Tectonophysics 470 (2009) 205–213

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Short-term earthquake prediction: Current status of seismo-electromagnetics

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ARTICLE INFO

Article history:
Received 9 March 2008
Received in revised form 4 June 2008
Accepted 27 July 2008
Available online 31 July 2008

Keywords:
Earthquake prediction
Short-term prediction
Seismo-electromagnetism
LAI coupling

ABSTRACT

Loss of human lives as a result of earthquakes is caused overwhelmingly by the collapse of buildings within less than a few minutes of main shocks. The most urgent countermeasure consists of two key elements. One is strengthening of weak structures and the other is short-term earthquake prediction. Short-term prediction needs precursors. Although some promising precursors are reported, the prevailing views in Japan and elsewhere are overly pessimistic. The pessimism largely roots in the fact that short-term precursors are generally non-seismic and tools developed for seismology are not designed to detect them. Nonetheless, nationally funded large-scale earthquake prediction programs always emphasize the need to reinforce seismometer networks. They do not take into account the views of those in the science community who point to the importance of non-seismic precursors. While there are well-founded causes to be skeptical, the situation needs to be improved. One reason for skepticism is that the observations of precursors have not yet been perfect enough and another is that some important fundamental aspects of non-seismic precursors are still unresolved. We review some of these problems.

1. Introduction

Earthquakes (EQ hereafter) cause disasters of all kinds. For the 1995 Kobe EQ, monetary loss was estimated at 10 billion US dollars. For the anticipated Tonankai–Nankai event, the loss may reach at least 80 billion US dollars, more than 15% of the GDP according to the Central Disaster Management Council of Japan. However, more fatal and utterly non-recoverable is the loss of lives, exceeding 6300 during the *M*7.2 1995 Kobe EQ in Japan, 15,000 during the *M*7.4 1999 Izmit EQ in Turkey, and over 30,000 during the *M*6.7 2003 Bam EQ in Iran.

Experiences all over the world show that, with the notable exception of the Giant *M*9.3 2004 Sumatra EQ which generated huge tsunami to cause some 150,000 casualties, the majority of victims are killed by the collapse of buildings right at the arrival of the main shock waves. For example, in the case of the *M*7.2 1995 Kobe EQ (officially named Hyogoken Nanbu EQ), almost 90% of the victims were killed in their own houses before any rescue operation could have been started (Nishimura et al., 1997). Therefore, structural issues are of the highest priority to prevent the loss of human life. In addition, however, we emphasize here that EQ prediction, in particular the short-term prediction, is equally valuable.

Unfortunately, short-term prediction that led to practical actions has seldom been achieved and pessimistic views are widespread in seismological community. First we review the history of short-term EQ prediction research, analyzing how the present pessimism was brought about. Second, we review the present state of the research from both optimistic and discreet points of view.

2. Short-term earthquake prediction: impossibility myth

EQ prediction is customarily classified into three categories: long-term, intermediate-term, and short-term predictions. They differ in their methods, accuracy, and purpose. Both long-term and intermediate-term predictions are in essence estimates of the statistical probability of earthquakes to occur. Long-term prediction deals with the probability of EQ occurrence on time-scales of 10 to 100 years, based mainly on geologic studies of faults and historic records of seismicity. Intermediate-term prediction (1 to 10 years) uses more of recent instrumental data of seismology and geodesy. Notwithstanding the negative views like Geller et al. (1997), significant progress has been made in the research of precursory pattern changes of seismicity (e. g., Wyss and Martirosyan, 1998; Huang et al., 2001; Huang, 2006) and the intermediate-term prediction of large EQs world-wide is already in the statistically proven stage (e g., Kossobokov et al., 1999). More recently, even the efforts to shorten the lead time to the "short-term" range are being made (e. g., Keilis-Borok et al., 2004).

Seismicity as a critical phenomenon has been actively discussed by many authors (e.g., Bak and Tang, 1989; Turcotte, 1997; Sornette, 2000; Rundle et al., 2003; Keilis-Borok and Soloviev, 2003). In relation to this aspect of EQs, we may draw attention to the recent work by Varostos and his group (Varotsos, 2005 and references therein), based on the new time domain called Natural Time. This work may constitute a novel contribution to short-term prediction. It has been shown that SES (Seismic Electric Signals, see later) and the seismicity just before an

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0040-1951/$ – see front matter
doi:10.1016/j.tecto.2008.07.019

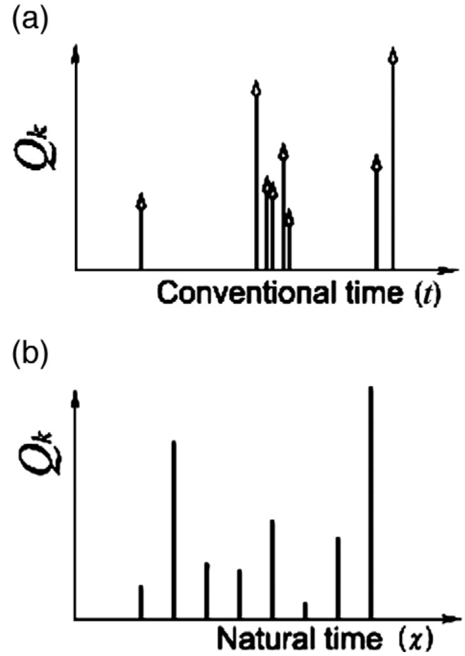

Fig. 1. Time series of events, (a) in conventional time t, and (b) in the natural time χ.

impending EQ reveal infinitely long range temporal correlations, if their time series are analyzed in the framework of Natural Time χ. The correlations show a self-similar structure, indicating that the system has entered a dynamical critical stage. In a time series comprised of N events, the natural time $\chi_k = k/N$ serves as the index for the occurrence of the kth event, which implies that the time proceeds when an event takes place, according to the "self-clock" of the system. In natural time analysis, the evolution of the pair of two quantities (χ_k,Q_k) is investigated where Q_k denotes the energy of the kth event. The time series of events as shown in Fig. 1 (a) is expressed in natural time as shown in Fig. 1 (b). It was indeed shown for a number of events that the seismicity entered the critical stage a few days before the catastrophe of the following EQs; 1995 *M*6.6 Kozani-Grevena EQ, 1995 *M*6.5 Eratini-Egio EQ, 1997 *M*6.4 Strofades EQ, 2001 *M*6.6 Aegean Sea EQ, and other major EQs (Varotsos, 2005; Varotsos et al., 2008 and reference therein). This suggests a striking possibility to narrow the time window for the prediction of EQs to a few days.

