dimensions of the ULF geomagnetic time series): FFT procedure, Burlaga–Klein approach and Higuchi method. It is found that fractal characteristics of the ULF emissions manifest specific precursory behavior with some common and individual peculiarities in both seismic active areas. As the common feature, we have revealed the same increase of the ULF time series fractal dimensions (and the corresponding decrease of spectral exponents) before the both events. As the distinctive peculiarity, we have found different character of such dynamics: gradual increase (decrease) in the case of the Guam earthquakes and relatively sharp alteration in the case of the Izu earthquake swarm. For the case of Japanese earthquakes, it turned out to be possible to reveal the most effective frequency range (around $f = 0.01$ Hz), in which precursory behavior of fractal characteristics is more pronounced and manifested earlier than in the other frequency ranges. We give a physical interpretation of the peculiarities revealed taking into account possible specifics of the SOC processes at different depths of the earthquake focuses.

Keywords: ULF emissions; Earthquake precursors; Fractal analysis

1. Introduction: our approach

The concept of self-organized criticality (SOC), which have been first introduced by Bak et al. (1987, 1988) for explanation of I/f noise (flicker noise) and scale-invariant (fractal) structure, can be considered as a general principle governing the behavior of a certain class of complex dissipative dynamic systems. Now the SOC theory is widely used for investigation of the dynamics of natural hazard systems, including the hazard system of earthquakes (see Bak and Tang, 1989; Sornette and Sornette, 1989; Bak, 1997; Jensen, 1998). This SOC concept is included as one of the principal points in our complex approach for study of the earthquake preparation processes. Such complex approach has been developing since 1999 (see Troyan et al., 1999; Hayakawa et al., 1999, 2000; Smirnova et al., 1999, 2001; Gotoh et al., 2003). We have suggested a phenomenological model of the large-scale evolutionary

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processes occurring between two violent earthquakes based on the SOC concept. We consider four principal stages in the earthquake preparation process: initial phase (random chaos just after the first violent earthquake, when tectonic energy is fully released, and therefore the strong earthquake is next to impossible), subcritical, critical and supercritical stages. Supercritical stage is the final stage of the SOC evolution, when there is a strong (high) probability of the next violent earthquake. Subcritical and critical phases are intermediate stages of the SOC evolution. Since the principal feature of the SOC dynamics is a power-law distribution (or fractal organization) of the system parameters both in space (scale-invariant structure) and in time ($1/f$ fluctuations), fractal methods can be used to investigate scaling characteristics of such a distribution at different stages of the strong earthquake preparation. In our approach, we mainly concentrate on ULF ($f = 0.001$–1 Hz) geomagnetic measurements in seismo-active regions, since electromagnetic waves of such frequency range are the most sensitive to variations of geo-electric parameters of the earth crust at typical depths of earthquakes (for every details, see Park et al., 1993; Smirnova, 1999; Hayakawa et al., 2000; Kopytenko et al., 2001). So we study precursory behavior of the ground-observed ULF emissions in seismic active zones before strong seismic events. And we try to answer the question: are there any common peculiarities in the behavior of fractal characteristics of ULF emissions in different seismic zones, and what are their specific peculiarities. In this relation, it is interesting to consider two independent seismic events and compare the corresponding behavior of the ULF emission parameters. The actual study is founded to a great extent on our preceding experimental results reported in Hayakawa et al. (1999, 2000); Smirnova (1999); Smirnova et al. (1999, 2001); Gotoh et al. (2003).

2. Experimental data

2.1. Seismic events

We focus our attention on the two massive earthquake events: the Guam earthquake of August 8, 1993 ($\varphi = 12.98°$N, $\lambda = 144.80°$E, depth = 60 km, $M = 8$), and a swarm of Japanese earthquakes of June–August 2000 ($\varphi = [33.5$–$34.6]°$N, $\lambda = [138.8$–$139.6]°$E, depth = 5–10 km $M = 5.5$–6.5) occurred near Izu Peninsula. Epicenters of both events were located at seas. Seismic activity of the first (Guam) event was characterized by a strong isolated earthquake, whereas the second (Izu) event was composed of many shocks (swarm of earthquakes) of different magnitudes up to $M = 6.5$. Spatial distribution of seismic activity in the corresponding area of Japan ($\varphi = [33$–$37]°$N, $\lambda = [136$–$142]°$E), which includes the Izu Peninsula area, is presented in Fig. 1a for the period June–August 2000. The earthquake swarm under question is shown in the bounded area of Fig. 1a. The locations of the ULF measuring stations Seikoshi, Mochikoshi and Kamo at Izu Peninsula are indicated by black dots with corresponding marks. In Fig. 1b, the temporal evolution of seismic activity in the investigated bounded area is presented. The data are taken from the Japanese Meteorological Agency (JMA) catalogue. Magnitude is represented by the Mj value: $Mj = \log A + 1.73 \log \Delta - 0.83$, where A is the maximum amplitude of ground moving at the observation area, and Δ is the distance between the epicenter and the observation place. It is seen from Fig. 1b, that rather quiet seismic period took place up to June 27, when the swarm of earthquakes with initial magnitudes $M = 4$–5 was started. The first massive earthquake with $M > 6$ occurred on July 1 ($Mj = 6.5$). The other strong earthquakes with $Mj > 6$ were registered on July 8, 15, 30 and August 18 (see Fig. 1b). All earthquakes in the swarm were shallow ones: their depths did not exceed 10 km. Here we focus the main attention at the first strong earthquake of July 1 to study its preparation stage.