Although much more difficult than the long- and intermediate-term predictions, the short-term prediction is evidently most effective for the purpose of directly saving human life. Short-term prediction, say hours to weeks, needs short-term, desirably deterministic, precursors. The so-called Earthquake Early Warning system, now at implementation stage in Japan and elsewhere, is based on real-time seismological technology to determine the characteristics of the EQ just occurred. Under favorable circumstances, it can provide a few tens of seconds of warning (Kanamori et al., 1997; Horiuchi et al., 2005). However, in spite of its name, this is not an EQ prediction method.

Systematic EQ prediction research started in the 1960s in several countries including Japan, USA, Soviet Union, and China (e. g., Rikitake, 1976). In the 1970s, optimism prevailed due to the developments of new concepts such as those embodied in the dilatancy models (e. g., Scholz et al., 1973) and due to the successful prediction of the 1975 *M*7.3 Haisheng EQ in China (Chen et al., 1992; Hui, 1996). However, no further broadly recognized successful predictions followed, causing the community to become pessimistic. The failure of predicting EQs in Parkfield, California (e. g., Andrews, 1992) heavily discouraged American researchers. This is understandable but today's widespread pessimism is largely ill-founded as will be described below.

In 1978, the Japanese Prediction Program designated eight "areas of special observation" and two "areas of intensified observation" (inset of Fig. 2) (Hamada, 1992). This can be taken as a set of nationwide intermediate-term predictions. Comparison of the two maps in Fig. 2 indicates that these intermediate-term predictions have been more or less fulfilled because many of the large EQs after 1978 occurred in or near the "areas of special observation". However, none of them, including the Kobe EQ, was predicted in short-term. The reason for this lack of short-term prediction is simple: monitoring for potential short-term indicators has not actually been conducted in any of the "areas of special observation". Monitoring (mainly by geodetic means) has been tried only in the two "areas of intensified observation", in which the

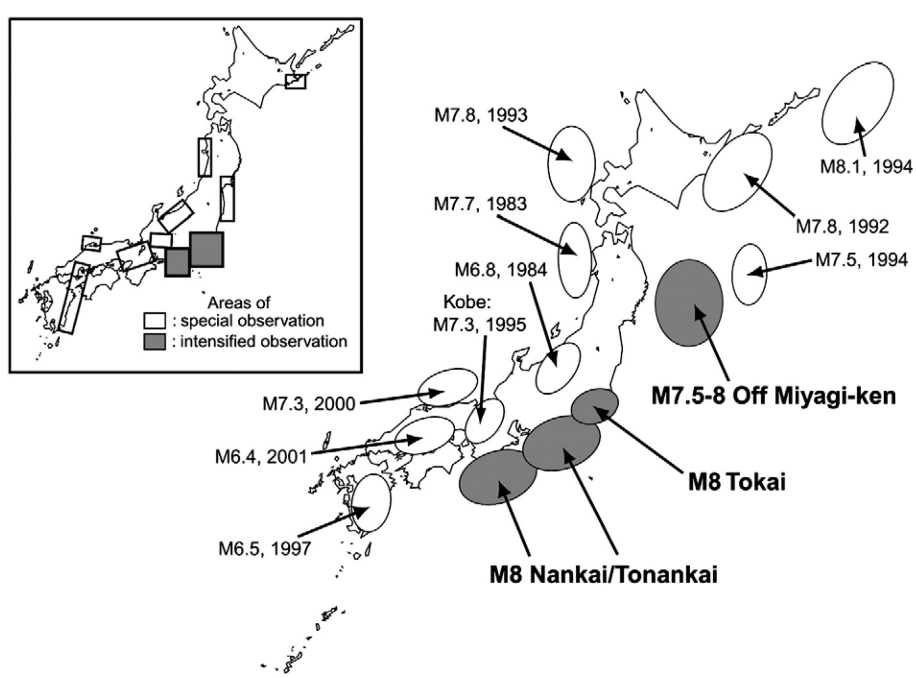

Fig. 2. Inset shows the eight "areas for special observation" (empty rectangles) and two "areas for intensified observation" (filled rectangles), selected by the Japanese EQ Prediction Program in 1978. Main figure shows the roughly estimated source regions of major EQs which occurred afterwards (smaller letters) and expected earthquakes (larger letters) (after Uyeda and Meguro, 2004).

anticipated Tokai EQ has not yet occurred. Indeed, a great EQ exceeding magnitude 8, named Tokai (meaning East Sea in Japanese) EQ, was expected to occur "at any moment" (Ishibashi, 1981). After more than 20 years, this intermediate-term prediction should be considered failure. At the same time, as to short-term prediction, there has been neither success nor failure because neither prediction nor large EQ has taken place.

After the Kobe disaster, vigorous reviews of the national EQ prediction program were made at various levels. Although the program had never claimed that an EQ in that area with that magnitude could be short-term predictable, it was natural for funding agencies and the public to question the effectiveness of the entire national EQ prediction program that had enjoyed many decades of considerable funding. The conclusion of these deliberations was a curious one, namely, "because the search for short-term precursor was too difficult, short-term prediction research should be put aside and the national effort should instead focus on fundamental research" (Hirata, 2004). This led to more funding than ever before to seismological research programs, now freed from the burden of aiming at short-term prediction. Fundamental research is always important, but the question might be raised if it merely meant "more seismological networks". Instead, what was really needed at that stage in Japan was fundamental research into short-term prediction. However, as a result of the post-Kobe deliberations, a situation has now arisen where there is no funding for short-term prediction research. The general public is not informed about these circumstances because huge amount of funds are spent in the name of New EQ Prediction Research Program.

Those who assert that short-term EQ precursor search has proven useless seem to ignore the fact that, in actuality, neither truly scientific nor practically effective strives have ever been made for it. Instead, most of the dense elaborate monitoring systems have been only seismological and geodetic. To be fair, the extensive upgrades of seismic and geodetic networks have led to some very important discoveries such as deep low frequency tremors and slow slip at subduction zones (e.g., Obara et al., 2004), details of asperities at seismogenic faults (e.g., Yamanaka and Kikuchi, 2004), the characteristic earthquakes (e.g., Matsuzawa et al., 2002) to name a few. These discoveries are certainly of fundamental importance in understanding the EQ phenomena and contribute to the progress of prediction science. But, seismometers cannot detect useful non-seismic short-term precursors. This is a simple fact, which should be obvious to those who run the EQ prediction programs. However, they seem not to welcome the idea that the solution to their problems may come from somewhere else. "Since we cannot, nobody else can." In actuality, however, some serious strives for shortening the lead time of prediction using seismological data are continued as mentioned above. Evidently, we need to develop a much closer cross-disciplinary cooperation for the common cause.

An EQ is a sudden mechanical failure in the earth's crust, which, unlike a flawless piece of glass, has highly heterogeneous structures. It is reasonable to expect that its preparatory process has various facets which may be observed before the final catastrophe: namely geochemical, hydrological (e. g., Silver and Wakita, 1996; Koizumi et al., 1999), and electromagnetic changes. Therefore, the science of EQ prediction should, from the start, be multi-disciplinary. Someday, even phenomena such as the reported anomalous animal behaviors may receive closer scientific attention (e. g., Ikeya, 2004). Moreover, there have been a number of positive reports, during the last decades, on the electromagnetic phenomena in a wide frequency range from many parts of the world, including Greece, Japan, Russia, China, Taiwan, Armenia, Italy and Mexico (e. g., Yepez et al., 1995; Lighthill, 1996; Balassanian et al., 1997; Uyeda and Park, 2002; Hayakawa and Molchanov, 2003; Pulinets and Boyarchuk, 2005; Kamagowa, 2006; Uyeda et al. in press, and references therein). These aspects of research should be encouraged with more funding.

There were two major pitfalls in the post-Kobe EQ prediction research policy in Japan. One is that precursor search was thought to be too difficult before any serious short-term precursor search has been tried, although some effort to catch intermediate-term precursors was continued on personal level (e. g., Huang, 2006). Second is that the rising possibility of precursor finding by non-conventional methods was disregarded. The world EQ science community and funding agencies must be freed from the spell of this deceitful "impossibility" myth. In the following, a review is made on Seismo-electromagnetics as one of the most promising approaches to short-term prediction.

3. Seismo-electromagnetics

Some level of scientific research on seismo-electromagnetic phenomena in a wide frequency range was initiated more or less simultaneously in many countries in the 1980s and has since been persistently pursued. This relatively new branch of science is now called Seismo-Electromagnetics (Seismo-EM hereafter). If EM phenomena are observed shortly prior to EQs, they can uniquely serve as precursor signals. The extremely inter-disciplinary character is a distinct feature of Seismo-EM and the backgrounds of research fore-runners are diverse, including solid state, statistical, ionospheric and atmospheric physics, radio, space, and even biological sciences. This situation tends to make their accomplishments difficult to be comprehended by the conventional EQ community. Inter-disciplinary communication is not highly developed even within the Seismo-EM community itself. In view of the need to promote cross-disciplinary cooperation and to assist this new area of science in the developing world, IUGG established, in 2002, an IAGA/IASPEI/IAVCEI Inter-Association Working Group on Electromagnetic Studies of Earthquakes and Volcanoes (EMSEV: S. Uyeda: First Chair. Now chaired by Jacques Zlotnicki).

EQ related EM signals may be conveniently classified into the following two major groups, each covering wide frequency ranges: i) EM signals believed to be emitted from within the focal zones and ii) Anomalous transmission of EM waves over epicentral regions.

4. The emission type signals

4.1. Telluric current and magnetic field anomalies in DC-ULF (< a few Hz) band

Electric currents flowing in the surface layers of the earth's crust (telluric currents hereafter) are measured as electric potential difference between separately buried electrodes. These currents mainly consist of the currents induced by extra-terrestrial geomagnetic field variations (called magneto-telluric or MT current). MT currents carry information on the electrical structure of the deeper layers of the earth: higher (lower) frequency for shallower (deeper) structures. A part of the telluric currents can also be of man-made origin leaking from electric sources such as factories and trains. In addition to these, there may be telluric currents related to EQs. The VAN method (Varotsos and Kulhanek, 1993; Lighthill, 1996; Varotsos, 2005), named after initials of the founding Greek scientists, P. Varotsos, K. Alexopoulos, and K. Nomikos, has been monitoring the so-called Seismic Electric Signals (SES) at stations shown in Fig. 3 to conduct actual short-term predictions of $M \geq 5$ Greek EQs for well over a couple of decades. The VAN method has been successful in making predictions within the following error range: < a few weeks in time, <0.7 units in magnitude (M, hereafter), and <100 km in epicentral distance. The length of time window depends on the type of signals.