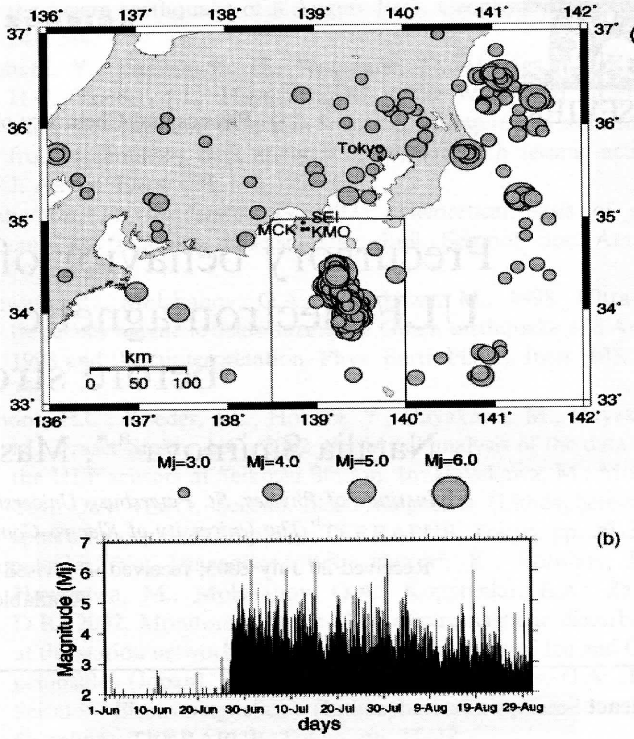

Fig. 1. Distribution of seismic activity in space (a) and time (b) for Japanese (Izu) earthquakes of June–August 2000. A swarm of the earthquakes under question is shown in the marked bounded area containing Izu Peninsula. Positions of the ULF magnetic stations Seikoshi (SEI), Mochikoshi (MCK) and Kamo (KMO) are shown by black dots. The seismicity data are taken from the JMA catalogue. Magnitude is represented by the Mj value ($Mj = \log A + 1.73 \log \Delta - 0.83$, where A is the maximum amplitude of ground moving at the observation area, and Δ is the distance between the epicentrum and the observation place).

2.2. ULF magnetic data

For both seismic events, digital records of the magnetic field components (H(NS), D(EW) and Z(vertical)) obtained at the nearby geophysical observatories were used for our analysis. In the case of the Guam earthquake, ULF emission data with digital step 1s were taken from the magnetic observatory at Guam Island distanced 65 km from the epicenter. Detailed description of the magnetometric measuring system installed at the Guam observatory is contained in Yumoto et al. (1996). In the case of the Izu earthquake events, the ULF magnetic data were taken at the Mochikoshi station situated on Izu Peninsula. Its distance from the earthquake epicenters was about 50–100 km (see Fig. 1a). At the Mochikoshi station (as well as at the Kamo and Seikoshi stations), a special ULF measurement technique—the MVC-2DS instrumentation, designed in SPbF IZMIRAN (Russia), has been installed for the period of the ULF magnetic measuring campaign of 2000 in Japan (see Kopytenko et al., 2003). MVC-2DS instrumentation was provided by a special system for protection of the magnetic-sensitive sensor from mechanical vibration. That allowed us to detect real electromagnetic signals and exclude the signals of mechanical origin. Magnetic data of the Mochikoshi station were digitized at 2-s sampling rate. In Fig. 2, examples of the daily records of geomagnetic field variations at the Guam (a) and Mochikoshi (b) observation points are presented. The records correspond to seismic quiet periods. One can see near a similar behavior of geomagnetic variations at both observatories, despite of the different equipment used. In order to exclude the local time effects, we analyzed separately each 1-h local time interval. On the inserts in Fig. 2, the original 1-h ULF records (H-component, local noon (12–13 LT) interval) are presented. Such 1-h ULF geomagnetic records were used for a fractal analysis.