Among several types of signals, the most frequently used for EQ prediction are single SES and SES Activity. Single SES precedes single EQ, whereas SES Activity, which consists of a number of SES in a short-time (say in a few hours), is followed by a series of sizable EQs before the main shock. In addition, there are pulses of a few msec duration which appear shortly (some minutes) before EQs (Varotsos et al., 2007). Up to now, these pulses have not been used for prediction purpose because of their too short lead time (minutes).

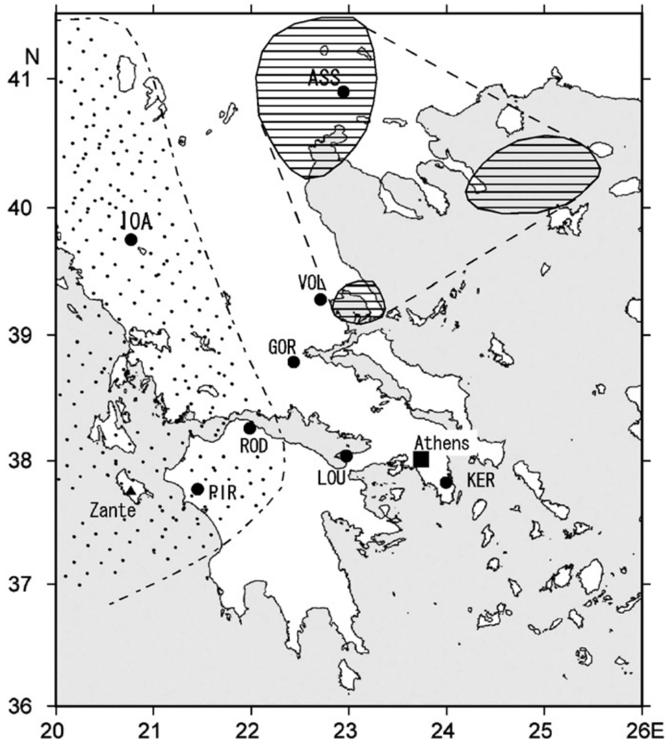

Fig. 3. Distribution of some VAN stations (solid circles) and "Selectivity map" of IOA and ASS stations as of 2005 (after Varotsos, 2005). For Zante (solid triangle), see text.

The VAN methodology is based on two major discoveries. One is the so-called "Selectivity" stating 1) There are sites sensitive to SES (sensitive sites), while most of randomly chosen sites were insensitive. 2) A sensitive site is sensitive only to SES from some specific focal area(s). A map identifying those focal area(s), SES from which are sensed by a site, is called "Selectivity map" of that site (Fig. 3). This map provides information on the epicentral location of the impending EQ. It has been proposed that the Selectivity originates from inhomogeneities in the subterranean electrical structures, i. e., SES are transmitted only through conductive channels (e. g., Varotsos and Lazaridou, 1991; Varotsos et al., 1998). This model can explain the long distance transmission of SES, which was shown to be difficult for a homogeneous or a simple layered earth (Bernard, 1992). So far, however, the real existence of such subterranean channels has not been convincingly verified by commonly used MT or other electric exploration techniques. The other discovery by the VAN research is the relationship among the epicentral distance, r, EQ magnitude, M and the observed intensity of SES. Once the epicentral location is estimated from the Selectivity map, M of the impending EQ can be assessed, since both intensity and epicentral distance r are known.

The VAN method, however, has been a target of a heated debate (e.g., Mulargia and Gasperini, 1992; Geller, 1996; Lighthill, 1996). As far as we have critically examined, VAN successes are convincing (e. g., Nagao et al., 1996; Uyeda et al., 1999; Kondo et al., 2002). Fig. 4 shows the score of VAN predictions for the period 1985–2003. The public impact of VAN's predictions has been large because lives have actually been saved at some disastrous earthquakes (Uyeda, 2000). In Greece, VAN type work has been conducted by other groups also (e. g., Nomikos and Vallianatos, 1997). In the present authors' view, VAN has well survived the test of time.

In Japan, both VAN type monitoring and ULF magnetic monitoring (see later) have been implemented during the last two decades (Uyeda et al., 2000). Despite the high level of artificial noise, in particular from DC driven electric trains, the existence of the VAN type SES and ULF signals has been confirmed as illustrated in Fig. 5. In the year 2000, a two-month long seismic swarm, with ~7000 $M \geq 3$ shocks and five $M \geq 6$ shocks, occurred in Izu Island region, Japan. For this swarm activity, significant pre-seismic electric disturbances were observed (Uyeda et al., 2002). From about 2 months before the swarm onset on June 26, 2000, innumerable clear unusual geo-electric potential changes started (Fig. 6).

Co-seismic electric signals have been observed for many EQs in Japan, Greece and Indonesia. In all cases, however, they started at the time of the arrival of the seismic waves, not at the origin time of the EQs (Takeuchi et al., 1997; Nagao et al., 2000; Mogi et al., 2000; Skordas et al., 2000).

Beginning late in the 1980s, pre-seismic ULF (lower than several Hz) magnetic signals were also reported. ULF signals have advantages over those at higher frequencies because of their large skin depth $\delta = \sqrt{2/\mu\sigma\omega}$, where μ and σ are magnetic permeability, and electric conductivity of the medium and ω is the angular frequency of the wave. For the earth crust, δ is of the order of some tens of kilometers for 1 Hz and hundreds of meters for 10 kHz. Early work in ULF magnetic changes includes the 1988 M6.9 Spitak (Kopytenko et al., 1993), 1989 M7.1 Loma Prieta (Fraser-Smith et al., 1990), 1993 M8.0 Guam (Hayakawa et al., 1996), , 1996 M7.1 Hetian EQ (Du et al., 2002) and 1997 M6.5 Kagoshima EQs (Hattori et al., 2002). In the case of the Loma Prieta EQ in 1989, the signals were recorded at a site at 7 km from the epicenter. The amplitude of the horizontal component started to show an anomalous enhancement about 2 weeks prior to and a sharp increase a few hours before the EQ. These changes were not of solar origins because they were not observed at other stations in the region. Moreover, such signals had never been observed at any other time during the whole period of observation of more than 15 years.