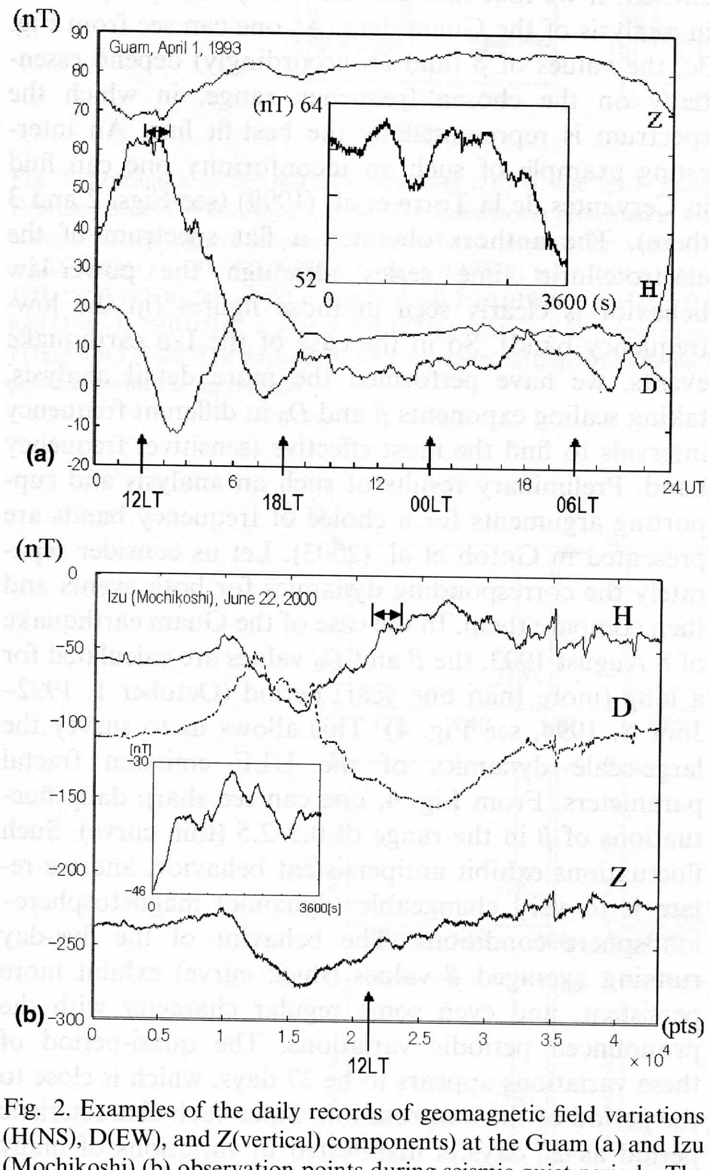

Fig. 2. Examples of the daily records of geomagnetic field variations (H(NS), D(EW), and Z(vertical) components) at the Guam (a) and Izu (Mochikoshi) (b) observation points during seismic quiet periods. The original ULF records for the local noon (12–13 LT) intervals are shown in the inserts. Points (pts) of X-axis in (b) represent two-second time intervals.

3. Analysis procedure

ULF geomagnetic data are usually represented by irregular time series. To get a quantitative estimation of the time series irregularity, we can use methods of fractal analysis (see Feder, 1989; Turcotte, 1997). The simplest of those methods is power spectrum analysis. In the case when the power spectral density follows a power law, the spectral exponent can be considered as an index of time series irregularity. We have used the FFT technique to calculate the power spectral density of the ULF signals $S(f)$ in each 1-h interval along the preparation phase of the earthquake events described. If $S(f)$ followed a power law behavior $S(f) \propto f^{-\beta}$, we calculated the spectral exponent β from the slope of the best-fit straight line in the log–log plot of the spectrum in the chosen frequency range. An example of such a processing is given in Fig. 3. The original ULF record of 1-h duration (Fig. 3a) is recalculated to get the zero mean record (Fig. 3b). The linear trend is initially removed from the original signal, and the Hanning window is used for correction of signal before applying the FFT procedure. Then we have plotted power spectrum in log–log form (Fig. 3c) and calculated the spectrum slope (spectral exponent) β. Then we have analyzed the evolution of β at different time distance from the earthquake date. Since the power-law behavior of the spectrum is a feature of self-affine (fractal) time series, we can estimate fractal dimension D_0 of the ULF time series using the well-known Berry equation: $D_0 = (5 - \beta)/2$ (Berry, 1979). But some problems arise when applying the FFT procedure. So in Fig. 3c, the noisy fluctuations superimposed on the power-law spectrum are clearly seen, which does not allow us to calculate

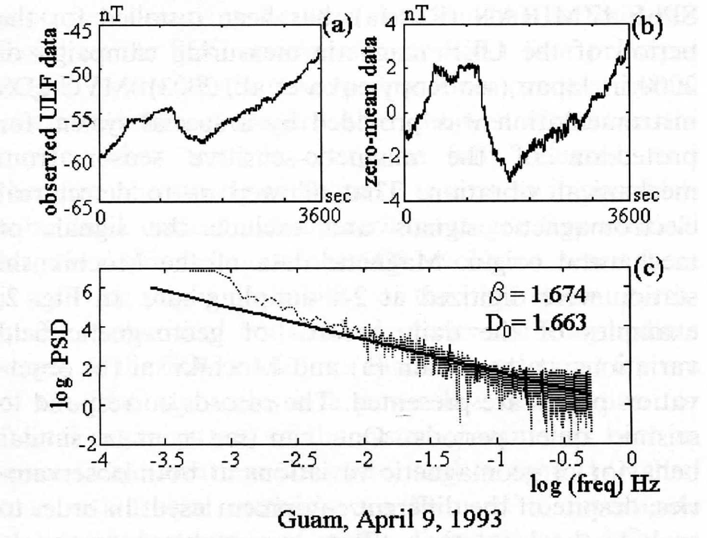

Fig. 3. An example of the ULF signal processing by FFT method. a—an original signal (Guam, 9 April 1993, H-component, night sector); b—the zero mean signal without trend; c—the power spectrum. The best fit line represents the spectrum slope β (spectral exponent in the relation $S(f) \propto f^{-\beta}$). Fractal dimension D_0 is calculated from β using Berry relation: $D_0 = (5 - \beta)/2$. Noisy fluctuations, superimposed on the power law spectrum, are clearly seen.

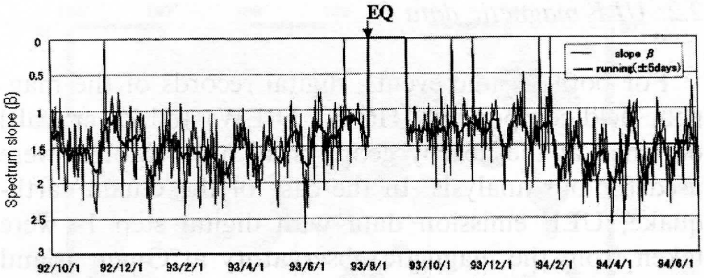

Fig. 4. Dynamics of the spectral exponent β of ULF emissions registered at Guam Island in the noon sector (12–13 LT) for the period October 1992–June 994. The thin line indicates the daily values of β, the thick line represents the five day running average values. The date of the Guam earthquake (August 8, 1993) is marked by the arrow with symbol EQ. One can see the break in the magnetic record, which have lasted till the middle of September.

spectral exponent β (and the corresponding fractal dimension D_0) within the necessary accuracy. To do that more precisely, one can use Burlaga–Klein approach (Burlaga and Klein, 1986) or Higuchi method (Higuchi, 1988, 1990). In such approaches, the lengths of the curve $L(\tau)$ representing time series are calculated using different time intervals τ. For statistically self-affine (fractal) curves, the length is expressed as $L(\tau) \propto \tau^{-D_0}$. From this relation, one can estimate fractal dimension D_0, and then the power-law index β using the Berry's expression. The detailed description of those methods and comparison of their efficiencies for analysis of the ULF emission time series of different types (persistent, random and antipersistent noises) are contained in Smirnova et al. (2001), and Gotoh et al. (2003). In this study, we apply appropriate fractal methods for calculation of the spectral exponents β and fractal dimensions D_0 of the ULF emission time series, using FFT procedure, Burlaga–Klein approach or Higuchi method depending on specific experimental conditions.

4. Results and discussion

Dynamics of fractal characteristics of the ULF emissions registered in the noon sectors (12–13 LT) is presented in Fig. 4 for the Guam earthquake, and in Figs. 5 and 6 for the Izu seismic events. The results are presented in different ways: scaling is taken only in one frequency range ($f = 0.003$–0.3 Hz) for Guam (see Fig. 3c), whereas for Izu earthquakes, the available ULF frequency range is divided into nine frequency ranges of different bandwidths, and scaling is taken in each of these frequency ranges (see corresponding figures in the captions to Figs. 5 and 6). Such specification seems to be efficient if we take into account our primary experience in analysis of the Guam data. As one can see from Fig. 3c, the values of β (and D_0 accordingly) depend essentially on the chosen frequency range, in which the spectrum is represented by the best-fit line. An interesting example of such an inconformity one can find in Cervantes de la Torre et al. (1999) (see Figs. 2 and 3 there). The authors obtained a flat spectrum of the electrotelluric time series although the power-law behavior is clearly seen in those figures (in the low-frequency band). So in the case of the Izu earthquake events, we have performed the more detail analysis, taking scaling exponents β and D_0 in different frequency intervals to find the most effective (sensitive) frequency band. Preliminary results of such an analysis and supporting arguments for a choice of frequency bands are presented in Gotoh et al. (2003). Let us consider separately the corresponding dynamics for both events and then compare them. In the case of the Guam earthquake of 8 August 1993, the β and D_0 values are calculated for a long (more than one year) period (October 1, 1992–June 8, 1994, see Fig. 4). This allows us to survey the large-scale dynamics of the ULF emission fractal parameters. From Fig. 4, one can see sharp daily fluctuations of β in the range of 0.5–2.5 (thin curve). Such fluctuations exhibit antipersistent behavior, and we relate it to very changeable (dynamic) magnetosphere–ionosphere conditions. The behavior of the five-day running averaged β values (thick curve) exhibit more persistent, and even some regular character with the pronounced periodic variations. The quasi-period of these variations appears to be 27 days, which is close to the period of the Sun rotation. Since such characteristic period as 27 days is manifested in variations of many solar wind parameters and magnetosphere–ionosphere disturbances, we can also attribute such a quasi-periodic behavior of β to variation of the near-Earth space