4.2. Higher frequency EM waves

In the VLF(3–30 kHz)–LF(30–300 kHz) range, Gokhberg et al. (1982) reported that emissions at 81 kHz increased 1 or 2 h before

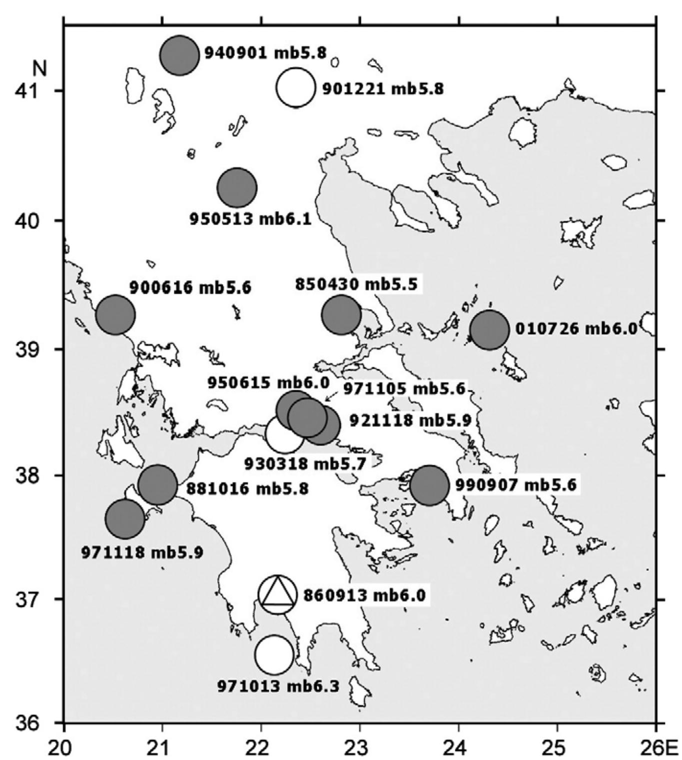

Fig. 4. Evaluation of VAN prediction. All the earthquakes with USGS PDE magnitude larger than 5.5 for 1985–2003 (Uyeda and Meguro, 2004). Shaded circles, white circle with triangle, and plain white circles represent "successfully" predicted, unsuccessfully predicted, and: missed events, respectively.

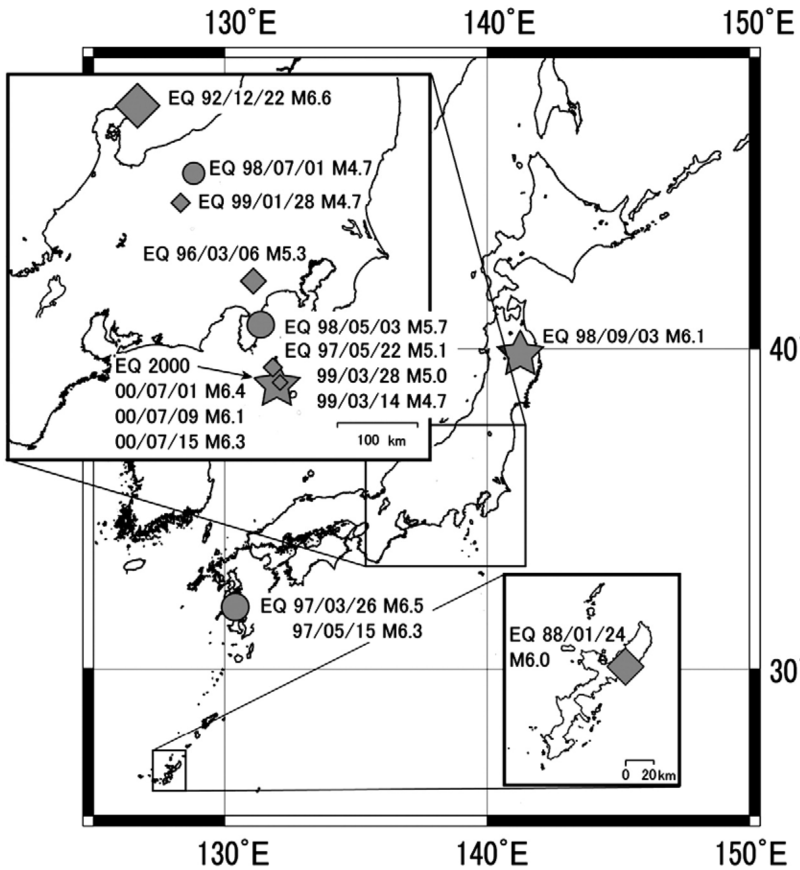

Fig. 5. Distribution of $M \geq 5$ EQs with observed pre-seismic signals in Japan. Diamonds and circles show EQs with observed pre-seismic electric signals and ULF magnetic signals, respectively. Stars show EQs with both electric and magnetic signatures. Arrow EQ 2000 in the bottom of the upper left inset map points to the Izu island region (after Uyeda and Meguro, 2004).