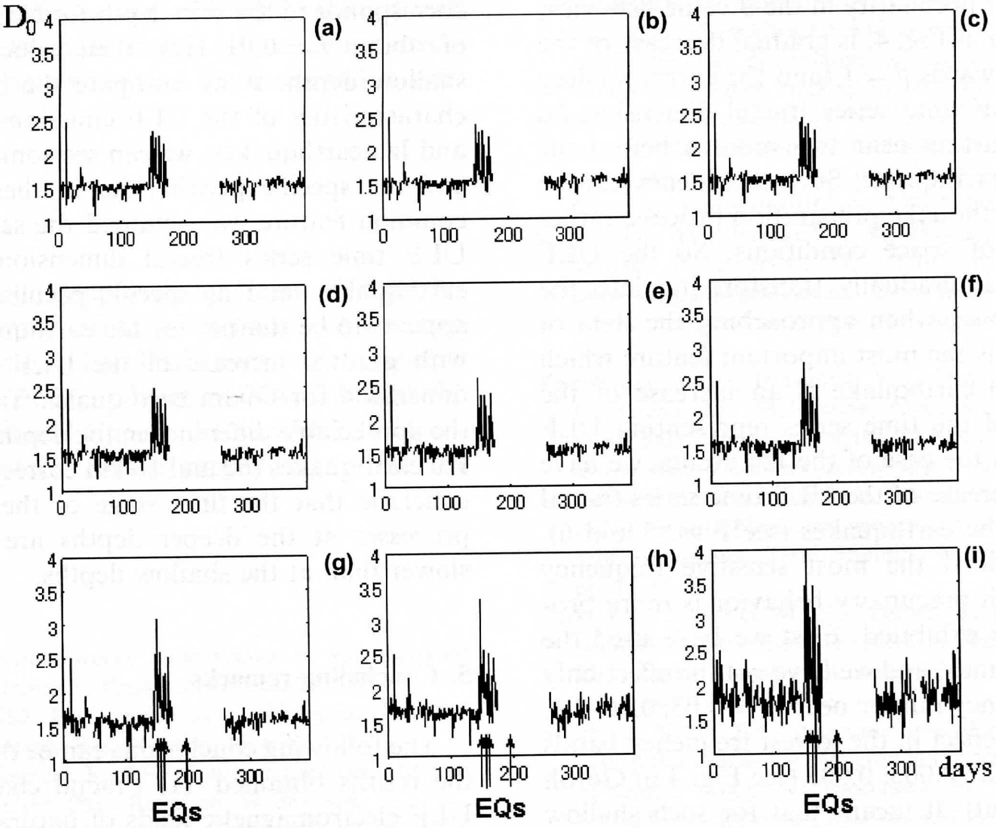

Fig. 5. Dynamics of the fractal dimensions (D_0) of the ULF geomagnetic time series registered at Mochikoshi station, Izu Peninsula, Japan, February 3, 2000–February 28, 2001. The dynamics is presented in nine frequency bands. The frequency bandwidth decreases from (a) to (i) in such a way that the highest frequency in each band remains the same ($f = 0.17778$ Hz): (a) $-3.00 < \log(f) < -0.75(0.00100 < f(\text{Hz}) < 0.17778)$ (b) $-2.75 < \log(f) < -0.75(0.00178 < f(\text{Hz}) < 0.17778)$ (c) $-2.50 < \log(f) < -0.75(0.00316 < f(\text{Hz}) < 0.17778)$ (d) $-2.25 < \log(f) < -0.75(0.00562 < f(\text{Hz}) < 0.17778)$ (e) $-2.00 < \log(f) < -0.75(0.01000 < f(\text{Hz}) < 0.17778)$ (f) $-1.75 < \log(f) < -0.75(0.01778 < f(\text{Hz}) < 0.17778)$ (g) $-1.50 < \log(f) < -0.75(0.03162 < f(\text{Hz}) < 0.17778)$ (h) $-1.25 < \log(f) < -0.75(0.05623 < f(\text{Hz}) < 0.17778)$ (i) $-1.00 < \log(f) < -0.75(0.10000 < f(\text{Hz}) < 0.17778)$. The days of the four strongest earthquakes are marked by arrows with symbol EQs (A gap in the data results from some technical problems with the amplifiers).