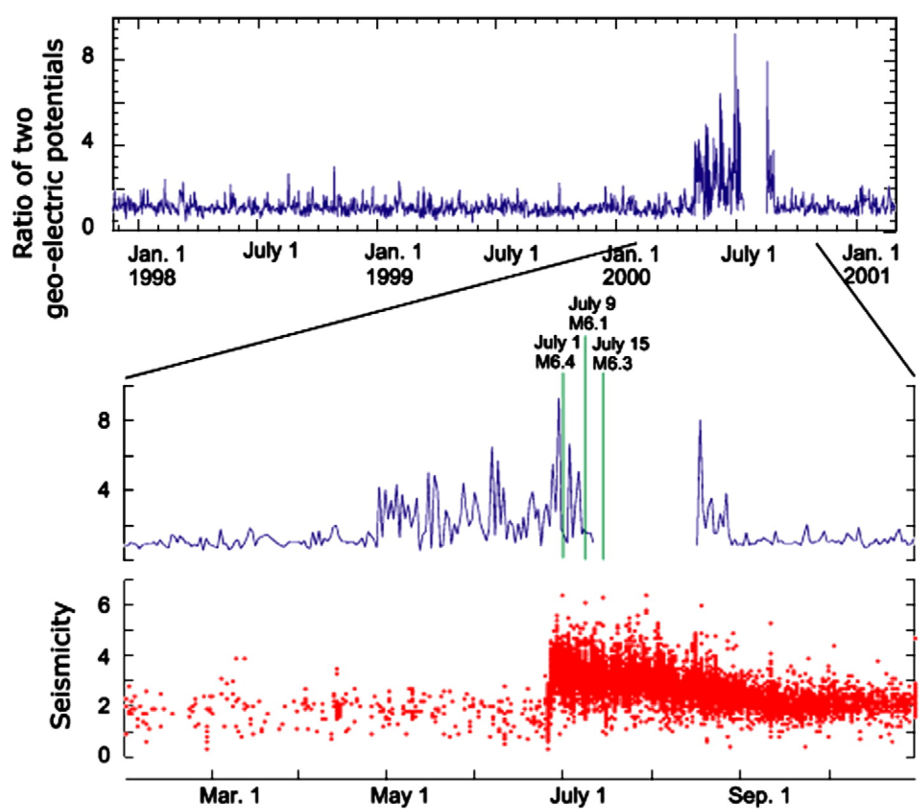

Fig. 6. Anomalous geo-electric potential changes prior to 2000 seismic swarm activity in the Izu island region, Japan. The bottom panel shows seismicity (modified from Uyeda et al., 2002).

*M*6.1 and *M*5.3 EQs in Japan and decreased back after the second shock. In early 1990s, Asada, a seismologist and ex-chair of the Coordinating Committee for Earthquake Prediction, Japan (acronym in Japanese is *Yochiren*), and his seismology group dared to embark on a Seismo-EM research by starting to monitor the wave forms of two horizontal magnetic components of incoming VLF pulses and determined their incoming directions goniometrically (Asada et al., 2001). They found that, before *M*4–5 class land-based EQs within 100 km of their stations, EM pulses with a fixed incoming direction appeared and the EQs actually occurred in that direction, whereas the directions of other VLF signals, overwhelmingly more numerous and stronger, were changing with time following the movements of lightning sources (Fig. 7).

For the higher frequency range covering MF (0.3–3 MHz), HF (3–30 MHz), VHF (30–300 MHz), and UHF (300–3000 MHz) bands, Enomoto et al. (2006) recorded anomalous pulsed geo-electric currents in the MF-band at Erimo station, Hokkaido, Japan, from February 2000 to March 2001 and from August to September 2003. The earlier anomalies occurred before and during the volcanic activity of Volcano Usu (200 km to the west), while the later one started 1 month before the 2003 September 26 *M*8.0 Tokachi-Oki EQ (80 km to the east). These were the only anomalies observed during their 10-year observation period.

For the Kobe EQ, while measuring sporadic Jovian decametric emissions with a radio interferometer at an observatory at about 80 km from the epicenter, unusual pulsed emissions at 22.2 MHz were detected tens of minutes before and after the main shock (Maeda and Tomisaka, 1996). Such unusual pulses were never observed at other times and the possible source was estimated to lie in the direction of the main surface exposure of the EQ fault. There was no clear co-seismic radiation.

Eftaxias et al. (2002) reported results obtained in Greece in a wide frequency range. Since 1994, they have been running a station on Zante Island in the Ionian Sea (see Fig. 3), where they measure ULF (<1 Hz), 3 and 10 kHz, and 41, 54, 135 MHz EM waves. They report that MHz–kHz EM anomalies have been detected during a few days to a few hours prior to shallow land-based EQ with $M>6$. No co-seismic anomaly was observed.

Even if high frequency EM signals are generated in a seismic focus region, they would be attenuated before reaching the earth's surface. Kamogawa and Ohtsuki (1999) proposed a plasmon model to explain how the higher frequency EM waves can appear in the air, i. e., longitudinal plasma waves excited by exo-electrons (see next section) emitted from the stressed region may propagate to ground surface and be transformed into EM waves by surface roughness. As mentioned earlier, transmission of EM waves in the conducting earth beyond the skin depth distance is an important unresolved problem.

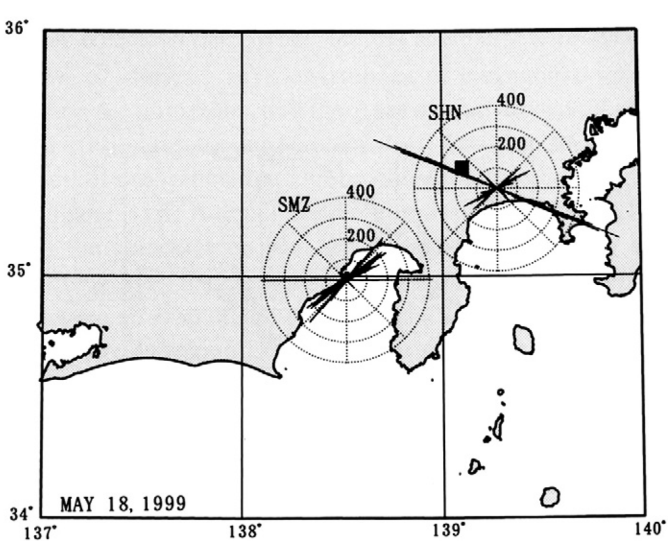

Fig. 7. Rose diagram of incoming VLF signals observed on May 18, 1999 at two sites. *M*4.1 EQ occurred at black square point on May 22 (Asada et al., 2001).

4.3. Generation mechanism of signal emission

Various possible mechanisms have been proposed for the generation of EM signals, including the electro-kinetic effect, effects related to defects in condensed matter, piezo-electric effects, and exo-electron emission.

Electro-kinetic effect, also called streaming potential, is a well established phenomenon. It is caused by the presence of the solid–liquid interface where a double layer of ions is formed. The double layer consists of ions (mostly cations) retained on the solid surface and ions of the opposite sign (anions) in the liquid phase loosely attached to the cation layer. Thus, the bulk liquid phase is in surplus of anions so that when the liquid flows due to a pressure gradient, an electric potential gradient is formed. It is expressed as grad $V=-(\varepsilon\zeta/\eta\sigma)$ grad P, where ε, σ and η are the dielectric constant, electric conductivity and viscosity of the fluid, whereas ζ is a constant called zeta potential. The electro-kinetic effect can be a plausible source for SES (DC) and ULF EM emission. Mizutani et al. (1976) proposed a model in which, during the dilatancy stage, water flows into the dilatant region, generating electric currents (and a magnetic field) by the electro-kinetic effect. Since then, many models have been proposed (e. g., Fitterman, 1978; Yoshida, 2001). Fedorov et al. (2001), however, suggested that the expected magnitude of seismo-EM signals in the DC-ULF range from electro-kinetic sources may reach detectability threshold only for an exceptionally favorable set of crustal parameters.

Pressure stimulated polarization currents (PSPC) proposed by Varotsos and Alexopoulos (1986) for SES (and magnetic field) are emitted from a solid containing electric dipoles upon a gradual increase of the pressure P (or stress σ). Aliovalent impurities in a crystal form point defects for electrical neutrality. Electric dipoles are formed between the impurities and the defects. Their directions usually distribute randomly. Under an electric field, they will align in its direction. The alignment is an activation process in which the time constant τ is supposed to depend not only on temperature but also on pressure or stress. Therefore, an avalanche of alignment would take place when the stresses approach a critical level. It has later been suggested that, instead of an electric field, inhomogeneous deformation mentioned in the next paragraph may align the dipoles in the direction of the stress gradient (Fischbach and Norwick, 1958). The PSPC model is unique among other models in that SES would be generated spontaneously during the gradual increase of stress without requiring any sudden change of stress such as micro-fracturing. This model is attractive but it has not been thoroughly verified by laboratory experiments, which admittedly are hard to perform because one would need to run an electrically well insulated stress machine for a long time with extremely slow stress rates until PSPC flows. However, proving that the effect exists would be extremely important for validating the VAN method.

In relation to SES generation, deformation-induced flow of charges is an interesting possibility (Norwick, 1996). Such a flow was observed as a result of inhomogeneous plastic deformation of ionic crystals, such as NaCl, in the direction of the stress gradient without applying an electric field. It was interpreted that charge carriers are charged dislocations.

Independent of these effects, Freund and his colleagues have recently been proposing a unique mechanism for ULF electric signals (Freund et al., 2006 and references therein). They have discovered in the laboratory that when a block of igneous rock is put under stress locally, the rock turns into a battery, which generates its own electric field. This striking phenomenon is interpreted as follows: A fraction of the oxygen anions in the rock-forming silicate minerals is not in their usual 2-valence state (O^{2-}) but in the 1-valence state (O^{1-}), which represent defect electrons, i. e., positive holes (p-holes). The O^{1-} ions are unstable and tend to form positive hole pairs (PHP), chemically equivalent to peroxy links, $O_3X/^{OO}\backslash XO_3$, which are electrically inactive. These dormant PHPs are awaken by deviatory stress, and make the insulating host material a p-type semi-conductor. The p-holes flow out of the stressed volume because of mutual electrostatic repulsion.

For the generation of EM signals, popular models resort to micro-cracking. They are, for instance, (1) Discharge of screening charge of piezo-electric polarization (e. g., Ikeya and Takaki, 1996; Yoshida et al., 1997). Piezo-electricity is the electric polarization produced in certain crystals and ceramics by the application of mechanical stress. Among rock-forming minerals, quartz is most strongly piezo-electric, but its effect is much reduced unless crystals are favorably oriented. Moreover, piezo-electric polarization in rocks is kept canceled by screening charges. At rapid stress drop by micro-cracking, bulk polarization may appear because the screening charge cannot disappear instantly and decays with a time constant $\tau = \varepsilon/\sigma$, where ε is dielectric constant and σ electric conductivity. But even this time constant seems too short to account for the observed non-impulsive signals. (2) Electrification of fresh crack surfaces (Yamada et al., 1989) and (3) Exo-electron (Enomoto and Hashimoto, 1990) are other examples calling for micro-cracking.

It may be worth noting that in all these models much stronger co-seismic signals would be expected unless some ad hoc mechanism is provided. Actually, however, all the routinely observed signals at EQs are "co-seismic wave" signals and not "true co-seismic". One suggested ad hoc way out of this difficulty may be that the sliding of fault for main shock is no longer signal producing because signal producing cracking has been completed by then. No appearance of true co-seismic signals remains to be one of the important unresolved problems as it makes general scientific community intuitively skeptic about the reality of EQ related EM signals.

5. Anomalous transmission of EM waves

5.1. Observations

Active research on the second class of pre-seismic phenomena, i. e., the anomalous transmission of EM waves, began in the late 1980s in Russia, Japan, and Italy (e. g., Gokhberg et al., 1989; Gufeld et al., 1992). Pre-seismic variations of terminator-times, i. e., the sunrise and sunset for VLF radio waves for navigation purpose (~10 kHz), were demonstrated for the 1995 Kobe EQ and other large EQs in Japan (Molchanov and Hayakawa, 1998). Clilverd et al. (1999), on the other hand, did not obtain similar positive results, at an Antarctica station, from the terminator-time data of VLF waves from northern United States. Maekawa et al. (2006) showed the existence of statistically significant correlation between pre-seismic sub-ionospheric LF anomalies and $M \geq 6$ EQs in Japan. Thus, this issue is still controversial (Rodger and Clilverd, 2007; Kamogawa, 2007).