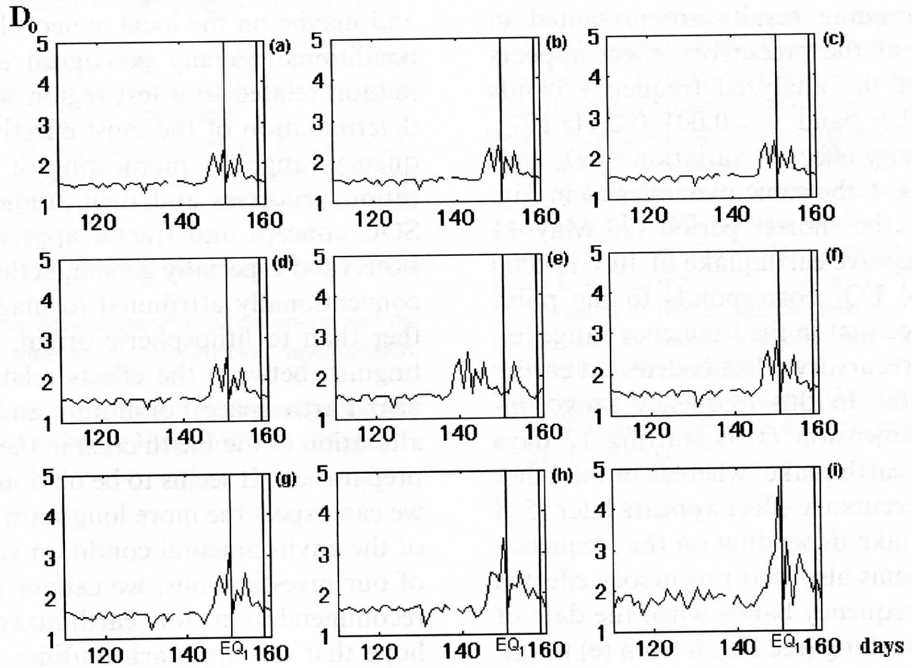

Fig. 6. The same dynamics as in Fig. 5 but presented for the shorter period (23 May–11 July, 2000) to get the better resolution of D_0 variations before the first massive earthquake of July 1, 2000 (marked by the symbol EQ_1 at the point number 150). One can see that in the frequency range (e): $f = 0.01$–0.2 Hz, the precursory effect is earliest exhibited (12 days before the earthquake, when it does five to eight days in other frequency ranges).

conditions. The next peculiarity in the β value behavior, which is clearly seen in Fig. 4, is gradual decrease of the spectrum slope β towards $\beta = 1$ (and the corresponding increase of the ULF time series fractal dimension D_0 towards $D_0 = 2$) starting near two months before the date of the Guam earthquake. Such a tendency can be attributed to the earthquake preparation process, rather than to variation of space conditions. So the ULF geomagnetic noise is gradually transforming into the more flicker-like noise, when approaching the date of the earthquake. Thus the most important feature which could be related to earthquake is an increase of the fractal dimension of the time series representing ULF emission records. In the case of the Izu events, we have also obtained an increase of the ULF time series fractal dimensions before the earthquakes (see Figs. 5 and 6). And we have revealed the most sensitive frequency range, in which such precursory behavior is more pronounced and earlier exhibited. First we have used the narrow frequency bands, and we have got the effect only in the highest frequency ranges: near $f_0 = 0.03$; 0.06; 0.1; 0.2 Hz without any effect in the lowest frequency bands near $f_0 = 0.001$; 0.002; 0.003; 0.005 (see Fig. 4 in Gotoh et al., 2003 for detail). It means that for such shallow earthquakes as Izu seismic events, ULF electromagnetic measurements at higher frequencies (may be up to $f = 10$ Hz) could be important. Unfortunately in this study we are limited by $f_{max} = 0.2$ Hz as the highest frequency corresponding to the sampling rate of 0.5 Hz. Since the high frequency band of the ULF emission spectrum appears to be very important for extraction of the earthquake precursory signatures, we have fixed the highest frequency range and extended gradually the analyzed frequency band in direction to the low frequencies. The corresponding results are presented in Fig. 5. One can see that the precursory effect appears everywhere, in each of the analyzed frequency bands including the entire ULF band $f = 0.001$–0.2 Hz (Fig. 5a). To see the precursory effect in variation of D_0 with better resolution, in Fig. 6 the same dynamics as in Fig. 5 is presented, but for the shorter period (23 May–11 July, 2000). The first massive earthquake of July 1, 2000 marked by the symbol EQ_1 corresponds to the point number 150. One can see that in the frequency range (e): $f = 0.01$–0.2 Hz, the precursory effect is detected earlier than in the other bands. In this frequency range, increase of the fractal dimension D_0 is starting 12 days before the first massive earthquake, whereas in the other frequency ranges the precursory effect appears later (5–8 days before the earthquake depending on the frequency range considered). It seems also that precursory effect is drifting to the higher-frequency bands when the date of the earthquake is approaching (see Fig. 6 from (e) to (g), (h), (i)). Such behavior could be interpreted as the earthquake preparation process, which started 12 days before the first massive event at the definite depth (that corresponds to the skin depth for electromagnetic waves of about $f = 0.01$ Hz), then relocated to the more shallow depth. If we compare the behavior of fractal characteristics of the ULF emissions before the Guam and Izu earthquakes, we can see some common features and the specific peculiarities in their dynamics. As a common feature, we obtained the same increase of the ULF time series fractal dimension before the both earthquakes, and as specific peculiarity—this increase appears to be sharper for Izu earthquake in comparison with gradual increase of the ULF time series fractal dimension for Guam earthquake. Taking into account the appreciable difference in the depths of the Guam and Izu earthquakes (60 and 10 km correspondingly), we can conclude that the final stage of the SOC preparation processes at the deeper depths are developing much slower than at the shallow depths.