As to the EM wave transmission anomaly in the higher frequency range, the pioneering work of Kushida and Kushida (2002), at the Yatsugatake South Base Observatory, Japan, may be worth noting. They were monitoring the transient reflections of VHF FM radio waves beyond the line-of-sight for the purpose of recording meteor entries into the upper atmosphere. They accidentally noted unusual signals from a distant FM station on the night before the 1995 Kobe EQ (Nagao et al., 2002). They interpreted that VHF FM radio waves traveling over the focal zone were anomalously scattered to reach their observatory. Since then, these authors have been conducting practical short-term prediction experiments (Kushida and Kushida, 2002). The performance of the Kushida method during 2000–2003 was evaluated for $M \geq 5.5$ EQ by checking their predictions against the actual seismicity (Uyeda and Kumamoto, 2004). Depending on the criteria for successful prediction, about 40% of their predictions were successful and about 30% of $M \geq 5.5$ EQ were predicted. The method apparently is still far from perfection and its physical basis is uncertain (Pilipenko et al., 2001). However, active cross-check experiments and improved monitoring are now underway by several independent groups [e.g., Sakai et al., 2001; Moriya et al., 2003; Fujiwara et al., 2004; Yonaiguchi et al., 2007].

5.2. Lithosphere–atmosphere–ionosphere coupling (LAI coupling)

For the anomalous EM wave transmissions to occur, some anomalies must be generated in the paths of the waves, i.e., the ionosphere or atmosphere over the epicentral region. If so, it should be verified independently by ionospheric observations. Liu et al. (2000) found in Taiwan that the critical frequency, foF2, as measured by an ionosonde, corresponding to the electron density of ionospheric F2 layer, significantly decreased during afternoons before $M \geq 6$ EQs, including 1999 *M*7.7 Chi-Chi EQ. EQ related electron density depression occurring above Taiwan Island was observed also by using GPS total electron density maps (TEC) (Liu et al., 2001). From such observations, Liu et al. (2006) demonstrated that the appearance of the anomalies within 5 days was statistically significant at a 5% level for the $M \geq 5.4$ EQs occurring within 150 km.

How pre-seismic processes in the earth's crust can possibly affect the atmosphere and ionosphere tens to hundreds of kilometers above the surface is a hot topic called the "Lithosphere–Atmosphere-Coupling (LAI coupling)" (Hayakawa and Molchanov, 2003; Pulinets and Boyarchuk, 2005; Kamagowa, 2006). One model assumes that an anomalous atmospheric electric field is generated at or near the ground surface during the pre-seismic period, which causes the ionospheric anomalies. Pulinets (2007) proposed that such an atmospheric electric field is caused by radon emission (e. g., Yasuoka et al., 2006). However, such an electric field on the ground has not been observed even during when pre-seismic ionospheric anomalies were observed (Kamogawa et al., 2004). Some researchers proposed that atmospheric gravity waves (AGW) propagate into the ionosphere, and disturb it before EQs (Molchanov and Hayakawa, 1998; Pilipenko et al., 2001). The proposed source of AGW are long-period ground oscillations or the appearance of thermal anomalies on the ground. Possibility of the former was inferred from some observations that co-seismic ground vibration actually excited AGW which propagated into ionosphere (e.g. Ducic et al., 2003). However, there is no report of long-period ground oscillations at the pre-seismic stage. Pre-seismic temperature rise, "thermal anomalies", reaching 2–4 °C or higher in a wide area around impending EQs, has been claimed as detected by satellite observation of enhanced infrared (IR) emission from the ground (e. g., Tramutoli et al., 2001; Dey and Singh, 2003). Many models have been put forward to explain the origin of the "thermal anomalies", including latent heat release at condensing water vapor due to enhanced radon emission. Pulinets (2007) develops a scenario how the "thermal anomalies" give rise to ionospheric anomalies. Freund et al. (2007) cast another interpretation on the enhanced IR emission based on their p-hole model mentioned above.

Thus, the research interest is now shared by a number of disciplines including space science. A micro-satellite dedicated to the investigation of the ionospheric perturbations, DEMETER (Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions) was launched in 2004 by CNES (French National Space Agency) (Parrot, 2007) and some significant pre-seismic decrease of intensity of VLF EM waves has already been reported (Nemec et al., 2008). Many other Seismo-EM satellite projects are actively discussed in various countries (e. g. , Pulinets and Boyarchuk, 2005).

6. Concluding remarks

Reinforcement of buildings is the highest priority in the fight against loss of human life due to seismic activity. At the same time, EQ science must make utmost efforts towards short-term EQ prediction to further reduce casualties. Disaster prevention measures and short-term prediction research are complementary activities. However, at the present stage, the general view on short-term prediction is overly pessimistic. There are reasons for this pessimism because mere conventional seismological approach is not efficient for this aim. Overturning this situation is possible only through multi-disciplinary science.

Despite fairly abundant circumstantial evidence, pre-seismic EM signals have not yet been adequately accepted as real physical quantities. Putting aside the common indifference and prejudice against new science, it seems appropriate at this stage to admit that there may be some legitimate reasons for the critical views. In fact, many of the problems of fundamental importance in Seismo-EM are unresolved. Real mechanisms of generation of pre-seismic signals and the non-appearance of co-seismic signals in varied frequency ranges, the propagation of high frequency EM signals in the conductive earth, and the origin of the LAI coupling are the typical unresolved important issues.

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