5. Concluding remarks

The following conclusions can be done on the basis of the results obtained. (1) Fractal characteristics of the ULF electromagnetic fields of natural origin registered in seismic active regions tend to exhibit precursory behavior before the strong earthquake events. The tendency manifested itself in increasing of fractal dimensions and decreasing of spectral exponents of the ULF time series. (2) Such precursory behavior exhibits specific peculiarities in every tectonically active zone. So for each zone, it is necessary to determine its own frequency range, in which precursory behavior is more pronounced. That depends on the characteristic depth of the fault zones, geological structure of the testing region and maybe on the local meteorological and geophysical conditions. So any geological and geophysical information related to a test region would be important for determination of the most effective electromagnetic frequency range for monitoring of the earthquake preparation processes and their studies on the basis of the SOC concept and fractal approach. Since ULF emissions (and especially geomagnetic pulsations) have been conventionally attributed to magnetospheric origin rather than to lithospheric origin, it is important to distinguish between the effects related to variation of the near-Earth space conditions and those related to the alteration of the Earth crust in the process of earthquake preparation. It seems to be obvious that in the latter case we can expect the more long-term effects than in the case of the environmental condition variations. On the basis of our investigations, we cannot give now any concrete recommendation for earthquake prediction, but we hope that our approach outlines the promising way for study of the earthquake preparation dynamics. The recent studies reported by Uritsky et al. (2004) and Kiyashchenko et al. (2003, 2004) in this issue give also appreciable support for using the SOC concept and fractal (and especially multifractal) approach for investigations of the earthquake critical dynamics and seismic hazard assessment.

Acknowledgements

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References

Bak, P., 1997. How nature works : the science of self-organized criticality. Oxford University Press, Copernicus, NY. 210 pp.

Bak, P., Tang, C., 1989. Earthquakes as a self-organized critical phenomenon. J. Geophys. Res. 94 (B11), 15, 635–15, 637.

Bak, P., Tang, C., Wiesenfeld, K., 1987. Self-organized criticality: an explanation of $1/f$ noise. Phys. Rev. Lett. 59, 381–384.

Bak, P., Tang, C., Wiesenfeld, K., 1988. Self-organized criticality. Phys. Rev. 38 (1), 364–374.

Berry, M.V., 1979. Diffractals. J. Phys. A Math. Gentile 12, 207–220.

Burlaga, L.F., Klein, L.W., 1986. Fractal structure of the interplanetary magnetic field. J. Geophys. Res. 91 (A1), 347–350.

Cervantes de la Torre, F., Ramirez-Rojas, A., Pavia-Miller, C.G., Angulo-Brown, F., Yepez, E., Peralta, J.A.., 1999. A comparison between spectral and fractal methods in electrotelluric time series. Revista Mexicana de Fisica 45 (3), 298–302.

Feder, J., 1989. Fractals. Plenum, New York.

Gotoh, K., Hayakawa, M., Smirnova, N., 2003. Fractal analysis of the ULF geomagnetic data obtained at Izu Peninsula, Japan in relation to the nearby earthquake swarm of June–August 2000. NHESS 3 (3/4), 229–236.

Hayakawa, M., Ito, T., Smirnova, T., 1999. Fractal analysis of ULF geomagnetic data associated with the Guam earthquake on August 8, 1993. Geophys. Res. Lett. 26 (18), 2797–2800.

Hayakawa, M., Kopytenko, Yu.A., Smirnova, N.A., Troyan, V.N., Peterson, Th., 2000. Monitoring ULF magnetic disturbances and schemes for recognizing earthquake precursors. Phys. Chem. Earth (A) 25 (3), 263–269.

Higuchi, T., 1988. Approach to an irregular time series on the basis of fractal theory. Physica D 31, 277–283.

Higuchi, T., 1990. Relationship between the fractal dimension and the power-low index for a time series: a numerical investigation. Physica D 46, 254–264.

Jensen, H.J. 1998. Self-organized criticality. In: Cambridge Lecture Notes in Physics, vol. 10. Cambridge University Press, pp. 1–153.

Kiyashchenko, D., Smirnova, N., Troyan, V., Vallianatos, F., 2003. Dynamics of multifractal and correlation characteristics of the spatio-temporal distribution of regional seismicity before the strong earthquakes. NHESS 3 (3/4), 285–298.

Kiyashchenko, D., Smirnova, N., Troyan, V., Saenger, V., Vallianatos, F., 2004. Precursory evolution of seismically active zones before strong earthquakes: fractal and multifractal aspects, Phys. Chem. Earth doi:10.1016/j.pce.2003.12.004.

Kopytenko, Yu., Ismaguilov, V., Hayakawa, M., Smirnova, N., Troyan, V., Peterson, Th., 2001. Investigation of the ULF electromagnetic phenomena related to earthquakes: contemporary achievements and the perspectives. Annali di Geofisica 44 (2), 325–334.

Kopytenko, Yu.A., Ismagilov, V.S., Hattori, K., Voronov, P.M., Hayakawa, M., Molchanov, O.A., Kopytenko, E.A., Zaitsev, D.B., 2003. Monitoring of the ULF electromagnetic disturbances at the station network before EQ in seismic zones of Izu and Chiba peninsulas (Japan). In: Hayakawa, M., Molchanov, O.A. (Eds.), Seismo-Electromagnetics: Lithosphere–Atmosphere–Ionosphere Coupling. Terra Scientific Publishing Company, Tokyo, pp. 11–18.

Park, S.K., Johnston, M.J.S., Madden, Th.R., Morgan, F.D., Morrison, H.F., 1993. Electromagnetic precursors to earthquakes in the ULF band: a review of observations and mechanisms. Revs. Geophys. 31 (2), 117–132.

Smirnova, N.A., 1999. The peculiarities of ground-observed geomagnetic pulsations as the background for detection of ULF emissions of seismic origin. In: Hayakawa, M. (Ed.), Atmospheric and Ionospheric electromagnetic phenomena associated with Earthquakes. Terra Scientific Publishing Company, Tokyo, pp. 215–232.

Smirnova, N.A., Hayakawa, M., Ito, T., 1999. Structure of the ULF geomagnetic noise in a seismoactive zone and its relation to the earthquake. In: Surya, C. (Ed.), Noise in Physical Systems and $1/f$ Fluctuations (ICNF'99, Hong Kong, August 23–26). World Scientific, Singapore, pp. 471–474.

Smirnova, N., Hayakawa, M., Gotoh, K., Volobuev, D., 2001. Scaling characteristics of the ULF geomagnetic fields at the Guam seismoactive area and their dynamics in relation to the earthquake. NHESS (1), 119–126.

Sornette, A., Sornette, D., 1989. Self-organized criticality and earthquakes. Europhys. Lett. 9 (3), 197–202.

Troyan, V.N., Smirnova, N.A., Kopytenko, Yu.A., Peterson, Th., Hayakawa, M., 1999. Development of a complex approach for searching and investigation of electromagnetic precursors of earthquakes: organization of experiments and analysis procedures. In: Hayakawa, M. (Ed.), Atmospheric and Ionospheric electromagnetic phenomena associated with Earthquakes. Terra Scientific Publishing Company, Tokyo, pp. 147–171.

Turcotte, D.L., 1997. Fractals and Chaos in Geology and Geophysics, Second edition. Cambridge University Press. 397.

Uritsky, V., Smirnova, N., Troyan, V., Vallianatos, F., 2004. Critical dynamics of fractal fault systems and its role in the generation of pre-seismic electromagnetic emissions. Phys. Chem. Earth doi:10.1016/j.pce.2003.11.015.

Yumoto, K., 210° MM magnetic Observation Group, 1996. The STEP 210° magnetic meridian network project, J. Geomag. Geoelectr., 48, 1297–1309.